Outer Continental Shelf Environmental Assessment Program

Beaufort Sea (Sale 71) Synthesis Report

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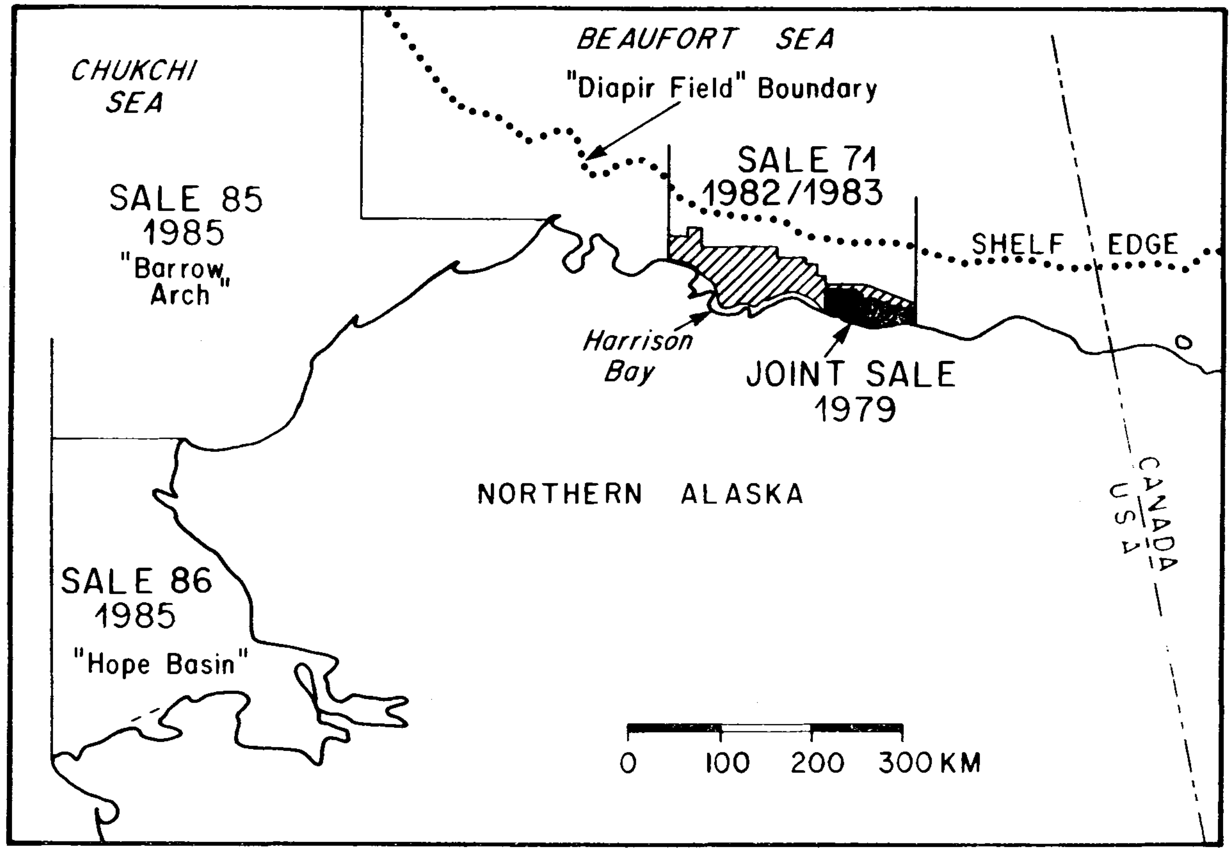

FRONTISPIECE

The location of the Sale 71 area on the Alaskan Arctic coast.

NOTICES

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PREFACE

The Alaskan Beaufort Sea is an unforgiving OCS frontier region, where continued exploration, discovery, and extraction of petroleum seem nevertheless to be highly probable events. The Department of the Interior's Proposed Sale 71 is the second major lease sale in a series of Beaufort Sea sales, and it is scheduled to follow that of the December 1979--Joint State/Federal Lease Sale by either 38 or 34 months. Although it might appear that because their acreages adjoin (see Frontispiece), Sale 71 will face the same environmental problems as did the Joint Sale, this is not the case, because both environmental and management conditions differ markedly between the two lease sales. Sale 71 is scheduled to offer more acreage and to offer tracts farther offshore, with more dynamic and severe sea ice conditions. It will involve a large region unprotected by offshore natural barrier islands, and would comprise an area of marine ecosystems influenced by freshwater influx from the largest river on the Alaskan North Slope.

As the Joint Sale followed a concerted field program by OCSEAP that began in 1975, up to five years' intensive investigations in the central portion of the U.S. Beaufort had been made by the time of the sale. There were also three OCSEAP synthesis meetings and reports devoted to the Joint Sale: Weller et al., 1977, Arctic Project Bulletin #15; Weller et al., 1978, Interim Synthesis Report: Beaufort/Chukchi; and Weller et al., 1979, Arctic Project Bulletin #25. The first two were comprehensive reports on the full range of disciplinary and interdisciplinary understanding of the environments and environmental hazards in the nearshore Beaufort Sea. The third was an analysis of 13 scientific issues relating to proposed stipulations and regulations governing the Joint Sale. Virtually every one of the recommendations made by the OCSEAP scientific community was adopted in stipulatory or regulatory provisions by the State or the Federal lease sale managers.

Part of the reason for the strong influence of the scientists on the Joint Sale was their having had a reasonable period to investigate the environments in and around the rather modest acreage of the Joint Sale. The State had first proposed to lease submerged lands in the Beaufort between 1975 and 1977, to prop up a sagging revenue forecast. In 1975, the first proposed five-year lease plan of the Department of the Interior under the accelerated leasing program known as Project Independence called for a Federal Beaufort sale in October 1977. When the sale date was rescheduled for December 1979, OCSEAP thereby had 26 extra months to conduct pre-sale environmental assessments.

Such fortuitous timing does not apply to Lease Sale 71. Compared to the 1979 Joint Sale, the Sale 71 schedule has required the scientific community to address four times the area in one-fourth the time with one-tenth the funding. Whether the sale is held in February 1983, as per the March 1980 federal proposed schedule plans, or is held in October 1982, under the current (1981) proposed acceleration of leasing, only a single 30-day field program has been conducted for all of the western Sale 71 region, in Harrison Bay. Even this brief field program in 1980 would not have taken place without provision of $1 million of extra FY 80 funding by the BLM shortly after the announced inclusion of Sale 71 in the five-year schedule in mid-fiscal year.

If there had not been three previous synthesis meetings and reports devoted to the Beaufort Sea, or if the principal contributors to those proceedings had not been funded (hence still available) through 1981, the present synthesis would not have been possible, or at least it would have been of dubious quality.

The Beaufort Sea Sale 71 Synthesis Report that follows represents our attempt to condense into one document the general synthesis of understanding, scenarios for development of the area, and a scientific issues analysis document that were three separate exercises for the previous Joint Sale synthesis process.

During the preparation of this report, there has been some uncertainty about the geographic scope of the material to be included, which we hope has been clarified. Some authors have chosen to restrict their contributions and discussions to Harrison Bay itself, because it makes up the main area and geographic focus of the western part of Sale 71. Nevertheless, the Federal sale does extend east as far as the easternmost offshore tracts of the Joint Sale, off Flaxman Island, which are being reoffered (Fig. P.1). Sale 71 will also be the first offering of tracts directly offshore of the Simpson Lagoon-Jones Islands system which OCSEAP has studied intensively and reported on elsewhere, NOAA/OCSEAP Final Reports, Biological Studies, Volumes 7 and 8, 1981. For reasons of economy of space, we have dealt with as much of the eastern Sale 71 area as possible by referring to already published materials.

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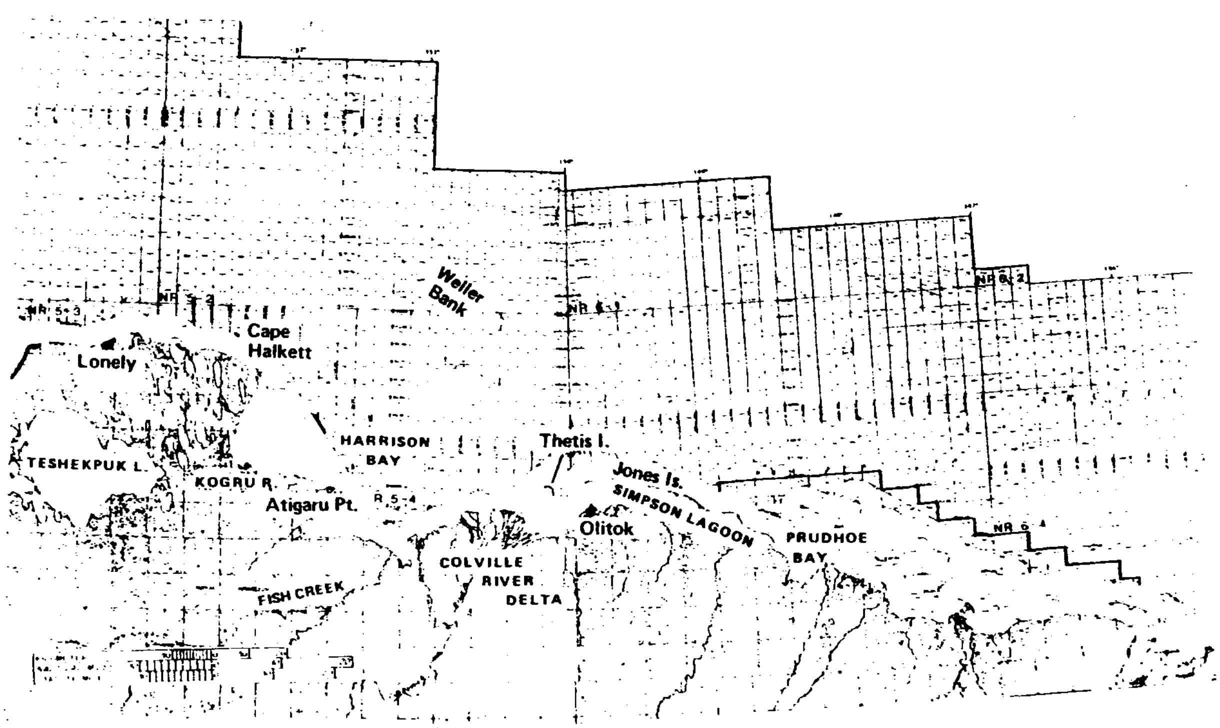
Synthesis Volume Editors



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SECTION I. CHARACTERIZATION OF SALE 71 ENVIRONMENTS

Chapter 1. Ecological Characterization of the Sale 71 Environment

S. R. Johnson, Editor

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1.1 PRIMARY PRODUCTION, ZOOPLANKTON, AND TROPHIC DYNAMICS OF THE HARRISON BAY AND SALE 71 AREA

By D. M. Schell and R. A. Horner

Introduction

This summary represents a distillation of data from the literature and information acquired by RU's 537 and 359 pertaining to the Sale 71 area and adjacent areas. Due to the similarities in hydrographic and physical conditions, extrapolation from nearby areas to the Sale 71 area is probably reasonable to a large extent. The sizable input of fresh water from the Colville River constitutes the major difference in comparison with other areas which have been studied such as Stefansson Sound. The information below is presented in three parts: primary production, authored by RU's 359 (Horner) and 537 (Schell); trophic energetics by RU 537; and zooplankton studies by RU 359.

Primary Production

Primary production studies by RU 359 (Horner) have included samples collected in Stefansson Sound (Boulder Patch) off Narwhal Island (Fig. 1.1.1) in November, February, March, April, May, and June over a two-year period. Sampling was not done in all months during both years. Data included water samples analyzed for plant pigments, ^{14}C uptake, and phytoplankton standing stock; ice cores analyzed for plant pigments, ^{14}C uptake, and ice algae standing stock; sediment cores analyzed for plant pigments, ^{14}C uptake, and benthic microalgal standing stock; and zooplankton net tows analyzed for species presence and abundance. (Not all kinds of samples were collected in all months.) Intensive studies of ice algae, phytoplankton, benthic microalgae, and zooplankton were done in April, May, and June. Conditions in other seasons have been extrapolated from work done at Barrow (Horner and Alexander, 1972; Clasby et al., 1973; Alexander, 1974).

Research by RU 537 consists of standing stock estimates of ice algae based upon chlorophyll a concentrations in ice cores collected along the coastline including the Sale 71 area. During August 1980, ^{14}C-uptake primary production was measured on a transect of Harrison Bay. These data were used to extrapolate seasonal production in conjunction with previous measurements by Alexander (1975). In addition, ice algae and zooplankton were sampled at two stations (north of Narwhal Island and DS-11, Stefansson Sound) on 9 November 1980 in cooperation with the National Institute of Polar Research of Japan.

Research Unit 537 has been investigating the nutrient chemistry and trophic system energetics and detrital food webs of nearshore marine and freshwater systems in the Simpson Lagoon and Harrison Bay - Lease Sale 71 area during the open water and winter periods since 1977. Details of field sampling periods and field and lab analysis techniques are given in Schell (1978, 1979, 1980 and in prep).

The annual cycle (Fig. 1.1.2) begins in the fall as the ice forms. Pennate diatoms and microflagellates present in the water column in low

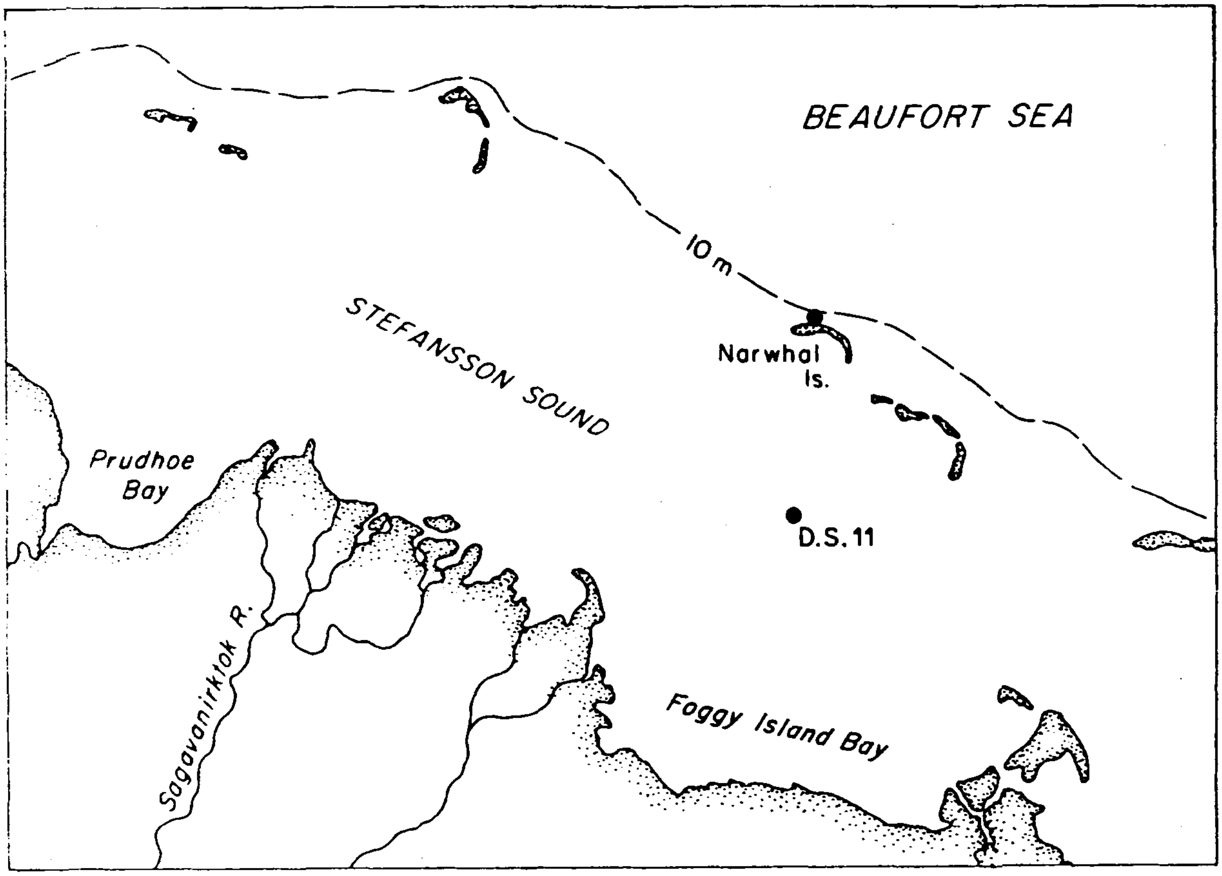


Figure 1.1.1. Location of study sites in Stefansson Sound (1978-1979) and off Narwhal Island (spring 1980) (Horner and Schrader, in press).

numbers are incorporated into the ice. The microflagellates are probably not photosynthetic. The diatoms remain viable during the dark winter months, although if conditions allow, a modest ice algae bloom can occur in the fall. Cores obtained off Narwhal Island in November 1980 contained approximately 5 mg chl a/m^2 in the bottom 10 cm, with a maximum concentration in the interface layer of 88 mg chl a/m^3. No ice algae bloom occurred in Stefansson Sound samples due to sediment entrainment, which rendered the ice virtually opaque. The cell densities and species of this fall bloom were similar to those found in the same area in spring 1980. It is not known if the fall bloom is a regular occurrence in the Beaufort Sea, although it has not been reported previously in fall studies near the Eskimo Lakes, Canada (Hsiao, 1980). Few cells are present in the water column in winter; the benthic microalgae have not been studied in winter, although some cells are probably present. Copepods are numerically the most important components of the zooplankton community, with all copepodid stages and adults present. A few mysids, amphipods, hydrozoans, and chaetognaths were also present.

By March, light returns with the lengthening days. Cells in the ice begin to photosynthesize and divide in response to a minimum threshold of

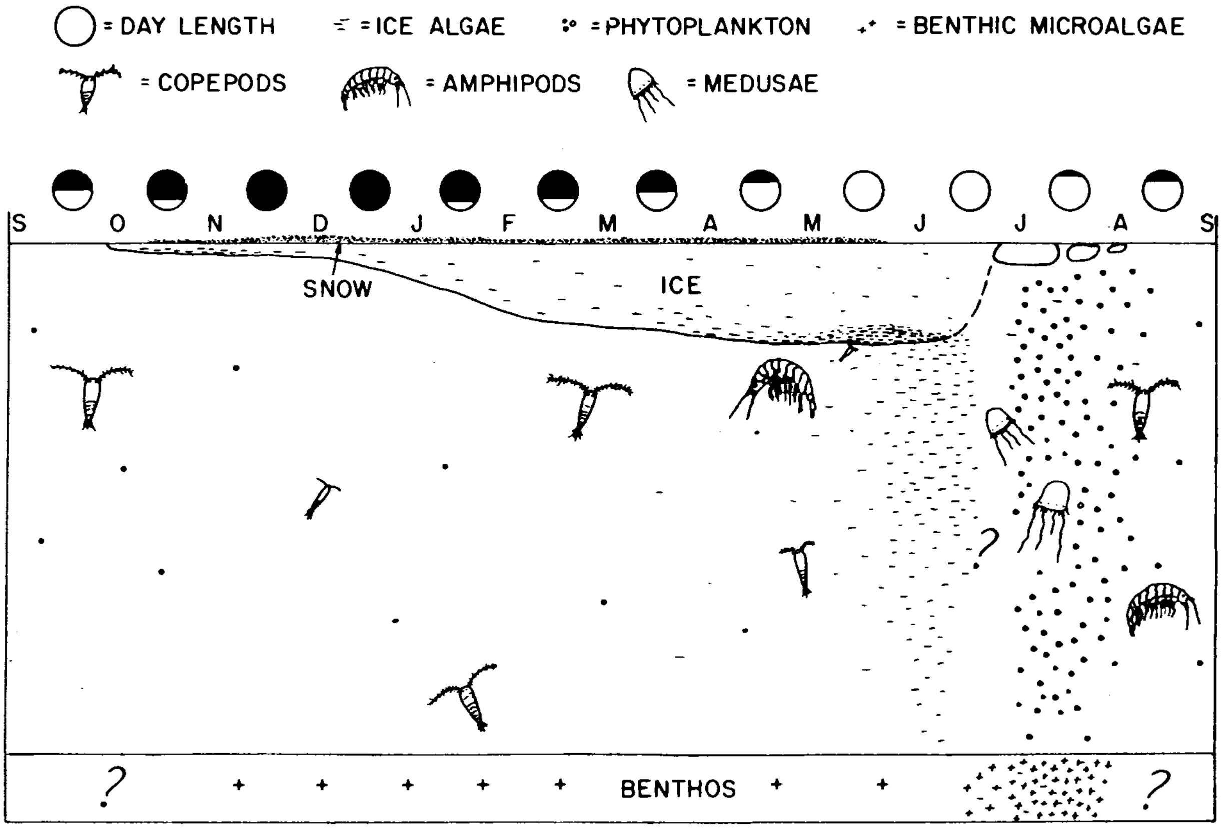


Figure 1.1.2. Schematic representation of the annual cycles of ice algae, phytoplankton, benthic microalgae, and zooplankton in the nearshore area of the Beaufort Sea and Stefansson Sound (Horner, RU 359).

light. Brine drains, and cells in the brine pockets are carried downward through the ice. A yellow-brown layer of ice algae, mostly pennate diatoms, is present on the underside of the ice by early April. Few cells are present in the water column, and chl a levels are low. Chl a levels in the sediments are relatively high.

Maximum ^{14}C uptake and chl a levels in the ice occur in late May. Primary production in the water column and sediments remains low because the ice algae and entrained sediment in nearshore ice effectively block the light reaching these habitats.

By early June, the soft bottom layer of ice containing diatoms is loosely associated with the ice and is rapidly eroded by water currents beneath the ice. The ice algae probably accelerate this process by selective absorption of radiation. The ice algae are gone from the ice by mid-June, but their fate is not known. Divers reported seeing clouds of cells in the water column at this time, but few cells were present in water samples collected with a Niskin bottle. Cells that were collected were unhealthy, with shrunken chloroplasts that were not golden brown. Cells may be so rapidly dispersed in the water column that they are not caught in sampling bottles, they may die and be rapidly dissolved, or they may settle to the bottom. However, ice diatom cells were not found in sediment samples collected at the same time as the ice algae and water column samples. This was also true at Barrow (Matheke and Horner, 1974).

The spring phytoplankton bloom probably occurs in June, but because of the difficulty of sampling in June efforts to document this bloom have not been fruitful to date. Sampling transects out to 56 km north of Prudhoe Bay in mid-June 1980 (RU 537) failed to detect water with high chlorophyll concentrations, although nitrogenous nutrient concentrations were less than 20 percent of April concentrations in the same area. This indicates that uptake may have occurred in the previous weeks, and the cells may have descended to below the maximum depth sampled (15 m).

In summer (late July and August), two phytoplankton communities may be present in the nearshore area in Stefansson Sound, with flagellates dominating in surface water where carbon uptake is low and centric diatoms dominating in deeper water where higher primary productivity occurs (Horner et al., 1974). No data are available on production of the benthic microalgae in the Sale 71 lease area in summer. Furthermore, no data are available for the Sale 71 lease area for early fall before freeze-up.

The importance of the ice algal community is that it is the only source of primary production in the early spring and is thus the only available source of food for those animals that can utilize it. Animals in the ice include nematodes, turbellarians, ciliates, and copepods; amphipods have been reported clinging to the underside of the ice and are known to feed on the ice diatoms. Arctic cod are also associated with the underside of the ice and are probably feeding on the amphipods but they may also scrape off the ice algae.

Alexander (1974) has discussed the summer phytoplankton in Simpson Lagoon and Harrison Bay. On transects from Oliktok Point to Thetis and Spy Islands, chlorophyll values were higher in deeper water than in surface water, with highest levels close to shore. Highest productivity was in deeper water in Simpson Lagoon and just outside Pingok Island, but on a transect from Oliktok Point to Thetis Island, highest productivity was at the surface, while the chlorophyll maximum was below the surface. Highest production was in early August. Many of the cells were small, and species composition varied with season and depth.

The close agreement between primary productivity measurements made by RU 537 and those by Alexander (1974) has permitted a seasonal estimate of carbon fixation by primary producers in the Sale 71 area. Assumptions included:

1) Ice algae production = 2 $gC/m^2/yr$ over 50 percent of Sale 71 area (based on standing crops and observed sediment-laden ice);

2) effective euphotic zone = 10 m in open water (based on average depth measurements to one percent of surface light);

3) mid-depth production rates were used over contour intervals less than 10 m;

4) annual effective illumination for phytoplankton above 10 m depth is 1,200 hrs (20 July - 30 September);

5) primary production in the Sale 71 area is negligible during the period between breakup and 20 July due to high suspended sediment loads in Colville River floodwaters, fresh surface waters and/or ice cover.

Total ice algae production is estimated to be approximately 9.2×10^6 kgC/ year, and total phytoplankton fixation equals about 1.8×10^8 kgC/ year for the Sale 71 area. The values per unit area 10-20 gC/m^2, are similar to those from other areas of the Beaufort Sea, reflecting the similar climatological and nutrient regimes.

Figure 1.1.3 shows the biological energy sources to the Sale 71 region resulting from river runoff, erosion, and primary production. Also shown is the allocation for carbon input to the entire Alaskan Beaufort Sea coastline out to the 10 m contour. Since the western Sale 71 region includes much deeper water, the primary production data are not directly comparable to the total coastal input diagram but serve as an estimate for the western sale area. In the Harrison Bay area proper, the contribution of the Colville River overwhelms that of primary production, with allochthonous (originating from outside the system) carbon constituting approximately 75 percent of the total.

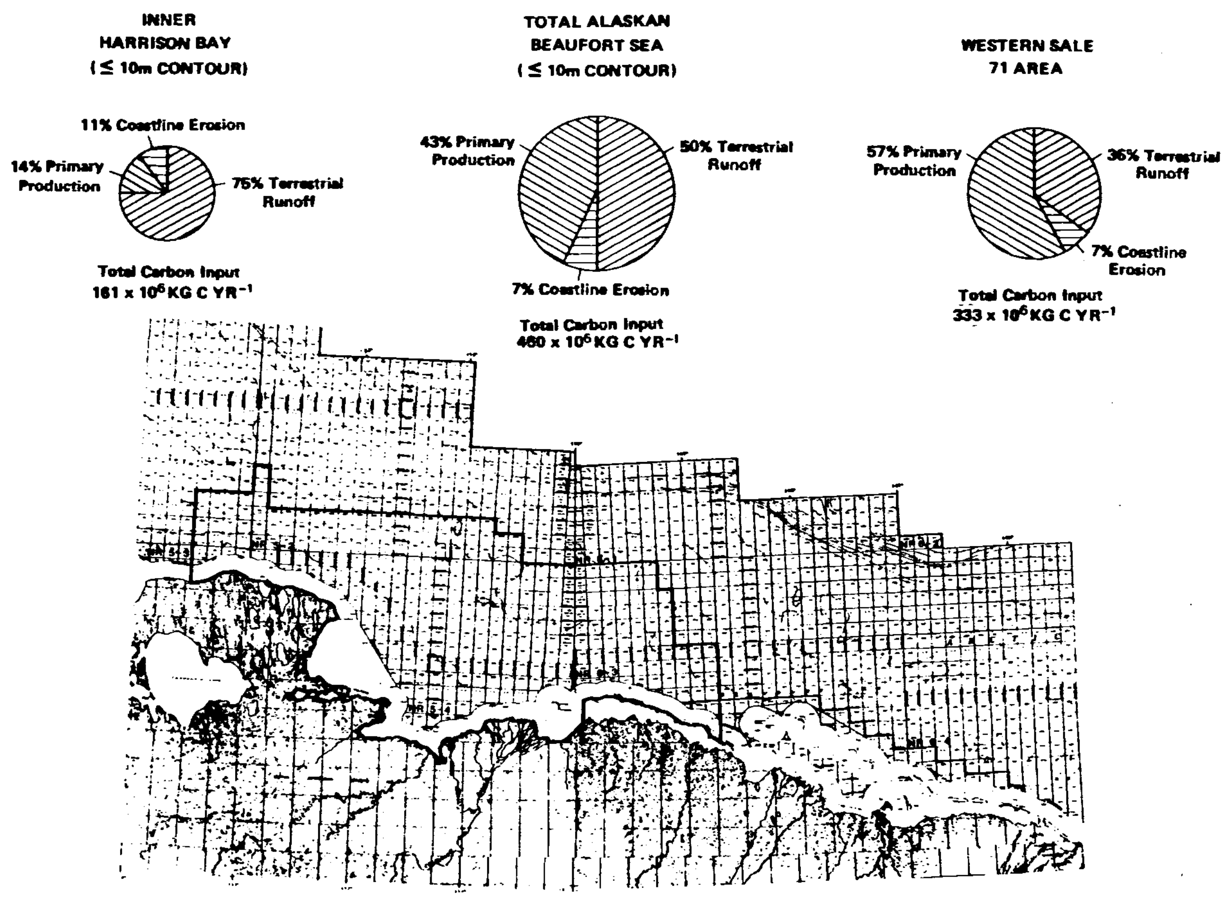


Figure 1.1.3. Examples of Carbon Input Budgets, Beaufort Sea.

Nutrient Chemistry

The Sale 71 area is strongly influenced by the runoff of the Colville River, the largest of the drainages on Alaska's North Slope.

Unlike rivers of temperate latitudes, the Colville River flows only during the summer and fall. By early December, the flow from tributaries has virtually ceased, and the ice freezes to the bottom at the shallow bars, sealing off downstream flow. In the delta, where the river channel bottom is below sea level for 60 km or so inland, seawater exchanges with freshwater upstream as far as the mouth of the Itkillik River tributary. No fresh water is present anywhere in the delta channels beneath the ice by spring, indicating that freshwater flow downstream in winter is negligible or nonexistent. The salt water is oxygenated throughout the winter, but microbiological nitrification and respiration processes reduce initial concentrations of dissolved oxygen by half over the course of the winter.

By late May, surficial meltwater begins to pond on the ice, and flow commences in the headwaters. The arrival of meltwater at the delta is usually sudden and dramatic; the entire saltwater content of the delta can be flushed out in 2-3 days (Walker, 1974). Flooding of the delta can be extensive as overflow water floods downstream on top of the bottomfast ice and onto Harrison Bay, where typically 500-700 km^2 are covered by sediment-laden water. Most of the meltwater which enters Harrison Bay on top of the ice rapidly drains through the ice via numerous cracks and holes. Typically, overflow water rarely extends more than 7 km seaward of the delta, whereas the freshwater wedge rapidly expands to extend finally over 35-40 km seaward. The most notable feature of break-up is that over 50 percent of the annual flow of about 12×10^9 m^3 is discharged in breakup and postbreakup flood in early June (Walker, 1973). Over 70 percent of the annual discharge of suspended load is also discharged during this period (Arnborg et al., 1967). Sediment carried by the water is left deposited on the ice, and the lowered albedo contributes to rapid melting of the sea ice. By early July, ice in the Harrison Bay region has melted completely, and by mid-July the Bay is usually ice-free in the shallower areas. In the northwestern area, grounded ice-ridge remnants persist until late summer.

The river-water influx to Harrison Bay rapidly declines following the spring melt. By late June, when river levels return to normal, large quantities of inorganic and organic matter have been transported into Harrison Bay. The peak concentrations coincide with peak flow; about 6×10^6 t (metric tons) of mineral sediment (Arnborg et al., 1967), 9×10^4 t of particulate organic matter reach the marine environment. Carbon isotope studies on the particulate organic matter transported reveal a progressive depletion in ^{14}C content as breakup progresses, indicating that the initial stages of runoff carry large quantities of leaf litter and twigs from the tundra surface. As the snow disappears and river levels fall, the composition of the river-borne organic matter shifts to that typical of peat derived from eroding riverbanks. Over the course of the hydrologic year, an estimated 120×10^6 kg particulate carbon, accompanied by 18×10^6 kg organic nitrogen, enters Harrison Bay. The inorganic nutrient concentrations represent a considerably smaller quantity, estimated at

4 x 10^3 kg nitrogen, principally as nitrate, and a much smaller quantity of phosphorus. Inorganic phosphate concentrations were often below limits of detection in river water samples (< 0.02 micromolar), and the total influx was not estimated. The Colville River is therefore a major source of both carbon and nitrogen to the marine environment in Harrison Bay.

The Harrison Bay region in summer represents an area where large quantities of organic nitrogen are entering a strongly nitrogen-limited environment. The atom ratio of nitrogen to phosphorus offshore in deep water is very low, ranging between 5 and 10, in contrast to biologically preferred uptake ratios of about 16. Thus the addition of organic nitrogen represents a potential benefit once mineralization occurs, as most phytoplankton cannot use organic nitrogen directly (Schell, 1975). Heterotrophic production followed by mineralization of organic nitrogen to ammonia and nitrate is the principal pathway of nitrogen transfer. Schell (1974) reported 0.05 µg N/ℓ-hr combined ammonification and nitrification rates during the winter in Colville Delta channels and in eastern Harrison Bay. Alexander (1974) reported August ammonification rates of 0-0.3 µg N/ℓ-hr for Simpson Lagoon and 0.012-0.019 µg N/ℓ-hr for coastal Beaufort Sea waters. The addition of amino acids to samples greatly increased mineralization rates, indicating that the limiting step is probably the microbial degradation of the polymeric structure of the peat detritus. Where a large quantity of organic matter is present, nutrient regeneration rates are higher--estimated at 0.13 µg N/ℓ-hr in the overall water column in the Colville Delta during winter. Actively feeding invertebrate and fish populations overwintering in the Delta also undoubtedly contribute to nutrient regeneration rates.

Phosphate is extremely depleted in the Colville runoff waters, and the sole source of dissolved inorganic phosphorus can be assumed to be advected to offshore waters. Some phosphorus (2 x 10^5 kg P/yr) occurs through the river influx of particulate organic phosphorus. No data are available on the rate of release to the water column or loss to sediments of this fraction.

Nutrient concentrations in under-ice waters of Harrison Bay during March are at the annual maximum. Nitrogen concentrations are typically between 4 and 7 µg-atoms nitrate-N/ℓ, and 1 and 3 µg-atoms ammonia-N/ℓ. Phosphate-P is highest in offshore waters, ranging between 0.6 and 1.5 µg-atoms/ℓ. The saline waters of the Colville Delta channels contain considerably higher concentrations of inorganic nitrogen during winter (10-20 µg-atoms/ℓ).

Uptake by ice algae and phytoplankton removes almost all of the available nitrate and ammonia from the water column as summer commences. Ambient concentrations during summer soon reach a dynamic equilibrium between uptake by plants and regeneration by grazing and bacterial mineralization of organic N. Typically, total inorganic nitrogen concentrations are less than 1.0 µg-atom/ℓ and phosphate concentrations range from undetectable to 0.5 µg-atom/ℓ.

Trophic Energetics and Detrital Foodwebs

Organic carbon from the Colville River and carbon from shoreline erosion are the principal sources of energy to Harrison Bay. Figure 1.1.3 shows the relative inputs and current best estimates of their magnitude. This large contribution of allochthonous carbon is utilized by micro-organisms; the secondary production is transferred up the food web to comprise a fraction of the carbon in organisms sampled from Harrison Bay.

The ^{14}C depression in peat, due to its chronological age, is passed up food chains in proportion to the dependency of the organism on peat as the ultimate source of carbon.

The relative abundance of ^{13}C distinguishes the marine food webs from terrestrial ones, and the ^{14}C content reflects whether the organism is dependent upon modern primary production or is dependent upon peat as an energy source.

Although some overlap and variation in isotopic signature is due to biochemical fractionation in carbon transfer in food webs, isotopic information allows considerable insight into food web dependencies. Anadromous fish entering marine waters attain an isotopic composition typical of marine fish by late summer. Upon entering the freshwater system, however, the fish diets shift drastically and by spring, the anadromous fish sampled (least cisco, broad whitefish) contained almost completely freshwater carbon, derived primarily from peat, as indicated by a large depression in ^{14}C content. It is thus evident that:

1) overwintering anadromous fish in the Colville River feed actively and turn over their entire body carbon during winter. They do not overwinter solely on fat reserves acquired during summer marine feeding;

2) overwintering fish are heavily dependent upon peat as an energy source, probably via insect larvae as chief consumers. By June, least cisco and broad whitefish are composed of 60-65 percent peat carbon.

The authors suspect (but carbon do not have supportive data other than the relatively high November peat carbon content in two amphipod samples) that Harrison Bay organisms are heavily dependent upon peat during winter months. The high terrestrial carbon inputs relative to marine carbon fixation would make this thesis probable, and the observed freshwater seasonal variations provide a ready example. ^{14}C content in Arctic grayling from the Colville River oscillates during the annual cycle. Since no marine carbon is consumed by this species, the observed oscillation represents seasonal variation in the contribution of peat to their diet via detrital food webs. Peat carbon content in these fish is at a minimum of about 25 percent in late summer but increases to nearly 50 percent by the end of the ice cover season (June).

Potential Effects of OCS Development

An oil spill that occured under the ice could destroy the ice algal community. The phytoplankton bloom in the water column and the benthic microalgae could also be damaged either by the reduction of light caused by the oil remaining at the ice-water interface, or by direct toxic effects if cells were to come into contact with the oil.

Recovery rates for these communities are not known, although in more temperate areas, the effects of oil pollution on phytoplankton are believed to be slight because of rapid regeneration and high recruitment rates. However, regeneration rates are not known for most arctic species, and they could be slow.

Of special concern is the scavenging or absorption of oil, heavy metals, and other pollutants by particulate organics and subsequent deposition in bottom sediments. This could lead to burial and prolonged storage of these pollutants until storms or ice gouging resuspend them.

Like phytoplankton, zooplankton populations may suffer only short-term impacts in temperate areas but the effects of oil pollution on zooplankton in arctic areas are unknown. It is not known what the effects on higher trophic levels might be if their food supply were suddenly depleted or polluted. Fish, birds, and mammals would have to travel farther to obtain suitable food, which could place additional stress on these animals.

Data Gaps

A. Aside from some data from the Canadian Arctic (Adams, 1975; Hsiao, 1978; Hsiao, et al., 1978; Percy, 1977; Percy and Mullin, 1975), virtually no information is available on the effects of oil, drilling muds, and other pollutants on primary and secondary producers. Data on the growth rates of primary producers and zooplankton are needed so that recovery rates can be predicted in the event of a serious spill.

B. The events occuring during and just after breakup are little known. How productive is the spring bloom? What species are present? What effect does the phytoplankton bloom have on the zooplankton population? What zooplankton species are present? Entrained sediment in Harrison Bay probably controls ice algae production through light limitation. How extensive is sediment-laden ice in this area?

C. Other major questions include:

   1. Is there a regular bloom of ice algae in the fall? How productive is the fall bloom? Do these cells remain in the ice and become the seed stock for the spring ice algal bloom? Do layers of diatoms occur in the ice in the Beaufort Sea in spring? (This phenomenon has been reported from the Bering Sea [J. Burns and C. Ray, pers. comm.].) How do the layers form?

   2. How important are the benthic microalgae in the lease area? Are large mats of benthic diatoms formed in summer? If so, how frequently and over how large an area? Are they utilized as food by invertebrates?

3. How important are the ciliates, nematodes, turbellarians, copepods, and other invertebrates that are found in the ice?

4. What are the reproductive rates of important zooplankton species, including copepods, gammarid amphipods, euphausiids, and mysids? What food sources are utilized by these animals? Do these sources change during the year?

5. To what extent do populations of invertebrates in Harrison Bay rely for over-winter survival upon contributions of terrestrial energy from the Colville River and shoreline erosion?

1.2 HARRISON BAY ZOOPLANKTON

By R. A. Horner

Introduction

The only sampling of zooplankton in Harrison Bay has consisted of eight samples collected from a small area on two days in August 1980 (Fig. 1.2.1, Table 1.2.1).

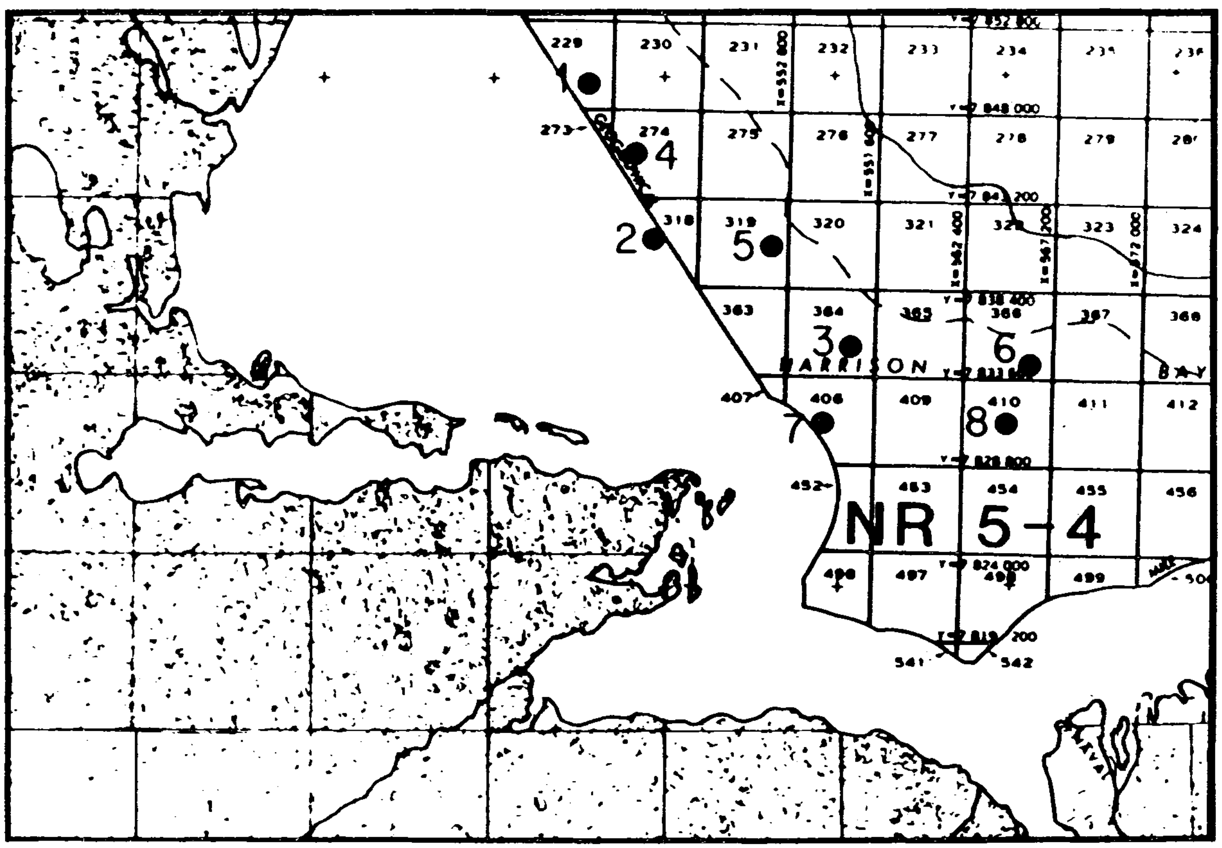


Figure 1.2.1. Location of Zooplankton Sampling Sites in Harrison Bay, 9-10 August 1980.

Table 1.2.1. Collection information for zooplankton samples collected in Harrison Bay, 8-9 August 1980.

Station	Date (GMT)	Time (GMT)	Latitude (N)	Longitude (W)	Maximum Depth Tow (m)
1	9 August	0105	70°45.0'	151°53.0'	6
2	9 August	0240	70°40.0'	151°46.0'	6
3	9 August	0432	70°37.3'	151°28.7'	6
4	10 August	0235	70°43.0'	151°47.0'	8
5	10 August	0204	70°40.0'	151°35.0'	9
6	10 August	0340	70°36.7'	151°13.9'	9
7	10 August	0704	70°35.0'	151°30.0'	9
8	10 August	0805	70°35.0'	150°15.0'	9

Farther offshore in the Beaufort Sea, samples have been collected during August-September in 1976-78 (Horner, 1981). Some short-term sampling has been done throughout the year in Stefansson Sound at the Boulder Patch (Dive Site 11); more intensive sampling has been done just outside Narwhal Island in spring (April-June) (Horner and Schrader, in press); and Horner et al. (1974) reported the results of summer zooplankton sampling off Prudhoe Bay.

Discussion

Copepods were the most abundant organisms (Table 1.2.2). Pseudocalanus elongatus, with all life cycle stages present, was the dominant species. Other copepod species present in large numbers were Microcalanus pygmaeus, especially stage V; Derjuginia tolli, all stages, Metridia longa, especially stages II and III; and Calanus hyperboreus, stages I, II, and III. Other abundant taxa were hydrozoans, Mysis spp. juveniles, and juvenile amphipods of several genera. Other taxa were present and sometimes abundant.

It is likely that P. elongatus and D. tolli breed in Harrison Bay since young copepodid stages and mature adults were present at the same time. Few adult males of P. elongatus were present, but many of the adult females had eggs attached to the genital segment, and eggs could be seen in the oviducts. This species was also the most abundant copepod in samples collected in Stefansson Sound in November, March, and May and off Narwhal Island from April to June.

C. hyperboreus stages I, II, and III were found in most plankton samples. This species, along with Microcalanus pygmaeus and Metridia longa, is known to breed independently of its food supply (Heinrich, 1962) and apparently does not feed much until stage II or III (Hansen et al., 1971). It probably overwinters as stage III (Hansen et al., 1971).

Table 1.2.2. Abundance (number per 1,000 m^3*) of zooplankton taxa found in net hauls from Harrison Bay, 8-9 August 1980. All samples collected with a 0.75-m ring net, mesh size 308 μm. Where no number is present, no animals were found.

Taxon	Station Number and Tow Type**							
	1, V	1, DO	2, V	2, DO	3, V	3, DO	4, V	4, DO
Cnidaria - Hydrozoa								
Aeginopsis laurentii	2,593	226	741	10		59	530	239
Aglantha digitale	1,111	50						25
Eumedusa birulai								
Euphysa flammea	370							
Halitholus cirratus		50	741	30	370	151		63
Obelia sp.								
Plotocnide borealis	741	25					265	25
Sarsia princeps		25			370		265	
Actinula larvae		251						163
Nematoda - unidentified	1,111							
Annelida - Polychaeta								
Iospilidae	22,222		370	20			265	
Polynoidae	370							
Unidentified larvae	11,111	478	370	90		8	530	704
Mollusca								
Gastropods								
Pteropoda								
Limacina helicina		25				17		25
Unidentified veliger larvae		25						13
Bivalvia - unidentified larvae				10				

*Volume of double oblique tows estimated as ship speed x mouth area of net x duration of tow; volume of vertical tows estimated as depth x mouth area of net

**V = vertical tow; DO = double oblique tow

Table 1.2.2 (cont.)

Taxon		Station Number and Tow Type** 1, V	1, DO	2, V	2, DO	3, V	3, DO	4, V	4, DO
Arthropoda - Crustacea									
Ostracoda									
Conchoecia sp.			25						
Polycope sp.									
Cyprideis sorbyana		1,481							
Cytheridea papillosa		4,815			10				
Cytheromorpha fuscata		2,593							
Cytherideidae		2,963			20			265	
Bythocytheridae									38
Copepoda									
Calanus glacialis	II								
Calanus hyperboreus	III		7,039	1,852	201		2,933	2,652	1,257
	II			35,185	4,223	240,741	6,285	2,652	8,798
	I			3,704	1,006	18,518	1,257	5,305	
Pseudocalanus elongatus	VI f	2,325,926	194,067	33,333	7,843	2,796,296	68,292	623,342	212,418
	VI m			1,852			838		
	V f	44,444	3,017		201			2,652	1,257
	V m		1,006				838	2,652	1,257
	IV f	14,815	2,001	20,370	5,631	629,630	7,542	5,305	5,028
	IV m			27,778	4,022	685,185	7,122	5,305	7,542
	III	162,963	8,044	233,333	43,841	2,018,518	31,423	106,101	62,846
	II			16,666	4,625	74,074	6,285	103,448	22,624
	I					18,518		2,562	
Microcalanus pygmaeus	VI f							5,305	
	VI m								1,257
	V f	59,259	1,006					5,305	1,257
	V m							23,873	1,257
Derjuginia tolli	V f								
	V m								
	IV f	74,074						18,568	3,771
	IV m	59,259	3,017		201	55,556		15,915	6,285

Table 1.2.2 (cont.)

Taxon		Station Number and Tow Type**							
		1, V	1, DO	2, V	2, DO	3, V	3, DO	4, V	4, DO
	III	59,259	1,006		402	74,074		31,830	7,542
	II					18,518	419	7,958	
	I								
Eurytemora herdmani	VI f	14,815			201				
	VI m								
Metridia longa	V m						419		
	IV f						419		
	IV m	14,815			201	55,556	838		1,257
	III	14,815		1,852		74,074	838	5,305	1,257
	II	29,630	2,011		201				
Limnocalanus macrurus	VI f								
	V f			3,704	201			2,652	
	V m		1,006	3,704			419		
	IV f							2,652	5,028
	IV m						419	2,652	
	III								
	II				201		419		
Acartia bifilosa	VI m								
Acartia clausi	VI m			1,852					
	IV f			1,852					
	IV m			1,852					
Acartia longiremis	VI f				201		419		
	IV f								1,257
	IV m					18,518			1,257
Oithona similis	VI f								1,257
Harpacticus uniremis	VI f	14,815						2,652	1,257
	VI m							2,652	
	V f								1,257
Cirripedia - unidentified nauplii								265	264
Mysidacea									
Mysis littoralis	f								13

Table 1.2.2 (cont.)

Taxon	Station Number and Tow Type**							
	1, V	1, DO	2, V	2, DO	3, V	3, DO	4, V	4, DO
Mysis littoralis m								25
Mysis littoralis juvenile								
Mysis spp. juvenile			21,481	151	14,074	8		
Unidentified damaged mysids								
Cumacea								
Leuconidae								13
Diastylidae	1,111							
Isopoda								
Unidentified epicaridean larvae	741	50		20		17		38
Amphipoda								
Gammaridea								
Onisimus glacialis juvenile	1,111	50					265	13
Onisimus litoralis f								13
Metopa sp. juvenile		25						
Acanthostepheia behringiensis								13
Monoculodes sp. juvenile	20,741	25						666
Monoculodes sp. damaged								13
Oedicerotidae juvenile	13,704		370	30				188
Apherusa glacialis f								
Apherusa glacialis juvenile		50		30			265	63
Apherusa megalops juvenile								
Weyprechtia pinguis m								
Weyprechtia pinguis juvenile								
Marinogammarus sp. *cf.* juvenile								
Gammaridae juvenile damaged								

Table 1.2.2 (cont.)

Taxon	Station Number and Tow Type** 1, V	1, DO	2, V	2, DO	3, V	3, DO	4, V	4, DO
Hyperiidea								
Parathemisto abyssorum juvenile								
Hyperia galba f								
Hyperia galba m						8		
Hyperia galba juvenile						8		
Unidentified hyperiid larvae		370	25	370				13
Decapoda								
Anomura								
Paguridae - unidentified zoea	1,852	151			1,481	126	265	88
Brachyura								
Hyas sp. stage 1 zoea						8		
Caridea								
Hippolytidae - unidentified zoea	741	25						13
Euphausiacea								
Thysanoësa *raschii* juvenile								13
Calyptopis stage III								
Unidentified crustacean larvae								
Unidentified crustacean eggs	1,111	1,408			370		7,958	1,458
Chaetognatha								
Sagitta elegans	1,111	201					1,592	364
Unidentified immature chaetognaths								13
Chordata								
Larvacea								
Fritillaria borealis	1,481	50			370		1,592	867

Table 1.2.2 (cont.)

Taxon	Station Number and Tow Type** 1, V	1, DO	2, V	2, DO	3, V	3, DO	4, V	4, DO
Pisces (larvae)								
Cyclopteridae								
Gadidae							265	
Unidentified damaged larvae								
Other organisms								
Foraminifera	18,148							138
Trochophore larvae	370	25						50

Table 1.2.2 (cont.)

Taxon	Station Number and Tow Type**							
	5, V	5, DO	6, V	6, DO	7, V	7, DO	8, V	8, DO
Cnidaria - Hydrozoa								
Aeginopsis laurentii	1,980	835	6,188	4,290	12,871	2,278	26,238	1,043
Aglantha digitale		13	248		248	15	495	38
Eumedusa birulai	248		248		248			
Euphysa flammea								25
Halitholus cirratus	495	188	1,733	2,011	2,723	603	2,228	75
Obelia sp.								13
Plotocnide borealis	248	25	495		248	136	248	50
Sarsia princeps	495		248	134	248		495	
Actinula larvae	990	126	3,218	3,888	11,634	1,840	10,396	1,358
Nematoda - unidentified						15		
Annelida - Polychaeta								
Iospilidae								
Polynoidae								
Unidentified larvae	5,693	75	1,485	536	1,238	60	2,475	327
Mollusca								
Gastropods								
Pteropoda								
Limacina helicina	248		248		495	75	495	13
Unidentified veliger larvae					743	30		
Bivalvia - unidentified larvae								
Arthropoda - Crustacea								
Ostracoda								
Conchoecia sp.								
Polycope sp.			248					
Cyprideis sorbyana								
Cytheridea papillosa								
Cytheromorpha fuscata								
Cytherideidae								
Bythocytheridae	248							

Table 1.2.2 (cont.)

Taxon		Station Number and Tow Type**							
		5, V	5, DO	6, V	6, DO	7, V	7, DO	8, V	8, DO
Copepoda									
Calanus glacialis	II		1,257				3,771		
Calanus hyperboreus	III	86,634	8,798	24,752	12,569			123,762	1,257
	II	37,129	2,514		8,379		7,542	24,752	3,142
	I								628
Pseudocalanus elongatus	VI f	1,893,564	358,220	5,866,337	2,547,344	4,084,158	1,591,252	6,311,881	166,541
	VI m	24,752		24,752	8,379	24,752	3,771		628
	V f	12,376	7,542	24,752	4,190		41,478	24,752	628
	V m	12,376	11,312	24,752	12,569	99,010	116,893		
	IV f	24,752	36,450	198,020	83,794	49,505	184,766	247,525	13,198
	IV m	37,129	57,818	396,040	150,830	74,257	297,888	198,020	7,542
	III	569,307	142,031	767,327	356,125	866,337	241,327	1,757,426	60,960
	II	49,506		24,752		99,010			1,257
	I								
Microcalanus pygmaeus	VI f							24,752	1,257
	VI m								
	V f	24,752		24,752				24,752	1,257
	V m	49,506		24,752				24,752	2,514
Derjuginia tolli	V f	12,376							
	V m							24,752	628
	IV f	24,752			50,276	123,762	7,542		1,885
	IV m	86,634		49,505	46,087	272,277	18,854		2,514
	III	86,634	2,514	420,792	113,122	396,040	33,937	247,525	2,514
	II	222,772		346,535	92,174	99,010	3,771		1,257
	I				4,190				
Eurytemora herdmani	VI f							49,505	
	VI m		1,257						
Metridia longa	V m								
	IV f								
	IV m							24,752	1,257
	III	24,752	2,514	24,752	12,569	74,257	3,771	247,525	5,656
	II	12,387			4,190		3,771	74,257	1,885

Table 1.2.2 (cont.)

Taxon		Station Number and Tow Type**							
		5, V	5, DO	6, V	6, DO	7, V	7, DO	8, V	8, DO
Limnocalanus									
macrurus	VI f		1,257		4,190				
	V f	12,376							
	V m		1,257			24,752	7,542	24,752	
	IV f				4,190		3,771		
	IV m						3,771		
	III		1,257		4,190				
	II								
Acartia bifilosa	VI m						3,771		
Acartia clausi	VI m								
	IV f								
	IV m								
Acartia longiremis	VI f								
	IV f								
	IV m				4,190				
Oithona similis	VI f					24,752			628
Harpacticus uniremis	VI f								
	VI m								
	V f								
Cirripedia - unidentified									
nauplii			38			1,733	106	13,366	1,571
Mysidacea									
Mysis littoralis	f								
Mysis littoralis	m								
Mysis littoralis juvenile						495			
Mysis spp. juvenile		495	666	14,356	57,919	24,010	1,659	248	
Unidentified damaged mysids						2,228			
Cumacea									
Leuconidae									
Diastylidae									
Isopoda									
Unidentified epicaridean									
larvae		743	38	2,228		1,238	90	990	88

Table 1.2.2 (cont.)

Taxon	Station Number and Tow Type**							
	5, V	5, DO	6, V	6, DO	7, V	7, DO	8, V	8, DO
Amphipoda								
Gammaridea								
<u>Onisimus</u> <u>glacialis</u> juvenile	248							
<u>Onisimus</u> <u>litoralis</u> f								
<u>Metopa</u> sp. juvenile						15	248	13
<u>Acanthostepheia</u> <u>behringiensis</u>								
<u>Monoculodes</u> sp. juvenile	495							
<u>Monoculodes</u> sp. damaged								
Oedicerotidae juvenile	990							
<u>Apherusa</u> <u>glacialis</u> f					248	15	495	38
<u>Apherusa</u> <u>glacialis</u> juvenile	1,485	63	248		248	15	990	63
<u>Apherusa</u> <u>megalops</u> juvenile			248	268				
<u>Weyprechtia</u> <u>pinguis</u> m		25				15		
<u>Weyprechtia</u> <u>pinguis</u> juvenile			248		248	15	248	
<u>Marinogammarus</u> sp. <u>cf</u>. juvenile		13				15		
Gammaridae juvenile damaged			248					
Hyperiidea								
<u>Parathemisto</u> <u>abyssorum</u> juvenile						15		
<u>Hyperia</u> <u>galba</u> f		25	248	268	248	30		
<u>Hyperia</u> <u>galba</u> m				134			248	
<u>Hyperia</u> <u>galba</u> juvenile				268	743	15	248	13

Table 1.2.2 (cont.)

Taxon	Station Number and Tow Type** 5, V	5, DO	6, V	6, DO	7, V	7, DO	8, V	8, DO
Unidentified hyperiid larvae	248	38			248	30	248	
Decapoda								
Anomura								
Paguridae - unidentified zoea	495	214	990	402	248	362	2,970	214
Brachyura								
<u>Hyas</u> sp. stage 1 zoea		25	248			15	248	
Caridea								
Hippolytidae - unidentified zoea		38				60		38
Euphausiacea								
<u>Thysanoësa</u> <u>raschii</u> juvenile					248		495	
Calyptopis stage III					248			
Unidentified crustacean larvae			248	268	743	30		38
Unidentified crustacean eggs	1,238	1,269	248	536	743	2,081	1,238	75
Chaetognatha								
<u>Sagitta</u> <u>elegans</u>	248		495		248	15	743	
Unidentified immature chaetognaths						15		
Chordata								
Larvacea								
<u>Fritillaria</u> <u>borealis</u>	2,970	767	3,713	402	1,980	468	18,812	2,313
Pisces (larvae)								
Cyclopteridae		25		536	743	90	248	25
Gadidae			248		248	106	495	75
Unidentified damaged larvae							248	

Table 1.2.2 (cont.)

Taxon	Station Number and Tow Type**							
	5, V	5, DO	6, V	6, DO	7, V	7, DO	8, V	8, DO
Other organisms								
Foraminifera	743	25	248		248			
Trochophore larvae		13	495	134	495	256	495	138

Other calanoid copepod species present included C. glacialis, M. longa, Acartia clausi, and A. longiremis, and the brackish-water species Eurytemora herdmani, Limnocalanus macrurus, and A. bifilosa. The cyclopoid copepod Oithona similis and the harpacticoid Harpacticus uniremis were also present.

Other taxa present included hydrozoans, polychaete and barnacle larvae, juvenile mysids, and amphipods. Decapod zoeae and unidentified crustacean eggs were found at all stations. Fish larvae of the families Cyclopteridae and Gadidae were identified.

All of the species identified in these samples except for A. bifilosa have been reported previously from the Beaufort Sea. The presence of many juveniles among the larger crustaceans and young stages of many copepods relatively late in the season suggests that much development of zooplankton must occur during winter when food from phytoplankton production is low. Some copepods have young stages that apparently feed little (Hansen et al., 1971), while others, such as C. hyperboreus, can complete their life cycles using stored lipids as an energy source (Conover, 1967). It is not known what most zooplankton species use for food in winter. Schneider and Koch (1979) have shown that few amphipods utilize carbon from terrestrial sources, and some copepods may be more opportunistic as feeders than previously thought. Berk et al., (1977) reported that ciliates were an important food source for one species of Eurytemora and suggested that ciliates may also be an important food source for copepods. Ciliates are known to feed on bacteria and particulate organic material as well as diatoms, flagellates, and other ciliates (Fenchel, 1968). Ciliates may play an important role in Beaufort Sea food webs.

The presence of young stages in late summer also suggests that life cycles may take more than one year to complete.

Potential Effects of OCS Development

Few studies have been done on the effects of oil contamination on arctic zooplankton species. Percy and Mullin (1975) found the copepod C. hyperboreus to be resistant to all oils tested, whereas the hydrozoan Halitholus cirratus was less tolerant; the pelagic larvae of the sculpin Myoxocephalus quadricornis were extremely sensitive to crude oil. Amphipods that come in contact with oil slicks have little chance for survival, so that oil trapped under the ice would be especially toxic to amphipods that feed on ice algae (Busdosh and Atlas, 1977).

The effects of an oil spill depend on the amount and kind of oil spilled; the season; kinds of organisms present, including life cycle stages; and previous exposure to oil (Sanborn, 1978). The response of different species to oil pollution varies tremendously. Larvae of many species are particularly susceptible to oil, and in the Arctic where direct development and brooding of young occur, recruitment is presumed to be largely from local stock. Major contamination might affect both adults and larvae, and replacement by stocks of some species from an adjacent area could be slow (Chia, 1970).

Sublethal effects are complex and may be important, contributing to death over an extended period or impairing physiological processes, such as mobility or respiratory metabolism (Percy and Mullin, 1975). The effects of pollution on the behavior of zooplankton organisms are not well documented, but there may be direct responses such as avoiding oil-tainted food, or indirect reponses caused by the impairment of chemoreceptors that could affect the ability of an organism to find food.

Changes or reduction in species diversity could have serious consequences in the Beaufort Sea, where food chains tend to be short and fewer links mean that each one is relatively more important and vulnerable (Grainger, 1975).

Data Gaps

A. We need to know the effects of pollutants on zooplankton species.

B. More information is needed concerning the food sources, and rates of recruitment and reproduction of important zooplankton taxa, such as copepods, amphipods, euphausids, and mysids. How long are individual life cycle stages?

1.3 INVERTEBRATES

By A. C. Broad, W. Griffiths, and A. G. Carey, Jr.

Introduction

The western Sale 71 area was sampled intensively only during the summer of 1980. Data from 81 trawl stations, 6 stations at which benthic infauna were sampled with the Smith-McIntyre 0.1-m^2 grab, and 4 stations at which motile epibenthic crustaceans were sampled with drop nets, were added to the existing base.

The data on the Harrison Bay region came from samples collected prior to 1980 by RU's 6, 356, and 467; this information has been presented in detail in the annual and quarterly reports of these research units and, to some extent, in Weller et al. (1978). More recent data, including the 1980 samples, are from 1981 annual reports of RU's 6, 356 and 467.

Zonation (Fig. 1.3.1)

Five components of the Sale 71 area may be distinguished on the basis of the invertebrate fauna and other considerations. These generally conform to zonation categories used earlier: nearshore, inshore or coastal; offshore or shelf; and slope. Simpson Lagoon, which differs from both nearshore and inshore environments, is classified separately. As the invertebrate fauna in the Sale 71 area resembles that of the Beaufort Sea as reported in Weller et al. (1978), it is described only briefly here.

Nearshore Zone. The nearshore zone extends from the shoreline seaward to about 2 meters depth. The superficial sediments are sand, silt, and

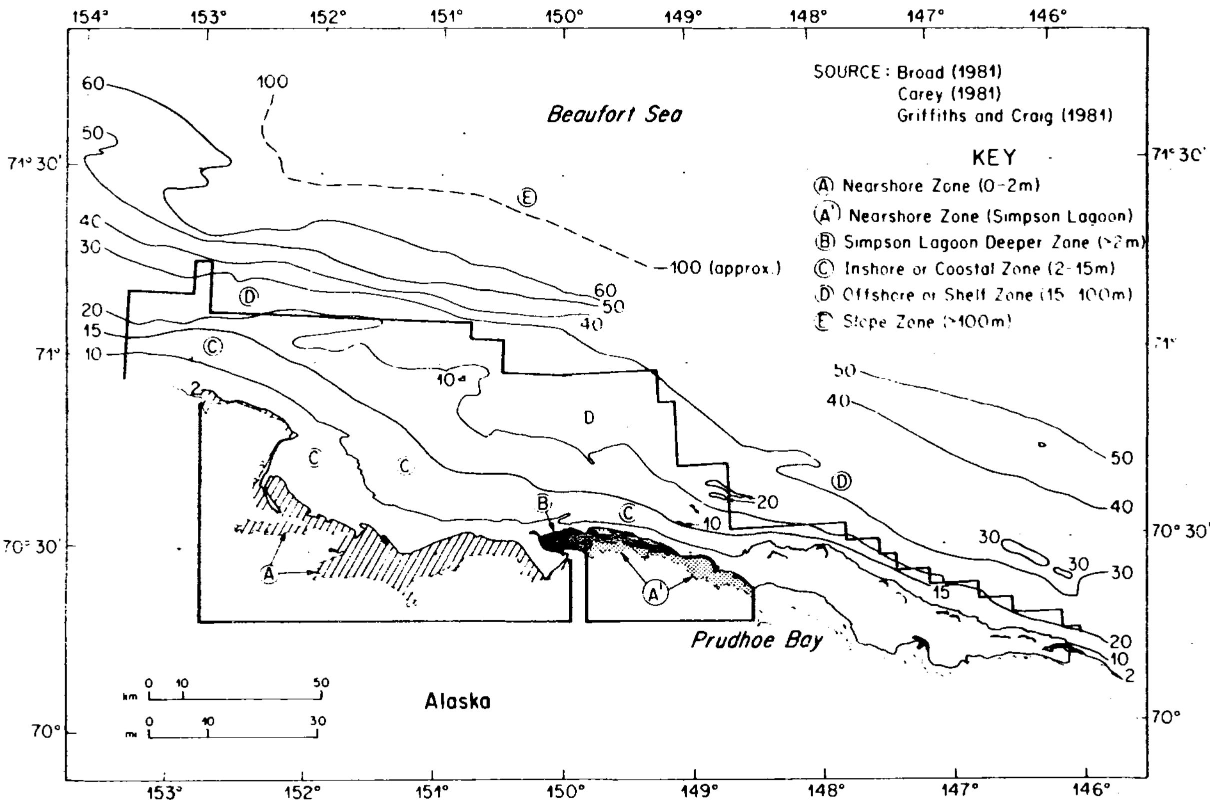


Figure 1.3.1. Zonation of Invertebrate Resources in the Western Sale 71 Area.

gravel and may contain large amounts of peat. Salinities, especially in Harrison Bay, are low, and the water is usually warmer than the bottom water farther offshore. The principal infaunal organisms are chironomid (midge) larvae (which may be important in introducing terrestrial carbon in the marine system) and enchytraeid (oligochaete) worms. Motile epibenthic animals of the nearshore include the isopod Saduria entomon and the amphipods Gammarus setosus and Onisimus litoralis. Throughout the system, biomass is low (3.1 ± 4.9 g/m^2, range 0-21 g/m^2) and lacking in diversity. The nearshore zone is generally frozen by the annual shorefast ice.

Simpson Lagoon. Simpson Lagoon has been discussed previously in reports by RU 467, and particularly in that of Griffiths and Dillinger (1981). The deeper parts of the Lagoon are generally less than 3 m deep, and the surface sediments are softer (siltier) and contain more peat than do those of the nearshore zone. The principal infaunal organisms are polychaete worms. The most abundant of the 12-15 common species present are Ampharete vega, Prionospio cirrifera, Scolecolepides arctius, and Tharyx sp. Of the bivalve mollusks present, Cyrtodaria kurriana and Portlandia sp. are by far the most prevalent. In addition, both tubificid and enchytraeid worms are abundant, as are the simple ascidian Molgula sp. and the priapulid Halicryptus spinulosus. Infaunal biomass is high by Beaufort Sea standards (42.05 ± 30.53 g/m^2, range 0-145.3 g/m^2), and the number of individuals also is high ($6{,}670 \pm 4{,}162$ individuals/m^2, range

87-17,707 individuals/m^2). As might be anticipated, both the number of species and species diversity in Simpson Lagoon are high. Of the motile epibenthic species, the mysids Mysis littoralis and M. relicta, the amphipods O. glacialis, G. setosus, and Pontoporeia affinis, and the isopod Saduria entomon are abundant. Calculations indicate that the mass of these crustaceans in the lagoon during the ice-free season far exceeds the feeding demands of fish and bird feeding there. These calculations thus confirm the importance of lagoon systems in Beaufort Sea food webs.

Inshore or Coastal Zone. The inshore zone of the Beaufort Sea has been defined as extending from the 2-m to the 20-m isobath. Based on samples by RU 6, the outer boundary of this zone is set at 15 m for the Sale 71 area, but the differences between this and the offshore zone are not believed to be significant. The surface sediments of the coastal zone of Harrison Bay and most of the Sale 71 area are silt, with sand primarily in the deltas. Peat is a minor component of the bottom deposits. At the inner edge of this zone in water 3-4 m deep (tracts 363-408) is a patchily distributed sand-silt substrate populated by neither epifauna nor attached plants. Despite extensive trawling in the ice-free portion of Harrison Bay in 1980, neither hard-bottom nor kelp communities were found. The Sale 71 area thus apparently does not include areas similar to the live bottom of Stefansson Sound.

The salinity of the bottom water in the coastal zone is high (24-32 °/$_{oo}$, with most determinations near the higher value), and the temperature is low (-1 to +4°C, with most of the readings near the lower value).

The principal organisms of the infaunal benthos are polychaete worms, amphipods, isopods (including the burrowing S. sabini), bivalve mollusks, and the priapulid H. spinulosus. The previous report (Weller et. al., 1978) of benthos in this zone is reliable for the Sale 71 area, with the majority of the data falling in the mid-ranges reported (9-43 species/station; 30.6 ± 39.4 g/m^2, range 1.0-160 g/m^2; diversity higher than in the inshore zone).

The most abundant of the motile epibenthic crustaceans are M. littoralis and M. relicta; amphipods including P. affinis (also in the infauna), Apherusa glacialis, G. setosus, and O. glacialis; and the isopods S. entomon and S. sabini. Samples collected in 1980 show fewer of amphipods and mysids in the coastal zone than are found in Simpson Lagoon. These important food organisms probably move from the Lagoon into the coastal zone in winter.

In general, the coastal zone of the western Sale 71 area can be judged as average for the Beaufort coast as a whole. The effects of development here probably would be similar to those arising from development elsewhere along the Beaufort Coast; the proposed Federal lease acreage of Sale 71 does not appear to contain such ecologically important and sensitive habitats as Stefansson Sound and Simpson Lagoon.

Offshore or Shelf Zone. The only data on this zone are those in Weller et al. (1978); that report should be consulted for the Sale 71 area. The shelf zone extends from about 15 m to about 100 m water depth. The sediments of the region are variable and may include clays and gravel. The bottom salinity usually exceeds 30 $^{o}/_{oo}$, and the water is cold. The principal infaunal organisms are polychaetes, bivalves, brittle stars, sea cucumbers, and crustaceans. The biomass is highly variable, indicating patchy distribution. The shelf zone has not been adequately sampled.

Slope Zone. Below 100 m depth, the bottom community belongs to the slope zone. There are no recent data from this area.

Epontic (under ice) Zone. Although the existence of an algal bloom on the undersurface of sea ice in the Arctic Ocean has been known for approximately one hundred years (Horner, 1977), the invertebrate fauna associated with the ice is not well known. The plants are mostly pennate diatoms; many species are benthic forms (Hsaio, 1980). The algal population grows rapidly from April through early June. Chlorophyll concentrations are high, and primary production can be significant (Alexander, 1980). Alexander has estimated that the ice algal blooms may account for up to 30-40 percent of the total annual production, though its areal extent is not fully known at the present time. The algal community may be a significant carbon source in the arctic environment and may support an extensive food web (Horner, 1976; Clasby et al., 1976). A pilot study (Carey, unpub.) was undertaken in Stefansson Sound during the spring of 1979, whereas a detailed time series study of the algae (Horner, 1981) and the associated invertebrates was completed during April-June 1980.

The sea ice algal community appears to be an important source of carbon to the Beaufort Sea food web. Studies on the fauna of the undersurface of the sea ice during the spring months indicate that both meiofauna (63 µm-500 µm) and macrofauna (> 500 µm) are present. In shallow oceanic waters, the meiofaunal groups increase significantly in numbers during May-June, while benthic species of amphipods (O. litoralis) are twice as abundant at the ice-water interface as on the sediments. Evidence indicates that these animals are grazing on pennate diatoms.

Data Gaps

A. We need more information on the abundance and distribution of invertebrates, especially motile epibenthic forms, and from 10- to 25-m depths in the Sale 71 area. Larger sample sizes would result in improved characterization of environments.

B. To make recommendations on possible seasonal activities in the Sale 71 area we need information on population dynamics. For the major species of invertebrates, information is needed concerning physiological constants such as longevity, reproductive activities and seasonal trends. Until we have information on turnover rates in benthic communities we cannot intelligently manage such petroleum-related activities as undersea gravel mining and island construction, and sediment limitation.

C. We have little information on the feeding of specific invertebrates, and our comprehension of trophics in general in the Beaufort Sea and in the Sale 71 area is inadequate. We recommend that the following subjects receive further study:

1. the relative importance of the sea-ice community and open-water algae (primary production) in the Sale 71 area;

2. trophic relationships within the infaunal and motile epibenthic communities;

3. efficiency of conversions and the relative contributions of marine production, terrestrial runoff, and coastal erosion at different depth zones in the Sale 71 area.

1.4 FISHES

By P. C. Craig

Introduction

The Sale 71 Harrison Bay and Joint Lease Sale areas adjoin and presumably share many physical similarities, but they differ in several respects. Harrison Bay lacks the barrier islands which help shelter nearshore waters in the Joint Lease Sale Area from wind and storms, and these islands also afford protection or migratory landmarks for some vertebrates. Harrison Bay also lies directly off the mouth of the Colville River, Alaska's largest North Slope drainage. The Colville's discharge extends much farther offshore than do those of smaller rivers elsewhere along the Alaskan Beaufort Sea coastline, resulting in an extensive mixing zone among fresh, brackish, and marine water masses.

Important biological differences between the two lease areas also arise from the influence of the Colville River. The Colville is the source of major stocks of anadromous ciscoes and whitefish, which are important constituents of the nearshore fish fauna along the Alaskan Beaufort Sea coast. These fish are harvested in both subsistence and commercial fisheries in the Colville Delta. The only commercial fishery on Alaska's North Slope occurs near the Harrison Bay lease sale area.

A description of fish resources in the Harrison Bay region is drawn from limited data. Much of the available information for offshore waters within the lease tracts is derived from an analysis of only 15 otter trawls collected during open-water seasons over a 5-year period (Lowry et al., 1981). Additional data were collected during hydroacoustic surveys in Harrison Bay (Craig and Griffiths, 1981) and supplementary information was provided by A. C. Broad (RU 356) during his trawling survey for invertebrates in the bay.

The data base for nearshore waters varies from region to region. Numerous summer and winter data have been collected between Simpson Lagoon and the Colville Delta (Kogl, 1972; Alt and Kogl, 1973; Furniss, 1975; Craig and Haldorson, 1981; McElderry and Craig, 1981), but few data are available from nearshore waters of western Harrison Bay: only three gillnet sets, one at Kogru River (Craig and Griffiths, 1981) and two near Pitt Point (Furniss, 1975; Hablett, 1979).

Species Composition and Relative Abundance

Fish species present in the Harrison Bay area are similar to those occurring elsewhere along the Beaufort Sea coastline. In the nearshore waters of Simpson Lagoon (Craig and Haldorson, 1981), 22 species were caught; the most abundant were three anadromous fishes (least and Arctic cisco, Arctic char) and two marine fishes (Arctic cod, fourhorn sculpin). These are the same five species identified in Weller et al. (1978) as key species in nearshore waters of the Beaufort Sea.

Considerable annual variation may occur in the numbers and relative abundance of nearshore fishes. For example, in Simpson Lagoon, all species present in 1977 were present again the following summer, but eight additional species were encountered during the second summer. Numbers of Arctic cod in the lagoon showed a 200-fold increase in 1978, and their relative abundance in fyke net catches from the lagoon increased from 8 percent in 1977 to 78 percent in 1978. In 1978, there was also a small run of pink salmon in the lagoon, whereas no salmon were caught in 1977.

In offshore waters, the most abundant fish species was the Arctic cod (Fig. 1.4.1). Fish collected in central Harrison Bay by A. C. Broad (pers. comm.) consisted of 75 Arctic cod, 3 liparids, 2 fourhorn sculpin, and possibly 2 gunnel. In waters deeper than 20 m, Arctic cod accounted for 25-78 percent of trawl samples collected between 1976 and 1980 (Table 1.4.1). In all, 19 marine species were caught offshore; other species that were occasionally common were eelpouts, sculpins, snailfish, and eel-blennies.

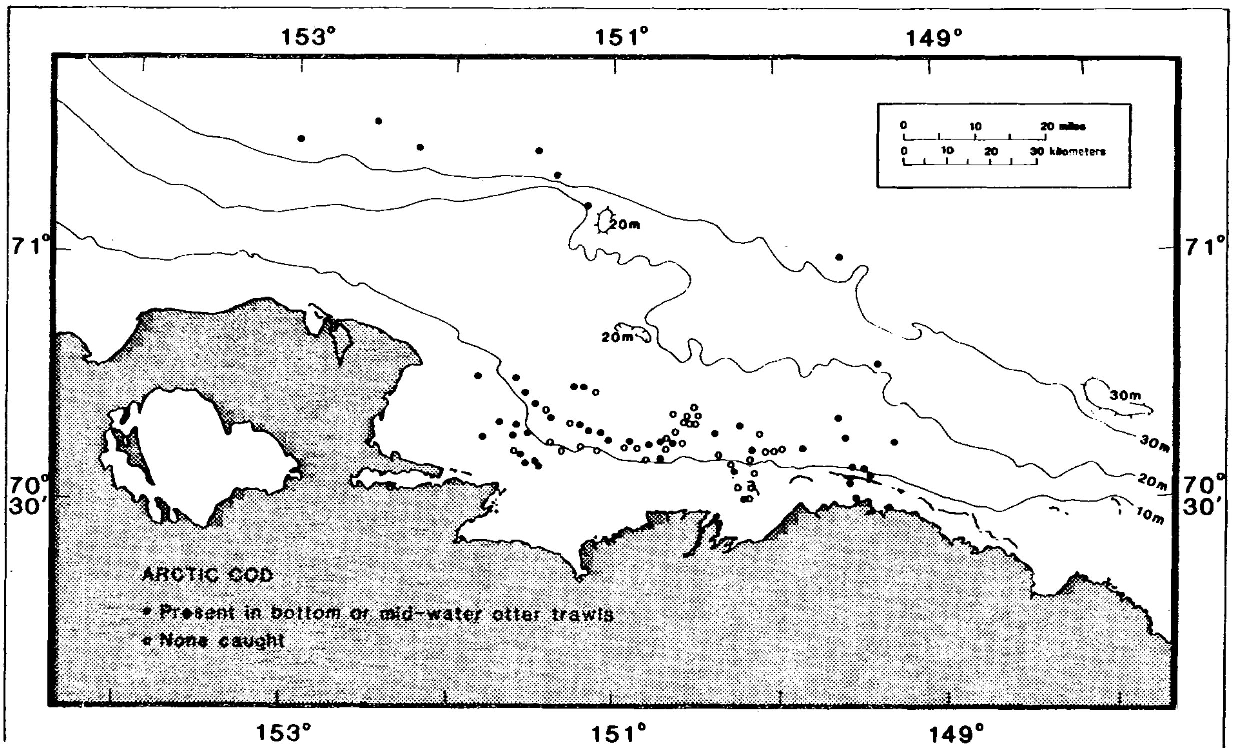


Figure 1.4.1. Distribution of Arctic cod, August 1980 (C. Broad, pers. comm.). Solid circles indicate the presence of Arctic cod in bottom or mid-water otter trawls; open circles indicate that no Arctic cod were caught. Catch records in waters deeper than 20 m are from Lowry et al., 1981.

Table 1.4.1. Fishes caught by otter trawl in the Sale 71/Harrision Bay area in 1976, 1977 and 1980 (Lowry et al., 1981).

Scientific name	Common name	Percent composition 1976	1977	1980
Boreogadus saida	Arctic cod	25	40	78
Lycodes polaris	Canadian eelpout	30	11	0
Liparis sp.	Snailfish	4	13	13
Artediellus scaber	Hamecon (rough hookear)	5	21	1
Aspidophoroides olriki	Arctic alligator fish	13	0	0
Lumpenus fabricii	Slinder eelblenny	8	0	0
Gymnocanthus tricuspis	Arctic staghorn sculpin	2	2	3
Myoxocephalus quadricornis	Fourhorn sculpin	0	0	4
Icelus spatula	Spatulate sculpin	5	0	0
Icelus bicornis	Twohorn sculpin	0	3	0
Triglops pingeli	Ribbed sculpin	1	0	0
Lycodes raridens	Eelpout	2	0	0
Lycodes mucosus	Eelpout	1	2	0
Lycodes rossi	Threespot eelpout	2	0	0
Gymnelis viridis	Fish doctor	3	2	0
Eumesogrammus praecisus	Fourline snakeblenny	1	2	0
Liopsetta glacialis	Arctic flounder	0	0	1
Eumicrotremis derjugini	Leatherfin lumpsucker	0	5	0
Lumpenus maculatus	Daubed shanny	0	2	0
	No. fish caught	133	63	216
	No. trawls	2	4	9

Distribution and Movement

In the previous synthesis report (Weller et al., 1978), three aquatic zones were described: (1) nearshore zone (< 2 m depth and enclosed or protected coastal waters), (2) inshore zone (2-20 m depth), and (3) offshore zone (> 20 m depth). While the use by fish of these zones in Harrison Bay probably is similar to that described previously (Weller, et al., 1978), an exception is that anadromous fish may range far from offshore in Harrison Bay by utilizing the plume of brackish water off the Colville River. This supposition has not yet been documented, but fish have been found in plumes off the mouths of other large rivers such as the Sagavanirktok (Moulton et al., 1980) and the Mackenzie (Galbraith and Hunter, 1979).

Densities of fish in Harrison Bay were highly variable, ranging from 0 to 39 fish/10^4 m^3 (Craig and Griffiths, 1981). Fish echos (presumably Arctic cod) were distributed throughout the water column, both above and below the temperature/salinity stratification in the bay. One accumulation of fish was detected at the edge of a brackish-water lens overlying cooler, more saline water. Moulton et al. (1980) also observed highest fish densities in upper brackish waters just above the leading (landward) edge of bottom marine waters in Prudhoe Bay. Moulton et al. (1980) postulate that planktonic prey may be relatively abundant in such transition areas.

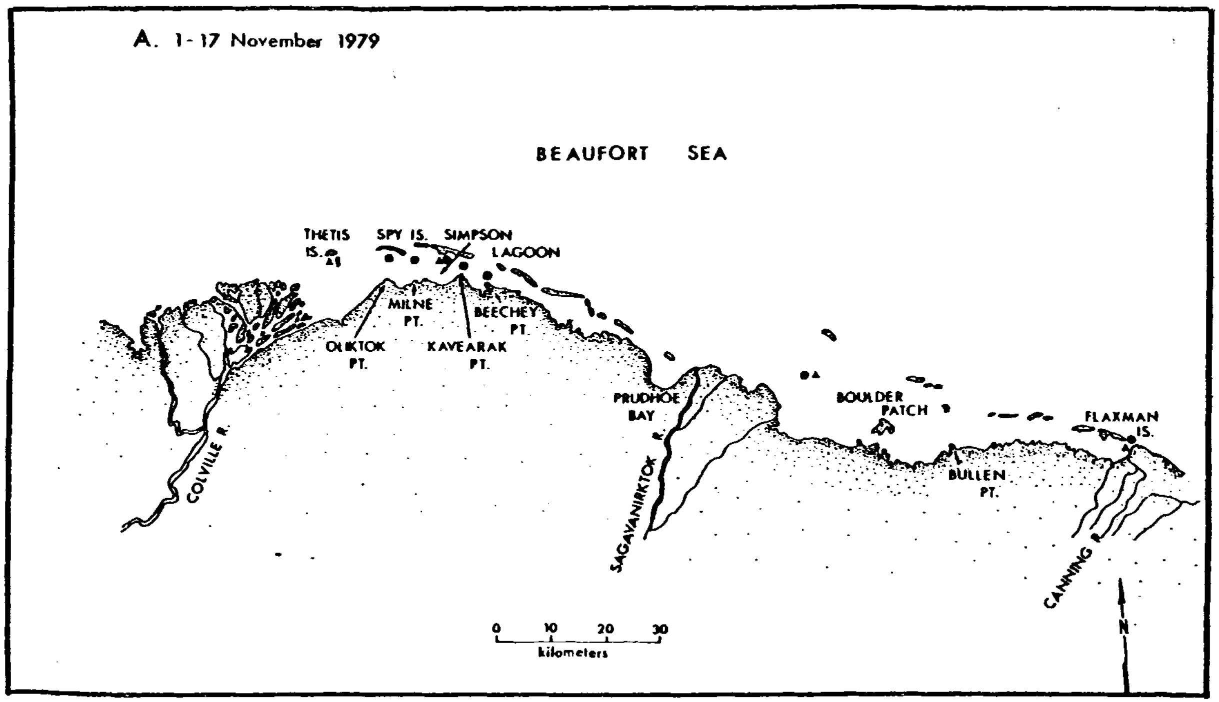
In winter, the abundance and distribution of the fish species utilizing nearshore habitats in the study area change dramatically. All of the dominant anadromous species (ciscoes, whitefish, and char) that are common during the brief summer disappear. Species caught in nearshore waters are Arctic cod, boreal smelt, fourhorn sculpin, saffron cod, snailfish, and Arctic flounder. With the exception of the anadromous boreal smelt, all of these are marine species. A summary of the winter catch data is presented in Fig. 1.4.2 and Table 1.4.2; most sampling sites were in nearshore areas but one station was 165 km offshore.

Arctic cod predominated at most winter sampling stations. They accounted for 100 percent of all fish caught at the 175-km offshore site (n = 65), 100 percent at Narwhal Island (n = 9), 80 percent at the Boulder Patch in Stefansson Sound (78 of 97), 56 percent at Flaxman Island (9 of 16), and 37 percent at Simpson Lagoon (26 of 70). In contrast, no cod were taken in the brackish waters within the Colville Delta (n = 150, mostly Arctic and least cisco) and few were taken in nearshore waters near the Colville River; at Thetis Island, only 0.4 percent of the catch was Arctic cod (n = 2,612, mostly boreal smelt and fourhorn sculpin).

Although Arctic cod were widely distributed, the catch per unit effort (CPUE) was greatest offshore. In a late winter collection (29 April - 6 May 1980) when a single type of sampling gear (fyke net) was used, the CPUE was over 30 times greater 165 km offshore than that of catches in the Boulder Patch in Stefansson Sound.

In winter samples, boreal smelt and fourhorn sculpin were most abundant at the Thetis Island station in Harrison Bay. The boreal smelt is a spring-spawning anadromous species, and it is assumed that its concentration in Harrison Bay is a prelude to a spawning migration into the Colville River. This supposition is supported by the observation that the great majority of boreal smelt captured were mature fish in pre-spawning condition. The apparent concentration of fourhorn sculpin, a marine species, near the mouth of the Colville River is not readily explained.

In late-winter sampling of the brackish waters of the Colville Delta (Craig and Haldorson, 1981), both anadromous and marine species were found overwintering:



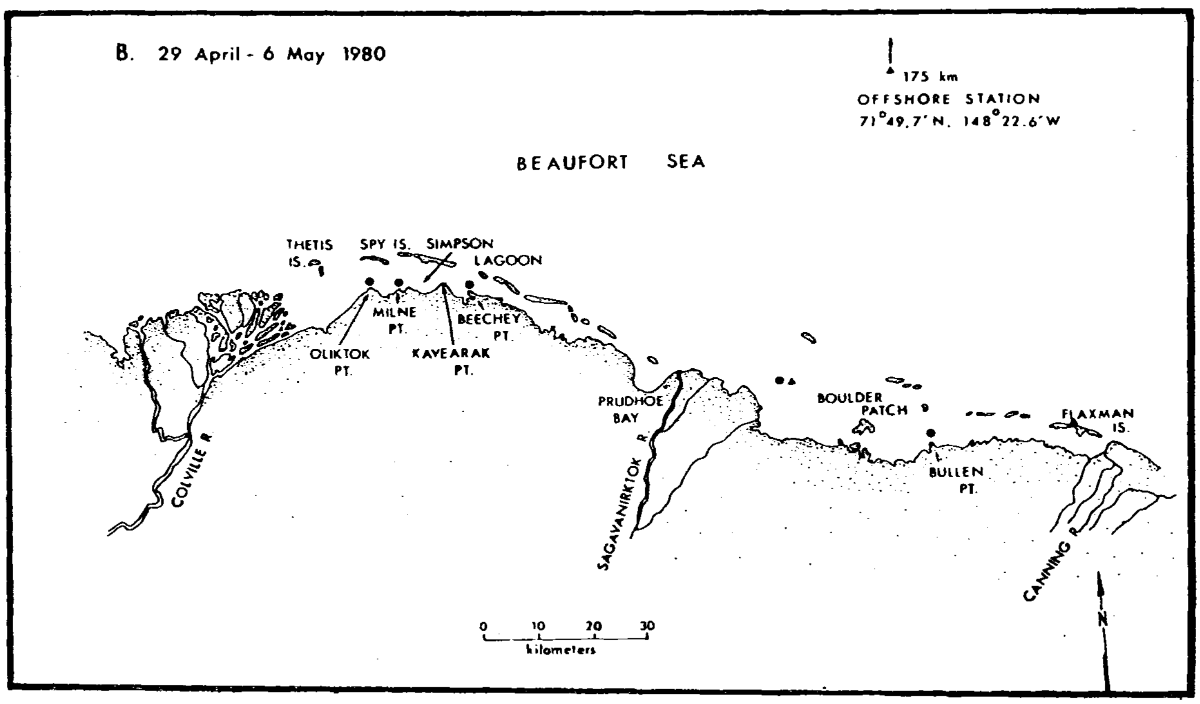


Figure 1.4.2. Winter sampling locations for fish (triangles) and invertebrates (circles) during (A) 1-17 November 1979, and (B) 29 April-6 May 1980.

Table 1.4.2. Summary of 1978-1980 winter catch data. Average catch per unit efforts (CPUE) are listed for combined sampling periods for fish caught by net (principally gill and fyke nets but also trammel net and box trap) per day. Source: Craig and Haldorson (1981), Craig and Griffiths (1981).

Date		Average CPUE (Fish/Net-day)						
		Thetis Island	Spy Island	Simpson Lagoon	Boulder Patch	Narwhal Island	Flaxman Island	175 km offshore
Early Winter (13-16 November 1978 4-15 November 1979)	Boreal smelt	13.3	-	0.8	0	0	0	-
	Fourhorn sculpin	1.0	-	0.2	*	0	3.5	-
	Arctic cod	0.7	-	0.6	0.5	0.5	4.5	-
	Saffron cod	0	-	0	0	0	0	-
	Snailfish	0	-	0	0.1	0	0	-
	Total effort (days)	14	0	44	33	1	2	0
Midwinter (11-27 February 1979)	Boreal smelt	22.2	-	0	0	0	-	-
	Fourhorn sculpin	6.8	-	0	0	0	-	-
	Arctic cod	0	-	0	3.7	0	-	-
	Saffron cod	1.0	-	0	0	0	-	-
	Snailfish	0	-	0	1.1	0	-	-
	Total effort (days)	20	0	7	14	16	0	0
Late Winter (1 March-1 April 1979 29 April-14 May 1979 29 April-6 May 1980)	Boreal smelt	14.0	0.2	0	0	0	-	0
	Fourhorn sculpin	11.0	0.3	0	0	0	-	0
	Arctic cod	0	0	0	0.4	0.5	-	10.8
	Saffron cod	0.1	0	0	0	0	-	0
	Arctic flounder	*	0	0	0	0	-	0
	Total effort (days)	65	10	10	24	15	0	6
Approximate late-winter water depth (m)		1.7	3.3	0.5	4.6	10.0	0.5	2,500+

*< 0.05 CPUE

Species	Catch Per Unit Effort (No./24-h gill net set)	
	East Channel	Kupigruak Channel
Arctic cisco	1.9	1.00
Least cisco	1.0	0.70
Boreal smelt	0	0.50
Fourhorn sculpin	0.5	0.20
Bering cisco	0.1	0.10
Saffron cod	0	0.02
Gillnet-Days	13.0	44.00

Food Habits

As indicated in Weller et al. (1978), anadromous and marine fishes in nearshore waters of the Beaufort Sea feed extensively on epibenthic invertebrates (mysids, amphipods), zooplankters (copepods), and occasionally fish. Small and variable percentages of other zooplankters and epibenthic invertebrates are also taken. In offshore waters, copepods and amphipods, rather than mysids, constitute most of the diet of Arctic cod (Frost et al., 1978; Craig and Haldorson, 1981). The significance of the epibenthic feeding pattern is that the fish do not rely on infaunal invertebrates (organisms living within bottom substrates) which might be physically disrupted by development activities.

Important Areas

Beyond the general statement that nearshore habitats in the study area are important to anadromous fish, it is difficult to single out particular habitats as being more or less important than other habitats. This situation reflects our current understanding of what fish do when they enter coastal waters. Anadromous fish enter 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 significance to these fish.

There are exceptions, however, in which particular habitats are of special importance to fish. These are the deltas of the Colville River and, presumably, Fish River, which are overwintering areas for ciscoes and whitefish in addition to being important migratory pathways and spawning areas for some fish.

Human Use of Fish Resources

The Sale 71 Harrison Bay lease area lies close to two fisheries in the Colville Delta, a commercial fishery (Helmericks) and a subsistence fishery (Nuiqsut Village) (Fig. 1.4.3). Both fisheries operate during summer and fall/early winter. The fall/early winter fishery, accounts for the greater amount of effort and yield. The commercial fishery has an average annual harvest of about 47,000 ciscoes and 18,000 whitefish. The Nuiqsut harvest is undocumented but is estimated at about that of the commercial catch (Craig and Haldorson, 1981).

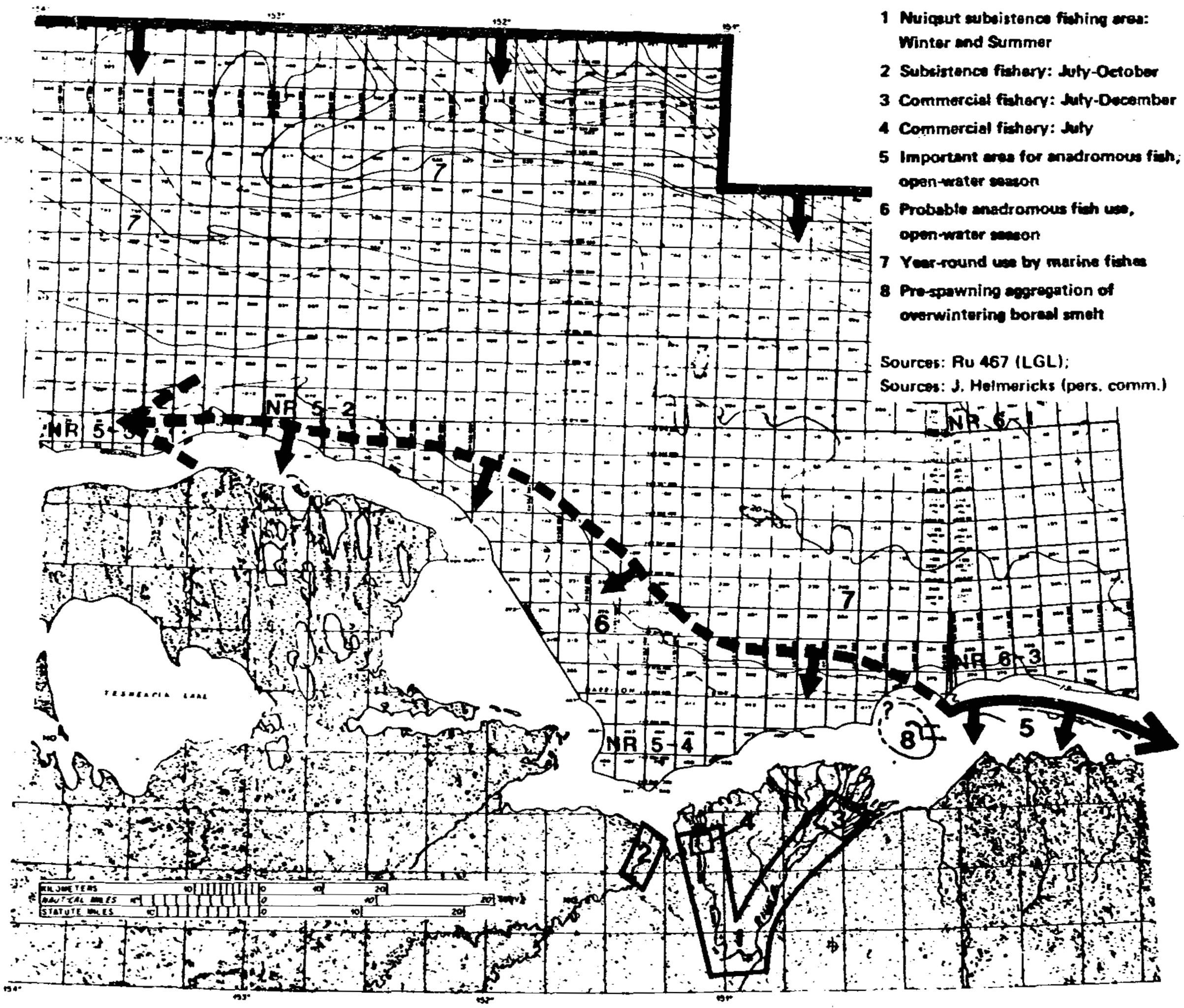


Figure 1.4.3. Fish Resources.

In addition to these local harvests, the fish may be caught in subsistence nets at considerable distances from Harrison Bay. For example, fish tagging and recovery data show that some fish passing through Simpson Lagoon are caught in nets from Barrow to Barter Island, a distance encompassing much of the Beaufort Sea Alaskan coastline (Craig and Haldorson, 1981).

Data Gaps

Information needed on fishes in nearshore and offshore areas remain as previously described (Weller et al., 1978), but we again emphasize the small data base available for the Sale 71 Harrison Bay lease area. Very few fisheries data for either summer or winter periods have been collected in western or offshore portions of this region.

1.5 BIRDS

By P. G. Connors, S. R. Johnson, and G. J. Divoky

Introduction

Several groups of birds occur in the Sale 71 area of the Alaskan Beaufort Sea; their distribution and abundance varies throughout the area and throughout the spring-to-fall open water period. The following review summarizes relevant information gathered by research units 172, 196 and 467.

Shorelines and Salt marshes

Shorebirds comprise one of the most conspicuous groups of birds in the lease area. Since many species spend part of each year in shoreline habitats which might be altered by offshore oil development, it is important to be aware of their seasonality of use, degree of dependence, and sensitivity of shorebirds to disturbances of these habitats.

Field investigations of shorebirds were conducted by RU 172 at Lonely during 11-14 August 1975, at Oliktok during 28-31 July, 14-16 August, and 27 August 1977, at the Fish Creek Delta during 24-26 June and 26 July-31 August 1980, and during a shoreline habitat survey of the region between the Colville River and Cape Halkett on 21-22 June 1980.

The data given in Table 1.5.1 refer only to data for the 1980 season. We know from other sites that densities may vary severalfold from one year to the next. Analysis of weather patterns and other qualitative observations suggest that 1980 was probably a year of below-average productivity in this area for many species of shorebirds, but no quantitative data are available.

Densities in other salt-marsh areas marked on Fig. 1.5.1 are probably comparable. Most sites not marked would be less used by shorebirds, except that the region near Cape Halkett and west to Lonely is less well known and may contain some areas heavily used by shorebirds.

The low densities in Harrison Bay of Red Phalaropes, Ruddy Turnstones, and Sanderlings, species which use gravel shorelines in August at Barrow, reflect the relative absence of this habitat in the Sale 71 area. These species are more common near barrier islands (Thetis Island), around spits (Oliktok Point), and occasionally along mainland shorelines, such as gravel at Lonely.

The salt-marsh areas of Harrison Bay are heavily used by Canada Geese, White-fronted Geese, and Black Brant for late-summer feeding and for some nesting. Whistling Swans nest in relatively high densities in the Colville Delta and concentrate during September in the Miluveach River drainage. Regions and periods of highest use by these species of waterfowl are marked on Fig. 1.5.1.

The salt-marsh areas of southern Harrison Bay are probably among the most extensive in the central Beaufort Sea; this habitat is important to

Table 1.5.1. Peak densities of shorebirds in the Fish Creek Delta, 1980.

Species	Peak Period	Average Peak Density (Birds/km²)
Golden Plover	20-30 August	35
Semipalmated Sandpiper	26 July - 9 August	437
Western Sandpiper		< 10
Pectoral Sandpiper	26 July - 24 August	10
Stilt Sandpiper	5-19 August	20
Dunlin	5 August - 10 September	282
Long-billed Dowitcher		< 10
Ruddy Turnstone		< 10
Red Phalarope		< 10
Northern Phalarope	5-19 August	26
Snow Bunting		< 10
Lapland Longspur	31 July - 24 August	399

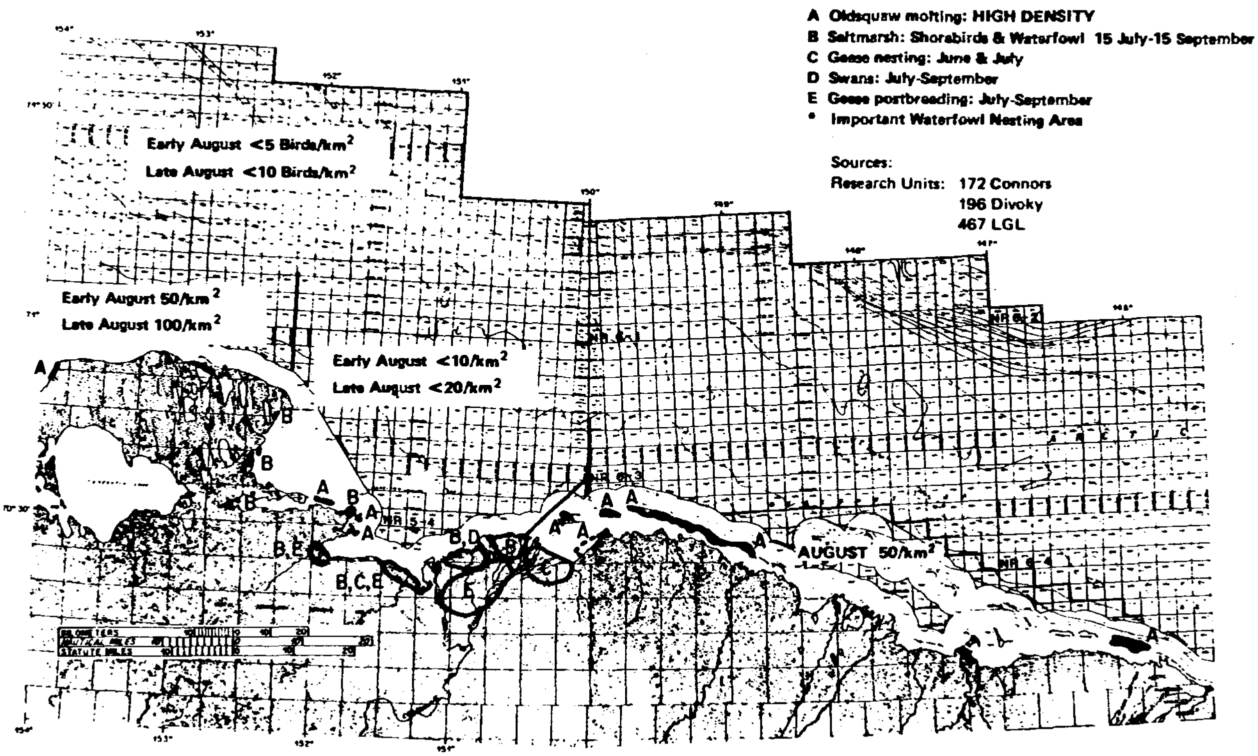


Figure 1.5.1. Waterfowl and Shorebirds.

several species of shorebirds, passerines, and waterfowl found along the Alaska Beaufort coast. Disruption of salt marshes through changes in drainage or elevation or through spills of crude oil or other pollutants might adversely affect large numbers of these birds.

At Barrow, shorebird numbers during post-breeding migration have been found to vary widely from year to year (P. G. Connors, pers. comm.). It is thus difficult to predict the effects of development in Harrison Bay from data collected sporadically over several seasons, and it will be difficult to assess the impact of development or accidents, should they occur.

Inner Harrison Bay and Thetis Island

Oldsquaws represent the single largest component of avian biomass in the nearshore waters of the central Beaufort Sea. Consequently Oldsquaw surveys in the inner Harrison Bay area (see Fig. 2, Johnson and Richardson, 1981) have been conducted during the open water period since 1977. Except for the area immediately south and west of Thetis Island and the area southwest of Oliktok Point, inner Harrison Bay has remarkably low densities (and numbers) of Oldsquaws. Table 1.5.2 compares Oldsquaw densities in this area during the peak of the flightless or molt period (20 July-10 August from 1977 to 1980. The densities and numbers of Oldsquaws in the Thetis Island and Oliktok Point areas are 1-2 orders of magnitude greater than in adjacent turbid and shallow waters of inner Harrison Bay.

Thetis Island represents a distinct habitat in the Harrison Bay -Sale 71 area. It is the only barrier island lying within Harrison Bay, and it provides nesting habitat for a relatively large colony (approximately 40 pairs) of Common Eiders and a small number of Black Brant (6-10 pairs), Arctic Terns (4-6 pairs), and Glaucous Gulls (8-12 pairs). Common Eiders are particularly sensitive to disturbance during incubation (July through early August) and often abandon their eggs at this time.

About 5,000-10,000 Oldsquaws concentrate in the shelter of Thetis Island from 15 July to 15 August. During the molt, Oldsquaws rest in the lee of the island and often move southward (and on calm days, seaward) to feed in an apparent regular daily cycle of activity. The daily cycle peaks with maximum densities of birds near the island in late evening and early morning. Preliminary analyses indicate that this cycle is disrupted by aircraft, boat, and human traffic and noise in the vicinity of the birds. On calm days Oldsquaws were observed moving from Thetis Island toward Oliktok Point indicating that Oldsquaws do have the ability to move from one molting location to another.

If it becomes necessary to construct docking facilities or a logistics center on a barrier island near the Sale 71 areas, it is our view that Spy Island is a more appropriate location than Thetis Island. Although 1,000-10,000 seaducks also molt in the lee of Spy Island from mid-July through mid-August, few birds normally nest on this island. Furthermore, Spy Island is farther seaward than Thetis Island, it lies somewhat in the wind shadow (calm water) of Pingok and Leavitt Islands, and it is closer to the airstrip and logistics facilities at the Oliktok DEW-line station than is Thetis Island.

Table 1.5.2. Average densities (birds/km^2) of Oldsquaws recorded in Harrison Bay compared with other sections of the Beaufort Sea coast.

Date	Harrison Bay	Simpson Lagoon	East of Simpson Lagoon
28, 29 July 1977	-	284.10	-
25 July 1978	50.78	134.94	28.10*
28 July 1979	45.11	148.52	743.86
2 August 1980	36.37	355.26	142.36
Average	44.09	230.71	304.77

*Surveys east of Simpson Lagoon on 25 July 1978 were incomplete because of poor weather (reduced visibility).

Offshore Marine

Shipboard and aerial bird surveys of the areas farther seaward in the lease Sale 71 area have been conducted since 1976. Overall densities of marine birds in nearshore and offshore zones during two periods of the open-water season are shown graphically in Fig. 1.5.1. Densities of marine birds in those areas are not markedly different from densities in other portions of the central Alaskan Beaufort Sea, and no unique species have been recorded in this area.

Data Gaps

A. The recovery rate of an arctic salt marsh after a major environmental insult is presently unknown and would be an important factor in determining the long-term effects of development.

B. Some areas, most notably near Cape Halkett and west to Lonely and the Plover Islands are even less well known than inner Harrison Bay. The basic descriptions of habitats and the seasonal census work remains to be done.

1.6 MARINE MAMMALS

By L. F. Lowry and K. J. Frost

Introduction

Although several species of marine mammals occur in and pass through the Sale 71 area, few occur regularly in significant numbers. Significant species include ringed seals throughout the year, bearded seals primarily in summer, belukha and bowhead whales in late summer-fall, and polar bears in winter-spring. Overall seasonal distribution patterns of major marine mammal species in the Beaufort Sea have been presented geographically and discussed by Eley and Lowry (1978). It should be noted that intensive studies of the distribution of specific marine mammals in the Sale 71 area have not been conducted.

Ringed Seal

Ringed seals occur throughout the ice-covered areas of the Beaufort Sea. During spring, adults give birth to and nurture young, then breed. In June, seals haul out during the annual molt. Adult seals are fairly well dispersed over the ice, usually occurring near collapsed birth lairs, while subadults congregate along leads and cracks. Estimates of density of hauled-out seals along the Beaufort Sea coast (Table 1.6.1) indicate lowest densities in the area between Lonely and Oliktok, which includes much of the Sale 71 area.

During summer, ringed seals are much more mobile, more difficult to enumerate, and often less uniformly distributed. Observations from icebreakers and small boats show that seals during summer are more common over the continental shelf than in deeper water. Observations made in August and September 1980 indicate similar overall abundance near Harrison Bay and eastward to the Canadian border (Fig. 1.6.1). Local areas of high seal abundance have been observed several times during August-September in the eastern portion of the sale area (Table 1.6.1). In one instance, seals in a high-density area were feeding intensively on hyperiid amphipods. Arctic cod, mysids, and gammarid amphipods are seasonally important foods in and near the sale area (Table 1.6.2).

Bearded Seal

Bearded seals are largely excluded from the sale area during winter by continuous heavy ice. During summer, bearded seals occur in low numbers along the entire Beaufort Sea coast. Abundance decreases from west to east; in August-September 1980, bearded seals were six times more abundant near Harrison Bay than east of Barter Island. In the central Beaufort Sea bearded seals eat a variety of benthic organisms including crabs, shrimp, isopods, amphipods, clams, snails, and fishes.

Polar Bear

In Alaska, polar bears usually maintain a year-round association with sea ice. During summer, pack ice normally carries bears north of the sale

Table 1.6.1. Ringed seal density estimates (number seals sighted/km^2) along various sectors of the Beaufort Sea coast.

Year	Barrow-Lonely[1]	Lonely-Oliktok[1]	Oliktok-Flaxman I.[1]	Flaxman I.-Barter I.[1]	Yukon Coast[2]	Average of Means
1970	0.68	0.32	0.41	0.73	--	0.54
1974	--	--	--	--	0.52	--
1975	0.84	0.42	0.30	0.54	0.21	0.46
1976	0.42	0.33	0.42	0.12	--	0.32
1977	0.30	0.15	0.21	0.36	--	0.26
Average of Means	0.56	0.30	0.34	0.44	0.36	

[1]Burns and Harbo 1972; Burns and Eley 1978

[2]Stirling et al. 1977

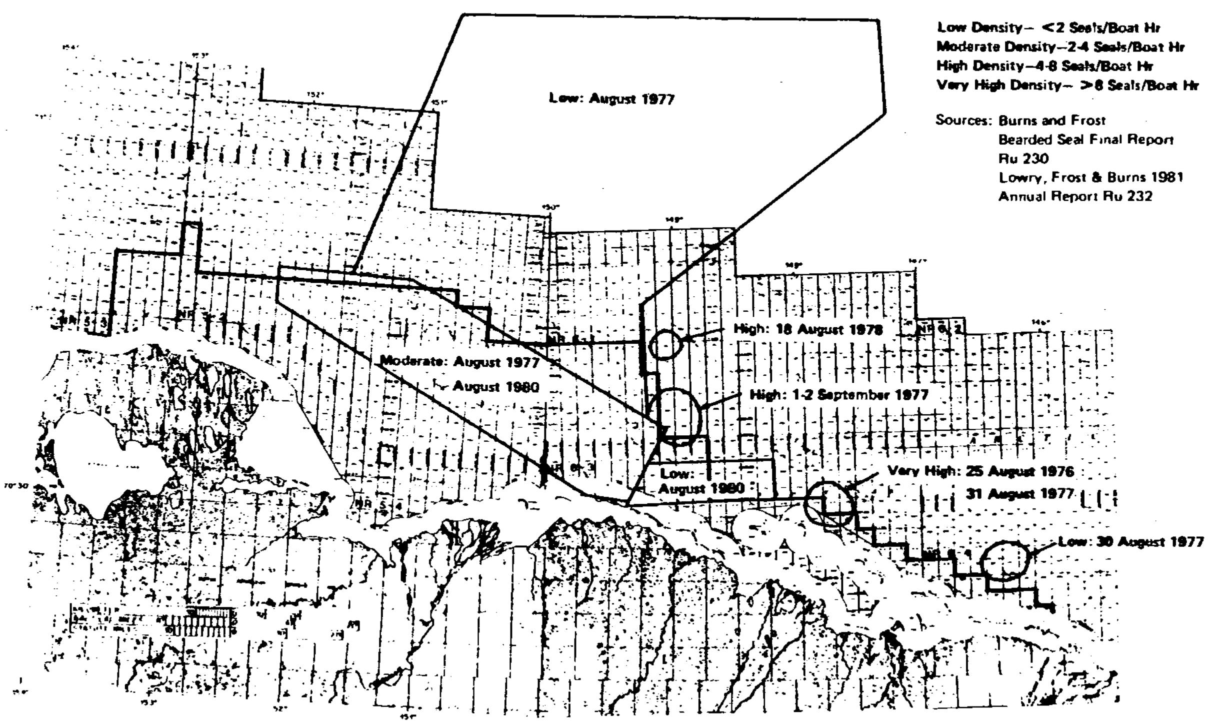


Figure 1.6.1. Summer Ringed Seal Abundance.

Table 1.6.2. Ringed seal stomach contents from samples collected in the central portion of the Alaskan Beaufort Sea. Values given are the mean percent of the total contents comprised of each prey type.

Prey Type	Prudhoe Nov 1977	Prudhoe Nov 1978	Prudhoe Feb 1979	Prudhoe May 1979	Pingok Aug 1980	Prudhoe Sept 1977
Euphausiid	--	--	2	--	< 1	--
Mysid	--	45	--	3	< 1	4
Hyperlid amphipod	12	7	--	--	< 1	92
Grammarid amphipod	--	30	--	44	< 1	1
Shrimp	--	--	--	13	1	--
Other invertebrate	--	--	--	29	--	--
Arctic cod	86	6	96	9	98	2
Other fishes	1	< 1	1	2	< 1	< 1
Mean volume of contents (mℓ)	168	148	248	22	150	216
Depth range (m)	30-60	4-10	20-40	20-40	14-21	20-30
Sample size	19	22	24	5	8	13

area. During winter, males and subadults roam the ice while females construct dens in which they bear and nurse their young. Maternity dens, which usually occur on land, have been located adjacent to the sale area near Prudhoe Bay and on Pingok Island. Mothers and young emerge from dens in spring and move onto the sea ice; there they join other bears in search of food, which is composed primarily of ringed seals.

Belukha Whale

A large proportion of the Alaskan population of belukha whales (probably 6,000-7,000 animals) summers in the Mackenzie River Delta area. While migrating to the delta in spring, belukhas use lead systems north of the Sale 71 area. During their fall westward migration, belukhas sometimes pass through the area. They have been seen north of Prudhoe Bay in August and offshore from Pingok and Thetis Islands in September. Their diet in the area is unknown, but Arctic cod are probably an important prey item.

Bowhead Whale

Bowhead whales migrate to their summer feeding areas in the eastern Beaufort Sea using offshore lead systems. Few summer along the Alaskan portion of the Beaufort Sea coast. Bowheads migrate westward during September and October, usually remaining in nearshore waters and passing through the Sale 71 area. Feeding has been confirmed in the areas east of Barrow and near Barter Island, and probable feeding behavior has been observed just northwest of Narwhal Island. Major known foods of bowheads are euphausiids and copepods.

Potential Effects of OCS Development

The potential effects of OCS development on marine mammals have been described in detail by Burns (1978) and Eley and Lowry (1978). The data are general and, though relevant to the Beaufort Sea as a whole, are not specific to the Sale 71 area.

Studies of the responses of bowhead whales to disturbance have recently been conducted in the Canadian sector of the Beaufort Sea (Fraker et al., 1981). The results suggest that on the summer feeding grounds in the Canadian Beaufort the response shown by whales varies with the type of disturbance. Experimental studies planned for 1981 are intended to quantify the type of response shown to disturbances of various types and intensity.

Data Gaps

A. Research is needed to determine the effects of industrial activities on marine mammals and to develop techniques to minimize these effects. In particular, the effects of seismic exploration and the operation of other noise-generating equipment on ringed seals should be examined. A pilot project undertaken in winter 1981 to address this issue should be continued. This problem will recur in other lease areas in the Chukchi and Beaufort Seas and must be resolved.

B. The denning areas of polar bears in the Sale 71 area in particular and in the Beaufort Sea in general are poorly known. Den sites have been reported on Pingok Island and near Prudhoe Bay. Studies should be continued to determine major denning areas.

C. Although winter foods of ringed seals in the Beaufort Sea are fairly well known, the summer foods and the factors affecting the relative importance of those foods are not.

D. Information is needed on the distribution, abundance, and natural history of Arctic cod. Arctic cod is the most numerous offshore fish in the Beaufort sea. It is a major prey of ringed seals, many species of seabirds, and probably belukha whales. It is a major consumer of zooplankton and nekton and may be a significant trophic competitor of bowhead whales and ringed seals.

E. The summer distribution of ringed seals in the Sale 71 area, particularly the easternmost area, should receive further study. Relatively high densities of ringed seals occurred at the eastern end of Harrison Bay (north of the Jones Islands) and north of Cross Island in 1976-1978. It is unknown whether high densities occur in the same areas from year to year or why seals are attracted to those areas.

1.7 BIBLIOGRAPHY

Adams, W. A. 1975. Light intensity and primary productivity under sea ice containing oil. Beaufort Sea Project Tech. Rep. #29. Beaufort Sea Project, Dep. Environ., Victoria, B.C. 156 pp.

Alexander, V. 1974. Primary productivity regimes of the nearshore Beaufort Sea, with reference to potential roles of ice biota, pp. 609-632. In: J. C. Reed and J. E. Sater (eds.), The Coast and Shelf of the Beaufort Sea. Arctic Inst. N. Am. Arlington, Va.

Alexander, V. 1975. Environmental Studies of an Arctic Estuarine System - Final Report. Environmental Protection Agency Report, EPA 600/3-75-026. U.S. Government Printing Office.

Alexander, V. 1980. Interrelationships between the seasonal sea ice and biological regimes. Cold Regions Sci. and Technol. 2:157-178.

Alt, K. T., and D. R. Kogl. 1973. Notes on the whitefish of the Colville River, Alaska. In: J. Fish. Res. Bd. Can., 30:554-556.

Arnborg, L., H. J. Walker, and J. Peippo. 1967. Syspended load in the Colville River, Alaska, 1962. Geografiska Annal 49:133-144.

Berk, S. G., D. C. Brownlee, D. R. Heinle, H. J. Kling, and R. R. Colwell. 1977. Ciliates as a food source for marine planktonic copepods. Microbiol. Ecol. 4:27-40.

Bernard, F. R. 1979. Bivalve molluscs of the western Beaufort Sea. Contrib. Sci. Natur. Hist. Mus., Los Angeles County, 313. 80 pp.

Bilyard, G. R., and A. G. Carey, Jr. 1979. Distribution of western Beaufort Sea polychaetous annelids. Marine Biology, 54:329-339.

Bilyard, G. R., and A. G. Carey, Jr. 1980. Zoogeography of western Beaufort Sea Polychaeta (Annelida). Sarsia, 65:19-26.

Broad, A. C. 1976. Littoral survey of the Beaufort Sea. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 7:579-592.

Broad, A. C. 1977. Reconnaissance characterization of littoral biota, Beaufort and Chukchi Seas. Environmental assessment of the Alaska continental shelf. NOAA/OCSEAP Ann. Rep., 9:109-274.

Broad, A. C. 1978. Reconnaissance characterization of littoral biota, Beaufort and Chukchi Seas. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 5:1-84.

Broad, A. C., A. Benedict, K. Dunton, H. Koch, D. T. Mason, D. E. Schneider, and S. V. Schonberg. 1979. Environmental assessment of selected habitats in the Beaufort and Chukchi littoral system. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 3:361-542.

Burns, J. J. (ed.). 1978. Probable impacts and consequences of oil development, pp. 288-320. In: Weller et al., Interim Synthesis: Beaufort/Chukchi. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP. 362 pp.

Burns, J. J., and T. J. Eley. 1976. The natural history and ecology of the bearded seal, Erignathus barbatus, and the ringed seal Phoca (Pusa) hispida. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 1:263-294.

Burns, J. J., and T. J. Eley. 1977. The natural history and ecology of the bearded seal, Erignathus barbatus, and the ringed seal Phoca hispida. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 1:226-302.

Burns, J. J., and T. J. Eley. 1978. The natural history and ecology of the bearded seal Erignathus barbatus, and the ringed seal Phoca hispida. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 1:99-162.

Burns, J. J., and F. H. Fay. 1976. The relationships of marine mammal distributions, densities and activities to sea ice conditions. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 1:387-430.

Burns, J. J., and S. J. Harbo, Jr. 1972. An aerial census of ringed seals, northern coast of Alaska. Arctic 25:279-290.

Burns, J. J., and L. F. Lowry. 1976. Trophic relationships among ice inhabiting phocid seals. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 1:303-332.

Burns, J. J., L. Shapiro, and F. H. Fay. 1977. The relationships of marine mammal distributions, densities and activities to sea ice conditions. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 2:503-554.

Busdosh, M., and R. M. Atlas. 1977. Toxicity of oil slicks to Arctic amphipods. Arctic 30:85-92.

Carey, A. G., Jr. 1976a. Summarization of existing literature and unpublished data on the distribution, abundance and life histories of benthic organisms of the Beaufort Sea. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 5:257-712.

Carey, A. G., Jr. 1976b. The distribution, abundance, diversity and productivity of the western Beaufort Sea benthos. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 5:219-256.

Carey, A. G., Jr. 1977a. Summarization of existing literature and unpublished data on the distribution, abundance and life histories of benthic organisms. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 5:54-858.

Carey, A. G., Jr. 1977b. The distribution, abundance, diversity, and productivity of the western Beaufort Sea benthos. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 6:1-53.

Carey, A. G., Jr. 1978. The distribution, abundance, diversity and productivity of the western Beaufort Sea benthos. Environmental Assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 4:127-252.

Carey, A. G., Jr. 1979. The distribution, abundance, diversity and productivity of the western Beaufort Sea benthos. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 3:208-360.

Carey, A. G., Jr., and R. E. Ruff. 1977. Ecological studies of the benthos in the western Beaufort Sea with special reference to bivalve molluscs. pp. 505-530. In: M. J. Dunbar (ed.), Polar oceans. Arctic Inst. N. Am., Calgary, Alberta.

Carey, A. G. Jr., R. E. Ruff, J. G. Castillo, and J. J. Dickinson. 1974. Benthic ecology of the western Beaufort Sea continental margin: preliminary results. pp. 665-680. In: J. C. Reed and J. E. Slater (eds.), The coast and shelf of the Beaufort Sea, Arctic Inst. N. Am., Arlington, Va.

Chia, F. S. 1970. Reproduction of Arctic marine invertebrates. Mar. Pollut. Bull. 1:78-79.

Clasby, R. C., R. Horner, and V. Alexander. 1973. An in situ method for measuring primary productivity of Arctic sea ice algae. J. Fish. Res. Bd. Can. 30:835-838.

Clasby, R. C., V. Alexander, R. Horner. 1976. Primary productivity of sea-ice algae. pp. 290-304. In: D. W. Hood, and D. E. Burrell (eds.), Assessment of the Arctic marine environment. Inst. Mar. Science, Univ. Alaska, Fairbanks.

Connors, P. G., and R. W. Risebrough. 1978. Shorebird dependence on Arctic littoral habitats. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 2:84-166.

Connors, P. G., and R. W. Risebrough. 1979. Shorebird dependence on Arctic littoral habitats. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 1:271-329.

Connors, P. G., and R. W. Risebrough. 1977. Shorebird dependence on Arctic littoral habitats. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 2:402-554.

Connors, P. G., K. G. Smith, and J. P. Myers. 1981. Annual variation in numbers of breeding and post-breeding shorebirds in Arctic Alaska. Abstract of paper presented at Cooper Ornithological Society meeting, May 1981.

Conover, R. G. 1967. Reproductive cycle, early development, and fecundity in laboratory populations of the copepod Calanus hyperboreus. Custaceana 13:61-72.

Craig, P. C. 1978. Beaufort Sea barrier island-lagoon ecological process studies: Ecology of fishes in Simpson Lagoon. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 7:587-664.

Craig, P. C., and W. Griffiths. 1979. Beaufort Sea barrier island-lagoon ecological process studies: Ecology of fishes in Simpson Lagoon, Beaufort Sea, Alaska. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 6:363-471.

Craig, P. C., and W. Griffiths. 1981. Studies of fish and epibenthic invertebrates in coastal waters of the Beaufort Sea. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. (in press).

Craig, P. C., and L. Haldorson. 1981. Beaufort Sea barrier island-lagoon ecological process studies: Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Final Rep. Biol. 7:384-678.

Divoky, G. J. 1976. The distribution, abundance and feeding ecology of birds associated with the Bering and Beaufort Sea pack ice. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 3:53-106.

Divoky, G. J. 1977. The distribution, abundance and feeding ecology of birds associated with pack ice. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 2:525-573.

Divoky, G. J. 1978. Identification, documentation and delineation of coastal migratory bird habitats in Alaska. Part I: Breeding bird use of barrier islands in the northern Chukchi and Beaufort Seas. Part II: Feeding habitats of birds in the Beaufort Sea. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 1:482-569.

Divoky, G. J., and A. E. Good. 1979. The distribution, abundance and feeding ecology of birds associated with pack ice. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 1:330-559.

Eley, T., and L. F. Lowry (eds.). 1978. Marine mammals. pp. 134-151. In: Weller et al. Interim Synthesis: Beaufort/Chukchi. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP, 362 pp.

Fenchel, T. 1968. The ecology of marine microbenthos. II. The food of marine benthic ciliates. Ophelia 5:73-121.

Fraker, M. A., C. R. Greene, and B. Wursig. 1981. Disturbance responses of bowheads and characteristics of waterborne noises. pp. 91-95. In: W. J. Richardson (ed.), Behavior, disturbance responses and feeding of bowhead whales in the Beaufort Sea, 1980. LGL Ecological Research Associates, Inc. Unpub. MS.

Frost, K., L. Lowry, and J. Burns. 1978. Offshore demersal fishes and epibenthic invertebrates of the northeastern Chukchi and western Beaufort seas. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 1:231-365.

Furniss, R. 1975. Inventory and cataloging of arctic area waters. Alaska Dep. Fish Game Ann. Rep. 16.

Galbraith, D. F., and J. G. Hunter. 1979. Fishes of offshore waters and Tuktoyaktuk vicinity. Interim Beaufort Sea Tech. Rep. No. 7, Canada Dep. of Environ., Victoria, B.C.

Grainger, E. G. 1975. Biological productivity of the southern Beaufort Sea: the physical and chemical environment of the plankton. Beaufort Sea Project Tech. Rep. #12a. Beaufort Sea Project, Dep. Environ., Victoria, B.C.

Griffiths, W. B. 1978. Beaufort Sea barrier island-lagoon ecological process studies: Invertebrates in Simpson Lagoon. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 6:665-757.

Griffiths, W. B., and P. C. Craig. 1979. Beaufort Sea barrier island-lagoon ecological process studies: Ecology of invertebrates in Simpson Lagoon, Beaufort Sea, Alaska. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 6:471-601.

Griffiths, W. B., and R. E. Dillinger. 1981. Beaufort Sea barrier island-lagoon ecological process studies: Invertebrates. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Final Rep. Biol. 8:1-198.

Hablett, T. R. 1979. Fish inventories conducted within the National Petroleum Reserve on the North Slope of Alaska, 1977-78. In: Studies of selected wildlife and fish and their use of habitats on and adjacent to the national petroleum reserve in Alaska 1977-1978 2. U.S. Dep. Interior 105(c) Land Use Study.

Hansen, W., E. Bulleid, and M. J. Dunbar. 1971. Scattering layers, oxygen distribution and copepod plankton in the upper 300 meters of the Beaufort Sea. McGill Univ. Mar. Sci Centre Ms. Rep. 20, 84 pp.

Heinrich, A. K. 1962. The life histories of plankton animals and seasonal cycles of plankton communities in the oceans. J. of Cons. Perm. Int. Explor. Mer. 27:15-24.

Horner, R. A. 1976. Sea ice organisms. Oceanogr. Mar. Biol. Ann. Rev. 14:167-182.

Horner, R. A. 1977. History and recent advances in the study of ice biota. pp. 269-284. In: Dunbar, M. J. (ed.), Polar Oceans, Arctic Inst. N. Am., Calgary, Alberta.

Horner, R. A. 1978. Beaufort Sea plankton Studies. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 5:85-142.

Horner, R. A. 1979. Beaufort Sea plankton studies. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 3:543-639.

Horner, R. 1981. Beaufort Sea plankton studies. Final report on Beaufort Sea icebreaker studies. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Final Rep. Biol. 13:65-314.

Horner, R., and V. Alexander. 1972. Algal populations in Arctic sea ice: an investigation of heterotrophy. Limnol. and Oceanography 17:454-458.

Horner, R., K. O. Coyle, and D. R. Redburn. 1974. Ecology of the plankton of Prudhoe Bay, Alaska. Univ. of Alaska, Inst. of Marine Science Rep. R74-2; Sea Grant Rep. 73-15. 78 pp.

Horner, R., and G. C. Schrader. In press. Beaufort Sea plankton studies: winter - spring studies in Stefansson Sound and off Narwhal Island, Nov. 1978 - June 1980. Environmental assessment of the Alaskan continental shelf. Final Rep. Biol.

Hsiao, S. I. C. 1978. Effects of crude oils on the growth of Arctic marine phytoplankton. Environ. Poll. 17:93-107.

Hsiao, S. I. C 1980. Quantitative composition, distribution, community structure and standing stock of sea ice microalgae in the Canadian arctic. Arctic 33:768-793.

Hsiao, S. I. C., D. W. Kittle, and M. G. Foy. 1978. Effects of crude oil and the oil dispersant Corexit on primary production of Arctic marine phytoplankton and seaweed. Environ. Poll. 15:209-221.

Johnson, S. R. 1978. Beaufort Sea barrier island-lagoon ecological process studies: avian ecology in Simpson Lagoon. Environ. assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 7:467-586.

Johnson, S. R. 1979. Beaufort Sea barrier island-lagoon ecological process studies. Avian ecology in Simpson Lagoon, Beaufort Sea, Alaska. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 6:238-363.

Johnson, S. R., and W. J. Richardson. 1981. Beaufort Sea barrier island-lagoon ecological process studies: Birds. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Final Rep. Biol. 7:109-383.

Kogl, D. R. 1972. Monitoring and evaluation of Arctic waters with emphasis on the North Slope drainages: Colville River. Alaska Dep. Fish Game Ann. Rep. 12:23-61.

Lowry, L. F., K. J. Frost, and J. J. Burns. 1977. Trophic relationships among ice inhabiting phocid seals: Final report on Beaufort Sea activities. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Final Rep. Biol. 1:391432.

Lowry, L. F., K. J. Frost, and J. J. Burns 1978. Trophic relationships among ice inhabiting phocid seals. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 1:161-372.

Lowry, L. F., K. J. Frost, and J. J. Burns. 1979. Trophic relationships among ice inhabiting phocid seals and functionally related marine mammals: Final report of Beaufort Sea activities. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Final Rep. Biol. 6:573-629.

Lowry, L. F., K. J. Frost, and J. J. Burns. 1981. Trophic investigations. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. (in press).

Matheke, G. E. M., and R. Horner. 1974. Primary productivity of the benthic microalgae in the Chukchi Sea near Barrow, Alaska. J. Fish. Res. Bd. Can. 31:1779-1786.

McElderry, H., and P. Craig. 1981. A fish survey in the lower Colville River drainage with an analysis of spawning use by arctic and least cisco. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Final Rep. Biol. 7:657-678.

Montagna, P. A. 1979. Cervinia lagni n.sp. and Pseudocervinia magna (Copepoda: Harpacticoida) from the Beaufort Sea (Alaska, USA). Trans. Amer. Micros. Soc. 98:77-88.

Montagna, P. A. 1980. Two new bathyal species of Pseudotachidius (Copepoda: Harpacticoida) from the Beaufort Sea (Alaska, USA). J. of Nat. Hist. 14:567-578.

Montagna, P. A., and A. G. Carey, Jr. 1978. Distributional notes on Harpacticoida (Crustacea: Copepoda) collected from the Beaufort Sea (Arctic Ocean). Astarte 11:117-122.

Moulton, L., K. Tarbox, and R. Thorne. 1980. Beaufort Sea fishery investigations: Summer 1979. Woodward-Clyde Consultants. Unpub. MS.

Percy, J. A. 1977. Responses of Arctic marine benthic crustaceans to sediments contaminated with crude oil. Environ. Poll. 13:1-10.

Percy, J. A., and T. C. Mullin. 1975. Effects of crude oils on Arctic marine invertebrates. Beaufort Sea Project Tech. Rep. #11. Beaufort Sea Project, Dept. Environ., Victoria, B.C., 167 pp.

Sanborn, H. R. 1978. Effects of petroleum on ecosystems, Vol. 2. pp. 337-357. In: D. C. Malins, (ed.), Effects of Petroleum on Arctic and Subarctic Marine Environments and Organisms. Academic Press, New York.

Schell, D. M. 1974. Regeneration of nitrogenous nutrients in arctic Alaska estuarine waters. pp. 649-664. In: J. C. Reed and J. E. Sater (ed.), The coast and shelf of the Beaufort Sea. Arctic Inst. of N. Am., Arlington, Va.

Schell, D. M. 1975. Seasonal variation in the nutrient chemistry and conservative constituents in coastal Alaskan Beaufort Sea waters. pp. 233-398. In: Alexander et al. (eds.), Environmental studies of an Arctic estuarine system. Environ. Protec. Agency Rep. EPA-660/3 75-026.

Schell, D. M. 1978. Nutrient dynamics of near shore under-ice waters, Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 6:469-496.

Schell, D. M. 1979. Nutrient dynamics in nearshore Alaskan Beaufort Sea waters. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 5:143-190.

Schell, D. M. 1980. Food web and nutrient dynamics studies in nearshore Alaskan Beaufort Sea waters. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 2:467-515.

Schell, D. M. 1981. Primary production trophic dynamics and nutrient regimes of the Harrison Bay-Sale 71 area. Research Summary Report to OCS Arctic Project Office. Unpub. MS.

Schneider, D. E., and H. Koch. 1979. Trophic relationships of the Arctic shallow water marine ecosystem. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 3:503-542.

Stirling, I., W. R. Archibald, and D. DeMaster. 1977. Distribution and abundance of seals in the eastern Beaufort Sea. J. Fish. Res. Bd. Can. 34:976-988.

Walker, H. J. 1973. Spring discharge of an Arctic river determined from salinity measurements beneath sea ice. Water Resources Res., 9:474-480.

Walker, H. J. 1974. The Colville River and the Beaufort Sea: Some interactions. pp. 513-542. In: J. C. Reed and J. E. Sater (eds.), The Coast and Shelf of the Beaufort Sea. Arctic Inst. N. Am., Arlington, Va.

Weller, G. E., D. W. Norton, and T. Johnson (eds.), 1978. Interim Synthesis: Beaufort/Chukchi. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP 362 pp.

SECTION I. CHARACTERIZATION OF SALE 71 ENVIRONMENTS

Chapter 2. Circulation in the Sale 71 Area
J. B. Matthews, Editor

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2.1 WINDS

By T. L. Kozo

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

Except for that from the few NWS stations, wind information for the coastal and offshore regions is sparse, although recent work is filling data gaps. The traditional method of obtaining surface winds from geostrophic winds computed from the surface pressure field is hampered by a lack of data, both inland from the coast and offshore. Carsey (1977) has shown that data from coastal stations with some 550 km separation, viz. Barrow and Barter Island, can lead to significant forecasting errors. For example, Fig. 2.1.1, taken from Carsey, shows the increased detail in the pressure field when data from OCS buoys and additional measuring sites on land were added to the NWS data set. Geostrophic wind directions in the two analyses differ by as much as 60°.

The use of inland stations (e.g., Umiat or Prudhoe Bay Airport) to deduce coastal winds is further complicated by a sea breeze circulation (cf. Moritz, 1977), which is generated by the land-sea temperature gradient. During summer, the air over the land may warm to 15-20°C, while that over the water is only -1° to 5°C. Studies by Kozo (1979b) in the summers of 1976 and 1977 suggest that the sea breeze occurs about one-third of the time. The sea breeze is most pronounced in the shallow nearshore region, precisely where one would expect an important wind-driven effect on the circulation.

In August, the main open-water month, wind statistics for the North Slope (based on 20 years of data [Brower, et al., 1977]) from Oliktok, Lonely, Barter, and Barrow compare favorably with measurements by Kozo (1979a). There is a striking correlation in speed and direction data from coastal surface wind stations that are less than 100 km apart (Leavitt, 1978). During normal August wind conditions, the surface winds blow from between 30° and 90°, 60 percent of the time, and wind speeds are less than 6 m/s 65 percent of the time. The wind data collected in August 1980 for the Sale 71 lease area (Harrison Bay and vicinity) were atypical because the winds were predominantly from 270°-210° (39 percent of the time). The

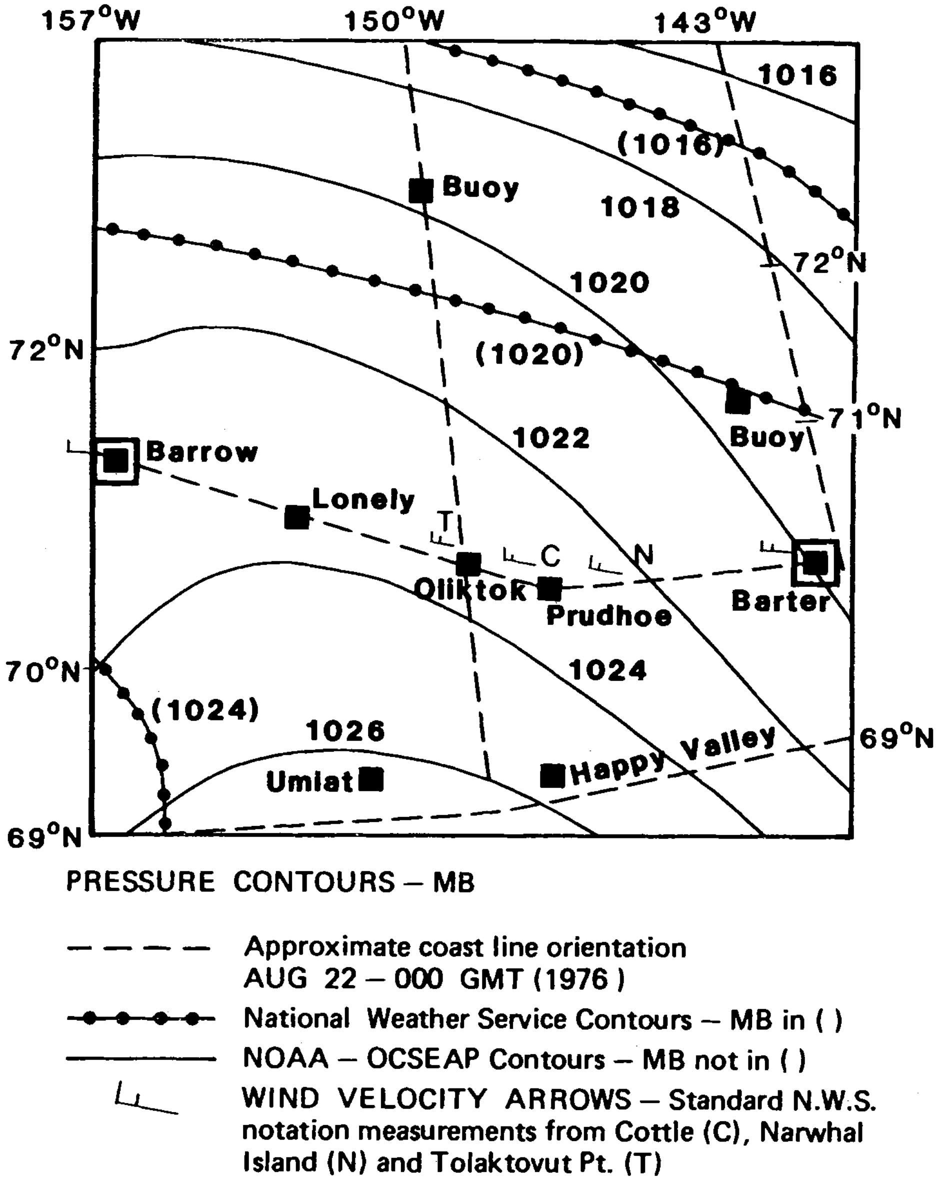

Figure 2.1.1. Example of increased resolution in National Weather Service surface pressure map, shown when data from OCSEAP buoys and additional shore stations supplement data from the two NWS coastal stations (Carsey, 1977).

period 17 August - 10 September 1980 was characterized by predominantly westerly winds. This phenomenon brought the sea ice edge close enough to the shoreline to fill the unprotected portion of Harrison Bay by late August. The normally greater fetch area of the bay led to larger wave-wave heights and wind-induced shallow water disturbances, resulting in more resuspended sediments.

Two mesoscale atmospheric effects operate on coastal winds: mountain barrier baroclinity (orographic effects) and sea breezes. The mountain barrier effects are induced during the arctic winter when the atmosphere is very stable. Since Harrison Bay is more than 160 km from the axis of the Brooks Range, this effect is small in the Sale 71 area (Kozo, 1980) and would be negligible during the summer open-water season when the boundary layer over land approaches neutral stability. The summer land-sea temperature gradient generates a sea breeze circulation (Kozo, 1979b) which occurs during about 25 percent of the summer data collection season. Evidence indicates that the sea breeze will affect the resultant surface wind direction for geostrophic winds (synoptic scale) of less than 10 m/s velocity in at least a 40-km zone centered on the coastline. A E-directed sea breeze following storm surge relaxation can push oil spills onto the unprotected shoreline previously covered by water. The sea breeze can also have a masking effect when one tries to relate coastal wind measurements to ice edge motion. In Fig. 2.1.2, the actual surface wind direction at Cross Island (1979) is compared to the calculated geostrophic wind (VG). At 0600 GMT (1500 ADT) on 3 August, the sea breeze caused the surface wind to change from 240° to 70°. A similar change began on 5 August. The resultant ice-edge position on 5-7 August and movement of buoys seen in Fig. 2.1.3 are evidence that the wind stress applied out on the polar pack was continuously from the northwest from 2 to 5 August.

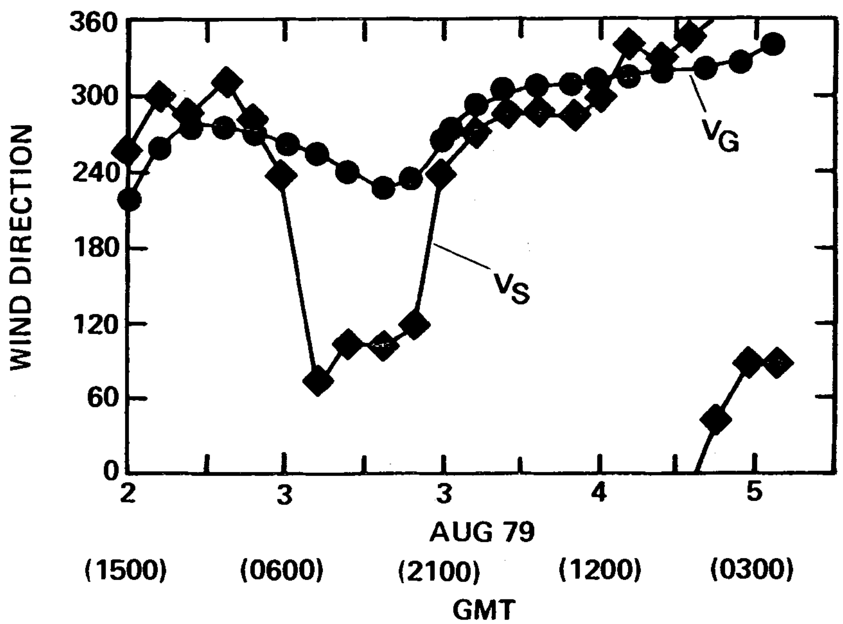

Figure 2.1.2. A simultaneous comparison of the calculated geostrophic wind (V_G) direction with the surface wind (V_S) direction on Cross Island from 2 August to 5 August 1979. This is the time period designated period 2-3 in Figure 2.1.3.

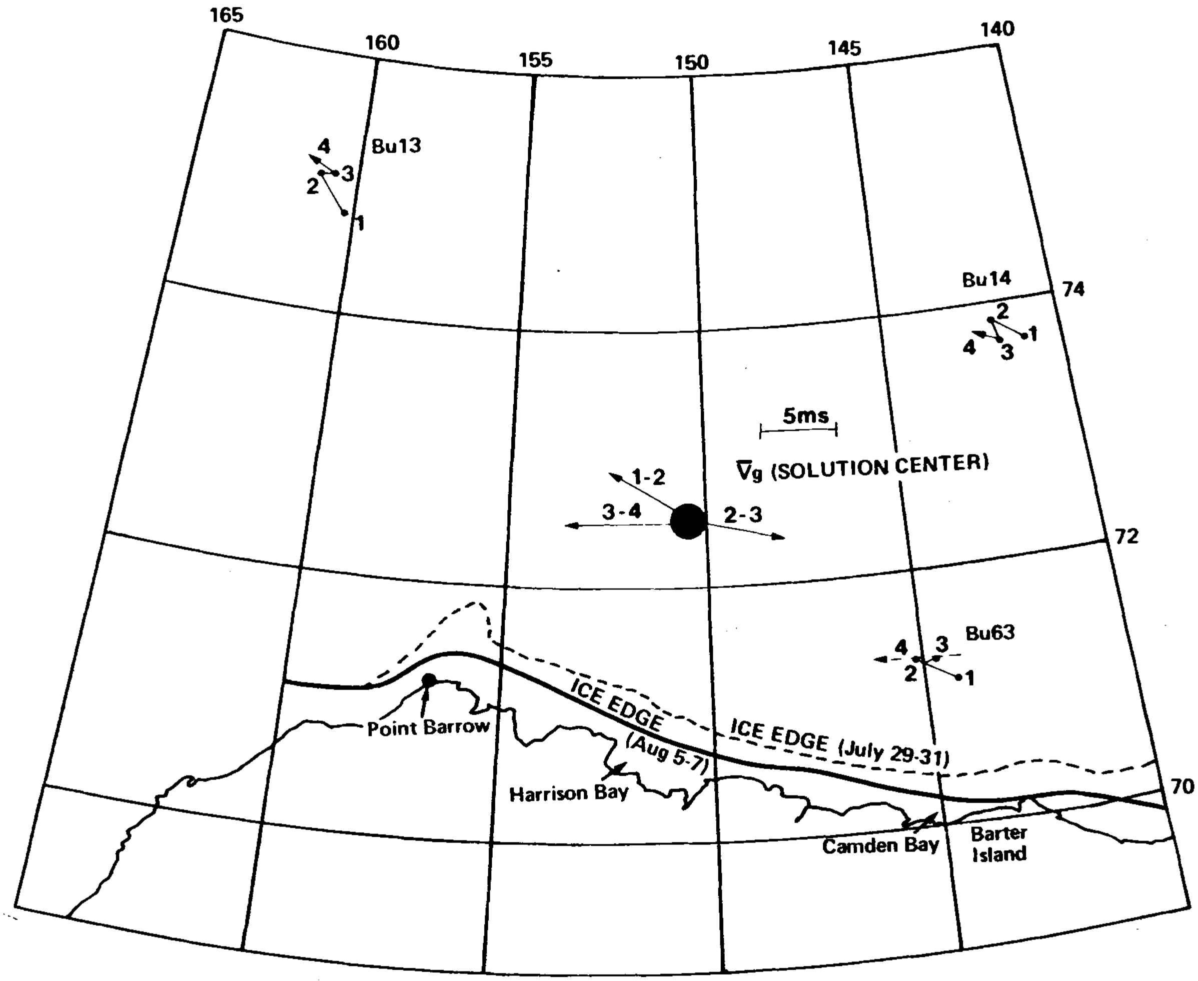

Figure 2.1.3. The ice edge position on days 29-31 July 79 compared to the position on 5-7 August 79. Buoy movements for Bu 13, Bu 14 (ABB array) and Bu 63 (OCS) are shown. The solution center for the calculated geostrophic winds is plotted. The arrows indicated the average geostrophic wind velocity for 27 July - 2 August (1-2), 2-5 August (2-3) and 5-7 August (3-4). The dashed line for Bu 63 means that the buoy position was known 3 August and 7 August but not between these dates.

A data collection system has been established which allows analysis over triangular areas between stations. Pressure station (P) triangles (Fig. 2.1.4), now exist for the following combinations of sites.

A. Point Barrow (NWS), Franklin Bluffs (permanent OCS buoy station), and Barter Island (NWS), with a geostrophic wind solution center at B.

B. Point Barrow, Franklin Bluffs and Narwhal Island (permanent OCS buoy station - McClure Islands), with a geostrophic wind solution at A.

C. Narwhal Island, Franklin Bluffs, and Barter Island, with a geostrophic wind solution center at C.

The pressure data from buoys at Franklin Bluffs and Narwhal Island can be obtained within 3 hours after measurement through the French system ARGOS and can be coupled with data from Point Barrow and Barter Island to yield near-real-time estimates of coastal winds.

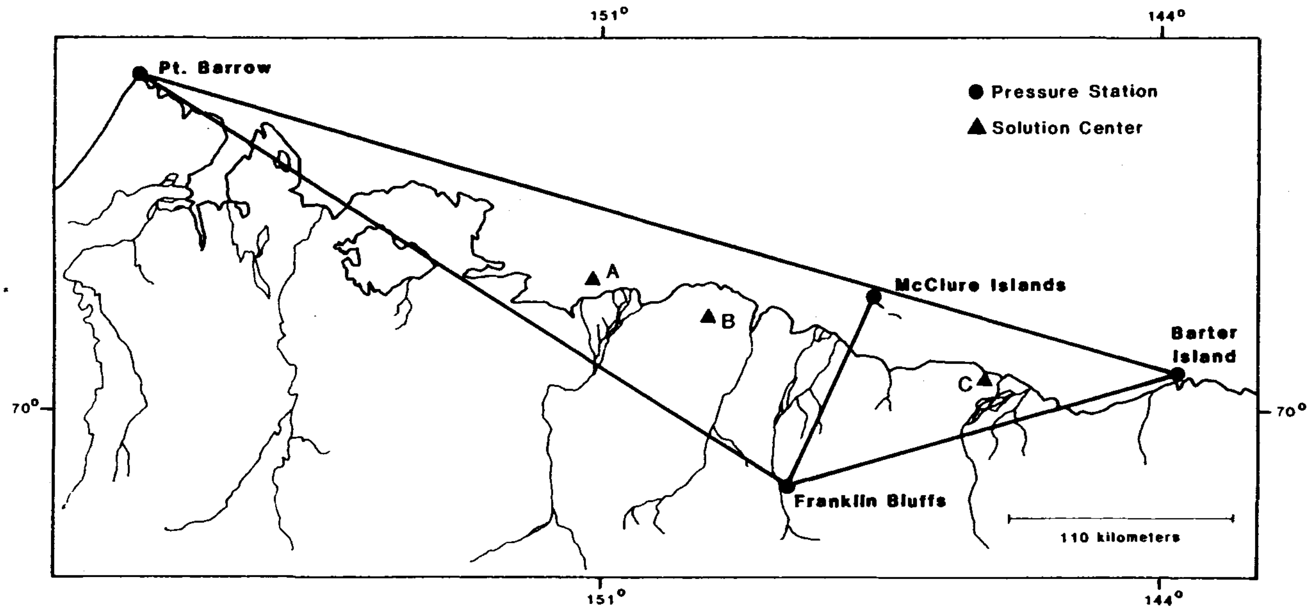

Figure 2.1.4. Positions of pressure stations (P) which can furnish year-round data to calculate geostrophic winds for the Beaufort Sea Coast. The Pt. Barrow, Franklin Bluffs, McClure Islands pressure triangle has a geostrophic wind solution center at A. The Pt. Barrow, Franklin Bluffs, Barter Island triangle has a solution center at B. The Franklin Bluffs, McClure Islands, Barter Island triangle has a solution center at C.

Nearshore Regime

Almost no data are available in the nearshore regions off Harrison Bay. There have been some modeling attempts but these are unverified. Emphasis is therefore given to field measurements.

In the summer 1980 data were taken from an array of current meters and tide gauges. As a result of severe storm conditions only a few of the instruments were recovered. The data from these instruments is very interesting since we can compare conditions under the prevailing wind regime and during storm conditions. Moreover, the loss of the scientific equipment clearly illustrates the exposed nature of Harrison Bay.

Fig. 2.1.5 shows the location of the current meters north of Atigaru Point and west of Thetis Island. Fig. 2.1.6 shows temperature and salinity records at 3 m and 6.25 m in 8 m water north of Atigaru Point. Mean salinities and temperature were 24.6 °/₀₀ and 3.6°C and 27.1 °/₀₀ and 3.9°C at the upper and lower instruments. It is evident that a two layer system exists with fresher water derived from river water overlying more saline oceanic water. On 3 and 4 August a bolus of brackish water (< 25 °/₀₀) was observed flowing past the instruments followed by colder more saline water. This has been observed for the Sag and Kuparuk Rivers (Matthews 1980b). The currents are variable with a net westward drift of about 15 km in 15 days. Fig. 2.1.7 shows salinity, temperature, and current vectors at 3-m depth in 5 m water off Thetis Island. Mean salinity was 23.7 °/₀₀ and temperature 3.3°C. This is more fresh than observed off Atigaru Point and reflects the proximity to the Colville River. Currents averaged only 2.5 cm to the southwest although peak currents were 95 cm/s at the beginning of a storm in mid August.

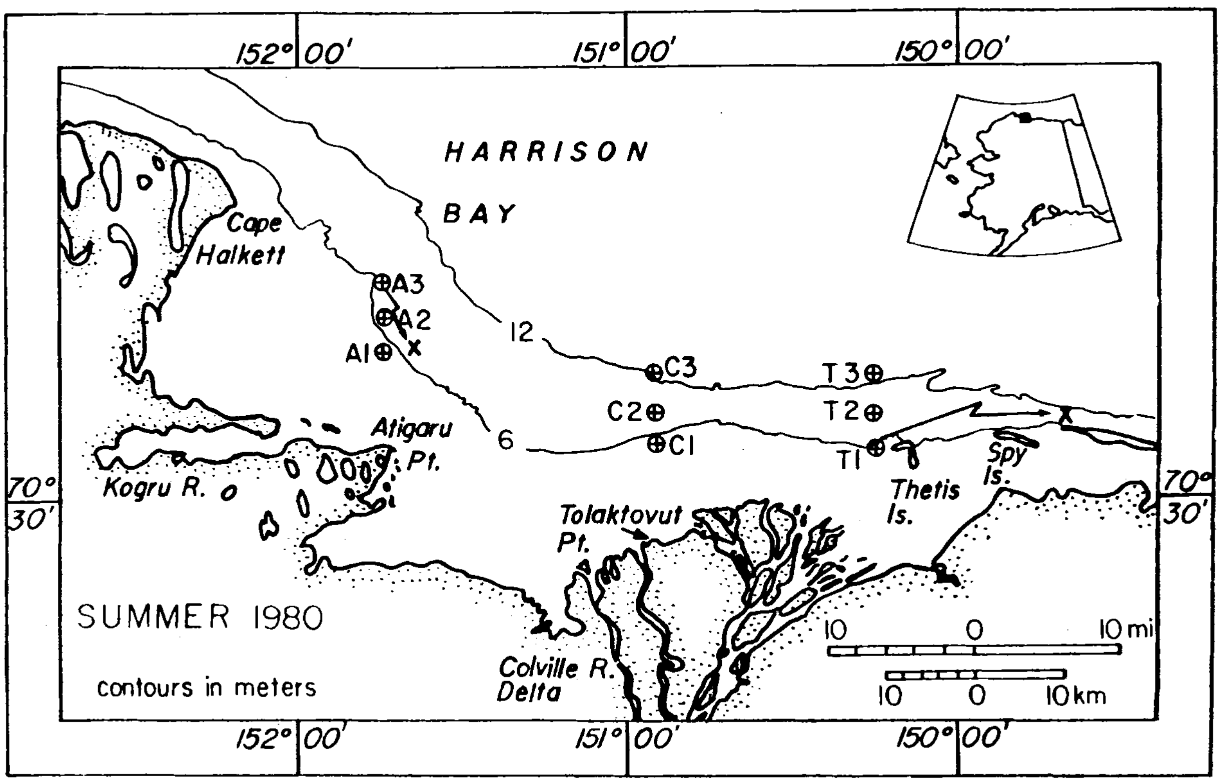

Figure 2.1.5. Location map showing current meter sites west of Thetis Island and north of Atigaru Point.

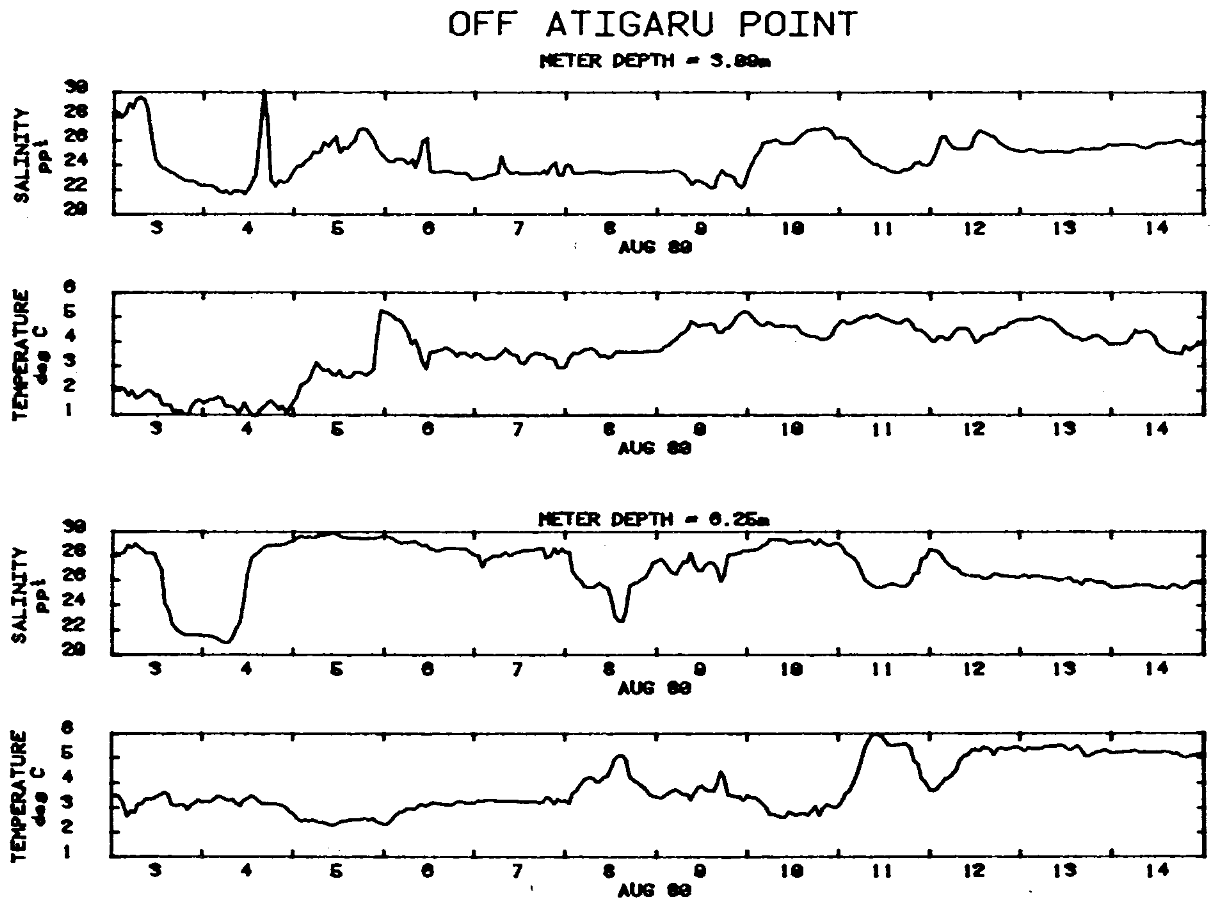

Figure 2.1.6. Temperature and salinity at 3.0 and 6.25-m depths in 8-m water off Atigaru Point, 3-14 August 1980.

Figure 2.1.8 shows data collected between 3-14 August on surface and bottom salinities and temperatures in Harrison Bay (Craig and Griffiths, 1981). The nearshore waters derived from river runoff and oceanic water are separated from oceanic waters. The two layer system is clearly shown with surface and bottom salinities of 25.1 °/oo and 27.2 °/oo nearshore and 27.4 °/oo and 28.7 °/oo offshore. The division between nearshore and offshore waters coincides with the 6-m isobath. Hufford and Bowman (1974) reported the same location for the interface based on airborne radiometer measurements.

In mid-August 1980 a storm characterized by strong winds from the west began and continued into September. The characteristics of the circulation and water quality changed abruptly with the onset of the storm. Fig. 2.1.9 shows the salinity and temperature at the Atigaru instrument array. Mean salinity and temperatures were 24.62 °/oo and 2.73°C in the upper layer (3 m) and 23.94 °/oo and 4.25°C in the lower layer. The wind transport and current transport are shown in Fig. 2.1.10. The winds show an easterly transport of 5,700 km from 17 August to 2 September, the water transport was 100 km to the southeast during the

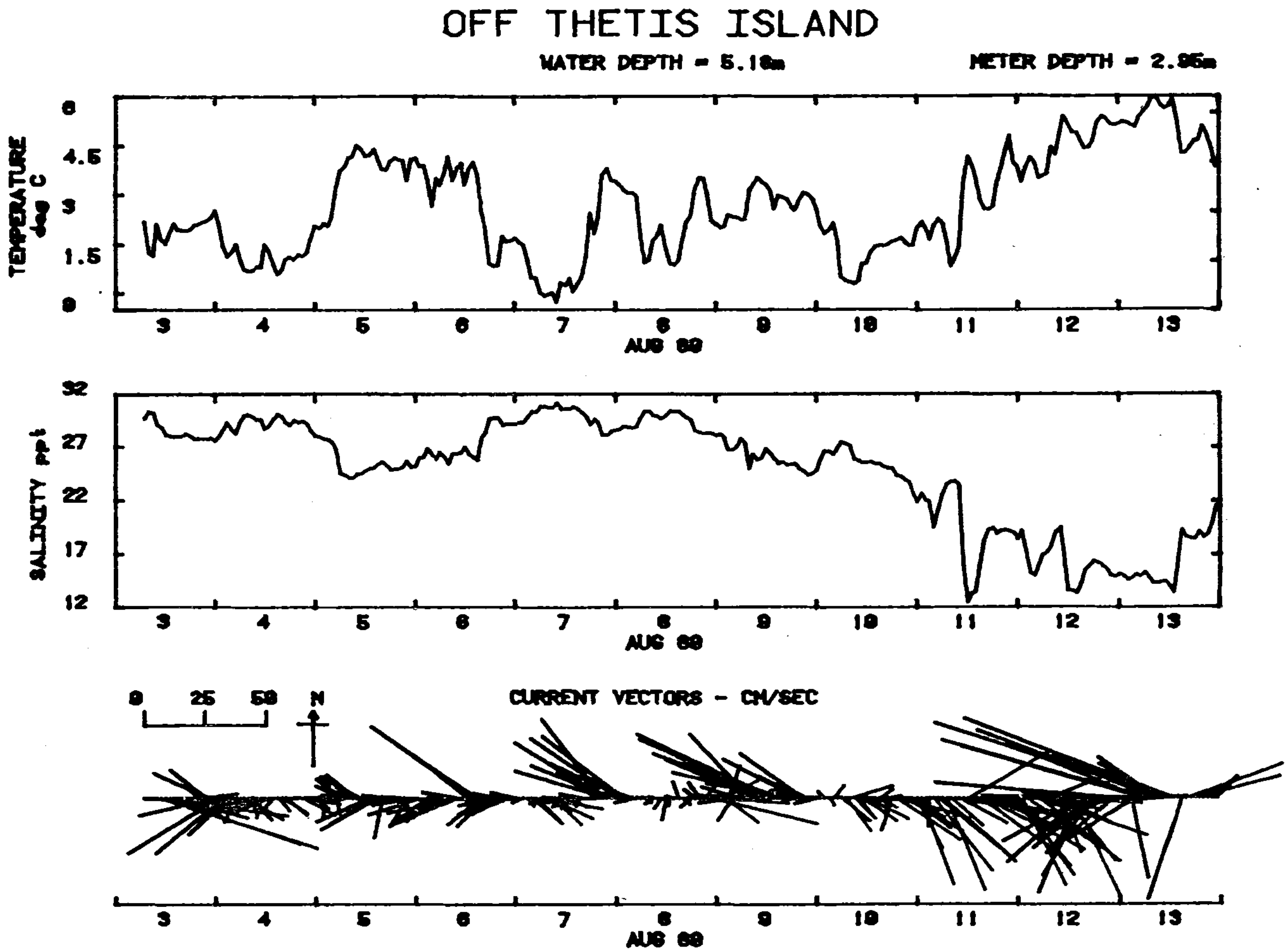

Figure 2.1.7. Salinity, temperature, and current vectors at 3-m depth in 5-m water off Thetis Island, August 1980.

same period. This water transport is at 6.25 m in 8 m water and is not comparable to surface drift. However, the water mass is clearly shown to be wind-driven and moving together. The bottom currents here are 2 percent of the wind speed and 45° to the right of the wind.

It is also noteworthy that the salinity at the Atigaru station decreases throughout the record (Fig. 2.1.9). This indicates that while the strong westerly winds are driving oceanic water into the Bay, they are also trapping Colville River water in the Bay.

These data illustrate the two types of summer circulation in the Harrison Bay. The former and more normal condition is the two layered system with net westerly drift of about 1 km per day. The storm condition in the second part of the month shows easterly drift of 6 km per day and well mixed conditions. Oceanic water and ice floes invade the Bay and if the condition is prolonged for several days, significant river runoff is trapped in the Bay.

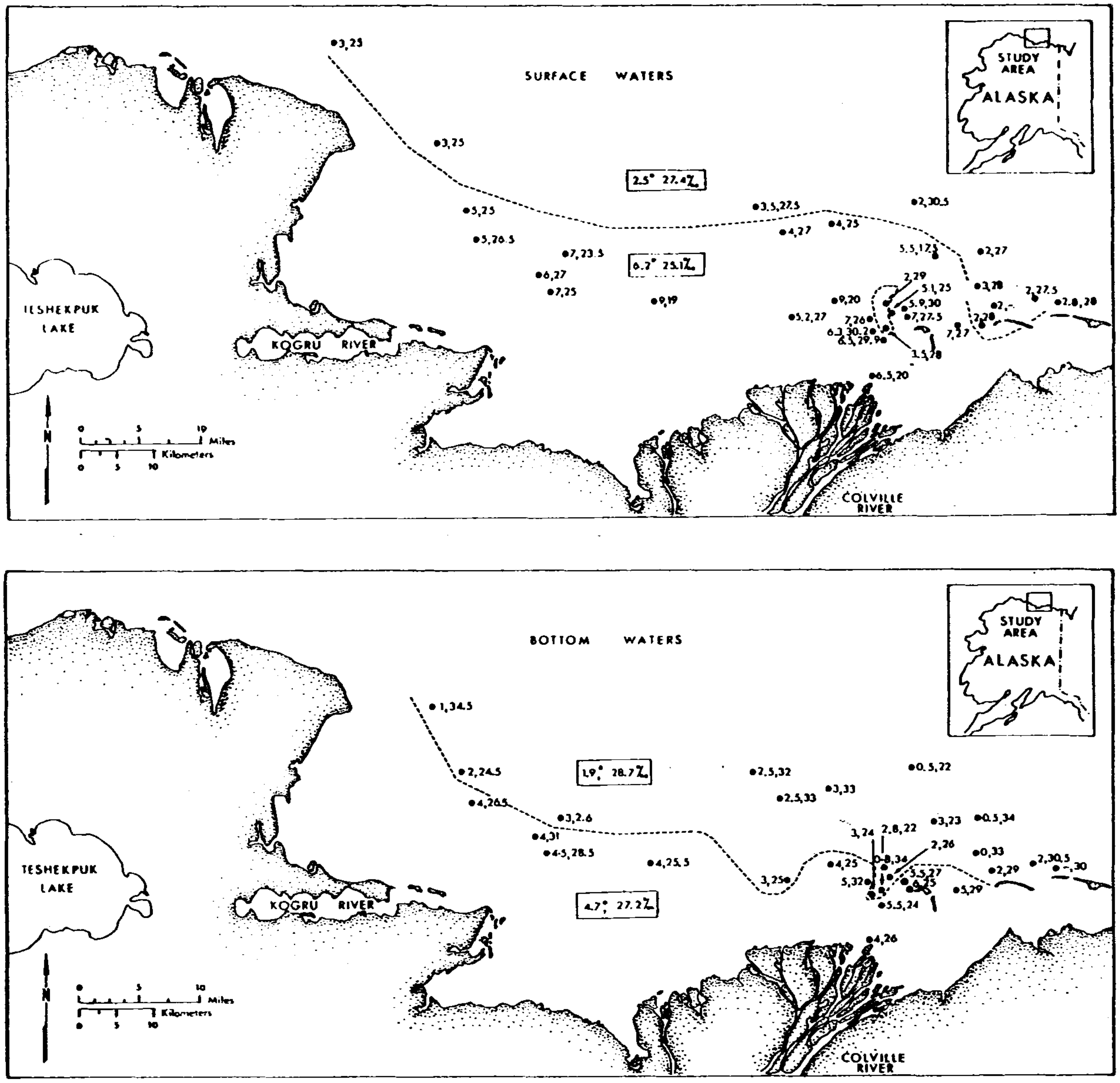

Figure 2.1.8. Surface and bottom temperature and salinity data, 3-14 August 1980. A dotted line separates offshore waters less than 4°C; average values are indicated in boxes (Johnson).

These data apply to Harrison Bay inside the 12-m contour. Hufford et al. (1974) reported some data from outer Harrison Bay taken from an icebreaker. Subsequently no data are available for the region beyond the 13-m contour. Logistical problems of data collection beyond the 13 m contour have yet to be solved. The lack of data from the region and the inability to obtain data with any reliability suggest that conditions in lease Sale 71 area are more severe than those encountered in regions protected by barrier islands. Techniques for obtaining oceanographic data from these regions need to be developed, and data recorded from the region, in order to provide the bases for any future development.

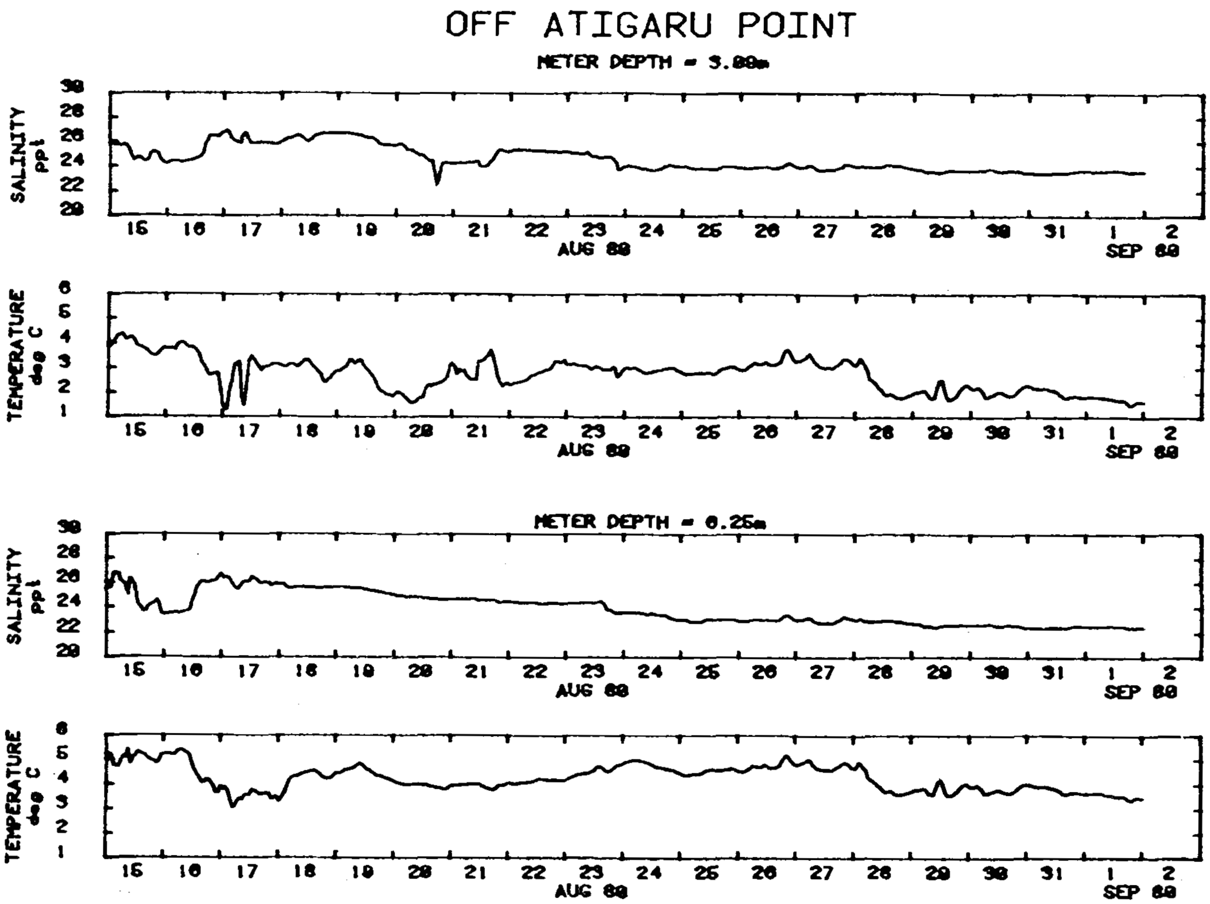

Figure 2.1.9. Temperature and salinity at 3.0 m and 6.25 m in 8-m water off Atigaru Point, 15 August - 2 September 1980.

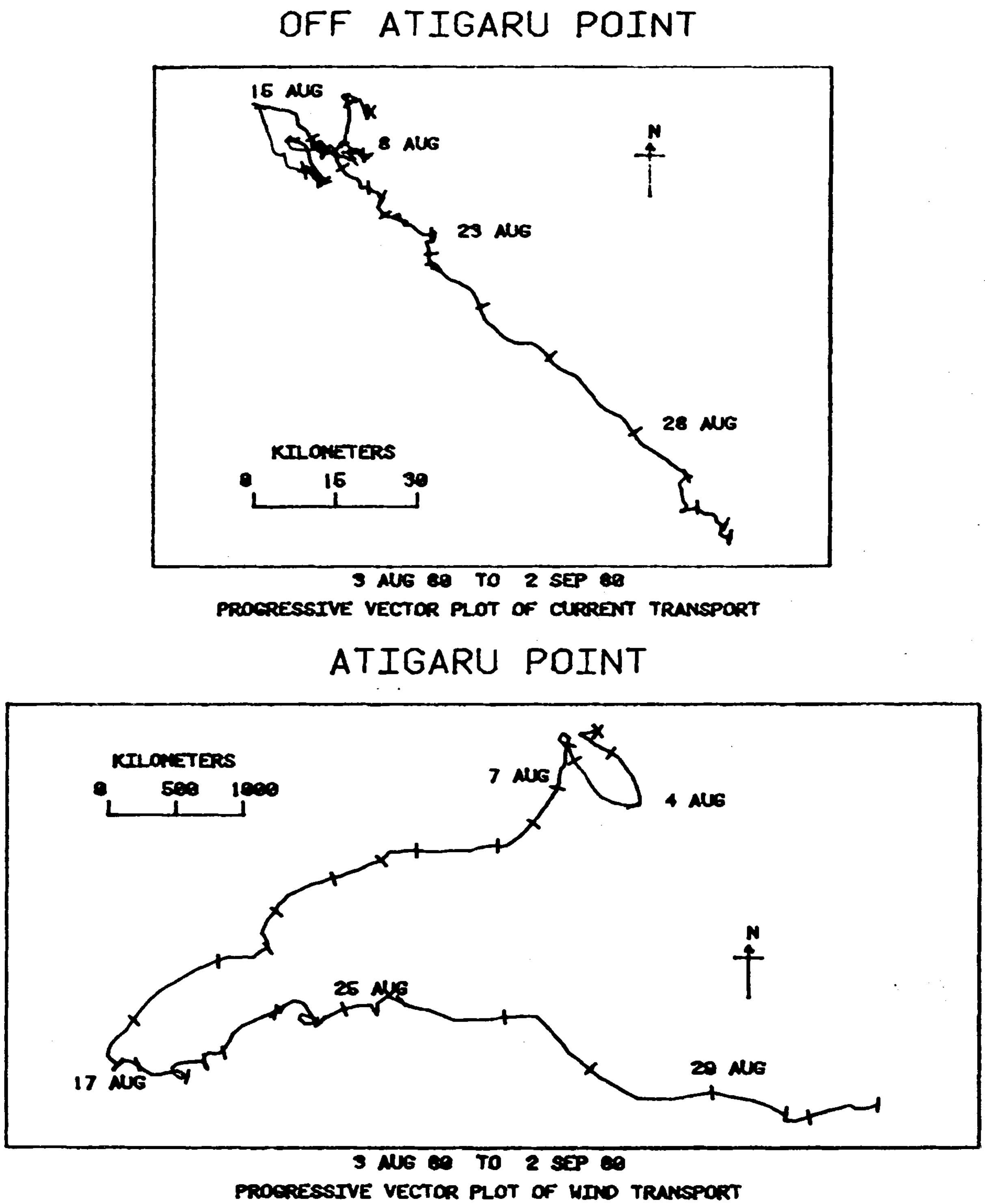

Figure 2.1.10. Current and wind transport for Atigaru Point, 3 August - 2 September 1980.

2.2 TIDES

By J. B. Matthews

The astronomical tides of the Beaufort Sea are very much smaller than the meteorological tides. The first tidal data were obtained by the Ray (Ray, 1885) and Mikkelson-Leffingwell Expeditions (Harris, 1911). Hunkins (1965) measured tides on the shelf northwest of Point Barrow from a grounded iceberg. Matthews (1971) carried out a long series of observations at Point Barrow. The National Ocean Survey has occupied a tide station in Prudhoe Bay in July and August since 1975. Matthews (1978; 1979; 1980a; and 1981c) has made tidal current and elevation observations and analyses for several stations between Brownlow Point and Cape Halkett as part of the OCS studies.

The tides are semidiurnal, with an M_2 component of 4.7 cm amplitude for Point Barrow (Matthews, 1971). The mean tidal range for Stefansson Sound is 15 cm (Matthews, 1981a). Mean currents under ice in winter over a 50-day period were reported to be 5.9 cm/s while the R.M.S. mean tidal current was 0.54 cm/s over the same period (Matthews, 1981a). These mean tidal currents are an order of magnitude smaller than mean currents in winter. This agrees well with the surface elevation data. During this period, a change in sea level of 161 cm was observed which compared with the mean tidal range of 15 cm.

Tidal models (e.g., those of Henry and Heaps, 1976; Kowalik and Untersteiner, 1978) have been used to examine tidal data from the U.S. and Canadian Beaufort Seas. The model and observational data suggest that there is little change in tidal characteristics in the U.S. Beaufort Sea. The M_2 tide approaches the coast orthogonally from the Arctic Ocean with only 1 or 2 degrees phase difference along the coast. By contrast the Canadian Beaufort has complex tidal characteristics with several amphidromes in the Mackenzie Bight.

2.3 STORM SURGES

By J. B. Matthews

Storm surges significantly increase or decrease sea level from its mean level; in the Beaufort Sea, surges are the most important sea level variation. Surges change the sea level by an order of magnitude more than the mean tidal range of 15 cm (Matthews, 1981a). They are usually associated with storm systems moving under the influence of the Siberian and Alaskan high-pressure systems. The storms are most frequently generated near the Aleutian chain and pass through Bering Strait, although occasional storms move eastward from the Siberian shelf (Searby and Hunter, 1971). The storm tracks generally lie north of the Alaskan Beaufort Sea coast, and the storms progress toward the east. The greatest increases in sea level occur in September and October, when long stretches of open water increase the fetch, resulting in large waves at the shoreline. However, winter surges in December and January (even as late as February) are not infrequent, though the elevations are generally less than in summer. Negative surges also occur and appear to be more frequent in the winter months.

Very little has been published on surges in the Beaufort Sea, and only one sea-level gauge has operated for more than a year, at Barrow in 1969-72 (Matthews, 1971). Consequently, information is based either on short-term sea level records or more frequently on secondary observations. Observations of strandlines along the entire Beaufort Sea coast tend to confirm extreme surge values of 1-3 m (Hume and Schalk, 1967; Wiseman et al., 1973; Henry, 1975; Henry and Heaps, 1976; Brower et al., 1977), with the highest values on westward-facing shores. Schaeffer (1966) reported a surge height at Barrow of 3.0 m on 3-5 October 1963. The storm causing the surge had sustained gusts of 42 knots and short gusts to 65 knots; it is assumed to be the 100-year event. Beach and cliff erosion was massive; the shoreline retreated 13 m southwest of Barrow (Hume and Schalk, 1967). The surge height decreased toward both the east and the southwest, with 1.5 m reported at Barter Island and 2.7 m at Point Lay. The very few simultaneous sea-level records indicate that the impact of surges may be major in one region but minor some distance removed along the coast. For example, surges reported by Henry (1975) at Tuktoyaktuk in 1972-73 were hardly noticeable at Oliktok Point (Matthews, 1978).

Negative surges, i.e., levels falling appreciably below mean sea level, can produce important effects, especially in winter when little water remains beneath nearshore ice. Extensive fracture of shorefast ice is possible, for example, affecting oil transport and breakup. Underwater structures previously in water under the ice may have to bear the full weight of an ice sheet. They can occur at all seasons, but Henry's (1975) observations in Mackenzie Bay suggest that they are most common in December and January. The heights are less (~ 1 m or less) than for positive surges. Kowalik and Matthews (unpub.) observed a negative surge of 60 cm at Barrow in December 1969, the largest observed during three winters. He also observed one of 89 cm at Oliktok Point in November 1972. A surge of 161 cm was observed in Stefansson Sound in November 1978 (Matthews, 1981a).

Sea-level changes due to surges are important in the Beaufort Sea for many reasons. They contribute to coastal erosion in the summer and are related to ice override in winter. These dominant, nonperiodic sea-level changes further complicate the establishment of tidal components.

2.4 OIL IN SEA ICE

By D. Thomas

Although the interaction of oil and sea ice in Harrison Bay is essentially similar to that in the Joint Lease Sale area around Prudhoe Bay, many aspects of the latter interaction were not mentioned or were treated only cursorily in the 1978 synthesis report. Additional research work on the effects of underice currents (Cox et al., in press) has been done since the 1978 synthesis. More knowledge of the character of the ice cover (Kovacs, 1979; 1980; Stringer 1978; Barnes et al., 1979; Tucker et al., 1979; Thomas and Pritchard, 1979). and the underice current regime (Weeks and Gow, 1980; Matthews, 1980a; 1981b) is now available.

Thomas (1980) reviewed the present state of knowledge of the near-shore ice cover and evaluated the relative importance of various aspects of oil-ice interactions. The important aspects of oil and sea-ice interactions are as follows:

A. The accidental release of gas beneath the ice cover would be of minor importance. Sufficient natural cracks exist in the ice cover to allow most of the gas to escape. In addition, large gas bubbles trapped beneath a solid ice cover will cause ice breakage (Topham, 1977).

B. Oil from depths of 3,000 m contains enough heat to warm and melt about 1 kg of ice for each 200 kg of oil released. The resulting slow rates of ice melt above a blowout therefore would have little effect on the events at the site, but oil which replaces melted ice near the blowout would be easier to clean up.

C. The skeletal layer of ice crystals beneath the ice sheet can contain about 5 percent by volume of oil. This is equivalent to a layer of oil about 2 mm thick. In the worst case, under smooth, flat ice, this can amount to about 20 percent of the oil released beneath the ice. With natural bottom side ice roughness or artificial barriers, the oil will spread much less, and therefore less than 20 percent of the oil will be incorporated into the skeletal layer. The skeletal layer oil containment is important, since this oil cannot possibly be cleaned up until the ice melts in the spring.

D. Oil spreads very little on the upper surface of the ice. During the winter, air temperatures are lower than the typical crude oil's pour point. Snow also stops the spread of oil. Oil will be forced downward through holes and cracks in the ice by the combined head of oil in the crack and a few-cm-thick layer of oil on the surface. This is more likely in very large surface spills, since the likelihood of open cracks through the ice increases proportionally with area covered. Oil on the upper ice surface can easily be cleaned up, but blowing snow can quickly cover the oil, making location of the oil difficult.

E. Weak currents tend to control the direction of oil spread beneath the ice but will not move the oil beneath an obstruction. Currents greater than 20-25 cm/s under stationary ice would move oil and could extend the size of underice oil slicks. But currents greater than 20 cm/s are rare in the nearshore region and of short duration, and could move the oil, at most, a few hundred meters. The effect of currents is therefore unimportant except to determine in which direction most of the oil spreads during the spreading phase. Spreading stops after an equilibrium thickness of approximately 2 cm is reached.

Weak counter-currents of low salinity water, induced by thermohaline convection, are presumed to move shoreward immediately beneath the sea ice. These currents were computed to reach a maximum speed of 22 cm/s during rapid ice growth in the early winter (Matthews, 1981a) although tidal pumping and pressure variations at times probably swamp this hypothesized component of under-ice circulation (Matthews, 1981b). Nevertheless, the possibility exists that toxic water-soluble-fractions (WSF) of petroleum trapped under the ice would be transported predominantly toward land by the counter-currents, so long as the oil was not isolated from the water column by further ice growth beneath (see next conclusion).

F. During the season of ice growth, a new layer of ice forms beneath subice oil layers. This takes from 5 days during the fall to 10 days in the spring, when ice growth is slowest. Ice also forms below oil on any open water. This entrapment of the oil is important, since it insulates the oil until spring from further effects of currents and from weathering processes until spring.

G. The effect of slush ice beneath the ice cover is unclear. Slush ice may restrict the spread of oil. New ice growth and incorporation of oil into the ice will not be affected. Slush ice may contain large amounts of suspended sediments, which may act to precipitate the oil.

H. Oiled ice may be built into ridges. This is particularly important during the fall/early winter in Harrison Bay before grounded ridges in the outer bay stabilize the fast-ice cover. Storms during this period frequently cause ice motion and deformation. In the most seaward regions of the lease area, ice motion and deformation may continue throughout the winter.

I. Ice motions during a blowout will also cause larger areas of ice to become contaminated with oil. This would be especially important in the outer part of Harrison Bay, which is beyond the shear zone. Oiled ice from an early-winter spill in inner

Harrison Bay may also be blown out to sea and become incorporated within the pack ice. The motion of oiled ice in the pack-ice zone is important because it makes the cleanup more difficult, and it exposes a much wider area of the Alaskan Coast to possible oil contamination during the following summer. Ice motions may also spread the oiled ice over such large areas that no large concentrations of oil would occur during the following melt season. Oil trapped in ridges may contribute to this last consequence.

J. Oil incorporation in the ice tends to migrate upward through annual sea ice, following brine channels. The migration is slow and unimportant during the winter when brine channels are small, but during spring when brine drainage enlarges the channels, the migration is accelerated and oil soon appears on the ice surface. Not all the oil can surface through brine channels, however. The annual ice must melt down to the enclosed oil layer before it is all released.

K. Surface oil may be present from a surface spill or from migration through brine channels. Oil on the ice surface lowers the surface albedo and accelerates the formation of melt pools and local ice breakup by about two weeks. This acceleration is important with respect to cleanup, since it would reduce the period when the ice is safe for surface operations. On the other hand, it contains the oil in a pool with access via surrounding ice before that ice is melted.

L. As soon as oil appears on the ice surface, weathering begins. By the end of breakup, as much as 50 percent of the oil may have evaporated. Emulsification and dissolution also occur in melt pools or open-water areas. Spring river runoff will also deposit large amounts of suspended sediments on or under the ice cover and in the water. This will tend to accelerate oil incorporation into the bottom sediments. All the weathering processes make it more difficult to burn the remaining oil. Weathering also increases the density of the remaining oil so that eventually the residue is more dense than sea water.

The following observations may be made concerning wintertime blowouts and oil spills: First, spills beneath or on top of the ice will spread over an area many orders of magnitude smaller than a spill in open-water. Even a very large spill will cover a few square kilometers, at most. Under-ice currents will not significantly affect the spread of a spill after equilibrium is reached. The only significant means for movement of oil in winter is the movement of the ice itself. Second, oil spilled beneath the ice will be incorporated into the ice cover and will remain isolated throughout the remainder of winter. Surface spills will experience some weathering of oil that remains on the surface, but some of the oil from large surface spills will likely end up beneath the ice. Third, oil incorporated into the ice cover will be released during the spring melt and breakup. This effect makes all winter spills which are not cleaned up the equivalent of spring spills. Breakup is probably the most difficult time of year to mount cleanup operations. The melting, rotten ice cover makes operating from the ice surface difficult and dangerous, whereas the remnants of floating ice can make boat operations difficult or impossible.

Data Gaps

Several data gaps concerning oil-ice interactions in Harrison Bay have been identified:

A. The extent and variability of ice motions are unknown during and after freezeup, before grounded ridges stabilize the ice in the fast-ice zone in Harrison Bay.

B. Little is known of the seasonal development of the ridge systems in the stamukhi zone. Needed is information on the number of ridges, the amount of ridged ice, the time of ridge building, and when and where ridges become grounded.

C. The process of spring breakup needs to be better documented. Useful information would include the timing and variability from year to year of the sequence of events during breakup inside and outside Harrison Bay. Ice motion and ocean currents are especially important.

D. For low concentrations of ice, oil slicks on the water will follow wind- and current-driven slick trajectories. For high ice concentrations, oil will mostly be carried along with the ice. For intermediate ice concentrations, however, the ice may not entrain the oil but may still affect where the oil goes. This problem needs further study, since it may be important during spring breakup and in other situations of intermediate ice cover.

E. Although large steady currents just beneath the ice are not expected in Harrison Bay, few current measurements have been made there.

2.5 REFERENCES

Barnes, P. W., E. Reimnitz, L. J. Toimil, and H. Hill. 1979. Fast-ice thickness and snow depth in relation to oil entrapment potential, Prudhoe Bay, Alaska. U.S.G.S. open file report 79-539. Menlo Park, California.

Brower, W. A., Jr., H. W. Searby, J. L. Wise, H. F. Diaz, and A. S. Prechtel. 1977. Climatic atlas of the outer continental shelf water and coastal regions of Alaska, Vol. III Chukchi-Beaufort Sea. NOAA/OCSEAP, Boulder, Colo. 409 pp.

Carsey, R. 1977. Coastal meteorology of the Alaskan Arctic Coast. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 15:538-578.

Cox, J. C., L. A. Schultz, R. P. Johnson, and R. A. Shelsby. In press. The transport and behavior of oil spilled in and under sea ice. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Final Rep. Phys.

Craig, P. C., and W. B. Griffiths. 1981. Studies of fish and epibenthic invertebrates in coastal water of the Alaska Beaufort Sea. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep (in press).

Harris, R. A. 1911. Arctic Tides. Government Printing Office, Washington, D.C. 103 pp.

Henry, R. F. 1975. Storm Surges. Tech. Rep. 19, Beaufort Sea Proj. Dep. of Env., Victoria, Canada. 41 pp.

Henry, R. F., and N. S. Heaps. 1976. Storm surges in the southern Beaufort Sea. J. Fish. Res. Bd. Can. 33:2362-2376.

Hufford, G. L., and R. D. Bowman. 1974. Airborne temperature survey of Harrison Bay. Arctic 27:69-70.

Hufford, G. L., S. H. Fortier, D. E. Wolfe, J. F. Doster, and D. L. Noble. 1974. Physical oceanography of the western Beaufort Sea. In: G. L. Hufford (ed.) Marine Ecological Survey of the Western Beaufort Sea. U.S.C.G. Rep. CG-373.

Hufford, G. L., I. M. Lissauer, and S. P. Welsh. 1976. Movement of spilled oil over the Beaufort Sea -- a forecast. U.S.C.G. Rep. CG-D-101-78, 87 pp.

Hunkins, K. 1965. Tide and Storm Surge Observations in the Chukchi Sea. Limnol. Ocean. 10:29-39.

Hume, J. D., and M. Schalk. 1967. Shoreline processes near Barrow, Alaska: a comparison of the normal and the catastrophic. Arctic, 20:86-102.

Kovacs, A. 1979. Oil pooling under sea ice. Environmental assessment of the Alaskan continental shelf. NOAA/OCAEAP Ann. Rep. 8:310-353.

Kovacs, A. 1980. Oil pooling under sea ice. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 7:333-340.

Kowalik, Z., and N. Untersteiner. 1978. A study of the M_2 tide in the Arctic Ocean. Deut. Hydrogr. Zeit., 31:216-229.

Kozo, T. L. 1979a. Meteorology of the Alaskan Arctic coast. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 8:1-56.

Kozo, T. L. 1979b. Evidence for sea breezes on the Alaskan Beaufort Sea Coast. Geophys. Res. Let. 6:849-852.

Kozo, T. L. 1980. Mountain barrier baroclinity effects on surface winds along the Alaskan Arctic coast. Geophys. Res. Let. 7:377-380.

Leavitt, E. 1978. Coastal meteorology of the Alaskan Arctic coast. Environmental assessment of the Alaska continental shelf. NOAA/OCSEAP Ann. Rep. 10:580-606.

Matthews, J. B. 1971. Long period gravity waves and storm surges on the Arctic Ocean continental shelf. Proc. Joint Oceanographic Assem. 8:332.

Matthews, J. B. 1978. Characterization of the nearshore hydrodynamics of an Arctic barrier island-lagoon system. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 10:607-627.

Matthews, J. B. 1979. Characterization of the nearshore hydrodynamics of an Arctic barrier island-lagoon system. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 8:57-97.

Matthews, J. B. 1980a. Characterization of the nearshore hydrodynamics of an Arctic barrier island-lagoon system. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 6:577601.

Matthews, J. B. 1980b. Modelling and verification of circulation in an arctic barrier island lagoon system--an ecosystem process study, pp. 220-231. In: J. Sundermann and K. P. Holz (eds.), Mathematical Modelling of Estuarine Physics. Springer-Verlag, New York.

Matthews, J. B. 1981a. Observations of under-ice circulation in a shallow lagoon in the Alaskan Beaufort Sea. Ocean Manag. 6:223-234.

Matthews, J. B. 1981b. Observations of surface and bottom currents in the Beaufort Sea near Prudhoe Bay, Alaska. J. Geophys. Res. 86:6653-6660.

Matthews, J. B. 1981c. Characterization of the nearshore hydrodynamics of the Arctic barrier island-lagoon system. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. In press.

Moritz, R. W. 1977. On a possible sea breeze circulation near Barrow, Alaska. Arctic Alpine Res. 9:427-431.

Ray, P. H. 1885. Report of the International Polar Expedition to Pt. Barrow, Alaska. Government Printing Office, Washington, D.C. pp. 1-8, 26, 200-209, 212-227, 262-285, 675-686.

Schaeffer, P. J. 1966. Computation of a storm surge at Barrow, Alaska. Archiv. fur Meteorologie, Geophysik und Bioklimatologie; Ser. A Meteorologie und Geophysik. 15:372-393.

Schwedtfeger, W. 1974. Mountain barrier effect on the flow of stable air north of the Brooks Range. pp. 204-208. In: Climate of the Arctic. Conf. Pub. Geophys. Inst., Univ. Alaska, Fairbanks.

Searby, H. W., and M. Hunter. 1971. Climate of the North Slope of Alaska. NOAA Tech. Mem. NWS AR-4, Anchorage, 53 pp.

Stringer, W. J. 1978. Morphology of Beaufort, Chukchi and Bering Seas nearshore ice conditions by means of satellite and aerial remote sensing. Geophys. Inst., Univ. Alaska, Vol I, 218 pp, Vol II, 576 pp.

Thomas, D. R., and R. S. Pritchard. 1979. Beaufort and Chukchi Sea ice motions, Part 1. pack ice trajectories. Flow Res. Rep. 133. Flow Res. Co., Kent, Wash.

Thomas, D. R. 1980. Behavior of oilspills and sea ice - Prudhoe Bay. Flow Res. Rep. 175. Flow Res. Co., Kent, Wash.

Topham, D. R. 1977. The deflection of an ice sheet by a submerged gas source. J. App. Mech. 1977:279-284.

Tucker, W. B. III, W. F. Weeks, and M. D. Frank. 1979. Sea ice ridging over the Alaskan Continental Shelf. CRREL Rep. 79-8.

Weeks, W. F., and A. J. Gow. 1980. Crystal alignments in the fast ice of Arctic Alaska. J. Geophys. Res. 85:1137-1146.

Wiseman, W. J., J. M. Coleman, A. Gregory, S. A. Hsu, A. D. Short, J. N. Suhayda, C. D. Walters, Jr., and L. D. Wright. 1973. Alaskan Arctic Coastal Processes and Geomorphology, Tech. Rep. 149. Coastal Studies Inst., Louisiana St. Univ., 171 pp.

SECTION I. CHARACTERIZATION OF SALE 71 ENVIRONMENTS

Chapter 3. Physical Characteristics of the Sale 71 Area
P. W. Barnes, Editor

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3.1 INTRODUCTION

By P. W. Barnes

This section emphasizes the physical characteristic of sea ice and the geologic environment. Some of the data presented here on ice dynamics and geological processes are also useful in discussing pollutant transport (Sec. 2). Similarly some data presented here on hazards and the oceanographic and meteorologic environment are also applicable to the discussion of circulation (see Section 3.4).

Four chapters of the 1978 synthesis reports (Weller et al., 1978) contain topics directly pertinent to the Sale 71 lease area: Ice, Oceanography, Geology and Hazards. Familiarity with this report is necessary to fully understand the following discussions.

The Sale 71 area extends from Cape Halkett on the west to Flaxman Island on the east. The eastern half of this region was considered in a synthesis report prepared for the 1979 Joint State/Federal sale (Weller et al., 1978). The following discussions emphasizes the western half of the Sale 71 area which encompasses most of Harrison Bay.

3.2 ICE CHARACTERISTICS AND SEA ICE MOTIONS

By R. S. Pritchard and W. Stringer

Ice Motion

From October through June the entire Beaufort Sea area is generally covered with ice. Near shore, during early winter, the "fast" ice may move several hundreds of meters. In midwinter and late winter, fast-ice motions of tens of meters are common, with occasional excursions over 100 m. Far from shore, along the outer shelf, the ice pack is highly mobile, with average daily motions of about 5 km and extremes during storms of about 35 km (Thomas and Pritchard, 1979). In summer, the pack ice rarely is motionless whereas, in winter, the pack may remain motionless for tens of days.

Gradients in the velocity of ice motion occur between the fast ice and the pack ice. Both shearing and compressional deformations occur, the latter usually when shearing dominates. Depending on ice dynamics, deformations are generally focused along a single "shear zone" parallel to shore with abrupt changes in ice velocity across this zone. The position of this zone changes through the winter. Shoreward, compression occurs over a wider front and can cause deformations and ridging at shore or at a fixed offshore relief feature such as a shoal, barrier, or grounded ice mass.

Seasonal Ice History

During the first stages of seasonal ice formation in October and November, ice velocities in the nearshore fast-ice zone are similar to those in the pack ice. At this time, the barrier islands protect only small areas downstream from ice motion and massive multiyear floes can invade the area (Kovacs and Gow, 1976), along with smaller ice blocks that have survived the summer melt season.

As freezing continues, the seasonal fast ice becomes thicker and stronger, ultimately becoming actually fast. A series of shearing and compressional ice motions create massive ice ridges at the unstable boundary between the fast ice and pack ice. Many ice ridges become grounded in the shallower waters. The open, broad, shallow geography and bathymetry of Harrison Bay (Fig. 3.2.1) allow the formation of early-winter ice ridges near the 10-m isobath (see Appendix C, late fall to early winter ice morphology map and accompanying caption) (Stringer, 1981) and on numerous shoals close to shore north and east of Oliktok Point (Stringer, 1974). This early-winter ridging in Harrison Bay is different from that observed to the east, where the barrier islands and steeper offshore slopes are associated with ridging in water depths between 12 and 17 m (Kovacs and Sodhi, 1980).

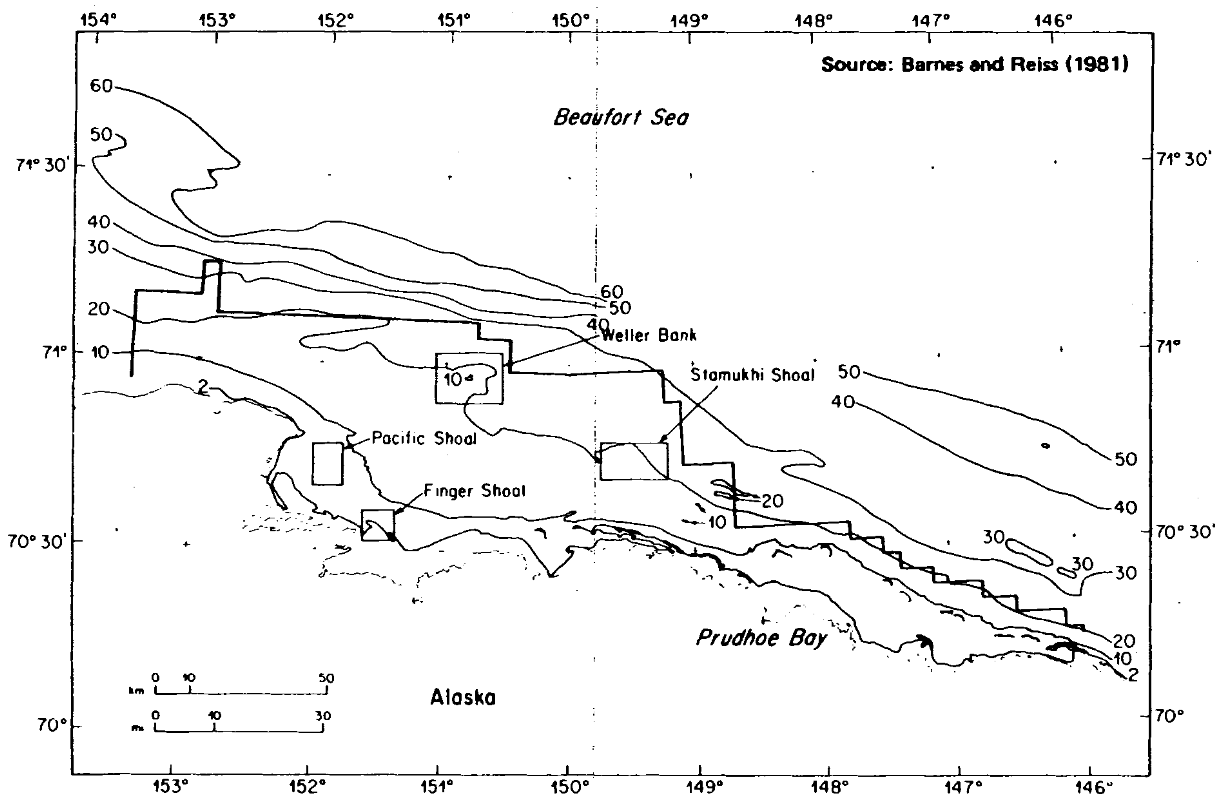

Figure 3.2.1. Updated bathymetry in Sale 71 area.

As freezing continues, the thicker and stronger grounded ice features (or other fixed features) become strong points which help to anchor the fast ice by obstructing flow. A pair of such fixed points will tend to reduce ice motion between them because of increased ice strength and an arching effect; similar ice arches have formed across the Bering Strait in winter. Since thicker, stronger ice can withstand loads large enough to break down the ice arch, the behavior of ice around obstacles varies as the ice thickens.

Figure 3.2.2. Pressure ridge formation located 11 km northwest of Oliktok Point (courtesy of A. Kovacs).

By January or February, a heavy ridge system composed of annual ice has usually become grounded on the shoals northeast of Harrison Bay (Figs. 3.2.1 and 3.2.2) in water about 20 m deep (Barnes and Reiss, 1981). All of the mechanisms that trigger formation of this large, grounded rubble field (also called stamukhi) are as yet unknown. It is generally believed that, during formation, ice motions shoreward of the grounded rubble field are small (tens of meters); the entire region is apparently partially protected from major ice movement and ice override along the coast by these grounded features (see Appendix C, edge of fast ice map) (Stringer, 1981). Without more complete data on ice motion, we lack a clear understanding of the physical forces and mechanisms that cause grounded rubble fields to move, however.

Stable grounded ridges and relatively stable fast ice inshore of these ridges continue to dominate the ice conditions through the remainder of winter (see Appendix C, early winter-late spring ice morphology map) (Stringer, 1981). Observations from drifting data buoys (Untersteiner and Coon, 1977) and satellite imagery, coupled with theoretical model studies (Pritchard, 1981), have shown that pack ice seaward of these ridges may move 30 km/d during midwinter heavy-ice conditions. Anecdotal information from local residents indicates that large motions occur in the outer part of the bay under appropriate driving forces (Shapiro and Metzner, 1979).

During June, rising temperatures and melting allow the bottomfast ice inside 2 m to float. Melting of this stabilizing bottomfast ice permits winds and currents to move the nearshore fast ice more easily. Within the constraints imposed by coastal features, residual grounded-ice formation, and shoals, the fast ice then tends to drift. Larger grounded-ice formations melt slowly or are broken into smaller fragments by waves and currents. Some ice remains grounded throughout the summer (Barnes and Reimnitz, 1979, 1980; Kovacs, 1976), particularly on shoals.

During the summer, the location of the pack-ice edge is variable and may be tens to hundreds of kilometers offshore, as shown in the 1978 synthesis report. However, shifting winds and currents can combine to drive the pack ice toward shore. During storms, winds and ocean currents increase ice velocities to as high as 35 km/d. Due to Coriolis forces, easterly winds drive ice offshore while westerly winds drive ice onshore.

<u>Summer Ice Conditions</u>. Knowledge of summer (open-season) ice conditions is important for estimating oil spill trajectories, planning logistics for ship and structure emplacement operations, and assessing the safety of long- and short-term structures. Figure 3.2.3 is a compilation of data from satellite imagery since 1972 (Stringer, 1981) showing the distance offshore to low, variable, and high ice concentrations. Ice-free conditions commonly extend 20 to 25 km off the coast by late August and September. Some ice cover occurs 100 km or more offshore in the Harrison Bay area, whereas at Prudhoe Bay one would encounter 90 percent ice cover within 75 km of the coast.

If we assume that ice drifts freely during summer when the pack is loose, then local winds and currents control ice velocity and direction. We must also assume that internal ice stress is negligible. As a result, local wind statistics and ocean currents (used herein as steady longshore currents) can be used to calculate ice velocity. Thomas and Pritchard (1979) have presented graphically the relationship between wind speed and ice displacement vectors. The relative direction between ice drift and wind will change with wind speed. If one neglects low-wind-speed conditions, because only low ice velocities occur then, one may approximate the relative vector angle by the constant angle $\delta = 45°$ (following Zubov, 1943). Similarly, the ice speed (relative to ocean currents at the bottom of the mixed layer) may be approximated by the linear function

$$G = N_a^{1/2} U_{10}$$

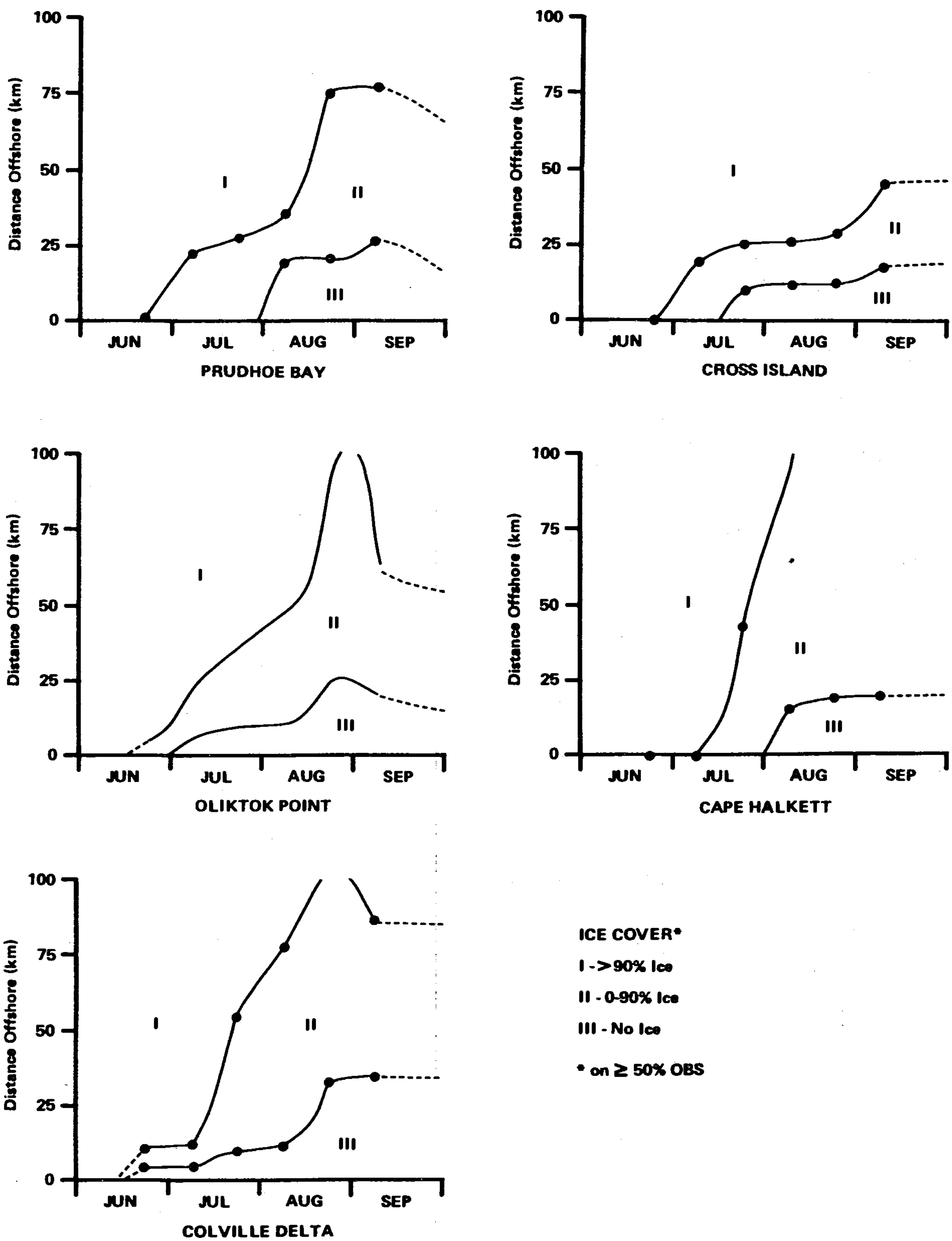

Figure 3.2.3. Distance offshore to ice cover of various intensities in summer (Stringer, 1981).

where G is the ice speed relative to ocean current, U_{10} is surface wind speed (at 10 m elevation), and

$$N_a = \frac{\rho_a C_{10}}{\rho_w C_w}.$$

The quantity N_a is the ratio of the mass density (ρ) and drag coefficients (C) of the atmosphere (a) and ocean (w). Typical values for these constants from AIDJEX (ρ_a = 1.3 kg/m^3, ρ_w = 1,030 kg/m^3, and C_{10} = 0.0027; C_w = 0.0055) give

$$N_a^{1/2} = .025,$$

implying that ice drifts at 2.5 percent of the wind speed, as a first approximation.

Using a linear relationship between wind speed and the 45° clockwise turning angle assumed above, one can modify a wind rose easily to show the ice vector in free-drift conditions. Wind statistics at sites along the North Slope, including Lonely and Oliktok, may be found in Brower et al. (1977). The wind distribution shown in Table 3.2.1 is taken as a first approximation to represent surface winds at Harrison Bay.

The ice vector statistics for free drift, assuming a 45° deflection angle and the above-stated velocity relations, are presented in Table 3.2.2. The bracketed portion of the chart represents the low-wind cases where the turning angle may be expected to exceed 45°.

Large ice velocities (in excess of 9 cm/s; shown as boxed data in Table 3.2.2) that have an onshore component in Harrison Bay (toward SE, S, SW, or W) occur about 38 percent of the time. No ice motions in excess of 28 cm/s are found in these directions. These conditions suggest that the velocities will be further affected by wind-driven currents which will follow trajectories similar to those of ice, adding to the ice-drift velocities determined from wind alone.

Wheeler (1979) studied the effect of summer ice invasions on offshore operations at a site in 10 m of water inside the barrier islands north of Prudhoe Bay and Cox and Dehn (1981) provide additional useful information bearing on the problem. Such information can be used to calculate the probability of completing jobs of different expected duration, given the ability of equipment to tolerate different ice conditions. The resulting probabilities are site-specific and vary widely as locations offshore of the barrier islands are considered. To make such calculations requires knowledge of the history of ice conditions (Cox and Dehn, 1981) that may not be available at some sites. Such a study has not yet been published for the Sale 71 area.

In summary, differences between ice zonation and ice motion are similar to those discussed in Weller et al. (1978). Harrison Bay is open and relatively unprotected except by shoals, whereas inshore areas to the east and west are protected by barrier islands. Conditions outside the islands are similar to the open areas of Harrison Bay. The location of ridges and rubble fields, and the ice motions, may vary during the year but appear to lie within the interannual variability in the two lease areas.

Table 3.2.1. Surface winds in Harrison Bay as percent of occurrence in the speed and direction category.

	Percent Occurrence							Total %	
NW	2	1	2	1			Onshore Winds	6	NW
N	3	2	1	1				7	N
NE	3	7	13	11	2			36	NE
E	2	5	5	2	+			12	E
SE	2	1	2	1				6	SE
S	2	4	2	1	+	+		9	S
SW	3	2	3	2	+			10	SW
W	2	4	4	3				13	W

0 4 7 11 17 22 28

Wind Speed (kts)

Table 3.2.2. Direction and velocity distribution of free drifting ice based on wind distribution in Table 3.2.1. Brackets encompass low ice velocities where turning angle may exceed 45°.

	Percent of occurrence							Total %	Total % @ 45° to wind (> 9 cm/s)
NW	2	5	5	2	+			12	7
N	2	1	2	1				6	3
NE	2	4	2	1	+	+		9	3
E	3	2	3	2	+			10	5
SE	2	4	4	3				13	7
S	2	1	2	1			Onshore	6	3
SW	3	2	1	1			Ice component	7	2
W	3	7	13	11	2		(> 9 cm/s)	35	26
								100	56

0 5 9 14 22 28 36

Ice speed (cm/s)

3.3 OFFSHORE BOUNDARY OF THE FLOATING FAST-ICE ZONE

By L. Shapiro and P. Barnes

A distinct boundary exists between relatively stable, unridged, floating fast ice near shore and intensely ridged ice immediately seaward. Although the position of the boundary along the coast varies widely within any one year and in different years at any one location, it can be recognized in most years, barring extraordinary events. The boundary is significant for development offshore because it marks the area which is stable for over-ice winter transport and which is subject to only small motions of annual ice against structures during the winter.

Within the floating fast-ice zone, heavy multiyear ice can be present in the winter but only if it is driven into the zone in the fall during freeze-up, where it is often grounded. During the fall, the first-year ice in the zone is mobile, thin, and weak. Therefore, the internal pack-ice forces which might be transmitted through the annual ice to drive multiyear ice floes against structures are low. The fast ice becomes stable in winter, in part from growth, but more important from the presence of the grounded ridge zone which absorbs most of the pack-ice stresses. Movements in the fast ice at this time are usually small, although large movements may occur; major ice-shove events have been observed occasionally in the fast ice in winter.

Outside of the floating fast-ice zone, within the grounded ridge and pack-ice zones, large motions are likely, during which thick ice formations can be driven great distances by the pack ice. Further, the magnitude of these movements increases the probability that large, thick, ice formations will cross any particular point which might be occupied by a structure or pipeline. Thus, observations indicate that the probability of thick multiyear ice damaging a structure is much greater in the grounded ridge and pack-ice zones than within the floating fast-ice zone. This hypothesis has not yet been supported statistically.

Although it would be desirable to establish a position for the boundary at the offshore edge of the floating fast ice zone which is applicable for any year, it is impossible to predict the geographic location in any particular year, as the boundary varies from year to year and from place to place (see Appendix C). In 1978 (Weller et al., 1978), the boundary in the Joint Sale Area was geographically set at the 15-m depth contour. This was later changed to 13 m based upon a few observations of the position of the boundary in the fall of 1978 (Kovacs, 1978). The 15-m depth contour, however, is an average geographic position for the boundary, while the 13-m position represents the extreme inshore occurrence of this boundary (1979) between Flaxman Island and Oliktok Point. The questions are whether a geographic line can or should be drawn and whether the boundary should be at 13 m for defining hazard zones or be moved to another depth or geographic location for the Sale 71 area.

The establishment of such a line is similar to the establishment of a classification for natural features or objects. Boundaries between classes of natural features are not sharp, and gradations between classes are the rule rather than the exception. Thus, the 15-m depth (or the 13-m depth) for the offshore boundary of the floating fast ice zone represents an average, while the magnitude of the deviation from the average can be large (0-20 m) and variable from place to place and year to year. Thus the 15-m or the 13-m contour could be onshore or offshore from the actual ice boundary in a given year or locality.

If the boundary is to represent a line across which the potential severity of hazards increases sharply, then that line should coincide with some recognizable, definable feature of the ice cover. With adequate data, a statistical definition might be made. However, in the absence of such data, we suggest that the outer boundary of little or no ridging, as observed from satellite data, be accepted as the innermost occurrence of the boundary of the floating fast ice (see Appendix C). Note that this boundary (Zone Ia, Figure C.4.) does not follow a single depth contour.

If the inner edge of ridging is rejected as a useful boundary in favor of the 13 or 15-m depth contour, then the boundary could be within the grounded ridge zone. Placing the boundary within the grounded ridge zone implies that there are sufficient data to subdivide the zone according to potential hazards, and that seems not to be the case at present.

As an alternative, the definition of the boundary line could be modified by the types of structures employed. This assumes a great deal of knowledge about ice-structure interaction, most of which has been developed in industry studies. Gravel islands have, however, been successfully employed for exploration in 20-m depths in the Canadian Beaufort Sea where ice conditions are less severe. Thus, the boundary line could possibly be set at the pack ice-grounded ice zone boundary for gravel islands and the more restrictive floating fast-ice boundary could be retained for other less-proven types of structures. However, the existence of fixed gravel islands in the Canadian Beaufort Sea tends to restrict motion of the ice, changing the edge of the grounded ridge zone.

3.4 HAZARDS

By P. W. Barnes

Harrison Bay is oceanographically unique, being an open shallow embayment with the largest north Alaska river emptying into its southern edge (Fig. P.1). A broad, shallow bench 1-2 m deep extends up to 10 km off the delta of the Colville River. Harrison Bay does not have the barrier island and lagoon system characteristic of much of the Beaufort Sea coast to the east and west.

Because of the breadth of this part of the coast, large areas of open water and longer fetches could develop in summer which would have higher waves than those within the lagoons and sounds to the east. The situation is similar to the wave regime seaward of the barrier islands. The broad shallows along the coast, particularly in the southwestern part of the bay, would dampen waves by bottom friction, thus diminishing their size at the coast. In winter, the growing ice canopy forces the tidal prism into a smaller cross section on the wide 2-m bench. Tidal currents at the end of the winter have been measured at 10-15 cm/s in water 3 m deep just north of the bench, compared with the weak currents in winter of 2 cm/s or less observed in water about 10 m deep, just north of the 2-m bench (Fig. 3.4.1).

A dramatic shift in inshore circulation, occurs after breakup when the melting and dispersal of the ice cover allows wind-driven currents to develop. Near-bottom currents measured northwest of Oliktok Point in 9 m of water were sluggish from May until the middle of July (Fig. 3.4.2). Currents were less than 5 cm/s, commonly 2 cm/s or less. From the middle of July, much stronger wind-driven currents parallel to the coast prevailed, with velocities commonly over 15 cm/s.

The large, open, shallow expanses would also allow the increased buildup of storm surges on the eastern shores (Reimnitz and Maurer, 1978a). This sea-level change may exceed 3 m with additional height provided by storm waves which would accompany a major surge. The surges are the most important oceanographic hazard in the lease area.

Long-term semistationary grounded ice features on shoals in the northeastern part of the bay may deflect, modify, or intensify currents near them. (See section on current-related bedforms, p. 99).

3.5 PERMAFROST AND RELATED FEATURES

By P. Sellmann, T. Osterkamp, and J. Morack

Introduction

The presence of fine-grained soils and ice near the sea bed suggests that permafrost may cause problems for offshore development in the Harrison Bay area. Probing (Harrison and Osterkamp, 1981), high-resolution seismic studies (Rogers and Morack, 1981) and velocity data derived from the study of industry seismic records (Sellmann and Neave, 1981) from the Sale 71 area indicate that penetration-resistant, high-velocity material interpreted to be bonded permafrost is common. Its distribution is probably as variable as it is to the east near Prudhoe Bay. Bonded permafrost should extend many kilometers offshore of the islands in the eastern part of the lease area. The deeper velocity data for Harrison Bay suggest that bonded permafrost can be subdivided into two categories. In the eastern part of the bay there is an orderly transition away from the shore, with the depth of bonded permafrost increasing and velocity contrast decreasing with distance from shore until the velocity contrast is no longer apparent. In the western part of the bay, it is less orderly, possibly reflecting the history of the original land surface. This western region may have been an extension of the low coastal plain characterized by the region north of Teshekpuk Lake, which could have contained deep thaw lakes. Shallow bonded permafrost should be common to the west of Harrison Bay based on observations made in the western part of the bay and offshore of Lonely.

Along some lines the high-velocity material in Harrison Bay extends approximately 25 km offshore, as shown in the selected cross section in Figs. 3.5.1 and 3.5.2. Additional seismic data from the Prudhoe Bay region indicate that ice-bonded permafrost extends at least 15 km north of Reindeer Island (Sellmann et al., 1981).

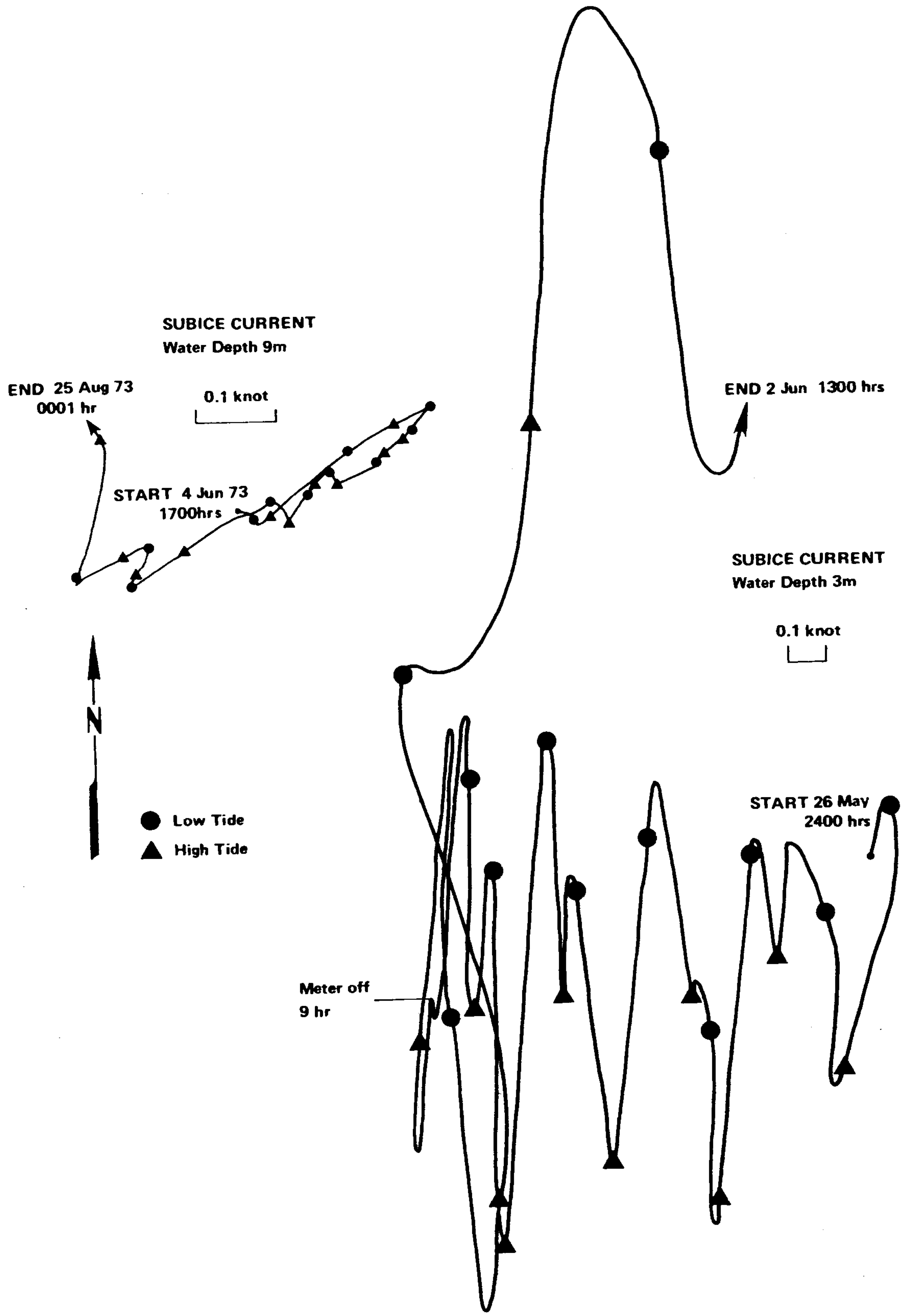

Figure 3.4.1. Progressive vector diagram of sub-ice currents in eastern Harrison Bay 1973. The 3-m station is 6 km WNW of Oliktok Point and the 9-m station is 15 km NW of Oliktok Point. Northerly pluses at the end of both shallow and deep records are from flooding and overflow of the Colville River.

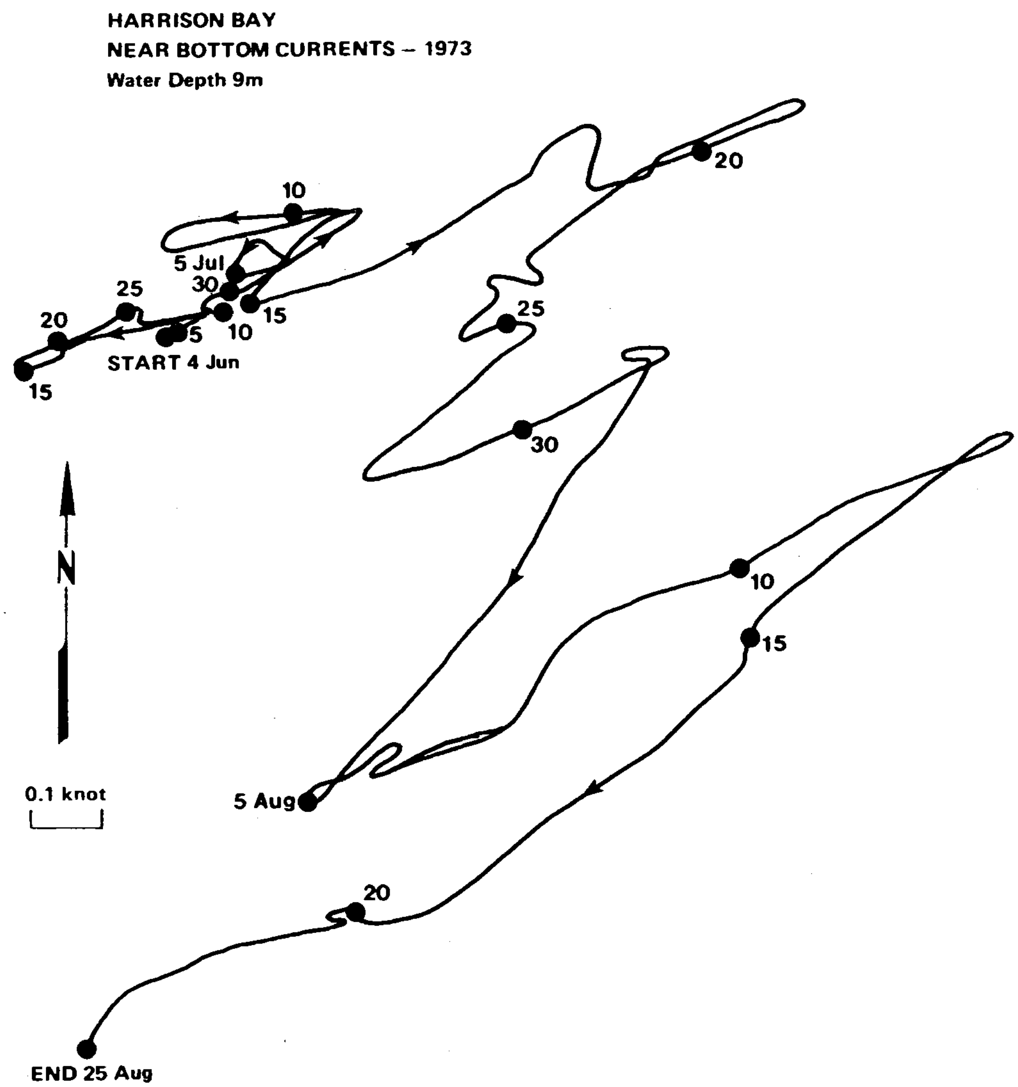

Figure 3.4.2. Progressive diagram of currents 1 m off bottom about 6 km NW of Thetis Island in eastern Harrison Bay, June-August 1973. The abrupt change in velocity on about 15 July is due to breakup of ice cover.

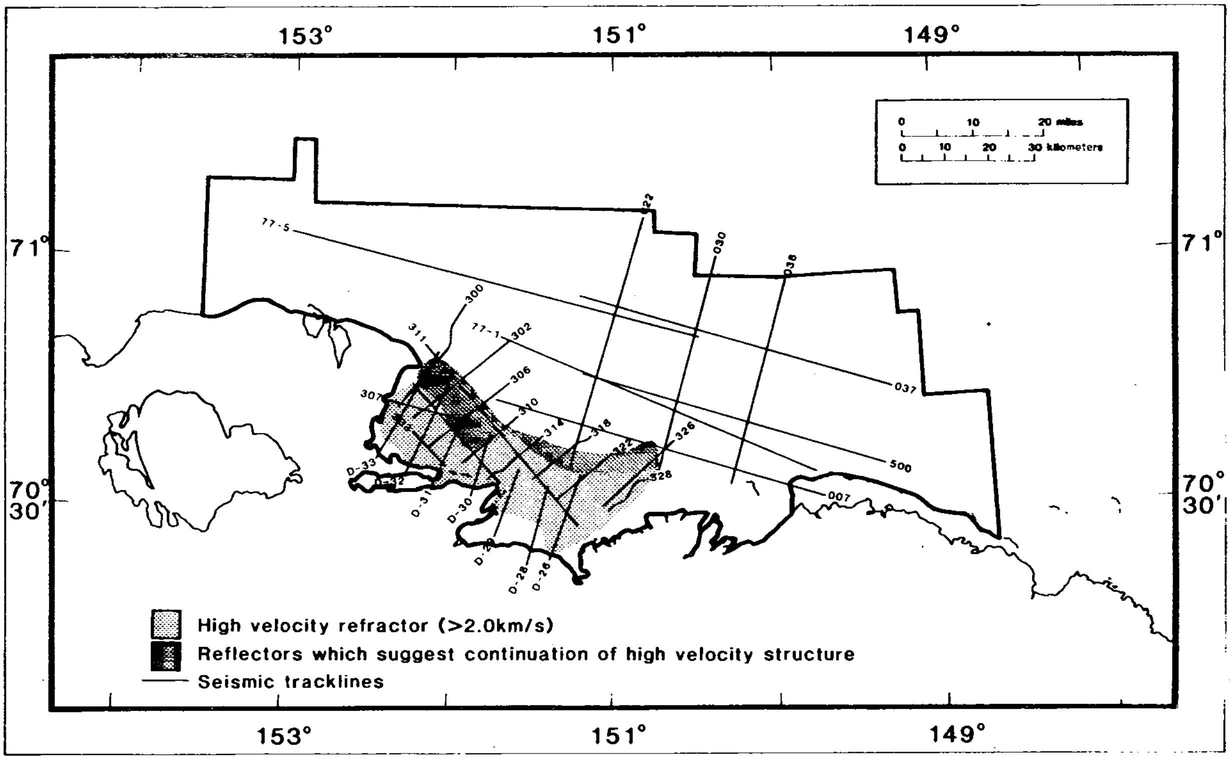

Figure 3.5.1. Preliminary map showing known distributions of high velocity material, from study of industry seismic records (Sellmann et al., 1981). Data along eastern and western tracklines are shown in Fig. 3.5.3.

Natural attenuation of the high frequency part of the seismic signals was frequently observed in the Harrison Bay region; it was interpreted to indicate that free gas in the pores of shallow sediments may be common. Deeper gas hydrates are also anticipated in the region since they appear to be more common in NPRA than near Prudhoe Bay (Osterkamp and Payne, 1981).

Information from this region comes primarily from seismic studies. No drilling and sample analysis was done, although temperature data were obtained from shallow probe observations. The lack of core analysis has resulted in critical data gaps, particularly since results from the past program to the east cannot be extrapolated into this region because of contrasting geology. Important topics for which no data exist include (1) ground ice volume, (2) ground truth from bore holes to calibrate seismic data, including position of ice-bonded permafrost, (3) sediment distribution with depth--including gravel, (4) strength properties, (5) index properties, (6) overconsolidation of the sediments, (7) gas distribution, and (8) temperature data.

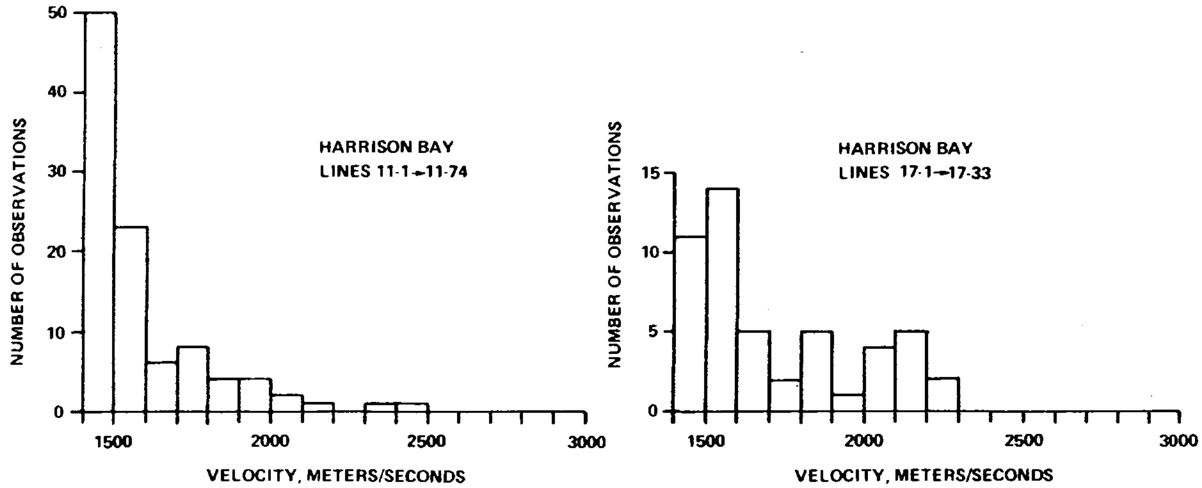

Figure 3.5.2. Histograms of velocities from shallow depths, based on high resolution seismic observations in the vicinity of Harrison Bay (Rogers and Morack, 1981).

The new data from this region, based on geophysical methods alone, were independently acquired as part of two separate OCSEAP seismic programs. The results from these studies and from probe and geological investigations tend to support one another, indicating the value of utilizing a number of approaches to understand the complicated permafrost, athough the lack of drill holes is a serious shortcoming.

Onshore Permafrost and Gas Hydrates

Bonded permafrost. The characteristics of onshore permafrost are useful in predicting permafrost conditions offshore. Unfortunately, there is no published onshore temperature data for this lease area as there was from the Prudhoe Bay and Joint Sale areas. However, thickness data acquired from well logs (Osterkamp and Payne, 1981) suggests that permafrost thins to the west. Onshore coastal permafrost is about 500 m thick east of Oliktok Point, 400-500 m thick in the Colville River Delta, and 300-400 m thick from the delta to the western boundary of the lease area. If the geology is similar offshore, the onshore values suggest the maximum thickness that might be expected near shore in the Sale 71 area.

Gas hydrates. Well log data also indicated that more of the wells west of the Colville River show evidence of gas hydrates than those in the Prudhoe field to the east (Osterkamp and Payne, 1981). Thus, the probability of encountering gas hydrates and free gas from hydrate decomposition is greater for the Sale 71 area.

Subsea Permafrost

Bonded Permafrost. The velocity map for Harrison Bay indicates two layers near shore (Fig. 3.5.1). The deep high-velocity layer in this zone increases in depth and decreases in velocity with distance from shore, as indicated by a high-velocity refractor. Farther offshore, the next zone is characterized by a deep reflector, suggesting continuation of the high-velocity structure.

The region beyond this zone lacks high velocities, making it difficult to determine whether materials are ice-bonded. However, slight velocity increases and inversions suggest that some ice-bonded sediments may exist.

The high-velocity materials are most common out to the 13-m isobath and are believed to represent ice-bonded permafrost.

High resolution seismic data (Fig. 3.5.2) taken in the eastern end of Harrison Bay (Rogers and Morack, 1981) indicate that shallow (< 50 m) bonded permafrost is present in the area adjacent to shore and offshore of the Jones Islands.

Probing has shown that the subbottom material changes from gravel to silt, as one moves westward in the area between Thetis and Spy Islands. However, no shallow bonded permafrost is suggested from the high-resolution seismic data taken near Thetis Island. A seismic line running from Oliktok Point to the west end of Spy Island indicates shallow bonded permafrost near shore at Oliktok Point and again north of Spy Island. The observed velocities were greater than 2,500 m/s, indicating gravels, and are in agreement with data from one shallow drill hole in this area. An additional high-resolution seismic line run from shore to the east end of Pingok Island does not indicate shallow bonded permafrost in Simpson Lagoon, and the conclusion is that the bonded permafrost dips quickly in an offshore direction. However, outside of Pingok Island, high velocities suggest that bonded permafrost is again present at shallow depths (<10 m), and the measure velocities (4,000 m/s) indicate that it has not yet significantly degraded (Rogers and Morack, 1981).

Two cross sections from a study of the industry records (Fig. 3.5.3) illustrate the two different velocity regimes found in Harrison Bay. High-velocity structures extend 25 km offshore on both lines; however, the eastern line (Fig. 3.5.3) has a more uniform depression of high velocity offshore. The eastern line also shows the systematic thickening of the low-velocity (unfrozen) layer with distance from shore. The velocity of this upper layer, 1,800 m/s, falls in the range that represents little or no ice bonding of the sediments. The second layer has velocities of 3,000-4,000 m/s, consistent with ice-bonded material. The decrease in the lower-layer velocities with distance from shore suggests that the layer has partially melted during progressive degradation of the permafrost.

The depth to the high-velocity layer is greater in Harrison Bay than it was near Prudhoe Bay at comparable distances from shore.

The second set of profiles (Fig. 3.5.3) illustrates the greater complexity encountered along the western line. The first segment, including the onshore and nearest offshore records, is anomalous because it has only low velocities. A second segment near the shore has a shallow, high-velocity refractor. The remaining offshore half of the line has two more distinct zones of material that may be partially bonded or may represent a change in material type, one deep zone and one shallow zone.

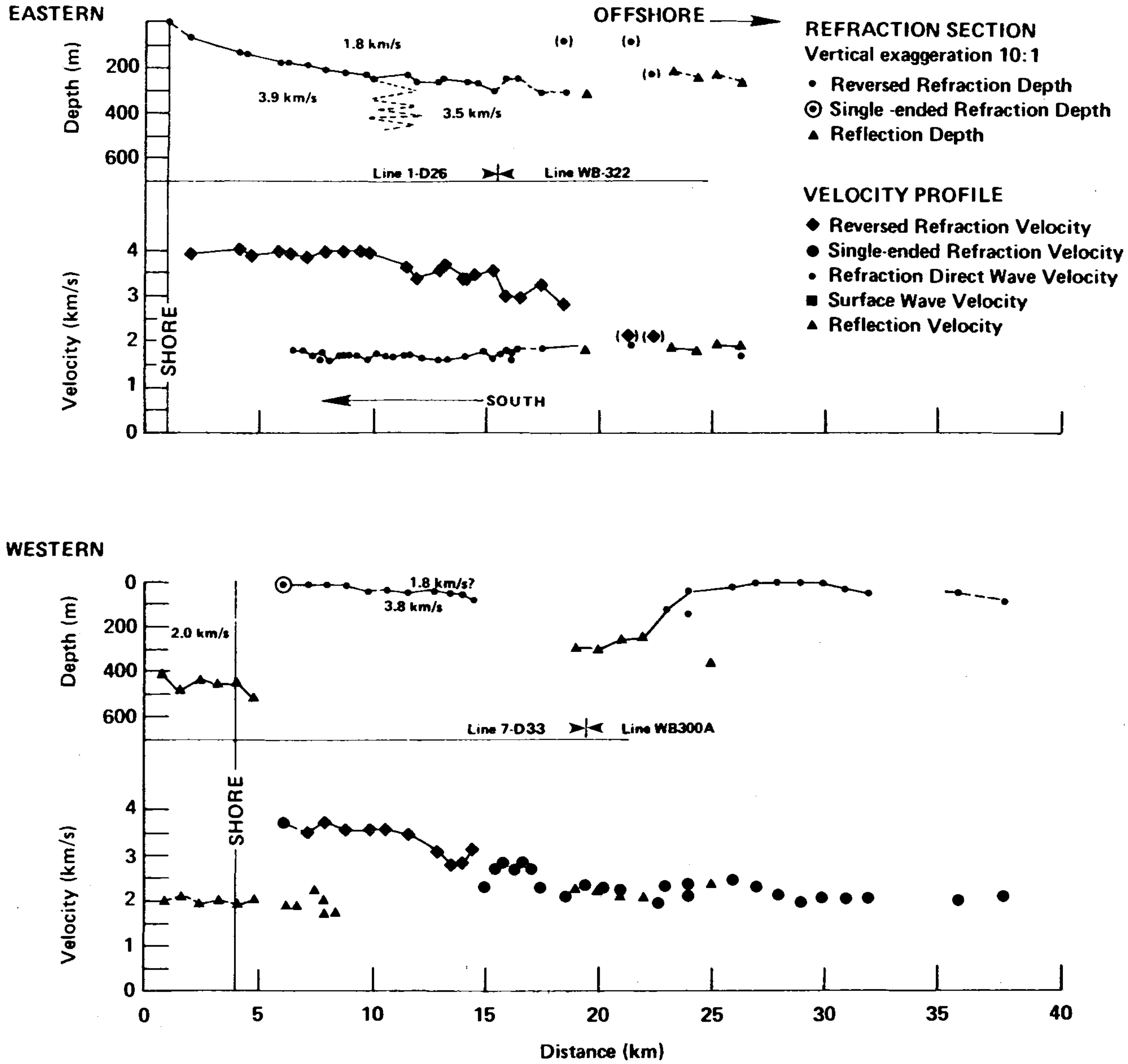

Figure 3.5.3. Velocity data from two sets of tracklines in Harrison Bay (Sellmann et al., 1981). These lines can be identified on Fig. 3.5.1. by locating the line numbers provided above.

<u>Offshore Gas and Gas Hydrates</u>. Seismic signals were highly attenuated in some zones: the dominant frequency of the reflected and refracted signals was reduced from about 30 Hz to less than 15 Hz. This phenomenon can best be attributed to the presence of gas in the pores of the shallow sediments. Figure 3.5.4 shows probable locations of free gas in the sediment at an estimated depth of 20-300 m. We can also infer from the presence of free gas above ice-bonded permafrost that gas in hydrate form, within and below the ice-bonded layer, is likely.

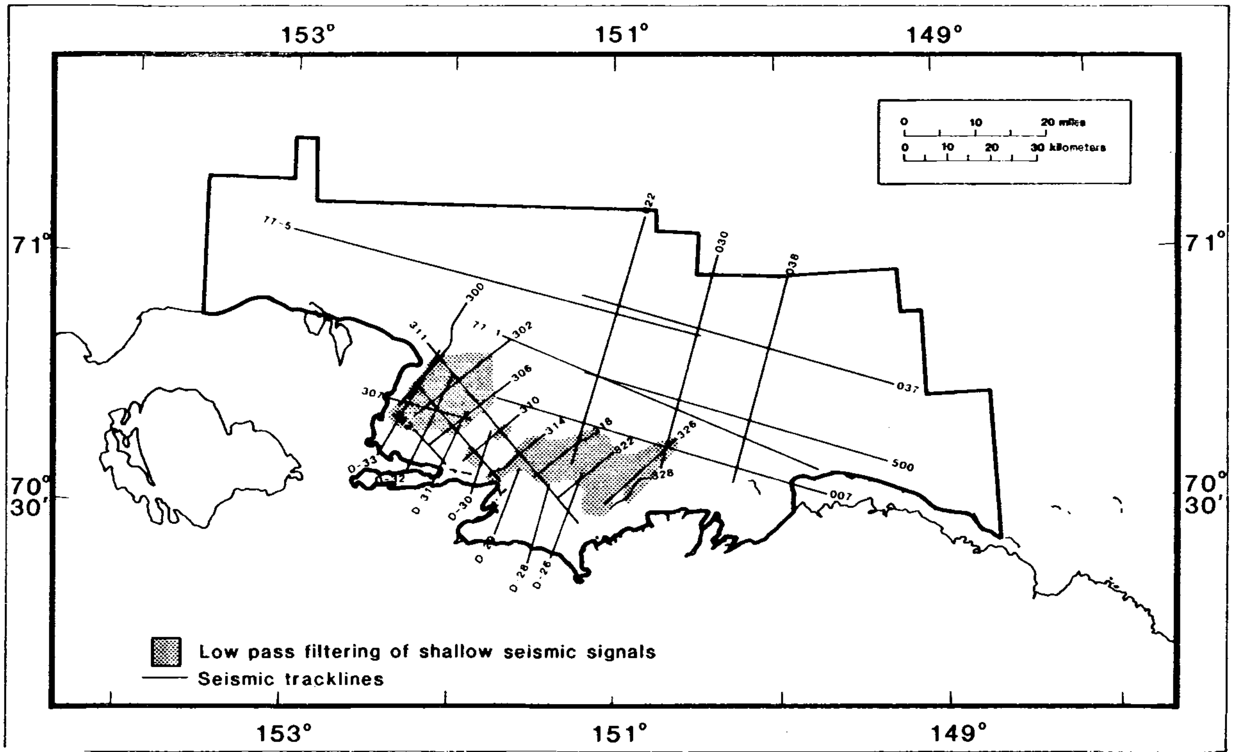

Figure 3.5.4. Probable locations of free gas in the sediment at an estimated depth of 20-300 m. Natural filtering of the high frequency part of the signal occurs in the shaded zone. This is an indication of shallow gas in the sediment (Sellmann, et al., 1981).

New Permafrost Information

Holes jetted on a line off Lonely extending 78 km offshore in water depths of about 2, 3, 5, 7, and 9.5 meters encountered fine-grained sediment and ice-bonded permafrost no deeper than 15 m (Harrison and Osterkamp, 1981). A hole drilled on Thetis Island penetrated fine-grained ice-bonded permafrost to 35 m. A hole south of Thetis Island in fine-grained sediments to a depth of about 18 m suggests that a major lithologic boundary may exist between Oliktok Point and Thetis Island, with fine-grained materials predominating to the west.

Seasonal freezing of the seabed has been reported in the Prudhoe area (Sellmann and Chamberlain, 1980). This freezing was obvious only where the sea ice formed on or near the seabed. In Harrison Bay, however, Osterkamp (unpub.) found the seabed to be frozen in a number of holes where the ice cover was not next to the bed. This seasonal freezing was thought to be the result of anchor-ice formation or freezing of fresh pore water in the bed sediments. The freshening of the sediment could take place by discharge from the Colville River and subsequent freezing by a cold sea-water wedge sometime during formation of the ice cover in the bay.

Recently acquired oil industry records from the Prudhoe Bay region indicate that ice-bonded permafrost may exist at least 15 km north of Reindeer Island (Sellmann et al., 1981).

Hazards

In addition to the hazards previously discussed for the Prudhoe area in Weller et al. (1978), several hazards are unique to Harrison Bay. The high ground-ice volumes of the onshore fine-grained permafrost in the western part of the Sale 71 area, coupled with high shoreline erosion rates, could complicate development of land-sea transitions in this region.

Gas Hydrates. Onshore permafrost studies (Osterkamp and Payne, 1981) suggest that gas hydrates are more likely to be encountered in Sale 71 area than in the Joint Lease Area. The variable and unpredictable distribution of hydrates will require great care to implement well-control procedures when drilling in potential hydrate zones. Consideration of the combined effect of casing load caused by hydrate decomposition along with the loads developed during thaw settlement of the permafrost will also be required.

Frozen Ground in New Man-made Structures. Causeways and artificial islands will be subject to the same seasonal freezing and formation of permafrost as similar natural features. The increase in strength caused by freezing has been suggested as an important factor in the design of some of these structures and of benefit in resisting ice forces.

No published data exist on the strength of newly frozen sediments in the marine environment. However, observations made in seasonally (Blouin et al., 1979) and perennially frozen marine sediment indicate that sediment properties are not likely to be as uniform as those found in sediment containing fresh water. Layers will often form due to exclusion of brine during downward freezing. Brine layers can have concentrations high enough to be preserved in late Pleistocene sediments, particularly in fine-grained material.

Lack of homogeneity should be considered in the design of offshore islands and causeways, since extensive brine layers could provide potential shear zones. The properties of brine zones can also change with time; additional cooling and associated ice formation could increase pore-water pressure in these zones.

Research Needs, Data Gaps

Complete assessment of problems associated with permafrost and associated features in this area cannot be accomplished because of the lack of detailed observations normally obtained through drilling, sampling, and core analysis. This lack of data from a drilling program creates gaps in our knowledge in the areas mentioned in the introduction. This scarcity of ground truth also leaves the seismic data analysis with a degree of uncertainty in its interpretation. A drilling program based on several carefully selected holes to 50-100 m depth and a number of shallower holes of less than 30 m would help greatly to reduce this problem.

The impact of an absence of drilling data goes beyond the problem of understanding the properties of permafrost and its mode of degradation in this new geological setting. The lack of direct geological data makes it impossible to anticipate sources of granular material for island and causeway construction and problems of acquiring this material.

3.6 SEDIMENTS

By P. W. Barnes, E. Reimnitz, and A. S. Naidu

The sediment character of the Sale 71 Area is similar to that described in the 1978 Synthesis Report (Weller et al., 1978). Fine-grained sediments predominate on the shallow delta platform of the Colville River (Barnes and Reimnitz, 1974). Seaward to about 10 m, wave- and current-worked muddy sands are dominant. Farther seaward to the edge of the lease area, finer muds are characteristic, except on shoals, where clean sands and gravels are found (Barnes and Reimnitz, 1980).

Recent work shows four other characteristics not mentioned earlier:

A. The short-range variability of sediment types usually is high (Barnes and Reimnitz, 1979) due to the interplay of ice gouging and hydraulic reworking in water depths less than 15 m.

B. Shoals, and wave- and current-related bedforms in the lease area are composed of moderately- to well-sorted sands and gravels (Reimnitz and Maurer, 1978b; Barnes and Reimnitz, 1980). These features are constructional and rest on semiconsolidated to highly consolidated muds to sandy muds.

C. The sub-bottom depth of sediment reworking on the inner shelf, between 2 m and about 15 m water depth, is about equal to the average ice-gouge incision in these water depths, 30 cm. The presence of lag, cross-bedded horizontal sand layers (wave- and current-related) interbedded with homogeneous muds (ice-gouge related) in ice-gouge terrain indicate that, on the average, recurring hydraulic events rework the sediments to depths that are not subsequently reworked by ice.

D. Intensive sediment reworking inside of 15-m water depth occurs, on an interval of 5 to 10 years, during extreme open-water seasons with intense fall storms. This completely destroys the prevalent ice-gouge terrain by infilling and reworking. In places these currents construct sand waves a meter or more in height (Barnes and Reimnitz, 1979). In the troughs between these sand waves, current-polished, grooved and fluted over-consolidated muds reflect the action of currents.

Hazards: Sedimentary Indicators of Intense Currents

<u>Inner shelf</u>. In numerous regions on the inner shelf, out to a water depth of 15 m, are a combination of smooth-surface sand waves or linear, current-shaped sand bars resting on highly jagged relief forms carved into overconsolidated silty clay which outcrops in the troughs between sand bodies (Reimnitz et al., 1980). These bedforms attest to highly active, and sometimes intensive current reworking.

A. The common lack of ice-gouge relief on crests of sand waves, where ice generally is grounded, indicates that the bedforms have recently been reshaped by currents and waves, while the ice-gouge relief in stiff silty clay exposed in troughs is preserved through long periods of current action.

B. Direct diving observations of the jagged relief forms in stiff, silty clay show that the detailed surface shapes range from sharp-edged vertical to overhanging ledges with fresh conchoidal fractures and narrow gullies to well-rounded and polished knolls. Even the narrow gullies and cracks, only 3 cm wide and 10 cm deep, commonly are devoid of sand fill, while containing well-rounded mud balls, shells, and pebbles. The scarcity of burrows made by marine organisms, like the lack of gouges on nearby sand bodies, again suggests recent current activity, and the currents capable of rounding ledges of overconsolidated silty clay must be very swift.

Central shelf. Recent studies reveal sediments and bedforms indicative of swift currents in the stamukhi zone as well as near shore (Barnes and Reiss, 1981; Reimnitz and Kempema, 1981). On the crests of the shoals (see Fig. 7.3.1) wave-formed ripples, 1.5 m in wavelength are found in clean gravel of 2 cm diameter. On Stamukhi Shoal these have formed since 1977, when gouges were prevalent. Orbital velocities of 100 cm/s are necessary to shape gravel into these bedforms (Reimnitz and Kempema, 1981). One-meter-high asymmetrical sand waves, 50 to > 200 m long, occur along the flanks of the shoals at 14-17 m water depth, suggesting strong, unidirectional, easterly currents.

3.7 ICE GOUGING

P. W. Barnes

New data on ice gouging have been gathered in the past two years, and progress also has been made in statistical data analysis (Barnes and Reimnitz, 1979, 1980; Kovacs and Weeks, 1980). Most of the qualitative observations in the 1978 synthesis are still applicable. However, additional quantitative aspects, both descriptive and statistical, can be reported.

The Average Gouge

Although regional and physical relationships control ice gouge distribution, the "average gouge" for the entire Beaufort Shelf would occur in water depths of about 17 m at a distance of 13 km from the coast. It would be incised into the bottom for 50 cm with ridges on the gouge side of 40 cm, thus presenting a total relief of almost 1 m (Table 3.7.1). The gouge would be 7.5 m wide and be oriented east-west, slightly onshore of the northwest-southeast coastline. Thus, the relief of the average gouge from crest of ridge to bottom of trough is about 1 m and is oriented onshore. There would be 63 gouges observed per kilometer.

Table 3.7.1. Summary statistics of Counted Gouges (Values for 1-km-trackline segments).

Type Measure	Maximum	Minimum	Mean	Standard Deviation ("Average")
Individual Gouges				
Water depth (m)	125.0		16.8	
Distance from coast (km)	42.7	0.2	12.9	
Gouge density (#/trackline km)	490	0	63.0	70.1
Dominant orientation (°T)				90
Subdominate orientation (°T)				87
Max. incision depth (m)	5.5	less than 0.2	0.5	0.6
Max. incision width (m)	62.0	less than 1	7.5	8.0
Max. ridge height (m)	2.7	less than 0.2	0.4	0.5
Multiple Incision Gouges				
No. multiple gouge events #/trackline-km	15	0	1.6	2.3
Max. no. incisions per event	27	2	4.8	3.7
Max. multi-incision disruption width (m)	150	2	28	
Dominant multi-incision orientation (°T)			162	

Gouge Variability

Gouge Density. The number of gouges observed per kilometer of trackline is greatest in water 15-30 m deep: generally more than 100. Fewest gouges occur in water less than 5 m or more than 45 m deep. In water 20-40 m deep, few gouges per kilometer are observed.

Maximum Incision Depth. The maximum incision depth of gouges in the seabed follows a pattern similar to that of gouge density; gouge depth is greatest in water 18-35 m deep. These incisions are commonly over 1 m deep, maximum incision depths are less than 10 m. As in the case of gouge density, maximum gouge depths observed in water 20-40 m deep show an absence of low values, with few incisions less than 0.5 m deep.

<u>Maximum Incision Width</u>. Generally, for single-incision gouges, the maximum incision widths increase with increasing water depth. Gouges range from about 5 m wide, in water less than 10 m deep, to over 50 m wide in water 20-30 m deep, although most of the gouges are less than 20 m wide.

<u>Maximum Ridge Height</u>. The sediment ridge piled up by a single plowing ice keel is highest in water 18-40 m deep, where ridges over 1-2 m are common. In shallower and deeper water, maximum ridge heights are usually less than 60 cm.

<u>Gouge Orientation</u>. The dominant orientation of ice gouging in trackline segments is clustered around the average 090° (true). With increasing water depth, the trend becomes more pronounced.

<u>Number of Multiple Incisions</u>. The number of multiple-keel incisions caused by pressure ridges (Reimnitz et al., 1973) again shows a similar pattern of gouge density, incision depth, and ridge height, with the highest values observed in water 15-30 m deep. In water greater than 20 m deep, eight or more multiple tracks are commonly observed in a 1-km trackline segment. In water less than 10 m deep and greater than 40 m deep, fewer than four multiple incisions are normally encountered in each 1-km trackline segment.

<u>Distribution of Incision Depths</u>. Using fathograms to plot the number of gouges in each trackline segment observed in 0.2-m depth increments provides a distribution of the number of gouges in each incision increment. In Fig. 3.7.1, a logarithmic distribution of gouges is shown ranging from the shallowest gouges to gouges 2.5 m deep. The incisions greater than 2.5 m that have been measured do not follow the same distribution, perhaps due to the small number counted. (See section on Statistical Treatment of Gouging for a detailed treatment.)

Character of Maximum Gouging

A maximum gouge density of 490 gouges per trackline kilometer was encountered on the Beaufort Sea shelf in water 20 m deep. Maximum incision depth of 5.5 m was found in water 39 m deep north of Smith Bay (Reimnitz and Barnes, 1974). Other large incisions (4 m deep) were observed northeast of Cape Halkett in water 31-37 m deep. Maximum single incision widths of 62 m were found in water 34 m deep and multiple gouges exceeding 50 m were found in water 20-33 m deep. Maximum ridge height of 2.7 m was encountered northeast of Cape Halkett in water 30 m deep. Thus, maximum seabed incisions occur in water over 30 m deep where seabed relief (incision depth plus ridge height) of more than 8 m could be found (5.5 m + 2.7 m). Where the bottom is saturated with gouges, fewer large gouges can be accommodated in any kilometer of trackline segment than is the case where gouges are small. Thus, the highest-density gouging does not correspond with the maximal incision. The most dense gouging occurs in slightly shallower water, at about 20 m water depth.

Maximum gouge incision depths show a strong statistical relationship to ridge heights. Increasing maximum ridge heights are found together with increased incision depths. Relief is commonly over 3 m and maximum

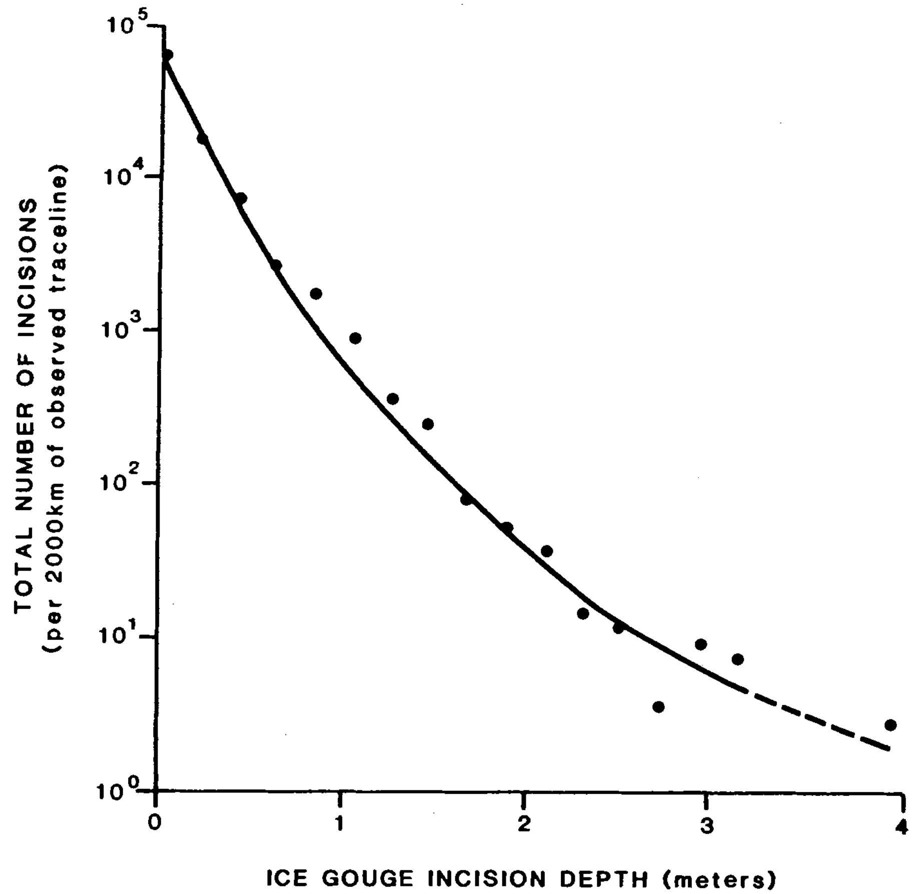

Figure 3.7.1. The distribution of the total number of ice gouge incisions observed versus their depth.

relief is over 7 m. This is reasonable, as the deepest gouge events must displace more sediment causing buildup of higher ridges (Fig. 3.7.2).

Regional Distribution of Ice Gouge Character

Highest densities of gouges are found in the stamukhi zone in water 20-30 m deep. Low values are encountered in the lee of the coastal islands and southwest of the offshore shoals which also cause a lee for the east-to-west ice motion. The central portion of Harrison Bay also has relatively low gouge densities (Fig. 3.7.3).

Maximum incision depths generally increase with increasing water depth, at least to the depth where our data become sparse, as on the westernmost trackline beyond the 30-m isobath. North of Cape Halkett, where we have obtained data to the shelf edge, the maximum incision depths decrease beyond about 45 m. Maximum incision depths are concentrated in deeper water (Fig. 3.7.4), whereas maximum densities are found in shallow water, i.e., the inner parts of Harrison Bay and Smith Bay.

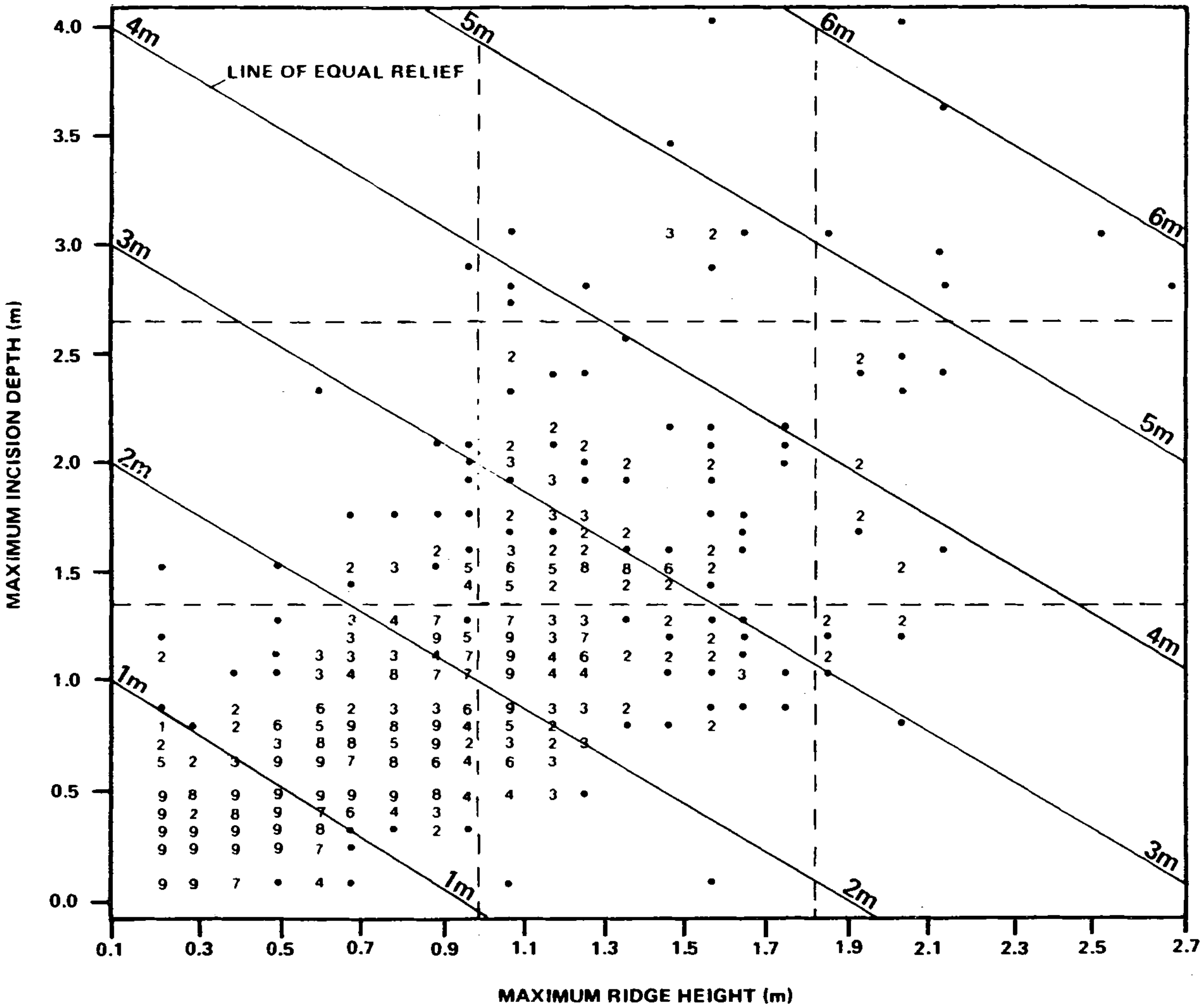

Figure 3.7.2. Scattergram of maximum ridge heights versus maximum incision depth. Relief (incision depth plus ridge height) is represented by the diagonal grid.

Dominant gouge trends illustrate the general coast-parallel trend of gouging, but with considerable scatter and local variation. The dominant orientation in the sounds, lagoons, and shallows of western Harrison Bay is particularly variable. Offshore, the orientation between the 20- and 40-m contours appears to be virtually all coast-parallel and slightly onshore. Another trend which needs further study occurs on several onshore-offshore transects. Gouge orientations trend onshore more and more frequently as they approach the coast. This is noticeable on the westernmost transect, off Cape Halkett, and north and northwest of Oliktok Point. This trend is not apparently depth-related (Fig. 3.7.5).

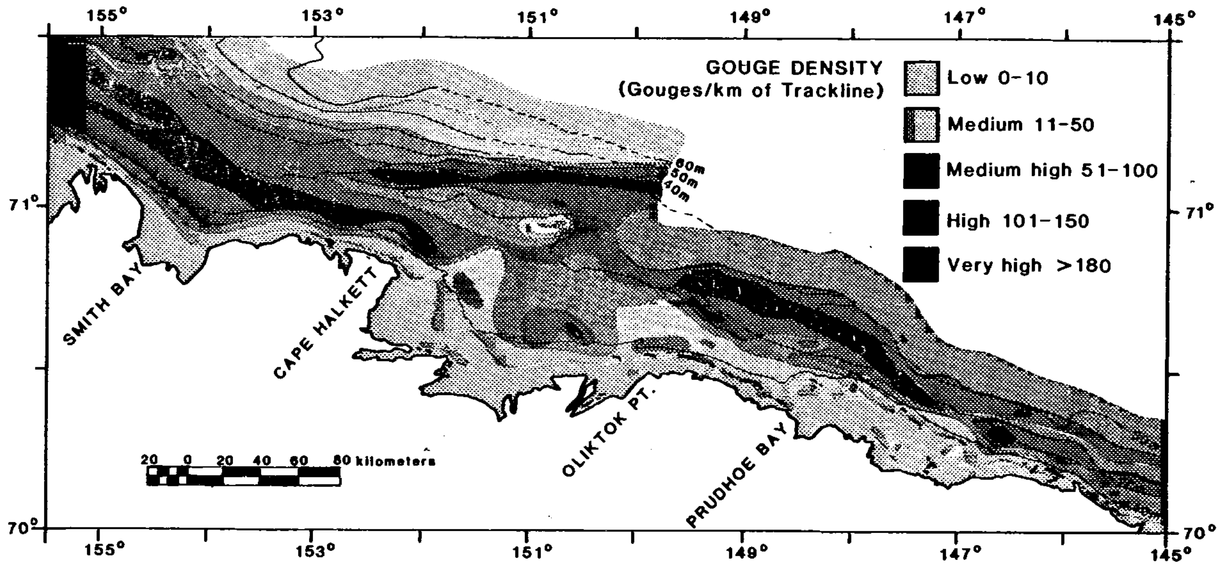

Figure 3.7.3. Contours of gouge density on the Beaufort Sea shelf. Note low densities on the inner shelf and around shoals and the high densities near the stamukhi zone.

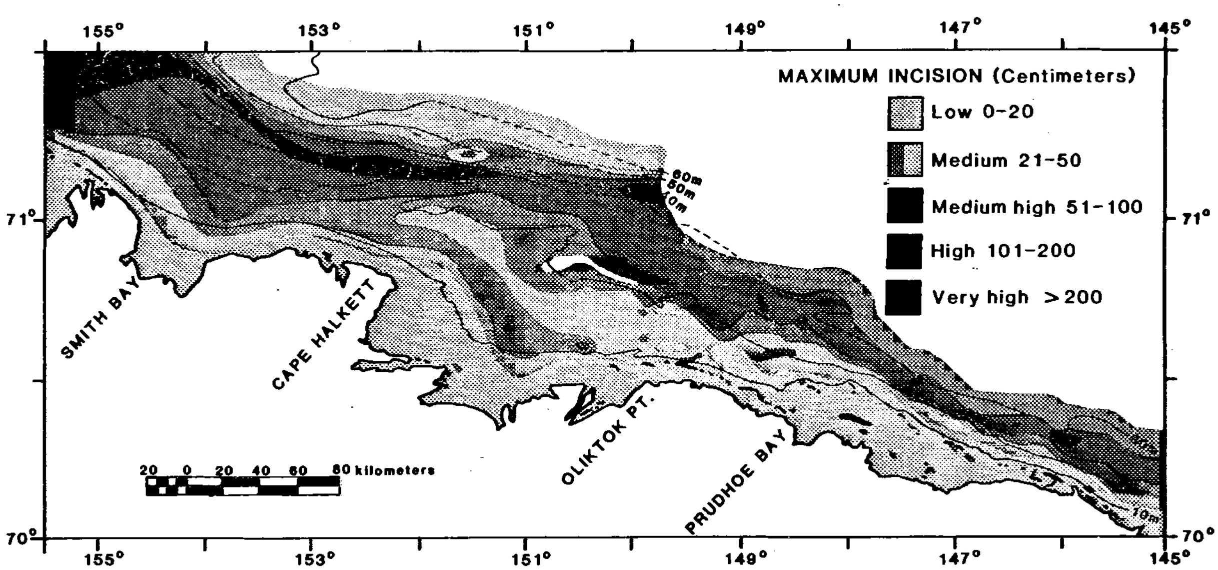

Figure 3.7.4. Contours of gouge incision depths on the Beaufort Sea shelf. Note the low values on the inner shelf and on shoals and the higher values at and just seaward of the stamukhi zone.

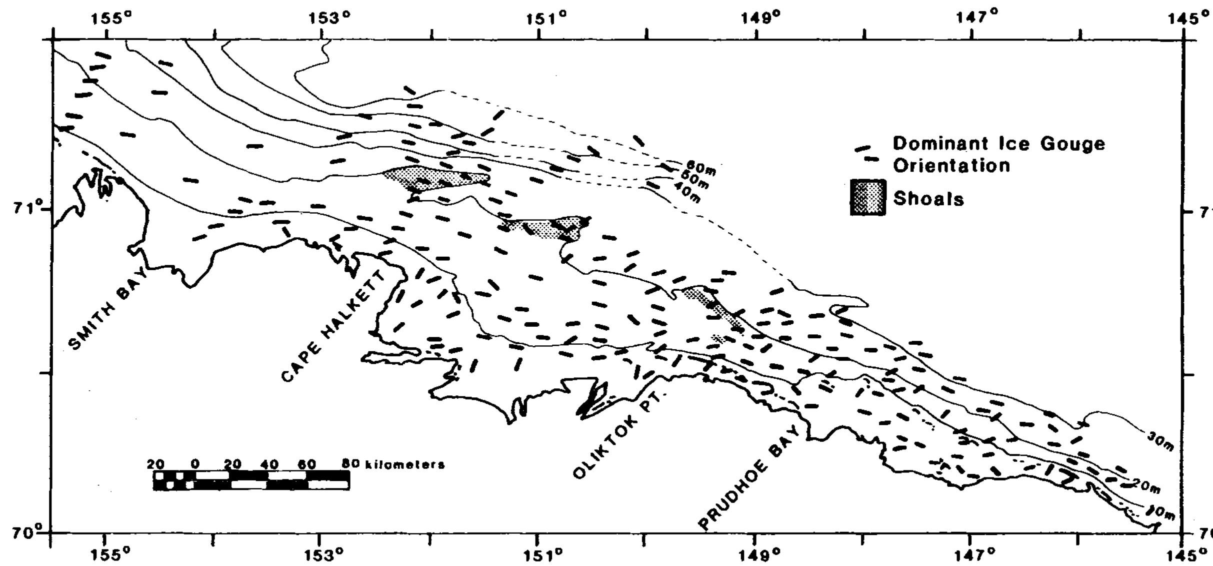

Figure 3.7.5. Dominant gouge orientations on the Beaufort Sea shelf. Note the gouging seaward of the islands on the central shelf is parallel to the isobath or oriented slightly onshore. Also note the varied orientation of gouging in the lagoons and on the inner shelf.

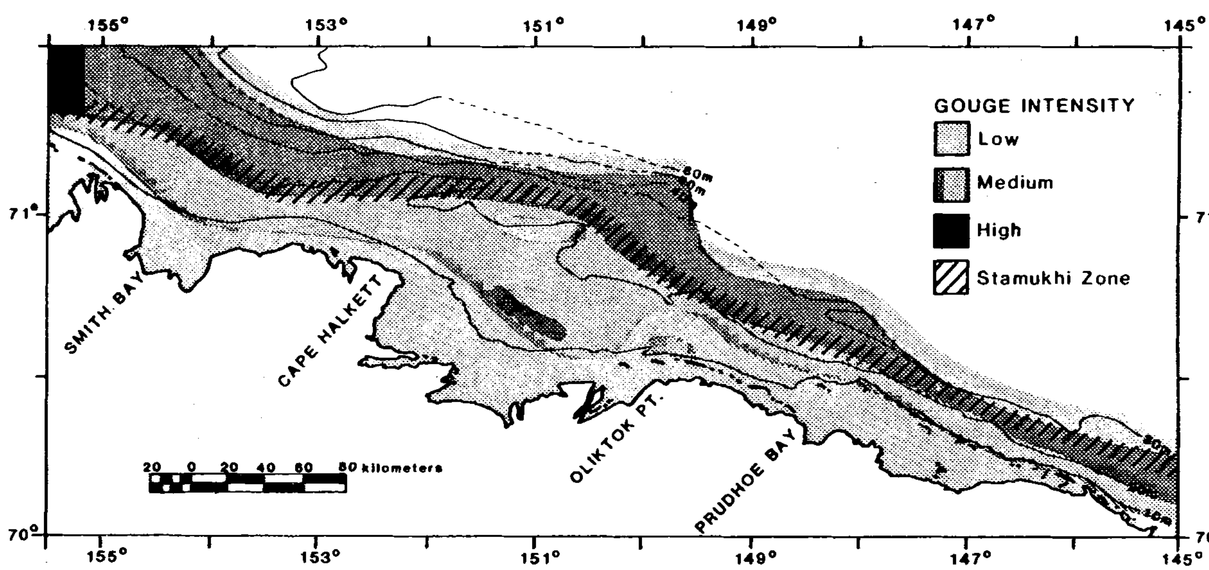

Figure 3.7.6. Interpretive map of gouge intensity of the Beaufort Sea shelf based on gouge density (Fig. 3.7.3), maximum incision depths (Fig. 3.7.4), and ice ridge intensities.

Relation of Ice Gouging to Ice Zonation and Dynamics

When all factors are considered, it is apparent that the most intense gouging is concentrated in water between 15 and 35 m deep. Gouge density, incision depth, ridge height, maximum incision width, and number of multiple incisions are all at a maximum in these water depths. The intensity of gouging is a function of the number of times ice strikes the seabed, rate of recurrence, and amount of bottom area disrupted by these collisions. Bottom disruption is described by the maximum incision depths, ridge heights, and incision widths.

The most intense ice ridging occurs in the stamukhi zone in waters 15-40 m deep (Reimnitz et al., 1978). This is the area where the polar pack shows the most intense energy dissipation in the Arctic Ocean (Thomas and Pritchard, 1980). In the stamukhi zone, the grounding of ice keels is indicated by ice-ridge stability after formation. As polar pack-ice forces would be expended on the seabed, and sediment disruption is at a maximum (as indicated by coring and seismic stratigraphy), the stamukhi zone should be an area of intense ice gouging. From gouge densities and maximum incision depths (Figs. 3.7.3 and 3.7.4) and data on incision width, ridge heights, and multiple incisions, a subjective gouge intensity map was created (Fig. 3.7.6). Unfortunately, however, the recurrence rate and seasonality of gouges in waters deeper than 15 m is not known.

In Harrison Bay, the relationship between ice zonation, seabed morphology, and gouging can be seen. Reimnitz et al. (1978) show two zones of ridging in Harrison Bay. One zone occurs near the 10-m isobath, and a second, more pronounced zone, runs seaward of the shoals in the northeastern and outer central part of the bay in the vicinity of the 20-m isobath. The contoured gouge densities and maximum incision depths (Figs. 3.7.3 and 3.7.4) show that these two areas have higher densities and deeper incisions than the rest of the Beaufort. This suggests a correlation between the intensity of gouging and that of ridging.

The dominant ice motions along the Beaufort coast in winter are from east to west (Kovacs and Mellor, 1974; Thomas and Pritchard, 1980); gouge orientation is associated with slightly onshore components of westerly ice motion (Fig. 3.7.5). These onshore motions result in less intense gouging in the lee of shoals and of the stamukhi zone. This is reasonable, since the most intense gouging would most likely result when keels plow into the seabed and move uphill. Thus, gouging will be more intense on steeper than on gradual slopes, although the gouges may not be as long.

Areas of shallow incisions and less dense gouges are associated with shoals in the northern and eastern part of Harrison Bay and outside the islands, but inside the stamukhi zone are related to ice zonation and its effect on the seabed. The shoals are composed primarily of sands and gravels. The observed refilling of these gouges is due to failure of non-cohesive sediments to maintain deeply incised features or due to hydraulic reworking of sediments; the latter may occur either by storms or by intensified flow during the open season near grounded, or nearly grounded, ice-ridge keels. To the east, the stamukhi zone is often associated with a change in sediment character. Seaward of the zone, cohesive but unconsolidated muds and muddy gravels offshore abut overconsolidated muds, often in association with a bench or a shoal 1-2 m high. Gouging of the seabed is much more intense in the area of unconsolidated sediment within, and just seaward of, the stamukhi zone. The origin of the overconsolidated sediments is uncertain. They may be the result of repeated freezing and thawing during the Holocene transgression, or they may be caused in part more directly by vertical, and perhaps more important, by horizontal forces associated with the intense ice-seabed interaction in the stamukhi zone.

3.8 STATISTICAL ASPECTS

By W. F. Weeks

As the polar pack ice drifts over the shallower waters of the Alaskan continental shelf, the grounding of the deeper pressure-ridge keels will commonly not stop the movement of the drifting ice field. Polar pack forces on the sides of the grounded ice features cause them to scrape and plough their way along the sea floor.

Along the Beaufort coast, gouging has been studied for some years (Reimnitz and Barnes, 1974; Reimnitz et al., 1977; Weller et al., 1978). The intensity of gouging is clearly a function of water depth. The maximum depth of contemporary gouging is roughly 50 m, corresponding to the depth of the largest pressure-ridge keels. Off the MacKenzie Delta, scours occur out to a water depth of 80 m (Lewis, 1977), but are most frequent at water depths of 23 m. A similar trend (maximum gouge frequencies occurring between water depths of 20-30 m) is observed off the Alaskan coast of the Beaufort Sea (Weeks et al., 1981), with some regions showing gouge frequencies in excess of 200 gouges/km. Figure 3.7.3 shows gouge frequency versus water depth for a region of the Beaufort coast offshore of the barrier islands and just east of Prudhoe Bay. As might be expected, gouge frequencies are much lower (usually less than 60) within the lagoons and sound protected by the barrier islands.

The distribution of gouge incision depths at any given water depth is well approximated by a negative exponential (there are many small gouges and only a few large gouges). Also, the character of the exponential fall-off is a function of water depth. Figure 3.8.1 shows the exceedance probability (the probability of occurrence of gouges having depths greater than or equal to the specified value) for several different water depths. This figure is based on data collected off the Alaskan coast of the Beaufort Sea from Harrison Bay and eastward. In water 5 m deep, a 1-m gouge has an exceedance probability of 10^{-4}, that is, one gouge in 10,000 will have a depth equal to or greater than 1 m. In water 30 m deep, a 3.4-m gouge has the same probability of occurrence.

To apply the above information to problems of pipeline design and burial, independent information is needed on gouging rates. Such data are extremely rare, even along the Beaufort coast. The problem here is that no reliable method for dating gouges exists. Therefore, at present, it is necessary to count new gouges on replicate sampling tracks repeated after

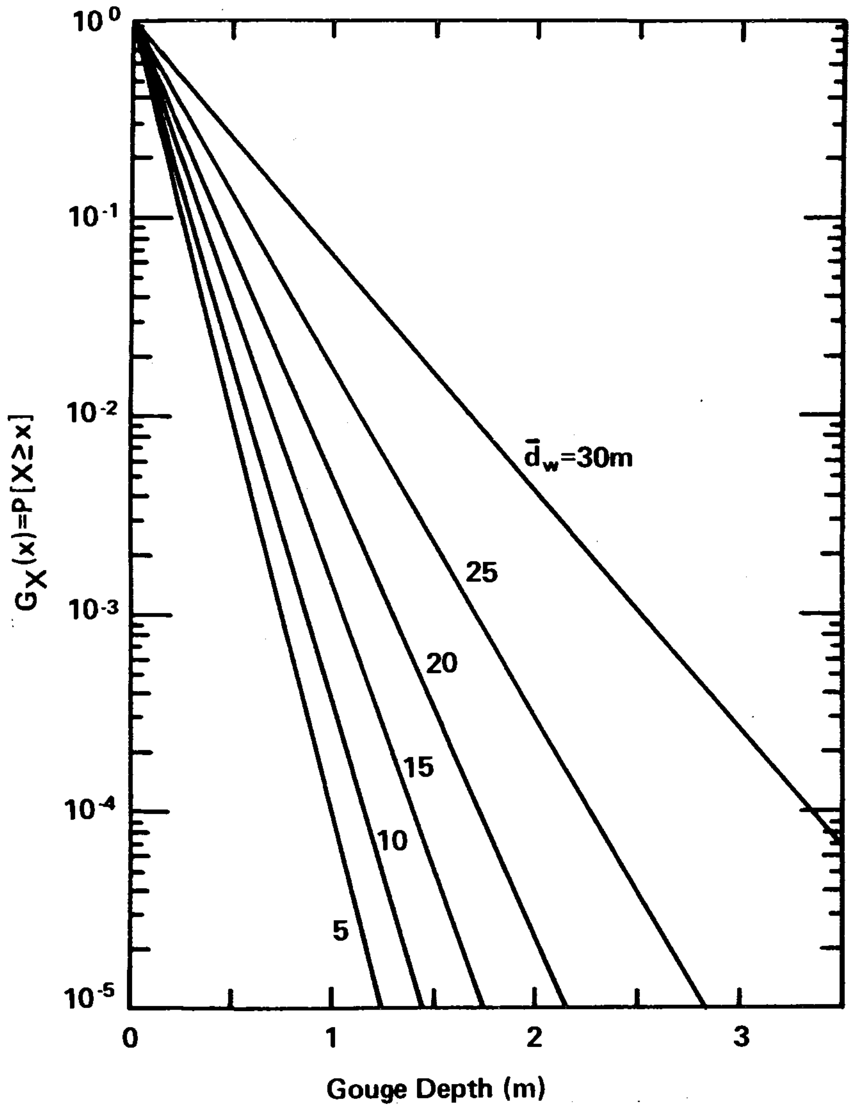

Figure 3.8.1. Exceedance probability $G_x(x)$ versus gouge depth for several water depths ($\bar{d}_w$) based on data from the Beaufort coast (Weeks et al., 1981).

a known interval. Limited data can be found in Barnes et al. (1978) and Weeks et al. (1981). There was a slight increase in g, the number of gouges/yr/km of sample track, with increasing water depth ($\bar{d}_w$), from 3.6 ($5 \leq \bar{d}_w \leq 10$ m) to 6.6 ($15 \leq \bar{d}_w \leq 20$ m). Data were not available for water depths in excess of 20 m. Allowing for one contact per 100 years (on the average) between a pressure-ridge keel and a 20-km pipeline buried in water less than 20 m deep or in a lagoon or sound, a burial depth of 1 m is required. For a similar pipeline buried in water 25-30 m deep, a burial depth of 3.2 m is needed. Needless to say, these estimates are very tentative and could be significantly improved by better data on gouging rates.

3.9 REFERENCES

Allyn, N., and B. R. Wasilewski. 1979. Some influences of ice rubble field formation around artificial islands in deep water, pp. 39-55. In: Proc. of the Fifth International Conference on Port and Ocean Engineering Under Arction Conditions, Trondheim, Norway, August 1979.

Barnes, P. W., D. M. McDowell, and E. Reimnitz. 1978. Ice gouging characteristics: their changing patterns from 1975-1977, Beaufort Sea, Alaska. U.S. Geol. Surv. Open-File Rep. 78-730.

Barnes, P. W., and E. Reimnitz. 1974. Sedimentary processes on Arctic shelves off the northern coast of Alaska, pp. 439-476. In: J. C. Reed and J. E. Sater (eds.), The coast and shelf of the Beaufort Sea. Arctic Inst. N. Am., Arlington, Va.

Barnes, P., and E. Reimnitz. 1979. Marine environmental problems in the ice covered Beaufort Sea shelf and coastal regions. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 9:164-267.

Barnes, P., and E. Reimnitz. 1980. Geologic processes and hazards of the Beaufort Sea shelf and coastal regions. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 4:257-355.

Barnes, P. W., and T. E. Reiss. 1981. Geological comparison of two Arctic shoals. Environmental assessment of the Alaskan continental shelf, Ann. Rep. (in press).

Blouin, S. E., E. J. Chamberlain, P. V. Sellmann, and D. E. Garfield. 1979. Determining subsea permafrost characteristics with a cone penetroometer--Prudhoe Bay, Alaska. Cold Regions Sci. Tec., 1:3-16.

Brower, W. A., H. F. Diaz, A. S. Prechtel, H. W. Searby, and J. L. Wise. 1977. Climatic Atlas of the Outer Continental Shelf Waters and Coastal Regions of Alaska, Vol 3: Chukchi/Beaufort Sea. NOAA/OCSEAP, Boulder, Colo.

Cox, G. F. N., and W. S. Dehn. 1981. Summer ice conditions in the Prudhoe Bay area, 1953-75, 2:799-808. In: B. M. Michel (ed.), POAC 81, Quebec P.Q.

Harrison, W. D., and T. E. Osterkamp. 1981. Subsea permafrost: probing, thermal regime and data analysis. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. (in press).

Kovacs, A. 1976. Grounded ice in the fast ice zone along the Beaufort Sea coast of Alaska. U.S. Army CRREL Rep. 76-32. 21 pp.

Kovacs, A. 1978. Recent ice observations in the Alaskan Beaufort Sea federal/state lease area. North. Eng. 10:7-12.

Kovacs, A. and A. J. Gow. 1976. Some characteristics of grounded floebergs near Prudhoe Bay, Alaska. U.S. Army CRREL Rep. 76-34.

Kovacs, A., and M. Mellor. 1974. Sea ice morphology and ice as a geologic agent in the southern Beaufort Sea, pp. 113-161. In: J. C. Reed and J. E. Sater (eds.), The coast and shelf of the Beaufort Sea. Arctic Inst. N. Am., Arlington, Va.

Kovacs, A., and D. S. Sodhi. 1979. Ice pile-up and ride-up on Arctic and Subarctic beaches, pp. 127-146. In: Proc. 5th Int. Conf. on Port and Ocean Engineering Under Arctic Conditons, Trondheim, Norway, August 1979.

Kovacs, A., and D. S. Sodhi. 1980. Shore ice pile-up and ride-up: field observations, models, theoretical analysis. Cold Reg. Sci. Tech., 2:209-288.

Kovacs, A., and W. F. Weeks. 1980. Dynamics of near-shore ice. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 6:9-28.

Kry, P. R. 1080. Implications of structure width for design ice forces, pp. 179-193. In: Symposium on Physics and Mechanics of Ice, Copenhagen, August 1979.

Lewis, C. F. M. 1977. The frequency and magnitude of drift ice groundings from ice-scour tracks in the Canadian Beaufort Sea, 1:567-576. In: POAC 77, St. John's, Nfld.

National Academy of Science/National Research Council. 1981. Research in sea ice mechanics, Mar. Bd. (in press).

Osterkamp, T. E., and M. W. Payne. 1981. Estimate of permafrost thickness from well logs in northern Alaska. Cold. Reg. Sci. Tech. (in press).

Pritchard, R. S. 1981. The mechanical behavior of pack ice. In: A. P. S. Salvadurai (ed.), The mechanical behavior of structured media. Elsevier, Amsterdam. (in press).

Reimnitz, E., and P. W. Barnes. 1974. Sea ice as a geologic agent on the Beaufort Sea shelf of Alaska, pp. 301-351. In: J. C. Reed and J. E. Sater (eds.), The Coast and Shelf of the Beaufort Sea. Arctic Inst. N. Am., Arlington, Va.

Reimnitz, E., P. W. Barnes, and T. R. Alpha, 1973. Bottom features and processes related to drifting ice on the arctic shelf, Alaska: U.S. Geol. Sur. Misc. Field Stud. Map MF-532.

Reimnitz, E., P. W. Barnes, L. J. Toimil, and J. Melchoir. 1977. Ice gouge recurrence and rates of sediment reworking, Beaufort Sea, Alaska. Geology 5:405-408.

Reimnitz, E., L. J. Toimil and P. Barnes. 1978. Arctic continental shelf morphology related to sea-ice zonation, Beaufort Sea, Alaska. Mar. Geol. 28:179-210.

Reimnitz, E., and E. W. Kempema. 1981. Pack ice interaction with Stamukhi Shoal, Beaufort Sea Alaska. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. (in press).

Reimnitz, E., E. Kempema, R. Ross, and R. Minkler. 1980. Overconsolidated surficial deposits on the Beaufort Sea shelf. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 4:284-312.

Reimnitz, E., and D. M. Maurer. 1978a. Storm surges on the Beaufort Sea shelf. U.S. Geol. Sur. Open-File Rep. 78-593. 18 pp.

Reimnitz, E., and K. Maurer. 1978b. Stamukhi shoals of the Arctic-Some observations from the Beaufort Sea. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 11:277-299.

Rogers, J. C., and J. L. Morack. 1981. Beaufort and Chukchi seacoast permafrost studies. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. (in press).

Sellmann, P. V., and E. J. Chamberlain. 1980. Permafrost beneath the Beaufort Sea: Near Prudhoe Bay, Alaska. J. Energy Resources Tech., Trans. ASME 102:35-48.

Sellmann, P. V., and K. G. Neave, and E. J. Chamberlain. 1981. Delineation and engineering characteristics of permafrost beneath the Beaufort Sea. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. (in press).

Shapiro, L., and R. Metzner. 1979. Historical references to ice conditions along the Beaufort Sea coast of Alaska. Geophys. Inst., Univ. Alaska Rep. UAG R-268, 55 pp.

Stringer, W. J. 1974. Shore-fast ice in vicinity of Harrison Bay. N. Eng., 5:36-39.

Stringer, W. J. 1981. Summertime ice concentration in the Prudhoe Bay/Harrison Bay region. Geophys. Inst. Univ. Alaska, Fairbanks. (Unpub.)

Thomas, D. R., and R. S. Pritchard. 1979. Beaufort and Chukchi Sea ice motions, Part 1. Pack ice trajectories. Flow Res. Rep. 133. Flow Research Company, Kent, Wash.

Thomas, D. R., and R. S. Pritchard. 1980. Beaufort Sea ice mechanical energy budget, 1975-76. Flow Res. Rep. 165. Flow Research Company, Kent, Wash.

Untersteiner, N., and M. D. Coon. 1977. Dynamics of nearshore ice. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 14:164-332.

Weeks, W. F., P. W. Barnes, D. Rearic, and E. Reimnitz. 1981. Statistical aspects of ice gouging on the Alaskan shelf of the Beaufort Sea. U.S. Army CRREL Rep., Hanover, N.H. (in press).

Weller, G. E., D. W. Norton, and T. Johnson (eds.). 1978. Interim Synthesis: Beaufrot/Chukchi. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP. 363 pp.

Wheeler, J. D. 1979. Sea ice statistics. In: Technical seminar on Alaskan Beaufort Sea gravel island design, EXXON Co., USA, Houston, Tex.

Zubov, N. N. 1943. Arctic ice. U.S. Naval Oceanographic Office and American Meteorologic Soc. Translation, 491 pp.

SECTION II. INTERDISCIPLINARY PROCESS ANALYSES, IMPACT PREDICTION, AND ISSUE DISCUSSIONS

Chapter 4. Ecological Processes, Sensitivities, and Issues of the Sale 71 Region

L. F. Lowry and K. J. Frost, Editors

With contributions from T. Albert, A. C. Broad, P. Connors, P. Craig, G. J. Divoky, B. Griffiths, J. Helmericks, R. Horner, S. Johnson, R. Meehan, and D. M. Schell.

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4.1 DESCRIPTION OF THE SALE 71 AREA

By L. F. Lowry and K. J. Frost

The Sale 71 area includes all of Harrison Bay and extends westward along the open coast past Lonely and eastward along the barrier island chain ending at Flaxman Island. The region comprises an area of approximately 7,700 km^2 covering approximately 15 percent of the continental shelf (< 200-m water depth) of the Alaskan Beaufort Sea. Water depths in this area range up to 30 m.

The physical condition of western Sale 71 inshore waters are strongly determined by the discharge of the Colville River. The Colville discharges through a complex delta into the eastern portion of Harrison Bay. Harrison Bay is the largest bay along the Alaskan Beaufort Sea coast and is second in size only to Mackenzie Bay in the Canadian Beaufort. Discharge of water and other materials from the Colville is great in quantity but short in duration. Flow commences in late May, initially as overflow water on top of the sea ice which rapidly drains through the numerous holes and cracks (Walker, 1974). The influence of fresh water can be detected 35-40 km seaward (Schell, 1981). Flow continues to decrease throughout the summer and has virtually ceased by late autumn. East of the delta, barrier islands occur along most of the coast and enclose Simpson Lagoon and Stefansson Sound. Much of this area was included in the previous Joint Lease Sale. In the western extremity, physical conditions are typical of other areas of exposed Beaufort Sea coastline. As would be expected, the habitats and associated biological organisms and processes at the eastern and western extremes of the area are similar to those of other open coast and barrier island-lagoon systems. However, associated with the Colville and its delta are habitats, processes, and populations of organisms unusual in the remainder of the Alaskan Beaufort Sea. The discussions at the synthesis meeting were concerned primarily with the Harrison Bay area, and that emphasis will be reflected in this report. Readers are referred to the previous synthesis report (Weller et al., 1978) for general descriptions of the environment and biota of the Beaufort Sea.

The initial spring flood of the Colville affects the surface of the sea-ice cover. Flooding may decrease the suitability of the area for molting seals, while providing early access to open water for birds arriving in the Beaufort. Large quantities of organic carbon (primarily from peat and tundra litter), sediment, and organic and inorganic nutrients, primarily nitrogen are discharged in the spring flood. The sediment and probably also the low salinity affect benthic communities and primary production by algae in the ice and water column. Carbon in the runoff has been estimated to contribute 36 percent of the total annual energy input to the Sale 71 area or about 75 percent of the input to the shallower (< 10 m) portion of the Harrison Bay system (Schell, 1981). In summary, the Colville contributes large quantities of organic nitrogen to the strongly nitrogen-limited environment of Harrison Bay (Hamilton et al., 1974).

The Colville River has the greatest diversity of anadromous fishes of any Alaskan arctic river (T. N. Bendock, pers. comm.). The river and delta support the largest runs of whitefish in the Alaskan Beaufort Sea (Craig and Haldorson, 1981). The area has traditionally supported a commercial whitefish fishery and, more recently, a subsistence fishery as well. Other brackish-water and anadromous species occur in the delta and Harrison Bay. Overwintering areas for several species, particularly ciscoes and boreal smelt, occur in the area (Craig and Griffiths, 1981). Unlike much of the remainder of the coast, the Colville and Fish Creek deltas provide extensive salt-marsh and mud-flat habitats of great importance to brant, Canada Geese, and several species of shorebirds (Connors and Risebrough, 1981).

Physical attributes of Harrison Bay affect sea ice characteristics and suitability of the area to ice-associated species. The area is a large embayment, unprotected by barrier islands but with offshore shoals in the western portion. Freezing sea ice is exposed to autumn storms which frequently cause ice ridging throughout much of the area, whereas extensive ridge development on shoals may help to stabilize the fast-ice sheet. Areas of stable fast ice with low ridges provide optimum areas for lair construction by ringed seals (Smith et al., 1978). High densities of ringed seals are sometimes associated with summer ice remnants that occur in and near the area (Lowry et al., 1981).

No species of plant or animal is known to be unique to the Sale 71 area. In fact, many if not most of the species found there occur widely in arctic and subarctic waters. However, the region is of particular importance to one species, the bowhead whale, which in addition to being legally considered endangered is indeed rare. The majority of the existing population of western arctic bowheads is believed to pass through or adjacent to the proposed lease sale area during their autumn migration westward (Frost and Lowry, 1981). The migration occurs through a linear corridor along the nearshore zone of the Beaufort Sea. The proposed sale area comprises about 55 percent of the length of that corridor in the Alaskan portion of the Beaufort.

Description of Major Habitats

Several major habitats or ecological zones were discussed with respect to their biological characteristics and possible discreteness. It is necessary to point out 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 based on extremely limited observations and samples which were considered inadequate by many investigators.

The Sale 71 area may be classified into four major ecological zones: 1) terrestrial areas, 2) the nearshore zone, extending to about 3-m water depth, 3) a neritic zone extending from about a 3- to 13-m water depth, and 4) an oceanic zone seaward of the 13-m depth contour.

Terrestrial habitats with significant associated fauna are of several types. Thetis Island is typical of Beaufort Sea barrier islands and provides bird breeding habitat, particularly for eiders. Mud flats created and maintained by the Colville discharge are feeding areas for many shorebirds. Salt marshes, which require periodic saltwater flooding, are important nesting and feeding areas for waterfowl and shorebirds. River bars in the Colville Delta are used as hauling areas by spotted seals. Coastal areas, particularly in the western portion, are used by caribou seeking relief from insects.

The region within the 3-m isobath is influenced to a large extent by the sediment discharged by the Colville. This sediment and low-salinity water stress the benthic biota and virtually preclude primary production. Terrestrial carbon from river runoff and coastline erosion is the greatest potential source of energy. It is utilized by microbial decomposers which in turn provide food for organisms such as chironomid midge larvae and gammarid amphipods. These in turn provide food for birds and fishes. During winter and spring, sea ice is frozen to the bottom throughout much of this zone. Infaunal organisms are therefore largely excluded, and the area is recolonized annually by mobile epifauna and vertebrates.

In the neritic zone, populations of infaunal and epifaunal invertebrates and fishes similar to those in other areas of the Beaufort Sea persist year-round. Turbid, low-salinity water reduces primary productivity during river runoff. Terrestrial carbon may be an important food source for invertebrates, particularly during winter. Both anadromous and some marine fishes occur in this zone and probably feed primarily on epibenthic crustaceans and neritic species of zooplankton. Marine mammals and seabirds occur in this area and feed on epibenthic organisms, zooplankton, and fishes (Lowry et al., 1981).

In the oceanic zone, reduced turbidity and higher salinity and nutrient levels contribute to greater primary productivity (Alexander et al., 1974). Diatoms are grazed by copepods and euphausiids, which in turn are preyed upon by carnivorous zooplankton, Arctic cod, ringed seals, bowhead whales, and birds such as phalaropes, Arctic Terns, and kittiwakes (Frost and Lowry, 1981). Arctic cod are a major food for some marine mammals and birds. Infaunal and epifaunal benthos are like those of offshore areas. Marine demersal fishes are numerous and diverse.

Seasonal Description of Major Biological Events

As is true virtually throughout the Arctic, biological events in the Harrison Bay area 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 the summer and early autumn period most of the area is open water, with the exception of the outermost portion, where pack ice remnants are common. Most of the annual primary production in the water 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

planktonic forms, this is the period of greatest growth. Fishes that have overwintered in the Colville River move seaward to feed on marine crustaceans which they share with the Arctic cod. Seabirds, shorebirds, and waterfowl arrive after breakup, and 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 Colville Delta 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, but this phenomenon has not been documented in Harrison Bay. Some anadromous species move into the Colville River system, where they will spawn and overwinter (Craig and Griffiths, 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 through and adjacent to 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 and mate 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 the polar bears.

From late May to early July, runoff from the Colville River combines with normal 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 into and through the area, stopping in tundra ponds and nearshore open-water areas to rest and feed. Bowhead and belukha whales pass well offshore of the Sale 71 area during their eastward migration. Polar bears move offshore with the ice, while Arctic foxes move ashore to den, feed, and raise their young.

4.2 CONTRASTS WITH JOINT SALE AREA

The Joint Sale area and Harrison Bay differ in several ways:

A. The Colville River, the largest river along the Alaskan Beaufort Sea coast, empties directly into Harrison Bay. While the river's discharge may be locally detrimental to many species of plankton, benthic fauna, and perhaps also seabirds, this delta, together with the Fish Creek Delta to the west, provides important spawning and overwintering habitat for key fish populations as well as nesting and feeding habitat for waterfowl and shorebirds. Such habitats are less extensive or absent in the Joint Sale area.

B. Only one major barrier island occurs in the Harrison Bay area, in marked contrast to the string of islands within the Joint Sale area. Therefore, conditions comparable to the highly productive Simpson Lagoon system do not occur in Harrison Bay, and much less habitat is available to bird species that preferentially nest on barrier islands.

C. No areas of "live bottom", like the boulder patches in Stefansson Sound, have been identified in Harrison Bay (A. C. Broad, pers. comm.).

D. In the vicinity of Harrison Bay, the Sale 71 area extends farther offshore and into deeper water than did the Joint Sale area. Many more bowhead and belukha whales will pass through the Sale 71 area. In addition, the eastern Harrison Bay area contains, and is adjacent to, summer ice remnants which are frequented by ringed and bearded seals and probably polar bears.

4.3 POTENTIAL IMPACTS OF OCS DEVELOPMENT

Concerns over the impact of petroleum exploration and development on the entire Beaufort Sea coast have been discussed in detail in Weller et al. (1978). For the most part, the issues raised in that report are also applicable to the Harrison Bay/Sale 71 lease area. In the following discussion only those potential impacts which are of particular concern to the Sale 71 area are considered.

Potential impacts fall into two major categories: those resulting from catastrophic events such as oil spills, which are unlikely but which have major consequences, and those associated with routine exploration and development activities which may be chronic but are of relatively low intensity. The latter types of effects may be of greater consequence to the biota.

Dredging (see also Chapter 7)

The need for gravel for construction of islands or causeways is of particular concern in the Harrison Bay area. Unlike the area east of the Colville where gravel is present under the tundra, the area to the west has few gravel sources. This may require either 1) that gravel be hauled in over long distances or 2) that new sources of gravel, such as offshore mining/dredging, be utilized. Long-distance hauling will require construction of gravel or ice roads across the tundra, or a combination of the two. Road construction on land should be planned to minimize disruption to salt marshes and wet tundra areas that are heavily used by birds in summer.

Offshore dredging for gravel may result in sediment plumes and associated turbidity, resuspension of toxic heavy metals, entrainment of fish and other organisms in dredge intakes, and disturbance of birds and mammals. Since the Colville dumps massive amounts of sediments into Harrison Bay each year and creates its own turbid plume, it is likely to swamp any other source of turbidity in the area. Concentrations of heavy metals are usually so low that resuspension is probably not a problem. Fish entrainment in dredge intakes could be a problem if intakes are poorly designed. Seabird densities are low in Harrison Bay, and since there are few barrier islands there are few breeding colonies. Consequently, offshore dredging is unlikely to be a major disturbance to seabirds.

Disturbance of bowhead whales during their autumn migration is the major concern associated with dredging activities. Although preliminary results of studies in the Canadian Beaufort Sea during Summer 1980 suggested that bowheads were either not disturbed by, or accommodated to, dredging noises, the effect of similar noises during migration is unknown (Fraker et al., 1981). Until further studies have been completed we suggest that major offshore dredging and construction activities be suspended during the autumn migration period.

Gravel Islands

The effects of artificial gravel islands in Harrison Bay, an area with few natural islands, are unknown. Islands will probably increase the stability of fast ice and alter patterns of sea-ice deformation. There are no data to predict the effects of these changes on shore ice which is ringed seal pupping habitat. If islands "hold" ice in spring and delay breakup, they may cause a reduction in primary productivity. However, since primary productivity is low in Harrison Bay compared to adjacent lagoon systems (Alexander, 1974; Schell, 1981), such a reduction would probably not be of major consequence. The presence of gravel islands in Harrison Bay may promote an increase in the number of birds, particularly adult Oldsquaws, that make extensive use of the moats that form around islands in early spring. Fish and/or zooplankton could build up around island perimeters due to the concentrating effect of shorelines, and this concentration might attract birds such as terns and phalaropes. Disturbance to the benthos is likely to be inconsequential compared with inherent natural disturbance to the bottom (such as ice scouring).

Causeways

Anticipated effects of causeways include possible alteration of circulation patterns and temperature-salinity regimes. Of particular concern in this lease area are causeways which would alter the flow of the Colville plume or which would alter the circulation in Simpson Lagoon, a biologically rich area to the east. Characteristics of proposed causeways such as their length and whether they contain breaches, their orientation, and their proliferation will moderate or exaggerate their effect on the system.

Noise/Disturbance

Exploration and development are accompanied by such noisy, disturbance-causing activities as helicopter and fixed-wing aircraft overflights, seismic profiling activity, vehicle traffic over the ice, boat traffic during the open-water season, dredging operations, and the operation and supply of drilling platforms. The effects of noise on wildlife are varied.

Brant and geese are disturbed by low-flying aircraft, particularly helicopters (USDI, 1979). Some of the most important nesting areas for those birds are found in the Colville River delta.

Eider ducks nest on Thetis Island (Divoky, 1979). Eiders are particularly sensitive to disturbance from about 3 days before eggs hatch until the chicks are dry. If nests are abandoned during that time, the female does not return. The peak hatching period is from approximately 15 July to 1 August.

Large concentrations of flightless Oldsquaws are present near Thetis Island from about 15 July to 15 August. Those birds, already stressed by molting, could be additionally stressed by continuous aircraft or vessel traffic during that period (Johnson and Richardson, 1981).

Spotted seals have traditionally hauled out at several spots in the Colville Delta. Haul-out areas are usually situated in remote, undisturbed areas. Continuous human activity near such areas will probably cause abandonment of the haul-outs (Burns and Morrow, 1975).

The Colville Delta is known to be an active polar bear denning area. Winter activity near dens may cause females to abandon dens, take the cubs out onto the ice prematurely, or prevent them from returning to the den in subsequent years.

High levels of seismic exploration and vehicular traffic on ice may disturb and displace ringed seals that are pupping on the fast ice. Preliminary data indicate that densities of ringed seals in seismically disturbed areas are lower than in adjacent, nondisturbed areas (Frost, Burns and Lowry, unpub.). Further studies are under way to further quantify the effects of disturbance.

Bowhead whales migrate through the Sale 71 lease area in the autumn on their return to the Bering Sea (Ljungblad et al., 1981). Preliminary studies in the Canadian Arctic suggest that they may be disturbed by a variety of sound sources (Fraker et al., 1981). Their responses apparently vary according to the type of disturbance. Engines operating at high speeds elicited greater responses than those at low speeds. High-intensity, sporadic noise (such as that associated with seismic work) and high-frequency noise (outboard boat motors) caused the whales to alter their behavior. Low-flying aircraft caused obvious disturbance.

Ice Roads and Winter Transport

The construction of ice roads may locally reduce ringed seal densities. However, the roads may localize traffic and noise that otherwise would be spread over much larger areas and thus reduce the total area of effect. Ice roads may change breakup patterns of the sea ice. The effects of such changes are unknown but would undoubtedly vary by location.

Transport by means other than ice roads may include supply boats with icebreaker support, especially early in freeze-up. The effect on an area of continuous use by icebreakers is unknown. Experience in Canada suggests that channels close up very quickly (D. Stone, Dept. Indian and Northern Affairs, Yellowknife, NWT, pers. comm.). However, the noise/disturbance itself may displace seals from winter shipping lanes.

Drilling Muds and Formation Waters

Recent studies indicate that drilling muds are nontoxic to biota and that dilution is so great that toxic components of muds are essentially undetectable within a few tens of meters of the discharge source (J. Ray, pers. comm.; Northern Technical Services, 1981). It is unknown whether the discharge of formation waters will be a problem.

Oil

Spilled oil could affect any part of the Sale 71 area. Possible effects are presented by season, and particularly sensitive areas or times are indicated.

<u>June</u>. Wherever open water is present, for example, around islands and in channels along islands, birds use the water for resting and feeding. Diving ducks, especially Oldsquaws and eiders, are numerous in early season open-water areas and are particularly sensitive to oil (Divoky, 1979; Johnson and Richardson, 1981). The number of birds varies by day and by year, but they are present in these areas mainly in late June.

Eggs and larvae of most fishes are the life history stages most sensitive to hydrocarbons. Arctic cod eggs and larvae are in surface waters from the time of spawning (February) until about August (Rass, 1968).

Seals may be contaminated as they haul out on the ice to bask and molt. Studies in Canada suggest, however, that the effects of such contamination could be relatively mild and short-lived in free-living animals (Geraci and Smith, 1976; Engelhardt et al., 1977).

Oil in the water may inhibit microbial activity and therefore nutrient regeneration, or it may cause the rapid selection for hydrocarbon-tolerant species, thus altering the base of the food web. The high sediment load in June from the runoff of the Colville River will serve as a natural agent for catching and sinking oil, perhaps altering nutrient regeneration or interfering with food chains in the nearshore region.

July. There is an increasing likelihood, as the ice continues to break up and melt, that oil could reach the salt marshes of inner Harrison Bay. These marshes are important to several species of geese and other wet-tundra birds. The impact of oil would be threefold: on the birds themselves, the foods they eat, and the marsh. Oil has been shown to inhibit the growth of marsh grass for about a year, after which it seems to enhance growth (A. C. Broad, pers. comm.).

Oil is likely be most harmful to birds in the nearshore area, where most feed by diving from the water's surface. Offshore (beyond 20 m water depth), more of the birds are aerial divers and surface-feeders that seldom rest on the water, and the impact there is expected to be slight.

Primary production might be depressed by shading by the oil or by toxic fractions, but effects would probably be local. Effects on zooplankton would probably also be local (Johansson, 1980).

During the open-water months, the noise and activity associated with cleanup operations might cause more disturbance than the presence of the oil itself.

August. In late summer, about 5,000 to 10,000 Oldsquaws concentrate near Thetis Island (Johnson and Richardson, 1981). There is another concentration near Oliktok Point. Those birds, molting and flightless for part of that time, would be extremely vulnerable to oil on the surface of the water.

Relatively high densities of birds (mostly phalaropes and Oldsquaws) occur near Lonely and Pitt Point (Connors and Risebrough, 1976).

September. Most birds leave the area this month. Since most birds fly straight across Harrison Bay without stopping, oil in the water probably would have little effect on them (G. Divoky, pers. comm.).

Bowheads, including young calves, migrate through the proposed lease area in September and October. Because of the endangered status of this whale and its importance in the culture and subsistence economy of Alaskan Eskimos, much attention has been given to its potential sensitivity to oil. It is unknown whether bowheads will swim through oil-covered waters. If they do contact oil with its hydrocarbon content intact, some of the possible effects (Albert, in press) include:

A. A modification in filtering efficiency of the feeding apparatus by matting the baleen (Braithwaite, 1980). The resulting increase in aperture size may allow small prey such as copepods to pass through, thus hindering a whale's ability to obtain sufficient food.

B. Severe conjunctivitis and perhaps ulceration or perforation of the cornea might result if oil were to enter the large conjunctival sac.

C. The adherence of oil to the tactile hairs and the numerous roughened areas (localized epidermatitis) commonly found on the skin of the head. Laboratory studies showed that these sites of damaged skin contained far more bacteria and diatoms than adjacent areas of undamaged skin. The effect of oil on such bacteria is unknown but if bacteria continued to grow under the oil film they could cause a more extensive dermatitis leading possibly to ulceration of the skin with bacteria entering the blood vessels (bacteremia). Oil-fouled tactile hairs around the blowhole and along the chin may not send the proper sensory information to the brain and therefore possibly interfere with breathing and feeding.

D. Lung irritation from the repeated inhalation of oil 'fumes' and possibly oil droplets. Such irritation may lead to pneumonia, since there is little lymphoimmune tissue associated with the lungs and there are pathogenic and potentially pathogenic bacteria known to be resident in the bowhead respiratory tract.

E. Blockage by matted baleen hairs of the narrow channel which connects two of the chambers of the bowhead stomach.

October-November. Autumn, especially during freeze-up, is the season when oil could possibly enter the Colville Delta. During these months, the water level is very low; Colville discharge is minimal and barotrophic surges are most likely to occur (P. Barnes, pers. comm.). Oil entering the delta would be unimpeded from moving upstream and could reach spawning and overwintering anadromous fishes. Storm surges are also most likely to move oil into the salt marshes of the Colville and Fish Creek Deltas and several less extensive salt-marsh areas in western Harrison Bay during this period. Although few birds are present in these salt marshes after September, oil effects on vegetation and invertebrates, and directly on the birds feeding there, might be serious in subsequent summers.

November-May. During the months when ice covers the lease area, most birds and mammals have migrated elsewhere. Ringed seals, polar bears, and Arctic foxes are the major species that remain. If oil under the ice reduces the local density of seals, it will affect not only the seals but the bears and foxes that depend on them for food. If seals remain in an oiled area they may suffer chronic effects. Females oiled in spring may contaminate their birth lairs and thus cause the oiling of small pups that depend on fluffy white fur, rather than on blubber, for insulation.

Arctic cod spawn in water under the ice. The eggs are buoyant and therefore present in surface waters where spilled oil is also most likely to be (Rass, 1968). In the Argo Merchant spill, cod eggs experienced high rates of mortality and abnormality (Grose, 1977, cited in Clark and Finley, 1977).

Oil under the ice would extirpate the ice algal communities on the undersides of floes it contacts. Recent data (see Transport. Sec. 2) suggest, however, that the spread of visible portions of oil under ice is very limited, and therefore the direct effects on ice-associated biota would probably be localized.

4.4 ISSUE ANALYSIS

Six of the issue statements presented in Weller et al. (1979) for the Beaufort Sea Joint Sale were considered at the Sale 71 synthesis meeting. Their relevance to the Sale 71 area was discussed and modifications suggested. To facilitate comparison with the earlier issue analysis, the roman numeral designations of Weller et al. (1979) are maintained in this report.

Issue III. Biologically Sensitive Areas. With respect to the Joint Sale Issue Statement, it should be pointed out that: a) activities relating to development in Harrison Bay which affect the vicinity of Cross and Pole Islands are subject to the same recommendations indicated previously; b) as surveys of the Harrison Bay area have not located boulder patches, provisions are not necessary to protect kelp communities ('live bottom areas') in that area; and c) many new data are available on the migration routes of bowhead whales which will be discussed below. Areas within Harrison Bay considered to be biologically most sensitive are shown in Fig. 4.4.1 and discussed individually below.

A. The Colville River and Fish Creek Deltas contain extensive salt marshes. Large numbers of birds, particularly brant and other species of geese, as well as shorebirds and ducks, breed and/or feed there (Connors and Risebrough, 1981; J. Helmericks, pers. comm.). Flooding by salt water during storm surges may deposit oil throughout this productive habitat. In addition, nesting birds are known to be sensitive to disturbance by human activities and aircraft noises (Schamel, 1974, 1977). The eastern portion of the Colville Delta, in particular, supports large numbers of nesting brant and other geese and requires special protection.

B. The river channels of the Colville Delta provide passage and spawning and overwintering habitat for large runs of anadromous fishes. These fishes support commercial and subsistence fisheries as well as a summer-autumn resident group of spotted seals (Helmericks, pers. comm.). The runs of whitefish in the Colville River are the largest on the north coast of Alaska (Craig and Haldorson, 1981; Craig and Griffiths, 1981). The Colville Delta is the easternmost known area in the Beaufort Sea where spotted seals regularly haul out. Alteration of anadromous fish spawning and overwintering habitats would have a deleterious effect on fish stocks and the fisheries and seals dependent on them.

C. Thetis Island and the surrounding area support concentrations of animals unlike those found in other parts of the Sale 71 area. Eiders nest there during July and August (Divoky, 1978). Eiders are particularly sensitive to disturbance; if they are displaced from the nest they frequently do not return. Molting Oldsquaws concentrate in the waters surrounding Thetis Island and particularly between Thetis and Oliktok Point (S. Johnson, pers. comm.). Development activities during the molt could displace and stress molting birds. The waters near Thetis Island are an overwintering area for boreal smelt (Craig and Griffiths, 1981).

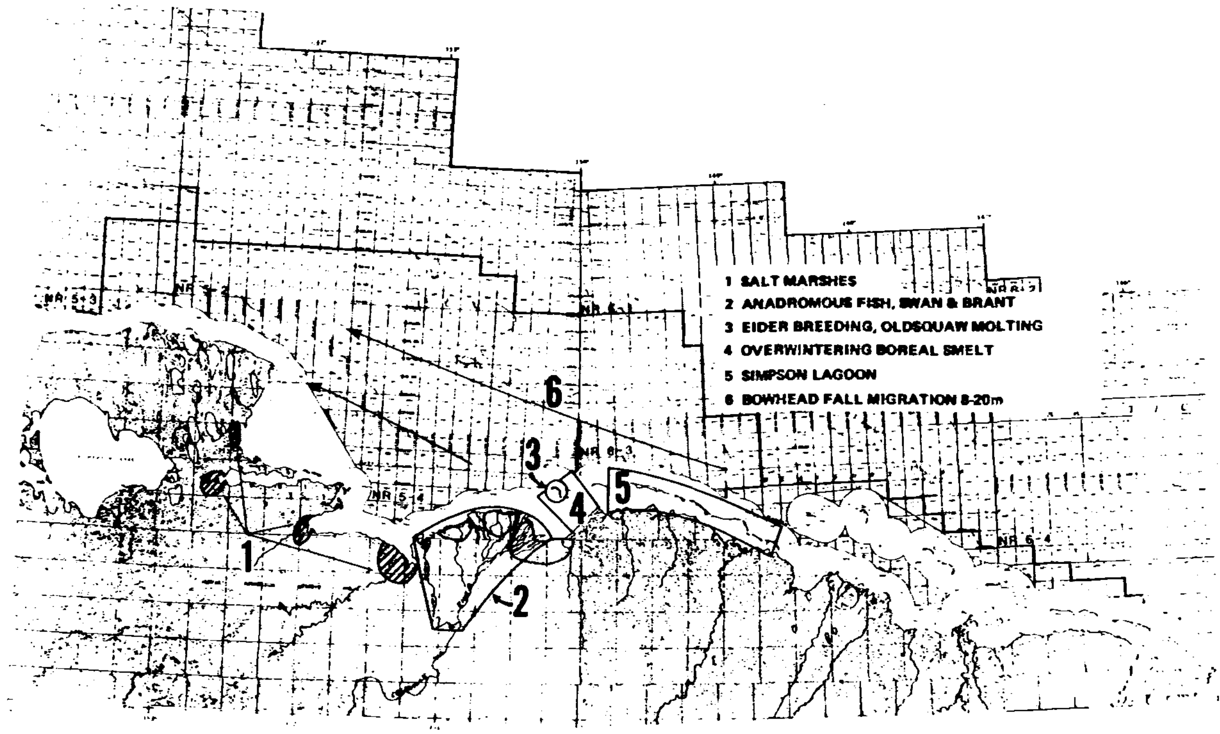

Figure 4.4.1. Biological sensitive areas.

D. Simpson Lagoon, at the eastern extreme of Harrison Bay, is an important area for birds and anadromous and marine fishes (Johnson and Richardson, 1981; Craig and Haldorson, 1981). Construction in eastern Harrison Bay could change the hydrographic and biological characteristics of Simpson Lagoon.

E. Recent studies have shown that, during their eastward migration, bowhead whales pass offshore well to the north of the Sale 71 area (Ljungblad et al., 1981). Although the whales probably occur in water as shallow as 5 m, most autumn sightings cluster near the 18-m depth contour, which passes through much of the Sale 71 area. The Sale 71 area occupies 55 percent of the length of the Alaskan Beaufort Sea coast. Therefore, activities in the sale area could affect over half of the bowhead migration corridor in the Alaskan Beaufort Sea.

The earliest documented sightings of bowheads near the sale area were 9 September (Ljungblad et al., 1981), while the latest was on 20 October (Ljungblad et al., 1980). In 1979, the peak of the migration passed the area between 27 September and 7 October (Ljungblad et al., 1980). The migration probably occurred somewhat earlier in 1980 (Ljungblad et al., 1981). Studies are continuing on the responses of bowhead whales to disturbance (Ljungblad et al., 1981, Fraker et al., 1981). Responses to similar disturbances have been observed to vary with season and perhaps with locations. Responses to low-flying aircraft appear to be greatest during spring and summer (Ljungblad et al., 1981). Alteration of behavior and movements has been observed near boats during summer (Fraker et al., 1981). It is not known how bowheads will react to disturbance during their autumn migration through the Sale 71 area.

Recommendations.

A. Human activity and disturbance in the salt marshes in the eastern Colville Delta be minimized from 1 June to 15 August. Aircraft should not be allowed to land on or fly low over this area. Facilities and transportation corridors should be located to minimize disturbance and alteration of drainage patterns here and near other salt marshes. All means should be utilized to prevent spilled oil from entering the salt marshes.

B. Alteration of river channels of the Colville Delta be prohibited. Dredging to construct channels or remove gravel could drastically alter nearshore nutrient regimes as well as passage, spawning and wintering areas for fishes.

C. Activities in the vicinity of Thetis Island be minimized from 1 July to 10 September. Aircraft overflight and landings should be minimized on the island from 15 July to 15 August to minimize mortality of eider ducklings. Construction of permanent facilities should not be allowed on Thetis Island, nor should the island be connected by causeway to the mainland.

D. Construction activities in the Sale 71 area not be allowed to alter circulation patterns in Simpson Lagoon. Of particular concern are solid-fill causeways spanning major passes or linking the mainland and barrier islands.

E. Activities that disturb bowhead whales not be allowed during their migration through and adjacent to the Sale 71 area. Since those activities causing significant disturbance cannot be clearly identified at present, a complete cessation of activity during migration appears warranted. This will be discussed further under Issue V.

Issue IV. Siting of Industrial Facilities and Activities

Since Harrison Bay has few natural barrier islands, is much farther from the Prudhoe Bay/Kuparuk industrial complex, and includes much deeper offshore water, a greater variety of facilities and activities than in the Joint Sale area can be anticipated. As the probable nature and extent of the facilities and activities is not yet known, the group recommends that:

A. Stipulations on design and construction of facilities be considered case by case and designed to minimize anticipated biological impacts.

B. The cumulative as well as the individual effects of facility construction be considered.

Issue V. Seasonal Drilling Restrictions

The group discussed at great length the applicability of seasonal restrictions on exploratory drilling. Opinions expressed ranged from maintaining the existing conclusions on the issue in Weller et al. (1979), to suggesting complete elimination of all seasonal restrictions. Recommendations for modification or elimination of the seasonal restriction were invariably based on economic considerations which were beyond the purview of the ecological discussion group. The following discussion and conclusions deal only with biological considerations.

The previous discussion of this issue with respect to the Joint Sale was considered applicable to the Sale 71 area. No evidence was presented to indicate that the probability of a blowout during exploration has diminished nor that the ability to clean up spilled oil during the moving ice period has improved. Since the Harrison Bay area has fewer barrier islands and extends into deeper water, technological problems of development and oil cleanup may be substantially greater than in the Joint Sale area. Although we recognize that relief wells are not always needed or effective for stopping blowouts and that 60 days may be a generous estimate of the time required for relief well drilling, we consider 31 March the most appropriate termination date, to allow time for a reasonable attempt at stopping and cleaning up a major winter spill, should a blowout occur on the last day of permissable drilling.

Several of the possible effects of industrial activity or oil on the environment during the open water and transition periods are of greater concern in the Sale 71 area than in the Joint Sale area. These are summarized as follows:

A. At breakup, usually in late May, the Colville River discharges much of its annual flow. Although the interaction of the river plume with oil in the water is not well understood, several events appear likely. Interaction of oil with organic materials could significantly disrupt energy flow in coastal waters. Much oil would probably sink with sediments and accumulate on the bottom, affecting benthic biota and their predators. Lighter fractions of oil might be carried seaward by the river outflow, affecting in-ice and underice communities over a large area. Drilling operations in the path of the spring runoff of the Colville should therefore, logically be suspended earlier than those in other parts of the Sale 71 area.

B. During freeze-up, salt water penetrates far upstream in the Colville Delta. Toxic components of oil carried into the delta might drastically contaminate spawning and overwintering areas for anadromous fishes.

C. Birds feed and breed in the extensive salt marshes of the Colville and Fish Creek Deltas. Oil carried into these marshes during surges could contaminate a large part of the habitat and the associated avifauna of the Beaufort Sea.

D. Molting Oldsquaws concentrate in the eastern part of the area. These flocks would be susceptible to oil on the water.

E. The Sale 71 area includes and is adjacent to a large portion of the migratory corridor used in autumn by bowhead whales. Oil in the water and disturbance by traffic and other industrial activities could affect the autumn migration of these whales.

For biological reasons, we recommend that exploratory drilling in the Sale 71 area be restricted to the period 1 November-31 March. This restriction will reduce the probability of oil in the environment during the open-water and transition periods. In addition, all industrial activities should be stopped from 1 September to 30 October unless it can be shown that the activity will not disturb migrating bowhead whales.

If economic or other reasons necessitate modifying the seasonal restriction, a number of options are available. All compromise protection of the biota, however. Four options are listed below, each of which involves successively greater risk to organisms in the sale area.

A. Prohibition of all activities not shown to be harmless to migrating whales during the period 1 September to 30 October. All normal exploratory activities allowed from 1 November to 31 March. From 1 April to 31 August, all operations would be permitted except for drilling into hazardous strata. Hazardous strata would be defined as those in which a blowout during drilling might occur.

B. All operations permitted during the entire year, with the exception that drilling into hazardous strata prohibited from 1 April to 30 October.

C. All operations permitted during the entire year, with the exception that all activities not shown to be harmless to migrating whales prohibited during the period 1 September to 30 October.

D. No seasonal restriction on exploratory activities.

Issue X. Freshwater Supply for Industrial Activities

The discussion and conclusions in the Joint Sale issue statement (Weller et al., 1979) are relevant to the Sale 71 area. Two major water sources, the Colville River and Teshekpuk Lake, are of particular biological importance in the Harrison Bay area. Activities affecting those two water sources should be carefully considered and regulated.

Issue XI. Aircraft and Noise Disturbance

Aircraft and noise disturbance are a major potential problem in both the Sale 71 and Joint Sale areas. Technology can significantly reduce airborne and waterborne sounds caused by traffic and other industry-related activities. Although sometimes costly, these technological improvements may result in more efficient and less costly operations. Reduction of industrial noise through improvements in technology should be strongly encouraged. A number of studies are under way which should eventually increase our understanding of the nature and magnitude of the effects of noise on wildlife.

Since exploration and development of the Sale 71 area may involve operations in the Joint Sale area, conclusions in the Weller et al. (1979) issue statement are directly applicable to Sale 71. In addition, we recommend that:

A. Aircraft avoid flying over at less than 500 m or landing near Thetis Island and salt marshes in the Colville Delta between 20 May and 15 August and caribou calving areas near Teshekpuk Lake between 15 May and 15 June.

B. During the autumn migration of bowhead whales, about 1 September to 30 October, no activities be allowed in the lease area unless they are shown to be harmless to the whale migration.

Issue XIII: Long-Term Monitoring and Assessment

The Joint Sale area issue statement is relevant to the Sale 71 area. Since most populations are migratory and distributed widely in the Beaufort Sea monitoring is not necessarily site-specific and areas chosen for monitoring studies need not be within Harrison Bay. Since few natural barrier islands occur in the area and many may be constructed, this area could be especially suited to monitoring the effects of island construction on bird distribution and sea-ice characteristics. Monitoring of anadromous fish stocks in the Colville River should be conducted so that the effects of harvesting can be distinguished from possible effects of OCS development.

Monitoring alone cannot substitute for, and is of little value without, adequate pre-development description of proposed sale areas. Well-designed programs of environmental research continue to be needed in each proposed lease area prior to preparation of an Environmental Impact Statement. In design of both pre-development and monitoring programs, consideration should be given to long-term environmental variability and the period of responses of the organisms under study.

4.5 REFERENCES

Albert, T. A. (ed.). Tissue structural studies and other investigations on the biology of endangered whales in the Beaufort Sea. Final Report to Bureau of Land Management for the period 1 April to 30 June 1980. Univ. of Maryland, College Park, MD, BLM Contract No. AA 851-CTO-22 (in press).

Alexander, V. 1974. Primary productivity regimes of the nearshore Beaufort Sea, with reference to potential roles of ice biota, pp. 609-635. In: J. C. Reed and J. E. Sater (eds.), The Coast and shelf of the Beaufort Sea, Arctic Inst. N. Am., Arlington, Va.

Alexander, V., C. Coulon, and J. Chang. 1974. Studies of primary productivity and phytoplankton organisms in the Colville River system, pp.283-410. In: V. Alexander et al., Environmental studies of an arctic estuarine system, Inst. Mar. Sci., Univ. Alaska Rep. R74-1.

Braithwaite, L. F. 1980. Baleen plate fouling, pp. 471-492. In: NARL investigation of the behavior patterns of whales in the vicinity of the Beaufort Sea lease area. Final Report to BLM; Naval Arctic Res. Lab, Barrow, Alaska, 753 pp.

Burns, J. J., and J. E. Morrow. 1975. The Alaskan arctic marine mammals and fisheries, pp. 561-582. In: J. Malaurie (ed.), Arctic oil and gas problems and possibilities. Mouton and Co., Paris.

Clark, R. C., Jr., and J. S. Finley. 1977. Effects of oil spills in arctic and subarctic environments, pp. 411-475. In: D. C. Malins (ed.), Effects of petroleum on arctic and subarctic marine environments and organisms, Academic Press, Inc., N. Y.

Connors, P. G., and R. W. Risebrough. 1976. Shorebird dependence on Arctic littoral habitats. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 2:401-456.

Connors, P. G., and R. W. Risebrough. 1981. Shorebird dependence on arctic littoral habitats. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. (in press).

Craig, P. C., and W. B. Griffiths. 1981. Studies of fish and epibenthic invertebrates in coastal waters of the Alaskan Beaufort Sea. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. (in press).

Craig, P. C., and L. Haldorson. 1981. Beaufort Sea barrier island-lagoon ecological process studies: Final Report, Simpson Lagoon, Part 4. Fish. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Final Rep. Biol. 7:384-678.

Divoky, G. 1978. Breeding bird use of barrier islands in the northern Chukchi and Beaufort Seas. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep., 1:482-569.

Divoky, G. J. 1979. The distribution, abundance and feeding ecology of birds associated with pack ice. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 1:330-599.

Engelhardt, F. R., J. R. Geraci, and T. G. Smith. 1977. Uptake and clearance of petroleum hydrocarbons in the ringed seal, Phoca hispida. J. Fish. Res. Bd. Can. 34:1143-1147.

Fraker, M. A., C. R. Greene, and B. Wursig. 1981. Disturbance response of bowheads and characteristic of waterborne noise, pp. 91-195. In: W. J. Richardson (ed.), Behavior, disturbance responses and feeding of bowhead whales in the Beaufort Sea, 1980. LGL Ecol. Res. Assoc., Bryan, Tex. Unpub. 273 pp.

Frost, K. J., and L. F. Lowry. 1981. Feeding and trophic relationships of bowhead whales and other vertebrate consumers in the Beaufort Sea. Final Rep. Nat. Mar. Fish. Serv., Nat. Mar. Mammal Lab., Seattle, Wash., Contract No. 80-ABC-00160, 142 pp.

Geraci, J. R., and T. G. Smith. 1976. Direct and indirect effects of oil on ringed seals (Phoca hispida) of the Beaufort Sea. J. Fish. Res. Bd. Can. 33:1976-1984.

Hamilton, R. A., C. L. Ho, and H. J. Walker. 1974. Breakup flooding and nutrient source of Colville River delta during 1973, pp. 637-648. In: J. C. Reed and J. E. Sater (eds.), The coast and shelf of the Beaufort Sea. Arctic Inst. N. Am., Arlington, Va.

Johansson, S. 1980. Impact of oil on the pelagic ecosystem, pp. 61-80. In: J. J. Kineman, R. Elmgren, and S. Hansson, (eds.), The Tsesis Oil Spill. NOAA/OMPA, Boulder, Colo.

Johnson, S. R., and W. J. Richardson. 1981. Beaufort Sea barrier island-lagoon ecological process studies: Final report, Simpson Lagoon, Part 3. Birds. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Final Rep. Biol. 7:109-383.

Ljungblad, D. K., M. F. Platter-Reiger, and F. S. Shipp, Jr. 1980. Aerial surveys of bowhead whales, North Slope, Alaska. Final Report: Fall 1979. Naval Ocean Systems Center, San Diego, Calif., Tech. Doc. 314. 181 pp.

Ljungblad, D. K., F. S. Shipp, Jr., D. VanSchoik, S. E. Moore, and C. S. Winchell. 1981. Aerial surveys of endangered whales in the Beaufort Sea, Chukchi Sea and northern Bering Sea. Draft Final Rep. 1980. BLM Contract AA 851-1A1-5, Naval Oceans Systems Center, San Diego, Calif.

Lowry, L. F., K. J. Frost, and J. J. Burns. 1981. Trophic relationships among ice inhabiting phocid seals and functionally related marine mammals. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. (in press).

Northern Technical Services, Inc. 1981. Beaufort Sea drilling effluent disposal study. Prepared by Northern Technical Services under the direction of SOHIO Alaska Petroleum Company for the Reindeer Island stratigraphic test well participants. 329 pp.

Rass, T. S. 1968. Spawning and development of polar cod, pp. 135-137. In: R. W. Blacker (ed.), Symposium on the ecology of pelagic fish species in arctic waters and adjacent seas. Int. Council for the Exploration of the Sea Report, 158.

Schamel, D. 1974. The breeding biology of the Pacific Eider (Somateria mollissima v-nigra, Bonaparte) on a barrier island in the Beaufort Sea, Alaska. Unpub. M.S. Thesis, Univ. Alaska, Fairbanks, Alaska, 95 pp.

Schamel, D. 1977. Breeding of the Common Eider (Somateria mollissima) on the Beaufort Sea coast of Alaska. Condor, 79:478-485.

Schell, D. M. 1981. Primary production, nutrient dynamics, and nutrient regimes of the Harrison Bay-Sale 71 area. OCS Arctic Project Office, Univ. Alaska, Fairbanks. 12 pp. Unpub.

Smith, T. G., K. Hay, D. Taylor, and R. Greendale. 1978. Ringed seal breeding habitat in Viscount Melville Sound, Barrow Strait and Peel Sound. Inst. of Northern Affairs Pub. No. Q5-8160-022-EE-A1, Ottawa, Canada. 85 pp.

USDI. 1979. Beaufort Sea final environmental impact statement. Proposed Federal/State Oil and Gas Lease Sale, Beaufort Sea.

Walker, H. J. 1974. The Colville River and the Beaufort Sea: some interactions, pp. 513-540. In: J. C. Reed and J. E. Sater (eds.), The coast and shelf of the Beaufort Sea. Arctic Inst. N. Am., Arlington, Va.

Weller, G., D. W. Norton, and T. M. Johnson (eds.). 1978. Interim Synthesis: Beaufort/Chukchi. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP, Boulder, Colorado, 362 pp.

Weller, G., D. W. Norton, and T. M. Johnson (eds.). 1979. Environmental stipulations relating to OCS development of the Beaufort Sea. Proceedings of a synthesis meeting of OCSEAP investigators. Arctic Project Bull. #25, OCS Arctic Project Office, Univ. Alaska, Fairbanks. 36 pp.

SECTION II. INTERDISCIPLINARY PROCESS ANALYSES, IMPACT PREDICTION, AND ISSUE DECISIONS

Chapter 5. Pollutant Behavior, Trajectories, and Issues Analyses

R. S. Pritchard, Editor

With contributions from P. W. Barnes, P. G. Connors, J. C. Mungall, A. S. Naidu, R. S. Pritchard, J. Ray, E. Reimnitz, D. R. Thomas.

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5.1 BEHAVIOR OF SPILLED OIL UNDER DIFFERENT CONDITIONS

By R. Pritchard

Introduction

Our knowledge of the transport oil from a spill has increased substantially during the past year. Therefore, this topic can be described in much more detail than was possible for the 1978 synthesis of knowledge of development offshore of the Prudhoe Bay oil field (Weller et al., 1978). The fate and behavior of oil spills in and under the sea ice cover around Prudhoe Bay has been the research topic of RU 567. Because oceanographic conditions and processes are similar at Harrison Bay, the results from Prudhoe Bay are extrapolated to Harrison Bay. Therefore, the results of the Prudhoe Bay study are outlined. In the research of RU 567, scenarios of the fate and behavior were developed for 12 conditions. These conditions depended upon the size of the spill (40,000-50,000 barrels per day for 5 or 90 days), the location of the spill (under fast ice, deforming unmoving ice, or moving ice), and on season (at the start of freeze-up on 1 November or the start of breakup at 31 May). The scenarios, summarized below are based on two reports by Thomas (1980a, 1980b).

The initial phase includes the blowout and the immediate rise of the oil and gas to the surface and interaction with the ice cover. A local plume and wave ring forms, the ice cracks because of gas bubbles, and melts due to the heat of the oil, and pools of oil forms on the surface.

The oil then spreads outward until it fills the relief on the underside of the ice cover. It was originally thought that large ridge keels would be necessary to restrict the spreading. However, recent work by Cox et al. (in press), has shown that small-scale roughness, about 0.1-0.20 m in relief, is enough to limit the spread of the oil. In fact, even the smoothest ice shows an equilibrium thickness of oil of about 10 millimeters. Because of this great thickness, the oil is contained in a small area throughout the freezing season. Even a spill of 200,000 barrels under smooth ice would be contained within an area of about 6 km^2 (Thomas, 1980a; Kovacs et al., 1981). This is several orders of magnitude less than the area that would be covered by a similar spill on the open ocean.

Although one might expect oil under the ice to be transported by the ocean currents, Cox et al. (1980), have shown that currents must exceed 0.20 m/s under even the smoothest ice to cause relative motion. Since currents of this magnitude occur only at tidal peaks and storm surges and then only for short periods, it is expected that oil will be carried no more 0.5-1 km by this means. Since this estimate is within the resolution of other spatial estimates, it can be ignored. During the freezing season, ice will continue to grow downward until it encapsulates the oil lying beneath it. Therefore, the oil may be assumed to be fixed to the ice and will move only as the ice moves. Therefore, winter spill under fast ice within Harrison Bay would move only tens of meters. In the outer area of the proposed lease tracts, which are at the edge of the multiyear pack, winter motions can be about 150 km per month. Whether motions are small or large, deformations of the ice cover will cause oiled ice to be built into ridges. Thomas (1980a) has calculated the probability of oiled ice being built into ridges during the course of the winter, according to the spill date and upon the location of the spill.

The time of release of oil from the ice during spring breakup will depend on the depth of the oil-contaminated ice layer on the ice sheet at the time of breakup. Therefore, different estimates have to be made for different conditions. It is known that local melting is enhanced by changes in albedo due to the presence of oiled ice. That factor causes the oil to be released about two weeks earlier than the date of normal mechanical breakup of the ice sheet. Because the oil is contained by the ice during the freezing season, at spring breakup it will be released essentially unweathered. If cleanup takes place during the winter, then the volume of the oil released at breakup will be reduced, but there will be no other changes. As the ice compactness is reduced during breakup, the oil slick will begin to act like one on an open ocean containing ice floes. Since biological activity in early spring is high and the amount of open water available for mammals and birds is small, and this is the most biologically sensitive time of year, the release of oil into these leads and polynyas could be disastrous. This is a compelling argument for the mechanical containment and effective wintertime cleanup of spilled oil.

In the remainder of this section we describe scenarios for oil spilled on top of or under the ice in the winter and follows the behavior of the oil into the summer. In addition we consider the problem of sediment resuspension and transport near shore. These scenarios are intended to replace the scenarios presented in the 1978 Beaufort Sea Synthesis report (Weller et al. 1978). Other scenarios which include effects expected from construction of a coastal settlement or from chronic localized fuel releases (Weller et al., 1978) also apply to Harrison Bay.

Winter Oil-spill Scenario

A winter oil spill scenario for the Harrison Bay-Sale 71 area has been prepared by modifying one of the Prudhoe Bay oil spill scenarios (Thomas, 1980b) to reflect the ice conditions in Harrison Bay. The most important modification is the extension of the scenarios through the spring breakup and into the open-water season by means of a wind-driven water circulation model.

A winter oil spill in the Harrison Bay area will spread over a relatively small area. Ice growth will incorporate any oil beneath the ice into the ice cover, while oil on the upper surface will soak into the somewhat porous upper layer of ice and into any snow. Except for cleanup, and some weathering of the oil on top of the ice, little change takes place in the oil before spring breakup. The oil will then have little effect on the environment during the winter. Only during and after spring breakup does the oil begin to interact significantly with the environment.

The location of the blowout which produces the spill is not as important as the location of the oiled ice at breakup. Winter blowout scenarios may follow two nearly equivalent courses. Early in the ice season, a spill may contaminate an area of ice anywhere within the lease area. Later, but still before grounded ridges immobilize the ice cover within the bay, the oiled ice may be moved. The new position may be within the lease area but it may also be seaward in the pack-ice zone. If a spill occurs after grounded ridges stabilize the fast-ice zone, the oiled ice remains in place until breakup or moves with the pack ice if the spill occurs seaward of the shear zone. The most significant difference between early and late winter spills is in the amount of oil incorporated into ridges. The earlier in the ice season a spill occurs, the higher the probability that oiled ice will be built into ridges. Spilled oil inside the system of grounded ridges will not be built into ridges, since the ice within the grounded ridge zone is virtually immobile and not usually subject to further ridging.

Oil from the blowout may emerge in at least two ways. One possibility is for the oil to come to the seafloor through faults in the rock, releasing oil at some distance from the drill hole. In this case the oil would come up beneath an initially unbroken canopy of sea ice. A second possibility is for a blowout to occur at the wellhead on an artificial island or drilling platform. In that case the oil can spill onto the top surface of the ice cover. When it reaches openings in the ice, such as thermal cracks and tide cracks, oil will tend to penetrate these openings, going beneath the ice as well. Although crude oils are usually less dense than sea ice, winter air temperatures in the Arctic will usually be less than the oil's pour point. This, combined with any snow on the ice surface, will restrict the spread of oil on the surface, causing it to collect on the surface. The oil will need to pool only a few centimeters above the ice surface before its static head can force oil beneath the ice. Thus, even for an above surface spill, it is possible for oil to move into and perhaps collect beneath the ice.

The major difference between above- and below-surface spills will be the ease of cleanup. Oil on the upper ice surface can easily be removed by mechanical means during the late winter.

In this scenario we assume that the oil is released beneath the ice or that an opening exists which allows a large quantity of oil to pool beneath the ice. The blowout is assumed to occur in November and is followed by a storm which moves and severely deforms the ice cover. Thus, the scenario must describe oil-ice interactions for several types of ice cover (undeformed fast ice, ridged ice in the stamukhi zone, and pack ice). Following breakup, oil trajectories will depend upon location of oiled ice at breakup, ice type, and ice concentration. Figure 5.1.1 outlines the sequence of possible events following an early winter blowout.

Harrison Bay Oil Spill Scenario

On 1 November, about four weeks after freezeup, an underwater oil well blowout is assumed to occur under the newly developed ice cover in Harrison Bay. The hypothetical blowout releases 2.8×10^4 m^3 (2×10^5 barrels) of oil over a period of five days.

Early Winter Oil Spill - Harrison Bay

1. Blowout
2. Spread of Oil
3. Incorporation of Oil into Ice
4. Motion of Oiled Ice

A. Fast ice Light ridging, oiled ice remains in place.	B. Fast ice Moderate ridging, motion ceases after ridges ground.	C. Stamukhi Heavy ridging motion ceases after ridges ground.	D. Pack ice Ridging plus ice motion throughout winter

5. Spring Breakup

A. Ice melts in place, releasing oil.	B. & C. Underformed ice melts in place, oiled ridges remain.	D. Oil release over wide area offshore.

6. Summer Season

(Oil trajectories depend upon ice type and concentration)

Open water	Low concentration	Medium concentration	High concentration	Oiled ridges	Pack ice

Oil motion occurs as open water drift	Open water drift but modified by ice presence	Oil motion corresponds to ice drift

Figure 5.1.1. Outline of stages of winter spill scenario in Harrison Bay.

At the time of the blowout, a thin (0.2-0.3 m thick), continuous ice canopy exists in Harrison Bay. Winds during freeze-up and immediately after have produced pancake floes with thick edges, and some rafting/ridging has occurred, but as the ice continues to thicken, these irregularities are smoothed out. The ice consists of large areas of flat ice with bottom relief of 0.01-0.02 m, possibly with occasional areas of greater relief where rafting or ridging has occurred.

Water depths in Harrison Bay vary from shallow near shore to about 30 m at the seaward edge of the lease area. Wind-driven currents died out as soon as the ice cover formed, and now the under-ice currents are driven by the tides, storm surges, and thermohaline circulation. The tidal component is weak (less than 0.01 or 0.02 m/s) and oscillatory. The thermohaline currents produced by cold, salty water flowing offshore along the bottom are small; maximum currents of 0.11 m/s have been observed. They are thought to be a combination of tidal peaks and storm surges that are amplified by the reduction in water draft as shore is approached. It is postulated that an onshore current of up to 0.2 m/s must exist just beneath the ice to replace the water flowing offshore along the bottom, but this has not been observed. This is compatible with the maxima mentioned by Barnes and Reimnitz (1979). In general, measured currents beneath the fast ice inside the barrier islands are small, about 0.02-0.03 m/s, and variable.

Water temperatures in the shallow sound are near freezing, and the 90th-percentile air temperature range during early November is about -35 to -6°C.

Blowout. The reservoir is assumed to be about 3,000 m deep and the crude oil similar to a Prudhoe Bay crude (density about 890 kg/m^3 and pour point about -9.5°C). Two possible blowout situations may be considered. One type of blowout is a ruptured casing near a fault in the bedrock which allows the oil and gas to escape under the solid ice canopy some distance from the wellhead. A second type of blowout can occur from a drilling platform or artificial island and will deposit oil on the upper ice surface near the well. Any gas will be vented directly to the atmosphere. Much of the oil on the upper ice surface will eventually make its way beneath the ice. Low air temperature and snow cover limit the surface spread of the oil. As a head of oil accumulates on the upper surface, openings in the ice (such as those next to the drilling island or holes melted by hot oil on the ice) allow the oil to pool to depths such that its draft is greater than the surrounding ice draft. Oil which remains on the ice surface plays no significant role during the ice season. In fact, it may disappear under drifting snow. Evaporation of oil on the surface takes place slowly. During the winter, as much as half of the surface oil may be evaporated.

With respect to oil under the ice, the two types of blowouts are identical. Differences arising from the presence of some oil on the upper ice surface probably will not affect our ability to make predictions.

A total of 3.18×10^4 m^3 of crude oil escapes over a period of five days before the flow can be controlled. An estimated 4.8×10^6 m^3 of gas is also released. Flow rates during the blowout average 4.4 m^3/min of oil and 670 m^3/min of gas.

The crude oil, at 60-90°C, contains enough heat to melt between 9.5×10^3 and 1.4×10^4 m^3 of sea ice. As the ice melts, occupying less volume after melting, the volume lost is replaced by crude oil which has about the same density as sea ice. This volume of oil involved in replacement is only about 0.6 percent of the total released during the blowout.

Except for release of dissolved gas and a decrease in temperature, the oil undergoes very little physical or chemical change during the blowout. Evaporation is insignificant from oil beneath the ice because so little oil is exposed to the atmosphere. Outside an underwater blowout plume there is no mixing energy to form emulsions. Dissolution occurs, but probably in very insignificant amounts. Sedimentation may be important in those years where slush ice has formed during freeze-up. The slush ice contains large amounts of suspended sediments with which the oil will come into contact. Sediment-laden oil may precipitate at this time and again when the ice melts.

It may be conjectured that the turbulence in the immediate vicinity of the blowout will cause the water column to become saturated with the water-soluble fractions of the oil. The total flux of oil-saturated water advected out of the area should be estimated.

Spread of Oil Beneath the Ice. Other than the small amount of oil in the central melt hole or on the upper ice surface, most of the oil will spread beneath the ice. Very little oil will flow onto the top surface of the ice through cracks in the ice or the melt hole. For example, in sea water (density 1,020 kg/m^3), a layer of oil (density of $890/m^3$) will have only 9 mm more freeboard than a 0.3-m thick ice sheet (density of 910 kg/m^3) when the oil draft is equal to the ice draft. Although this tends to spread oil on top of the ice, the air temperature below the oil's pour point, ice roughness, and snow on the ice will all tend to prevent the oil from spreading onto the ice surface and will increase the thickness of the oil pool beneath the ice.

Beneath a perfectly smooth sheet of ice, the oil will spread until an equilibrium thickness of about 8 mm is reached. Neglecting oil on the ice surface or in the central melt hole, 3.18×10^4 m^3 of oil will cover a maximum area of 4 km^2 (a circle of radius 1.13 km). In reality, the oil will cover less area than this for two reasons. First, even new, thin, fast ice will contain a small amount of bottom relief in an area of 4 km^2. This relief will cause oil to pool deeper than 8 mm until it can flow beneath or around the obstruction. Second, and more important, is the growth of new ice. During the 5-day blowout, the ice sheet outside the oil slick will thicken by about 0.01 m per day. As the oil spreads beneath the ice near the blowout site, the ice outside that area grows thicker, providing more containment volume near the blowout. If the first day's oil flow (6.4×10^3 m^3) fills an area of 0.8 km^2 to a depth of 8 mm, 0.01 m of ice growth outside the oiled area allows the second day's oil flow to fill the same area to a greater depth, and so on for five days. Thus, the final underice oil slick may cover an area as small as 0.8 km^2 even when under-ice roughness is neglected.

The currents near shore are usually too small to affect the size of the oil-contaminated area. Occasional brief currents of up to 0.25 m/s may occur during storm surges. Currents of this magnitude will move an oil slick under the ice, but they last only one or two hours. The oil will move at a fraction of the current speed, so that total oil transport is insignificant (about 100-200 m during each storm surge). The primary effect of currents will be to control the direction of the oil spread, not the extent of the spread.

If slush ice is present beneath the ice cover, it may also act to restrict the spread of oil. The effect may be small because of the small proportion of ice in the slush. The presence of large billows of slush ice argues against any large currents beneath the ice.

Incorporation of Oil Into the Ice. About five days after oil ceases to flow, new ice growth will have completely encapsulated all the oil which has spread beneath the ice. A small amount of oil (equivalent to a film about 2 mm thick) will soak into the 0.04- to 0.06-m thick skeletal layer above the oil. The new ice growing beneath the oil layer will contain no oil.

Ice also forms beneath the oil pool in the central melt hole. By May, when ice growth stops, about 1.4 m of ice will have grown beneath the oil.

Any oil on the ice surface will be covered by snow. The oil, in the ice and in the snow, being virtually isolated from the water and air, will experience negligible weathering throughout the winter.

Transport of Oiled Ice. A major storm before about mid-November can break up the fast ice behind the barrier islands. The fetch of winds in Harrison Bay can be over 50 km. A wind of 8 m/s (16 knots) acting over a fetch of 50 km is required to fail 0.5-m thick ice. In November, winds greater than 8 m/s blow only about 27 percent of the time, but most of these winds tend to hold the ice against the shore. Larger winds are less likely, and winds from some directions will have a shorter fetch. The ice cover will grow thicker and stronger daily. Therefore, the fast ice will most likely remain motionless and undeformed after December. The possibility of large ice motion exists during the early winter. The probability of Harrison Bay ice becoming incorporated into the offshore pack is about 10 percent, based upon the amount of time that large offshore winds occur.

Large-scale drift of the pack ice cover is used to estimate the range of trajectories expected for oiled ice. For oiled ice starting offshore of Harrison Bay on June 1 and November 1, trajectories are shown in Figs. 5.1.2 and 5.1.3, respectively. The range of monthly displacements has been found using a free-drift ice model and a 25-year history of winds (Thomas and Pritchard, 1979). Trajectories are determined by accumulating the most probable monthly displacements. Variations in winds from year to year cause variations in the motions. The end points of year-long trajectories are expected to be within the ellipse 50 percent of the time.

Release of Oil From the Ice. In late February or early March, as the air temperature begins to rise, brine trapped between the columnar ice crystals will begin to drain. By late April or early May, the brine

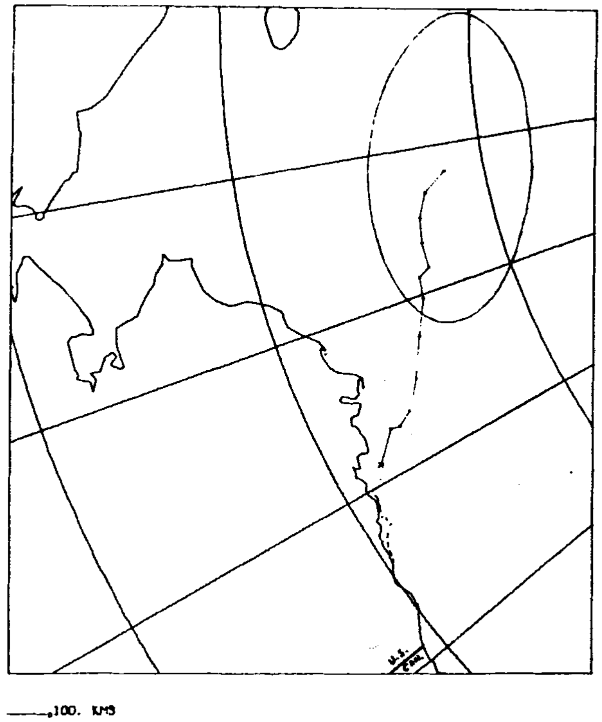

Figure 5.1.2. One-year pack ice trajectory beginning offshore of Harrison Bay on 1 June for an average year. Interannual variability would cause half of the end points to lie within and half to lie outside of the ellipse.

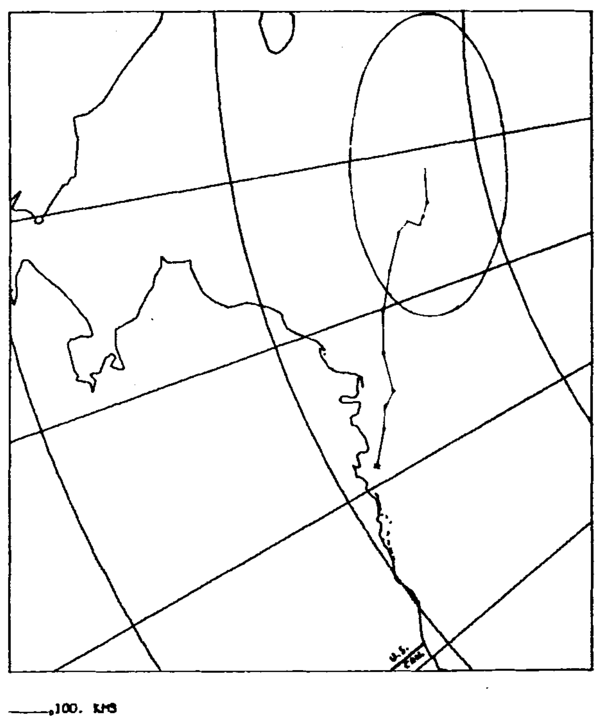

Figure 5.1.3. One-year pack ice trajectory beginning offshore of Harrison Bay on 1 November for an average year. Interannual variability would cause half of the end points to lie within and half to lie outside of the ellipse.

channels will have become large, and oil will begin to appear on the ice surface. Periods of cold weather will stop the oil flow temporarily, but by late May pools of oil will be collecting on the ice surface. Because of the lowered albedo of the oiled ice, melting of the ice surface also begins in late May.

The oil, being close to the ice surface, will have completely surfaced in early June and will accelerate the local ice breakup by about two weeks. Thus, by mid-June, the oil-contaminated ice will have broken up enough that it can be moved by the wind. In late May, the Colville River will begin flowing again, flooding the ice near the river mouth. By mid-June, shore polynyas will have been melted by the flowing rivers. The most likely ice motion will be toward the shore and the area of open water.

As soon as oil begins to appear on the ice surface in May, weathering will begin. By the end of June, about 50 percent of the oil will have evaporated. Some water-in-oil emulsions will form where oil is floating on surface melt pools exposed to agitation by the winds. Other weathering processes will take place as the oil is released from the ice, but only insignificant amounts of oil will be involved. The low temperatures, the reduced wind action due to the remaining ice cover, and the thick, viscous oil layer on the water surface will inhibit dissolution, bacterial degradation, and dispersion. The silt carried out by the flowing rivers may increase the rate of incorporation of oil into the sediments, however.

By early to mid-July, all of the ice contaminated by oil will have melted, leaving the oil slick on the water surface.

Open Water Oil Spill Transport. A mathematical model has been developed to predict motions of oil slicks on arctic waters during open water (Mungall, 1981). Although this model has not yet been exercised to determine the statistical likelihood of a particular trajectory, numerous examples have been presented for observed wind and current conditions. An information gap has until recently existed in exercising this model to determine the most likely trajectory that can be expected when a slick is deposited at a particular location, and also the range of behavior from year to year depending on the starting date and location. Open-water oil spill movement depends on ocean currents and winds. The change in sea level elevation is also important because the setup or setdown is often associated with the storms that cause slick motion. Should a spill reach the shore during a storm, a slick could be deposited on surfaces above or below the normal coast line, that is, on low-lying salt marshes or on shallow mud flats. Typical values of these sea-level elevation changes are listed in Table 5.1.1 for 15- and 30-knot winds that have been blowing steadily for 24 hours. The results are relative to a zero sea level occurring along a line parallel to the shore and some 80 km from it.

Also listed in Table 5.1.1 are typical ocean currents associated with the indicated winds. The currents, for the most part, tend to be parallel to the coast with little differences between current directions for 15- and 30-knot winds. These are mean water-column currents, and there is little or no tendency for pollutants within the water column to be transported toward the shore adjacent to the lease area. Slick movement

Table 5.1.1. Steady 24-hour wind results: Setup/setdown in southern Harrison Bay (70°26'N, 151°28'W), current speed and direction in central Harrison Bay (70°36'N, 151°19'W).

Wind Direction (°T)	15 knots Setup (ft)	15 knots Speed (ft/s)	15 knots Direction (°T)	30 knots Setup (ft)	30 knots Speed (ft/s)	30 knots Direction (°T)	Speed Ratio	Direction Difference
000	0.5	0.3	104	2.1	0.6	101	2.0	-3
022	0.3	0.1	068	1.7	0.4	060	4.0	-8
045	0.1	0.2	319	1.1	0.6	313	3.0	-6
067	-0.1	0.3	302	0.5	0.8	298	2.7	-4
090	-0.2	0.4	298	-0.4	0.9	293	2.25	-5
112	-0.4	0.4	295	-1.1	0.9	291	2.25	-4
135	-0.6	0.4	293	-1.7	0.9	289	2.25	-4
157	-0.6	0.3	290	-2.2	0.8	287	2.7	-3
180	-0.6	0.2	282	-2.2	0.6	282	3.0	0
202	-0.4	0.1	242	-1.6	0.3	245	3.0	3
225	-0.1	0.2	136	-0.9	0.5	132	2.5	-4
247	0.1	0.3	118	-0.7	0.7	118	2.3	0
270	0.3	0.4	114	0.5	0.9	114	2.25	0
292	0.4	0.4	111	1.2	0.9	112	2.25	1
315	0.5	0.4	109	1.8	0.9	109	2.25	0
337	0.6	0.3	107	2.1	0.8	106	2.7	-1
							$\bar{x} = 2.59$	$\bar{x} = -2.37$
							$\sigma = 0.49$	$\sigma = 2.92$

is not included in the above model; typically, this is computed by adding to the above vectors a second vector component equal to 3 percent of the wind speed in the direction of the wind.

Calculated from winds observed during 1977, 1978, and 1980, the surface slick motion shows much greater variability than the water-column motion. The region modeled is a 60 x 26 grid of elements; each element is 3.7 km (2 nautical miles) on each side. This grid covers the entire Sale 71 lease area, and the east and west boundaries are the limits of the lease area. For the most part, strong easterly winds cause the central and western parts of Harrison Bay to be affected. Typical winds extend the region affected eastward to the Sagavanirktok River region. For a year with offshore westerly winds, the region affected by the oil spill extends from Harrison Bay to the middle Simpson Lagoon, with perhaps 25 percent of the spills moving to the northeast toward the pack ice. The best available statistics are presented in Table 5.1.2. For this case, the single wind history was obtained by concatenating the wind records for 1977, 1978, and 1980; taking one length of the 1977 wind record, five lengths of the 1978 record, and one length of the 1980 wind record, so as to conform with the information from Kozo (pers. comm.) that these three seasonal types of winds tend to occur 10, 70, and 20 percent of the time. Results of numerous spill simulations have been made available to the USGS Water Resources Division (Mungall, 1981), and the statistical description of results is forthcoming.

Table 5.1.2. Milne Point Slick Movement Summary*

Year:	1977	1978	1980
Wind type:	Easterly storms	Typical ENE prevailing	Westerly storms
No. reaching north boundary	0	0	3
No. reaching east boundary	0	0	3
No.reaching west boundary	0	0	0
No.reaching shore or islands	25	25	19
Transit time (mean, days)	7.6	12.5	7.0
Transit time (standard deviation)	1.9	6.9	6.1

* Position: 70°39'N, 149°15'W

5.2 SEDIMENT RESUSPENSION, LATERAL TRANSPORT, AND DEPOCENTERS

By A. S. Naidu, J. Ray, and E. Reimnitz

Oil and sediments are known to have an affinity for one another, with oil sometimes sinking by adsorbing sufficent sediment. Thus the source, mechanisms of suspension, the pathways and depocenters of sediment will tell us likely impact areas for oil or pollutant-laden suspended sediments.

Sediment influx to the ocean occurs from coastal erosion during the open-water season and from the initial flood of the coastal rivers in early June prior to the breakup of coastal ice. The bulk of the sediment initially deposits on the 1- to 2-m delta front platforms and along the coastal shallows off eroding bluffs.

In mid- and late summer, when the fluvial outflow is low, much of the turbid coastal water transport is initiated by wave resuspension of the substrate particles from 1- to 2-m inshore regions. Subsequent to resuspension the particles are carried westward as a turbid plume. The southwestern corner of Harrison Bay could be an important depositional site for the muds resuspended off the Colville River mouth (Fig. 5.2.1).

The trajectory of the turbid sediment plume generated off the Sagavanirktok River skirts north of the Jones Islands chain, incorporating Simpson Lagoon/Kuparuk River sediments off breaks in the island chain, and progressively dissipates westward to Harrison Bay. The trajectories and depocenters for these rivers are substantiated by satellite imagery and clay mineralogies (Naidu et al., 1981).

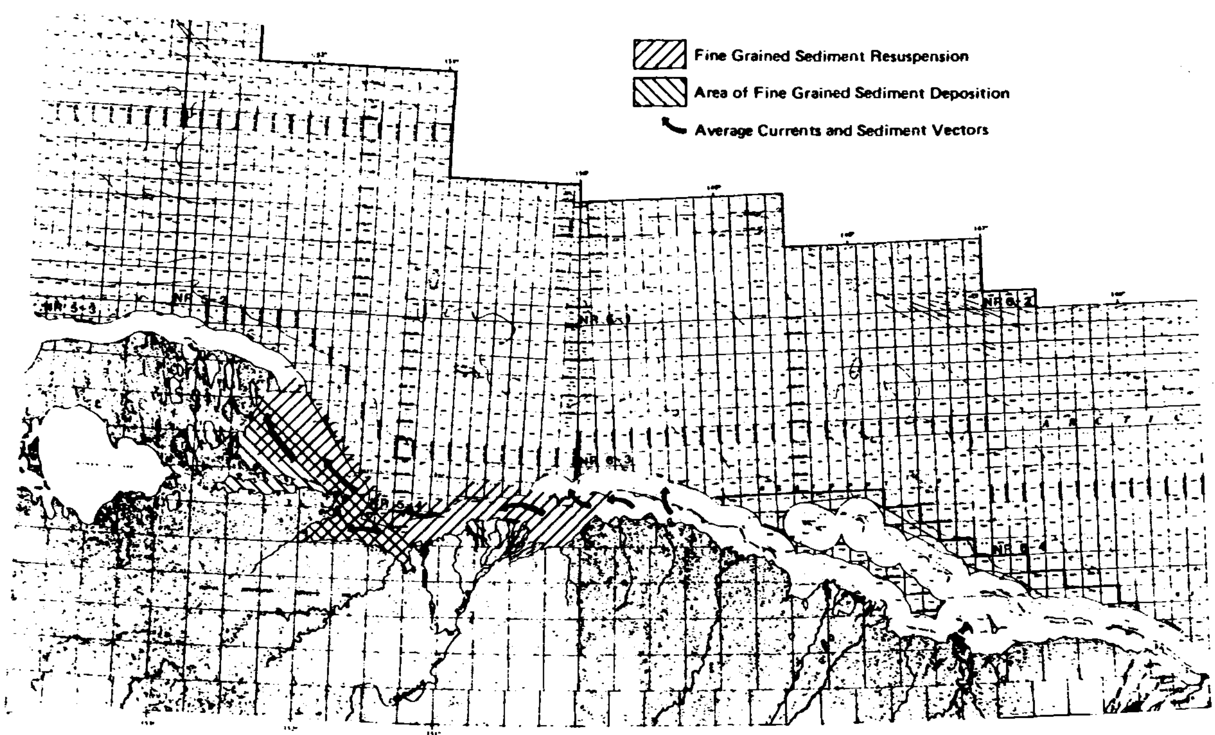

Figure 5.2.1. Sediment transport and deposition.

Freezing and fall storms combine to produce impressive quantities of frazil ice that is often laden with sediments from the turbulent resuspension. The resultant sediment-laden ice often becomes part of the ice canopy out to and including the stamukhi zone. The quantities of sediment entrained in the ice may approach half or more of the estimated river input. Once frozen in the ice canopy, these sediments are not transported great distances, although some portion is probably ultimately entrained in the pack ice. Pollutants entrained with sediments during the turbulence and frazil ice formation characteristic of the fall will remain in the ice canopy until the lower albedo of the turbid ice increases melting in the spring.

In winter, sediment resuspension and transport occur in inlets to lagoons and bays and the outer edge of the delta front platform, where tidal currents under a growing ice sheet can be magnified.

Sedimentation rates for the Beaufort Sea have been calculated from ^{210}Pb dating. The estimated rates are between 5 mm and 15 mm/yr in the shallow lagoons and on the Colville Delta front platform. Because no net linear exponential decrease in ^{210}Pb with depth has been detected in cores retrieved from the central continental shelf, sedimentation rates could not be estimated for that region. Lack of a decrease in ^{210}Pb presumably reflects massive reworking of sediments by ice gouging in the central shelf area.

5.3 ISSUE ANALYSIS

By R. S. Pritchard

Issue VIII. Disposal and Drilling Wastes

Drilling Mud

According to recent studies of drilling mud discharges, the absolute restrictions imposed for the previous joint lease sale are not necessary for Lease Sale 71. Winter discharge below the ice at total water depths greater than 4 m affects only small areas and therefore appears harmless to the overall environment. At shallower depths, however, sub-ice discharge should not be allowed, and alternatives considered for each site.

In particular, discharge close the the Fish Creek and Colville River deltas in winter might introduce pollutants or highly saline water into channels or winter pools under ice, which could affect overwintering fish, and the area behind Thetis Island, an oldsquaw molting area, should not be subjected to discharges, because of the importance of the benthic invertebrates as food for these birds.

Within areas inundated by the Colville River spring flood, disposal of drilling mud in confined pits on the ice is considered a safe alternative to disposal in man-made pits on the tundra. On-ice disposal might also be a viable alternative, but should be considered on a site-specific basis.

Cuttings

Whenever possible, drill cuttings should be incorporated into artificial islands. But in the open and exposed environment of Harrison Bay, local accumulations of cuttings from two or three wells per site should have no ill effect on the environment, and should soon be dispersed by natural processes. In all cases the formation of oil slicks from oil cuttings must be avoided.

Disposal of Formation Water

Until the composition of formation waters common to the lease sale area is known, decisions on methods of their disposal and treatment cannot be made. If found offensive to the environment, the same restrictions imposed on the disposal of formation water in the joint lease sale area should also apply to Harrison Bay.

Issue IX. Spill Countermeasures and Contingency

The recent increase in knowledge of the expected behavior of oil after an accidental oil spill in the Arctic makes it possible to specify useful mitigative measures. Oil spilled under or on the sea ice cover will be entrapped in the ice throughout the winter. It is now clear that neither ocean currents nor any other environmental influence will move the oil more than a few kilometers from the location of the original spill, except as the ice cover itself moves. As a consequence, the ice contains the oil in a small area, permitting cleanup measures to be taken. A maximum effort must be made, however, to contain the oil mechanically in the smallest possible area. There is a strong distinction between fast ice and pack ice with respect to movement of oil-contaminated ice in winter; the former moves only slightly, the latter moves great distances.

Any oil not cleaned up or removed from the ice cover during the winter will be released from the ice during spring breakup. Any residual oil from a winter spill will behave like that from a spring spill.

Oil-Spill Containment Countermeasures. Since the sea-ice cover restrains the spread of oil by trapping it in the bottomside ice relief, it is recommended that these natural features be enhanced. The bottom relief of the ice cover can contain a large volume of oil in a small area, e.g., 200,000 barrels, within a 10-km^2 area. The average thickness of such a pool is 10 mm. If this average thickness can be increased by one to two orders of magnitude, then the area of coverage can be reduced by a factor of 3 to 10. Mechanical berms of snow, ice, or other material both above and below the ice could be introduced to contain the oil. Alternate approaches might serve as well. Ditches cut to form a moat around a drill platform can serve the same purpose as a berm under the ice. Other proposed engineering solutions should be encouraged.

Oil-Spill Tracking. For spills that occur before spring breakup in the fast-ice zone, substantial ice motions that require tracking are unlikely. However, at the outer edge of Harrison Bay, early-winter spills could be incorporated into the pack ice and moved great distances during the winter. In that case, it would be necessary to predict the motion of the contaminated pack ice so that cleanup equipment could be deployed at the location of the contaminated pack ice in spring when the oil is released. It is recommended that data buoys be deployed on the ice cover at the location of the spill, and their location monitored by routine satellite telemetry throughout the course of the ice drift. It is expected that RAMS buoys with 400-meter positioning accuracy will be adequate. In addition to these direct measurements of pack-ice motion, a sea-ice dynamics model is recommended to predict the motion of the oil-contaminated pack ice throughout the winter. These ice-motion forecasts can be made for periods up to about ten days with present models, but further refinements may extend this interval. Such predictions will complement the knowledge obtained from the drifting buoys. The model will also utilize data on ocean currents and winds, leading to an increase in understanding of oil transport and an increase in the level of confidence in estimating oil motion caused by oil-contaminated ice.

Cleanup Technology. The present technology for cleanup of massive oil spills under adverse conditions of winds and waves is inadequate, even in temperate latitudes. In the Arctic, although the ice contains the oil spill during the winter, it also hinders cleanup efforts during winter and in spring when breakup causes the gradual release of the remaining oil to the ocean surface. The most serious problem is that when the oil is released in the spring, the ice is weak and unstable, and men and equipment cannot safely work on it. Under these conditions new strategies for cleanup must be devised. It is important that all government agencies and the petroleum industry accelerate their technical development of contingency measures. In spring, the oil is released into a small fraction of the total area covered by open water. Furthermore, this open water appears first near shore, and quick action is essential. Mechanical containment, observational tracking, and prediction of ice motion countermeasures will enhance the cleanup effort. What is required is a maximum effort with respect to technological development, planning, and coordination among all agencies involved.

5.4 REFERENCES

Barnes, P. W., and E. Reimnitz. 1973. The shorefast ice cover and its influence on the currents and sediment along the coast of northern Alaska. EOS, Trans. Amer. Geophys. Union 54:1108.

Barnes, P. W., and E. Reimnitz. 1979. Marine environmental problems in the ice covered Beaufort Sea shelf and coastal regions. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 11:148-299.

Cox, J. C., L. A. Schultz, R. P. Johnson, and R. A. Shelsby. In press. The transport and behavior of oil spilled in and under sea ice. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP. Final Rep. Phys.

Kovacs, A., R. M. Morey, D. F. Cundy, and G. Decoff. 1981. Pooling of oil under sea ice, pp. 912-922. In: B. Michel (ed.), POAC-81, Univ. de Laval, Québec, P. Q.

Mungall, J. C. 1981. Quasi-open water spill movement predictions. This volume Appendix A.

Naidu, A. S., L. H. Larsen, M. D. Sweeny, and H. V. Weiss. 1981. Sources, transport pathways, depositional sites and dynamics of sediments in the lagoon and adjacent shallow marine region, northern arctic Alaska. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. (in press).

Thomas, D. R. 1980a. Behavior of oil spills under sea ice-Prudhoe Bay. Flow Res. Rep. 175, Flow Res. Co., Kent, Wash.

Thomas, D. R. 1980b. Prudhoe Bay oil spill scenarios. Flow Res. Rep. 176, Flow Res. Co., Kent, Wash.

Thomas, D. R., and R. S. Pritchard. 1979. Beaufort and Chukchi Sea ice motion, Part 1. Pack ice trajectories, Flow Res. Rep. 133, Flow Res. Co., Kent, Wash.

Weller, G., D. W. Norton, and T. M. Johnson (eds.). 1978. Interim Synthesis: Beaufort/Chukchi. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP, Boulder, Colo. 326 pp.

SECTION II. INTERDISCIPLINARY PROCESS ANALYSES, IMPACT PREDICTION, AND ISSUE DISCUSSIONS

Chapter 6. Environmental Hazards

L. H. Shapiro, Editor

With contributions from P. W. Barnes, W. Harrison, A. Kovacs, T. E. Osterkamp, E. Reimnitz, P. Sellmann, W. Stringer, and W. F. Weeks.

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6.1 INTRODUCTION

The 1978 Interim Synthesis report (Weeks, 1978). reviewed hazards to offshore development in the Alaskan Beaufort Sea coastal area. The subject covered the area, range of activities, and the types of structures and transportation systems which might be employed in exploration and production. Based largely on a document prepared by the Alaska Oil and Gas Association (AOGA), the report presented a matrix of activities and facilities versus potential hazards. Within the matrix, each proposed activity or structure could be considered in terms of the potential environmental hazards in each ice zone during each season. Non-ice related hazards were also considered (Weller et al., 1978, pp. 351-355).

This chapter adds new information to the report of Weeks (1978) and identifies points particularly applicable to the Sale 71 area.

The Sale 71 area includes many of the farthest offshore tracts offered in the 1981 Joint Lease Sale. Potential hazards in these areas were discussed by Weller et al. (1978). The discussion here deals primarily with the tracts west of the 1979 sale area, and particularly with Harrison Bay.

Although an attempt has been made to identify all possible environmental hazards to a given activity or facility, it is not necessary for all to be addressed in detail in the actual design. As an example, for cone structures in the nearshore pack-ice zone, the design condition (in terms of the maximum force which the ice can exert on the structure) is likely to be impact from a multiyear pressure ridge. If this condition is met, then winter movements of the ice sheet, first-year ice ridges, and other features are accounted for in the design, because the effects of these are probably less than that of a multiyear ridge. No attempt has been made here to account for improvements in engineering design concepts which have occurred since preparation of Weeks (1978). Information in that field is largely proprietary or is outside the province and expertise of OCSEAP investigators.

6.2 ZONATION

The zonation of the ice adopted in the 1978 synthesis report is used here as well (Fig. 1.2, Weller et al., 1978, p. 9). Note that the term 'zone' is meant to apply to the area normally occupied by the ice of that zone, even when the ice is absent.

Bottomfast-ice Zone

The largest expanses of the bottomfast-ice zone along the Beaufort Sea coast are found in Harrison Bay, and some of the zone extends offshore into the sale area (see App. C). The important hazard within the zone is override resulting from large motions during freeze-up of the thin and weak ice sheet, and in spring of the thicker but deteriorated ice. Spring flooding of the bottomfast ice in the sale area by the Colville River can force early abandonment of ice roads traversing the zone.

Floating Fast-ice Zone

The floating fast-ice zone is widest within the western portion of the Sale 71 area, where it can reach more than 30 km offshore without the presence of barrier islands to stabilize the ice sheet. It was suggested in the 1978 synthesis that this might permit larger ice motions during freeze-up and breakup than occur elsewhere along the coast within this zone (Shapiro and Barry, 1978). The possibility of larger winter motions appears to depend upon the effectiveness of the grounded ridges (which define the offshore boundary of the zone) in anchoring the ice sheet. In addition, a line of pressure and shear ridges which forms near the (about) 10-m depth contour in Harrison Bay during the fall of some years might further stabilize the ice sheet (Reimnitz, et al., 1978). Anecdotal information from local residents, however, suggests that under certain conditions the ice in the Harrison Bay area can break up and move at any time of year (Shapiro and Metzner, 1979); a lead 150 m in width was observed in the floating fast-ice zone in mid-March of 1981 (Reimnitz, pers. comm.). No data are available in the open literature from continuous monitoring of winter ice movement at any location within the sale areas other than near Narwhal Island. Thus, the question is still open, and the possibility of large movements must be considered.

Freeze-up in Harrison Bay starts from shore and gradually extends into deeper water because of the wide expanse of shallow water and the lower salinities near the Colville Delta. However, the absence of barrier islands could permit ice to break up and be removed from this area by winds and currents earlier than in the areas protected by barrier islands. In addition, the inflow in spring of warm water from the Colville River causes early melting of the inner parts of the floating fast ice in Harrison Bay. Finally, there are no barrier islands to protect the nearshore zone from summer pack-ice incursions.

Early melting and the absence of barrier islands will limit the period when over-ice traffic is possible, and summer pack-ice incursions may interfere with boat traffic and summer construction activities in the nearshore area. In addition, the possibility of winter ice motion, the long distances between the shore and drilling sites, and the frequent occurrence of first-year ice ridges and rough ice will create problems in over-ice transport.

Drilling structures and causeways will probably have to withstand more ice movement and override than will be encountered in most of the Joint Sale area. In particular, override will be a major concern for production facilities.

As pipeline construction will probably be attempted during the summer open-water season, the disruption of operations because of ice incursions is a threat. Beyond this, gouging, scour, and shoreline crossings remain the primary hazards to pipelines; the last is particularly hazardous in the western part of the sale area (see section on thermal erosion of shorelines below).

Pack-ice Zone

The pack-ice zone includes the zone of grounded ridges which bounds the floating fast-ice zone. In the Sale 71 area, the boundary is taken at about the 13-m depth contour, but its variability within a single year, or between years at any particular location, is emphasized here as it was in the 1978 synthesis report (Shapiro and Barry, 1978). There are several shoals in the outer part of the lease area in water which would otherwise be more than 20 m deep (Reimnitz and Maurer, 1978). These are annually the sites of large pile-ups and ridges. Thus, they extend the grounded-ridge zone seaward, increasing its width locally (Reimnitz et al., 1978). Otherwise, there are no discernible differences between the morphology of the pack-ice zone in the Sale 71 area and that of other areas along the coast. Thus, the discussion of the hazards associated with development in this zone in the 1978 synthesis is relevant here. Large movements of cold, thick, first-year ice sheets and pressure ridges, multiyear ice floes and pressure ridges, and ice-island fragments and floebergs must be anticipated (Weeks, 1978).

6.3 OTHER HAZARDS

Hazards posed by wind, air temperature, superstructure icing, and seismicity were discussed in the 1978 synthesis report, and the conclusions given there apply to the Sale 71 area as well. However, the unique features of Harrison Bay, coupled with new data available since preparation of the 1978 synthesis report, require that additional consideration be given to the hazards of waves, surges, currents, and river flooding.

The open coast of the Harrison Bay area will permit longer wind fetches to develop, resulting in higher waves than in the protected areas to the east. Similarly, increased buildup of storm surges is also anticipated along the eastern shores of the bay.

The effects of locally strong currents have recently been observed through the examination of sedimentary bedforms (Section 3.6). Some of these may result from scour around grounded or wallowing ice masses, but others indicate strong unidirectional currents which are probably wind driven during the open-water season.

River flooding is important in Harrison Bay because of the extensive annual over-ice flooding of the area by the Colville River.

Thermal erosion of the coast in the western part of the Sale 71 area near Cape Halkett is not limited to stormy periods but is continuous and rapid, with rates as high as 10 m/yr in some localities (Hopkins and Hartz, 1978). This erosion causes problems in the design of shore crossings for pipelines and for the siting of onshore installations.

The distribution of subsea permafrost is probably as variable within the sale area as it is in the area of the 1979 lease sale. However, data are incomplete; although extensive seismic surveys have been made, there are no drill holes into the offshore permafrost within the lease area from which 'ground truth' data can be obtained. The distribution and properties of subsea permafrost deduced from seismic data (as discussed in Section 3.5) are unconfirmed. The seismic data suggest that the depth to the top of ice-bearing permafrost is greater beneath much of Harrison Bay than it is at similar distances from shore in Prudhoe Bay.

Subsea permafrost hazards are likely to be severe in the area of rapid coastal erosion west of Cape Halkett. Shallow drill holes off Pitt Point near Lonely indicate that ice-bearing permafrost is within 6-8 m of the sea bed for distances of at least several kilometers offshore (Osterkamp and Harrison, 1980).

Studies onshore west of Harrison Bay indicate that natural gas hydrates within or below the subsea permafrost layer are more abundant in the Sale 71 area than farther east (Osterkamp and Payne, 1981). That free gas is common above the permafrost is indicated by seismic data (Section 3.5). Gas emission was also observed in a 15-m deep driven hole about 8.5 km west of Oliktok (Harrison, pers. comm.). As a result, drilling and well completions in this lease area will require special care.

6.4 DATA NEEDS

Weeks (1978) called for information as follows:

A. Data on ice motion as a function of ice thickness and time of year are required for modeling fast-ice motion and for assessing hazards in the pack-ice zone.

B. Data are needed on rates of movement, ice concentration and floe size, and distribution of thickness of summer pack ice that pushes into the nearshore area. Retrospective studies of summer pack-ice invasions are also required to predict future inversions.

C. Statistical information on the abundance, distribution, size and thickness of ice islands, along with predictions of future calving rates, are needed.

D. Studies of interactions between ice and structures should be pursued.

E. Models for predicting surges and storm wave heights should be developed.

These needs still exist, and those regarding pack-ice incursions into the nearshore area, ice motion, and surge and wave height prediction are particularly applicable in the Sale 71 area. In addition, lack of data on the properties of newly formed ice-bonded permafrost in gravel islands and causeways makes it questionable whether a permafrost core will increase the strength of these structures (Section 3.5). Drill holes to verify the seismic information on the distribution of subsea permafrost are also needed. A study of ice motion using laser and radar ranging systems, such as was done from Narwhal Island in the 1979 lease sale area (Tucker, et al., 1980), would have been useful. Although it is believed that winter ice motions in the Sale 71 area might be larger than those measured for the floating fast-ice zone seaward of Narwhal Island, definitive data are lacking.

6.5 CONCLUSIONS

The hazards to be encountered in the Sale 71 area are similar to those anticipated for the Joint Sale area; difficulties in surface transportation and construction activity may be more severe. Because of the absence of barrier islands in most of the Sale 71 area, multiyear pack ice incursion during summer and fall is more likely. By the time exploration activities commence in the Sale 71 lease area, industry will have gained several years of operating experience in the Joint Sale area. Most of this will have been in the stable parts of the floating fast-ice zone which are protected by the barrier islands, although some activity will have occurred outside the barrier islands in less-protected areas. In addition, new data and models of physical processes may be available. However, it is doubtful that operations will have been conducted in the pack ice zone (as defined here), which constitutes a large fraction of the Sale 71 lease area. Thus, the Sale 71 area is likely to provide the first test of the ability of industry to operate in that zone where the most severe ice hazards will be encountered.

6.6 ISSUES

Issues I, II, and XII of Arctic Proj. Bulletin 25 (Weller et al., 1979) dealt with (respectively) the need for a test structure before drilling in water depths greater than the offshore boundary of the floating fast-ice zone (13 m for the 1979 sale area), long-term ice monitoring, and the option of 5- vs. 10-year lease periods. Regulations or stipulations regarding these issues appeared in conjunction with the Joint Sale in 1979. This discussion examines their applicability to the Sale 71 area.

Issue I Test Structures

Issue I test structures was discussed in Bulletin 25 under two options, depending upon whether the duration of the leases was to be 5 or 10 years. If leases were for 5 years, it was concluded that drilling structures should be permitted only in the area inside the 13-m depth contour, although directional drilling to deeper water could be done. Thus, the outer tracts would be deleted from the sale. If leases were for 10 years, structures should be permitted in water deeper than 13 m only after a test structure had been operated at that, or greater depth, for at least one year. One structure of each type (gravel island, monopod, cone, etc.) was to be required. During the operation of the structure, data were to be collected on the magnitude of ice forces, structural response, and ice characteristics, with additional studies of ambient ice stress, ice failure, adfreeze, and ice pile-ups around the structure.

The leases were sold for 10 years, and the regulation which addressed this issue was substantially different from that discussed above. It called for no drilling outside the 13-m depth contour until "... a test platform or structure of the same type to be drilled from has been...in existence in the sale area at a depth in excess of 13 m for a period of two winter seasons." No specific requirements regarding location, data collection on ice observations were included. Thus, the structure called for in the regulations can better be regarded as a 'demonstration' structure rather than a 'test' structure because, to satisfy the regulations, it need only remain in the sale area in water depth greater than 13 m for two years. It need not be instrumented or used as a study site, and there is no assurance that the structure would be adequately tested during the two winter seasons required. In contrast, a true 'test' structure would be designed to respond to ice forces so that the magnitude of the force could be deduced from the resulting deformation of certain structural elements. Such a structure would probably not be a suitable drilling platform; in fact, it could be designed to fail under certain conditions.

1.5 OPTIONS

A. Continue the Joint Sale stipulation requiring a demonstration structure (as defined above) with no change, except to specify the boundary of the floating fast-ice zone in place of the 13-m isobath (see discussion, Sect. 3.3; p. 89).

B. Stipulate that data from an experimental program involving a large-scale test structure, as discussed above, be required before drilling structures be constructed outside of the floating fast-ice zone.

In addition, three alternatives are also offered for consideration:

C. Drop the requirement for special precautions outside the floating fast-ice zone entirely for the Sale 71 area:

It is possible that the requirement will have been met in the Joint Sale area before any attempt is made to drill in deep water in the Sale 71 area. Even if it has not, the industry will have accumulated several years of operating experience in the nearshore Beaufort Sea before moving into deeper water. That might be judged to have provided adequate background information.

D. Require that structures outside the floating fast-ice zone be overly conservative in design, in use of defensive measures and monitoring systems (both for ice conditions and structural response), and in operating procedures regarding shutdown in response to perceived ice hazards:

Scientific and engineering data used in establishing the structure design should be open to the public; thus the operator would demonstrate that he has the data to guarantee the safety and integrity of structures placed seaward of the floating fast-ice zone. These requirements could be relaxed as operational experience and new data are obtained in these deep-water areas, but they would help assure that safe systems and procedures are employed while experience is gained.

E. Continue the Joint Sale stipulation, but require collection of data on the magnitude of ice forces, structural response, ice characteristics, ambient ice stress, ice failure, adfreeze, and ice pile-ups around the structure:

This is not the equivalent of a test structure; it is assumed that the structure would be designed as a drilling platform and would be situated where an exploration hole would be drilled on completion of the test phase. In this form, the option would require rewriting the stipulation presently in force in the Joint Sale area to include the suggestions which appeared in Weller et al. (1978).

From the above discussion, it is difficult to conclude that the present requirement for a 'demonstration' structure serves a useful purpose; it requires a large expenditure for minimal useful information. Design, construction, and operation of a true 'test' structure would provide information, but it would be extremely costly and would require several years to complete. It is questionable whether any company would underwrite such a study prior to acquisition of leases in a deepwater area. There may be few companies with such leases, so that substantial government involvement might be required to conduct such a program. Also, the decision to build a test structure should perhaps be left to those responsible for the design of the actual structures depending upon data needs and economic considerations. Conversely, it can be argued that there is no substitute for field testing structures to be placed in such a potentially hazardous area and that some test or demonstration structure should be required, even if government must contribute for the program to be accomplished.

Alternative D represents the views of most OCSEAP investigators who have considered this issue.

Issue II Monitoring of Ice Conditions

The conclusion remains that was stated in Weller et al. (1979). Monitoring ice conditions around structures is important for safety in operations, and the data will be useful for design of structures in the future.

Issue XII Lease Duration

Ten-year lease terms favored by Weller et al. (1979) should be retained. Oil fields should be developed slowly to allow the introduction of new technology and new information regarding environmental hazards.

"Issue XIV" All-year Transportation Capability

This additional issue was raised for the Sale 71 area, because large parts of the area are so distant from land and islands as to make the use of gravel causeways, successfully used in the 1979 sale area, impractical. For about four and a half months of the year, in fall and again in spring breakup, over-ice transport on thickened ice roads is not practicable with conventional wheeled or tracked vehicles. From about 1 October to near the end of December, thin ice, darkness, and ice movement can bring conventional transportation in the marine environment to a standstill. Thin ice prevents overice transport by most wheeled vehicles. Darkness limits flying by conventional helicopters to very short periods during the day. Furthermore, helicopters have a limited load capacity. It is believed that, during this period, ice motion in the Sale 71 lease area is extensive and that ridges are forming over the shoals in outer Harrison Bay.

During spring breakup, offshore transportation of men and heavy equipment again is hampered. From the end of May to mid-July, flooding of the sea-ice surface by rivers, and melting and breakup of the sea ice, restrict surface transport. Coastal fog near areas of open water and ice restricts helicopter support. Unfortunately, safe and reliable means to transport men and heavy equipment at these times in the marine environment have yet to be developed.

Thus, there is a total of four and a half months during the year when reliable offshore transportation is marginal. Support will be needed for oil spill cleanup operations or rig safety at this time.

Seasonal drilling restrictions have been suggested partially on the belief that the limitations on transportation by the environment are least in winter. There is no assurance however, that current seasonal restrictions will continue for the development and production phases.

Accordingly, there is a need for industry to increase its development and acquisition of offshore vehicles which will provide year-round, all-weather transportation for men and heavy equipment. These might include shallow-draft icebreakers, hovercraft, or all-weather helicopters. The capability should be demonstrated before development begins.

6.7 REFERENCES

Hopkins, D. M., and R. W. Hartz. 1978. Shoreline history of Chukchi and Beaufort Seas as an aid to predicting offshore permafrost conditions. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 12:503-575.

Osterkamp, T. E., and W. D. Harrison. 1980. Subsea permafrost: probing, thermal regime and data analysis. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 4:497-677.

Osterkamp, T. E., and M. W. Payne. 1981. Estimate of permafrost thickness from well logs in northern Alaska. Cold Regions Sci. Tech. (in press).

Reimnitz, E., and D. K. Maurer. 1978. Stamukhi shoals of the Arctic-some observations from the Beaufort Sea. USGS Open-File Rep. 77-666. 11 pp.

Reimnitz, E., L. J. Toimil, and P. W. Barnes. 1978. Arctic continental shelf morphology related to sea-ice zonation, Beaufort Sea, Alaska. Mar. Geol. 28:179-210.

Shapiro, L. H., and R. G. Barry, eds. 1978. The sea ice environment, pp. 3-55. In: Weller et al. (eds.), Interim Synthesis; Beaufort/Chukchi. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP. Boulder, Colo.

Shapiro, L. H., and R. C. Metzner. 1979. Historical references to ice conditions along the Beaufort Sea coast of Alaska. Geophysical Institute, Univ. Alaska Rep., Fairbanks UAG R-268. 56 pp.

Tucker, W. B., III, W. F. Weeks, A. Kovacs, and A. J. Gow. 1980. Nearshore ice motion at Prudhoe Bay, Alaska. pp. 261-272. In: R. S. Pritchard (ed.), Sea ice processes and models. Univ. Wash. Press. Seattle, Wash.

Weeks, W. F. 1978. Environmental hazards to offshore operations, pp. 335-348. In: Weller et al. (eds.), Interim Synthesis; Beaufort/Chukchi. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP. Boulder, Colo.

Weller, G. E., D. W. Norton, and T. M. Johnson (eds.). 1978. Interim Synthesis, Beaufort/Chukchi. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP. Boulder, Colo. 362 pp.

Weller, G. E., D. W. Norton, and T. M. Johnson (eds.). 1979. Environmental stipulations relating to OCSEAP development of the Beaufort Sea. NOAA-OCSEAP Arctic Project Bulletin, Spec. Bulletin #25, Fairbanks, Alaska.

SECTION II. INTERDISCIPLINARY PROCESS ANALYSES, IMPACT PREDICTION, AND ISSUE DECISIONS

Chapter 7. Gravel Sources and Management Options

D. M. Hopkins, Editor

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7.1 INTRODUCTION

The broad expanse of the Sale 71 area, extending far beyond the limits of shorefast ice, contrasts sharply with the Joint Lease Sale area (JLSA), most of which is accessible in winter over reasonably stable shorefast ice. Furthermore, whereas much of the JLSA can be safely explored from offshore islands, such islands are virtually absent in the Sale 71 area.

The nature and distribution of sand and gravel resources is different in the Sale 71 area from those in the JLSA. Exploration and development in the Sale 71 area may require movement of considerable quantities of sand and gravel fill for long distances. Thus, as exploration extends beyond the fast-ice limit in the Sale 71 area, obtaining necessary sand and gravel will probably result in a great deal more water traffic during the open season and also the use of icebreakers to extend the navigation season.

Most of the coast adjoining the Sale 71 area is much more open and exposed to wave erosion than that adjoining the JLSA, and coastal bluffs adjoining the Sale 71 area are composed of much more erodible material. As a result, most of the coast adjoining the Sale 71 area is eroding at rates several times that typical of the coast of the JLSA. This poses problems for the development and maintenance of docks, pipeline landfalls, and onshore logistic bases.

7.2 ANTICIPATED REQUIREMENTS

The importance of stable structures utilizing sand and gravel fill during offshore exploration and development was discussed by Weller et al. (1978). A requirement for 7-14 exploration platforms and 4-18 production platforms is anticipated within the Sale 71 area (Memorandum of Oct. 17, 1980, Director, U.S. Geological Survey to Director, U.S. Bureau of Land Management). Some sand and gravel fill used in exploration islands will probably be recycled for use in production islands. Platforms in water less than 5 or 6 m deep are likely to consist of artificial islands defended by sandbags or other coarse armoring material but otherwise unconstrained. Farther seaward, but within depths less than 30 m, artificial islands confined by concrete caissons are likely, especially during the earlier years of exploration and development. As exploration progresses, we anticipate that movable monocones as described by Jahns (1979) will be used in water deeper than 10 or 15 m. Ultimate sand and gravel requirements for offshore structures in the Sale 71 area will probably be between 1 and 10×10^6 m^3.

The greater distance from Prudhoe Bay may call for a new logistic base on the shore adjoining the Sale 71 area. A currently proposed causeway-dock that would extend the natural spit at Oliktok Point might serve the Sale 71 area as well as the nearby onland production areas for which the pier is intended. The proposed causeway-dock might also be used as a pipeline landfall if production begins in the Sale 71 area. Other likely sites for a new logistic base are promontories near deep water such as that of Camp Lonely, where a DEW-line Site and the logistic base for exploration of the National Petroleum Reserve of Alaska are already situated. A new logistic base would create a continuing and great need for gravel for storage pads as well as for maintenance of the landing dock. Total requirements would probably be about 1×10^6 m^3.

7.3 SOURCES OF SAND AND GRAVEL - ISSUES VI AND VII

Onshore Resources

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 Kogru River, but most of the region north of the Kogru Peninsula and Teshekpuk Lake is devoid of useful concentrations of sand and gravel (Fig. 7.3.1).

With respect to Issue VI of Bulletin 25, restrictions on barrow 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 onland gravel deposits adjoining the JLSA. West of the Colville River, almost unlimited quantities of frozen dune sand stabilized by turf or a thin cover of peat underlie the mainland south of the Kogru River and Teshekpuk Lake.

Immediately north of the belt of stabilized dune sand is a belt 25-35 km wide of marine silty fine sand which extends westward from Kogru River through Teshekpuk Lake. The sandy gravel is frozen and is overlain by peat, silt, and fine sand generally less than 3 m thick. These small bodies each contain about 100,000 m^3 of coarse fill material.

Small amounts of coarse fill can be obtained from small bodies of sandy gravel and pebbly sand (about 1.0×10^5 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 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-like 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. There are no other sources of material useful in construction of piers and offshore islands in this 30-km-wide belt of the arctic coastal plain north of Teshekpuk Lake and west of Harrison Bay.

The beaches along the coast of Beaufort Sea are narrow and thin and contain only small quantities of sand and gravel. Those adjoining the Sale 71 area are especially narrow and thin; in most places, they contain negligible quantities of coarse material. The DEW-line logistic base at Camp Lonely have already fully utilized the fairly large but still limited amount of sand and gravel from in the beaches there, and lack of a nearby source of additional coarse fill limits expansion of the site.

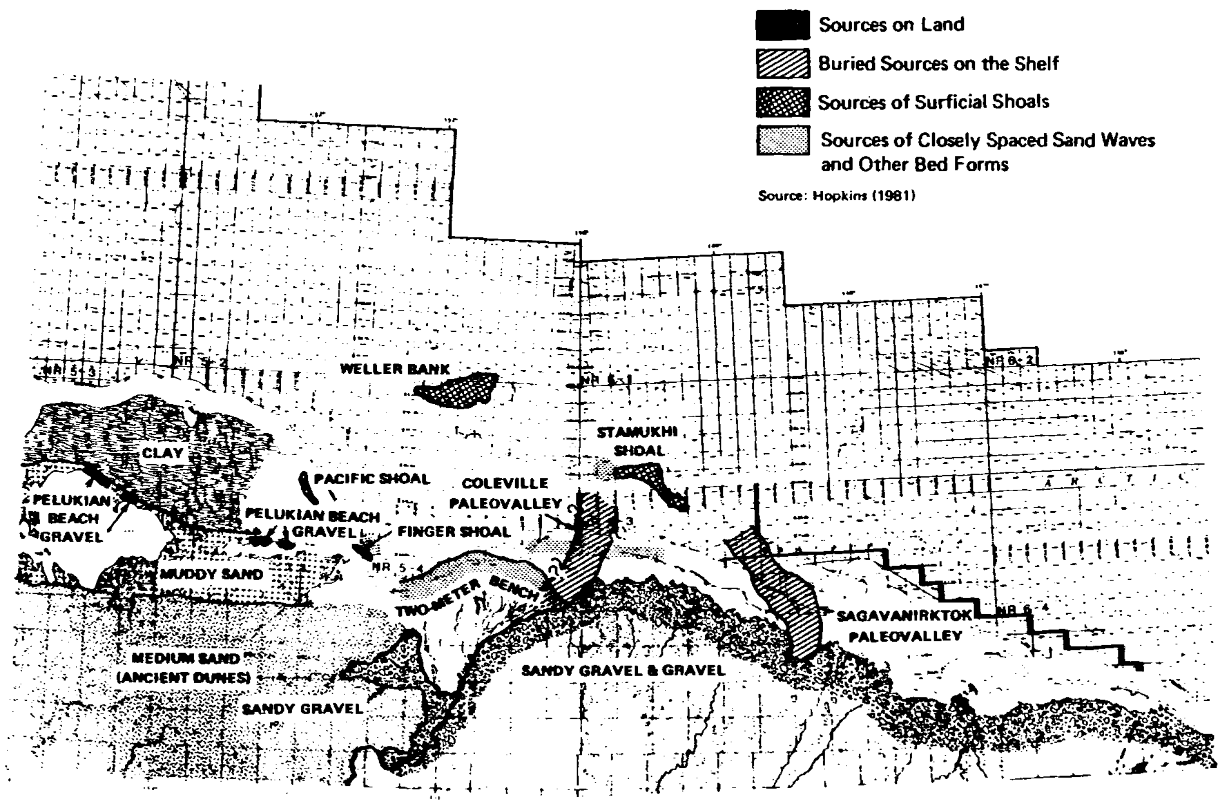

Figure 7.3.1. Sources of fill in and near the Sale 71 area.

Shelf Paleovalleys

Although several paleovalleys are believed to be present in the JLSA (Hopkins 1979), only the Sagavanirktok Paleovalley has been well delineated by offshore drilling (Smith et al., 1980)). The Sagavanirktok Paleovalley begins in Prudhoe Bay and turns northwestward to pass between the West Dock and Reindeer Island; it 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. Proprietary drilling and OCSEAP permafrost drilling by 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 very likely marks the western margin of the Colville Paleovalley.

Surficial Sources on the Inner Shelf

In Harrison Bay and elsewhere in the Sale 71 area, there are several potential sites for sand and gravel mining on the surface of the seabed. Most of these bodies are present because hydraulic forces are focused at these locations.

Pacific Shoal (Fig. 7.3.1) 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 sand. A well-defined shoal between Thetis and Spy Islands contains about 10,000 m^3 of clean gravel.

Active sand ridges, 1 or 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 (Fig. 7.3.1). Studies by Barnes and Reimnitz (1979) and Reimnitz et al. (1980) indicate that 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 here.

Shoals in the Stamukhi Zone

On the outer part of the Sale 71 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 surrounding 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, 1981). 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 (Rearic and Barnes, 1980; Reimnitz et al., 1977, 1978; and Reimnitz and Kempema, 1981). Because of this, Stamukhi Shoal should not be mined or reduced in any dimension; on the other hand, we are unaware of any objection to adding fill to build Stamukhi Shoal above sea level. The sand apron to the southwest possibly could be reshaped without adversely affecting ice dynamics, but the sand should not be removed from the area until a better understanding of the interaction of grounded ice and shoal sediments has been gained.

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. A cross section of a reshaped Weller Bank (Fig. 7.3.2) with a hypothetical dredged production island on top was prepared to show relative sizes (Barnes and Reiss, 1981). It appears to be safe to reshape Weller Bank, but export of the sand and gravel to some other part of the Sale 71 area would severely disrupt the ice zonation and probably would adversely affect the extent and stability of shorefast ice.

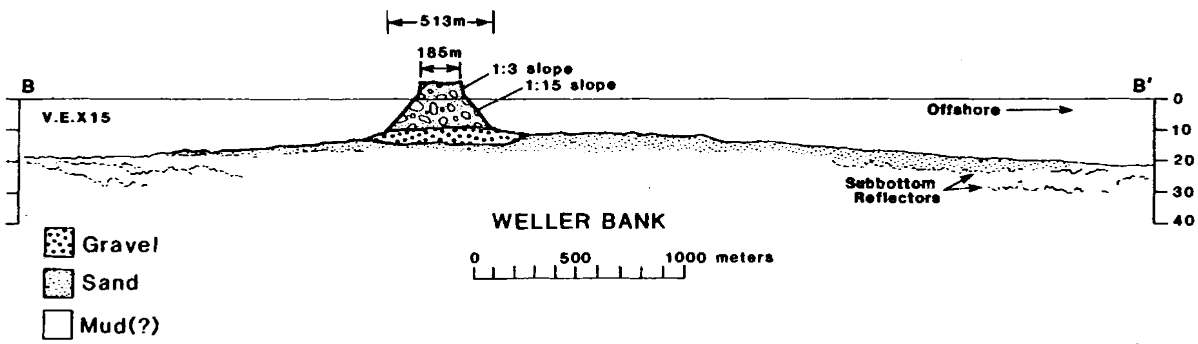

Figure 7.3.2. Hypothetical dredged production island sited on Weller Bank. The dimensions and slopes of the island are according to industry designs for this type of island, drawn at a vertical exaggeration of 15 x. Sub-bottom traces are from 7 KHz seismic records. Thickness and extent of gravel and of sand at Weller Bank are estimated from surface samples.

7.4 CONSEQUENCES OF GRAVEL MINING

Onshore and Beach Areas

The consequences of, and constraints upon, gravel mining from onshore and beach areas adjoining the Sale 71 area are similar to those outlined for JLSA (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 their value as nesting habitat. The immediate coastal area should be avoided because of the concentration of historic and prehistoric occupation and burial sites there. Quarrying of sand and gravel from beaches will accelerate the already exceptionally rapid rates of coastal erosion.

Quarrying of sand and development of roads to sand quarries in the large area of stabilized dunes on eastern NPRA 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.

Offshore Dredging

Earlier discussion of the consequences of dredging in the JLSA focused upon the disturbance of the bottom, potential burial of benthic organisms by siltation, and increases in turbidity with possible attendant clogging of gills of filter feeders. All of these disturbances seem comparable in intensity and effects upon the biota as such natural disturbances as 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). Not considered in earlier discussions is a possible darkening of the ice canopy due to incorporation of suspended material during freeze-up; the effects here seem comparable to those induced during some years by incorporation of sediment in the ice canopy as a result of resuspension of bottom sediments during late autumn storms. Not considered previously is the possibility of entrainment by suction dredges of anadromous fish migrating through a borrow zone. At least one such incident is believed to have taken place during dredging along the Canadian Beaufort coast.

Removal of fill from the bottom in certain areas can significantly affect the stability and permanence of offshore islands. As noted above, removal of sand waves off Pingok Island would result in accelerated erosion and rapid destruction of the island. Most of the other offshore islands are migrating landward at about 10 m per year. Development of a submerged borrow pit in the lee of one of these islands would 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 are likely to 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 group, as many as 10,000 flightless Oldsquaws may concentrate behind Thetis Island during the mid-July to mid-August molting period.

As we noted above, the shoals on the outer shelf control the position of the stamukhi zone. Removal of sand and gravel from 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.

Probably the most significant consequence of construction of artificial islands in the Sale 71 area will be greatly increased water traffic. Fill probably cannot be trucked in over the ice to the outer part of the area, and fill will almost certainly have to be carried to artificial island sites by barge, either from stockpiles on the beach or from submerged dredge pits. The problem is intensified by the scarcity of borrow sites in all except the easternmost part of the Sale 71 area. An increase in vessel traffic in the area will be attended by a higher probability of collisions and accidents and consequent pollution. Industry will probably press for lengthening the barging season through the use of icebreakers during early summer and late autumn; if so, ice hazards to water traffic will increase, and water traffic will be active during seasons that currently are relatively quiet.

Some interaction between whale movements and dredging, barging, and dumping of fill must be anticipated. During the spring bowhead migration, the whales migrate along the outer shelf beyond the area of anticipated activity. The September back-migration is more dispersed, and whales can appear anywhere on the shelf, but movement is concentrated between the 18-m and 35-m isobaths. Operations in this depth range should be avoided in September. In the Mackenzie Bight of northwestern Canada, whale movements are monitored by aircraft, and operations are simply shut down temporarily when interference with whale movements seems likely (D. Stone, pers. comm.).

The one or more large suction dredges that will probably be used to provide fill for artificial islands will need a deep and sheltered anchorage protected from moving ice. If dredges are sheltered in the lee of barrier islands, care must be taken to avoid creating sea-bottom depressions that can damage the islands.

7.5 ARTIFICIAL DOCKS AND CAUSEWAYS

With respect to Issue VII, restrictions on artificial islands and causeways, the possible consequences of and constraints upon construction of gravel-fill docks and artificial causeways in the Sale 71 area are similar to those discussed for the JLSA (Weller et al., 1978). The earlier statement that "it may be necessary to accumulate observations on natural circulation for about 2 years before designing causeways" (Weller et al., 1978, pp. 330-331) seems unnecessarily conservative.

7.6 REFERENCES

Barnes, P. W., and E. Reimnitz. 1979. Ice gouge obliteration and sediment redistribution event; 1977-1978, Beaufort Sea, Alaska. U.S. Geol. Sur. Open-File Rep. 79-848, 22 pp.

Barnes, P. W., E. Reimnitz, and C. R. Ross. 1980. Nearshore surficial sediment textures - Beaufort Sea, Alaska. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Quart. Rep. 2:132-170.

Barnes, P. W., E. Reimnitz, L. J. Toimil, D. M. McDowel, and D. K. Maurer. 1979. Vibracores, Beaufort Sea, Alaska: Descriptions and preliminary interpretation. U.S. Geol. Sur. Open-File Rep. 79-351, 103 pp.

Barnes, P. W., and T. Reiss. 1981. Geological comparison of two arctic shoals. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. (in press).

Hopkins, D. M. 1979. Offshore permafrost studies, Beaufort Sea. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 16:396-518.

Jahns, H. O. 1979. Overview of design procedure. In: Technical seminar on Alaskan Beaufort Sea gravel island design. Exxon Production Research Co., Houston, Tex.

Rearic, D. M., and P. W. Barnes. 1980. Reassessment of ice gouging the inner shelf of the Beaufort Sea, Alaska - A progress report. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 4:318-332.

Reimnitz, E., and E. W. Kempema. 1981. Pack ice interaction with Stamukhi Shoal, Beaufort Sea, Alaska. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. (in press).

Reimnitz, E., E. W. Kempema, C. R. Ross, and P. W. Minkler. 1980. Overconsolidated surficial deposits on the Beaufort Shelf. U.S. Geol. Sur. Open-File Rep. 80-2010, 37 pp.

Reimnitz, E., and D. K. Maurer. 1978. Stamukhi shoals of the Arctic - some observations from the Beaufort Sea. U.S. Geol. Sur. Open-File Rep. 78-666, 17 pp.

Reimnitz, E., and P. W. Minkler. 1981. Finger Shoal survey: An unusual field of bedforms in Harrison Bay. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. (in press).

Reimnitz, E., L. J. Toimil, and P. W. Barnes. 1977. Stamukhi zone processes: Implications for developing the arctic offshore area. Offshore Tech. Conference, Houston, Tex., May 2-5, 1977, OTC Proc. 3:513-528.

Reimnitz, E., L. J. Toimil, and P. W. Barnes. 1978. Arctic continental shelf morphology related to sea-ice zonation, Beaufort Sea, Alaska. Mar. Geol. 28:179-210.

Smith, P. A., R. W. Hartz, and D. M. Hopkins. 1980. Offshore permafrost studies and shoreline history as an aid to predicting offshore permafrost conditions. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 4:159-255.

Weller, G., D. W. Norton, and T. Johnson (eds.). 1978. Interim Synthesis Report: Beaufort/Chukchi. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP, Boulder, Colo.

Williams, J. R., W. E. Yeend, L. D. Carter, and T. D. Hamilton. 1977. Preliminary surficial deposit map of National Petroleum Reserve Alaska. U.S. Geol. Sur. Open-File Rep. 77-868.

APPENDIX A

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APPENDIX A

QUASI-OPEN-WATER SPILL MOVEMENT PREDICTIONS
By J. C. Mungall

The prediction of oil spill tracks is performed in two steps. The first step is the calculation of current tables, either one or two for each of 16 evenly distributed wind directions. The second step is to access these tables on the basis of an appropriate wind speed and direction record (either real or statistically generated).

The following discussion starts with a description of the current-prediction process and results and continues with a brief description of the tracking program, along with some generalizations. Finally, some sample plots and results will be presented.

Current Modeling

Depth-mean currents were predicted for the Harrison Bay/Prudhoe Bay region using a 60 x 26 grid of 3.7 x 3.7 km units. The grid was later extended to cover the entire lease area. Runs were typically made for 24 hours of real time, by which time the currents had nearly settled down to their steady-state values, a consequence of the shallow, wind-driven nature of the region. Verification of the currents, to be discussed below, was accomplished through comparison between measured and predicted progressive vector diagrams for currents at a fixed point. In addition to currents, sea-level changes were also computed, these values being of interest in the estimation of shoreline inundation. A brief summary of the results is included in the two following sections, since they may be of use in the estimation of oil-spill scenarios to cover cases other than those presented in this chapter.

Sea-Level Changes

Changes in sea level along the coast are often associated with storms. Should a spill reach the shore during a storm, a surface slick could be deposited on surfaces above or below the normal coastline, i.e., on low-lying salt marshes or on shallow mudflats. Typical values of the sea level change to be expected are listed in Table A.1 and shown in Figure A.1, for 15- and 30-knot winds that have been blowing steadily for 24 hours. The results are relative to a zero sea level occurring along a line parallel to the shore and some 80 km from it. Note that the model has not been verified for elevations, only for currents.

As can be seen in Fig. A.1, the setup/setdown is a nonlinear function of wind speed. Maximum values are ± 0.18 m and ± 0.66 m for 15- and 30-knot winds, respectively. Maximum setup and setdown occur respectively for winds from 337°/360° and 157°/180° true. Using the values in Table A.1, interpolated as necessary, the degree of inundation or recession can be estimated from topographic maps.

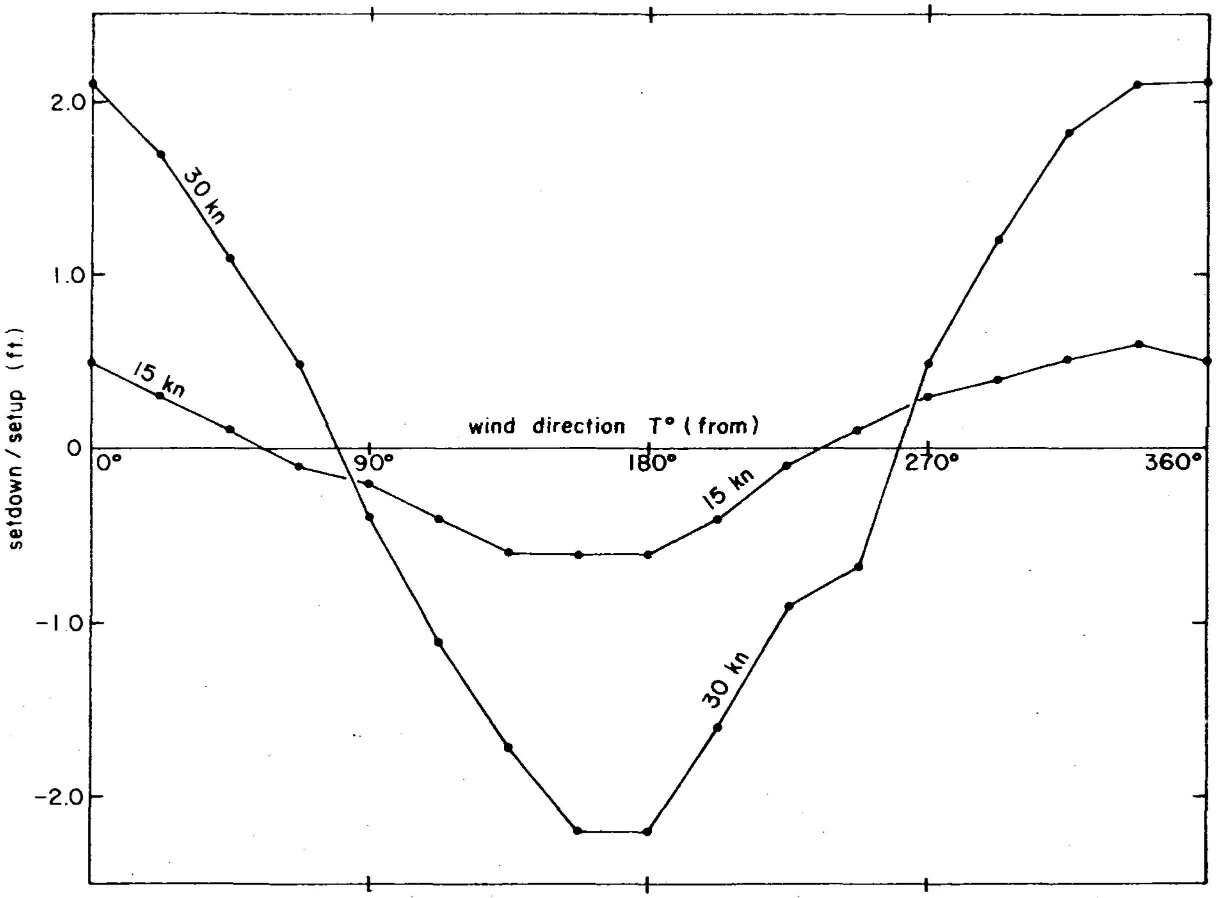


Figure A.1. Southern Harrison Bay setdown/setup resulting from steady winds of 24 h duration.

Currents

Also listed in Table A.1 are typical currents associated with a steady 15-or 30-knot wind that has been blowing for 24 hours. The location chosen is in central Harrison Bay (70°36'N, 151°19'W). The results are shown in Fig. A.2. As can be seen, the currents have values ranging between 0.03 and 0.12 m/s for 15-knot winds, and 0.09 and 0.27 m/s for 30-knot winds. The currents, for the most part, tend to be parallel to the coast, with little difference between current directions for 15 and 30 knots. As will be seen, there will be little or no tendency for pollutants within the water column to be transported toward the shores opposite the lease area.

Slick movement is not included in the above. Typically, this is computed by adding to the above vectors a second vector equal to some 3 percent of the wind speed in the direction of the wind.

Table A.1. Steady 24-hour wind results: Setup/setdown in southern Harrison Bay (70°26'N, 151°28'W), current speed and direction in central Harrison Bay (70°36'N, 151°19'W).

	15 knots			30 knots				
Wind Direction (°T)	Setup (ft)	Speed (ft/s)	Direction (°T)	Setup (ft)	Speed (ft/s)	Direction (°T)	Speed Ratio	Direction Difference
000	0.5	0.3	104	2.1	0.6	101	2.0	-3
022	0.3	0.1	068	1.7	0.4	060	4.0	-8
045	0.1	0.2	319	1.1	0.6	313	3.0	-6
067	-0.1	0.3	302	0.5	0.8	298	2.7	-4
090	-0.2	0.4	298	-0.4	0.9	293	2.25	-5
112	-0.4	0.4	295	-1.1	0.9	291	2.25	-4
135	-0.6	0.4	293	-1.7	0.9	289	2.25	-4
157	-0.6	0.3	290	-2.2	0.8	287	2.7	-3
180	-0.6	0.2	282	-2.2	0.6	282	3.0	0
202	-0.4	0.1	242	-1.6	0.3	245	3.0	3
225	-0.1	0.2	136	-0.9	0.5	132	2.5	-4
247	0.1	0.3	118	-0.7	0.7	118	2.3	0
270	0.3	0.4	114	0.5	0.9	114	2.25	0
292	0.4	0.4	111	1.2	0.9	112	2.25	1
315	0.5	0.4	109	1.8	0.9	109	2.25	0
337	0.6	0.3	107	2.1	0.8	106	2.7	-1
							$\bar{x}$ = 2.59	$\bar{x}$ = -2.37
							σ = 0.49	σ = 2.92

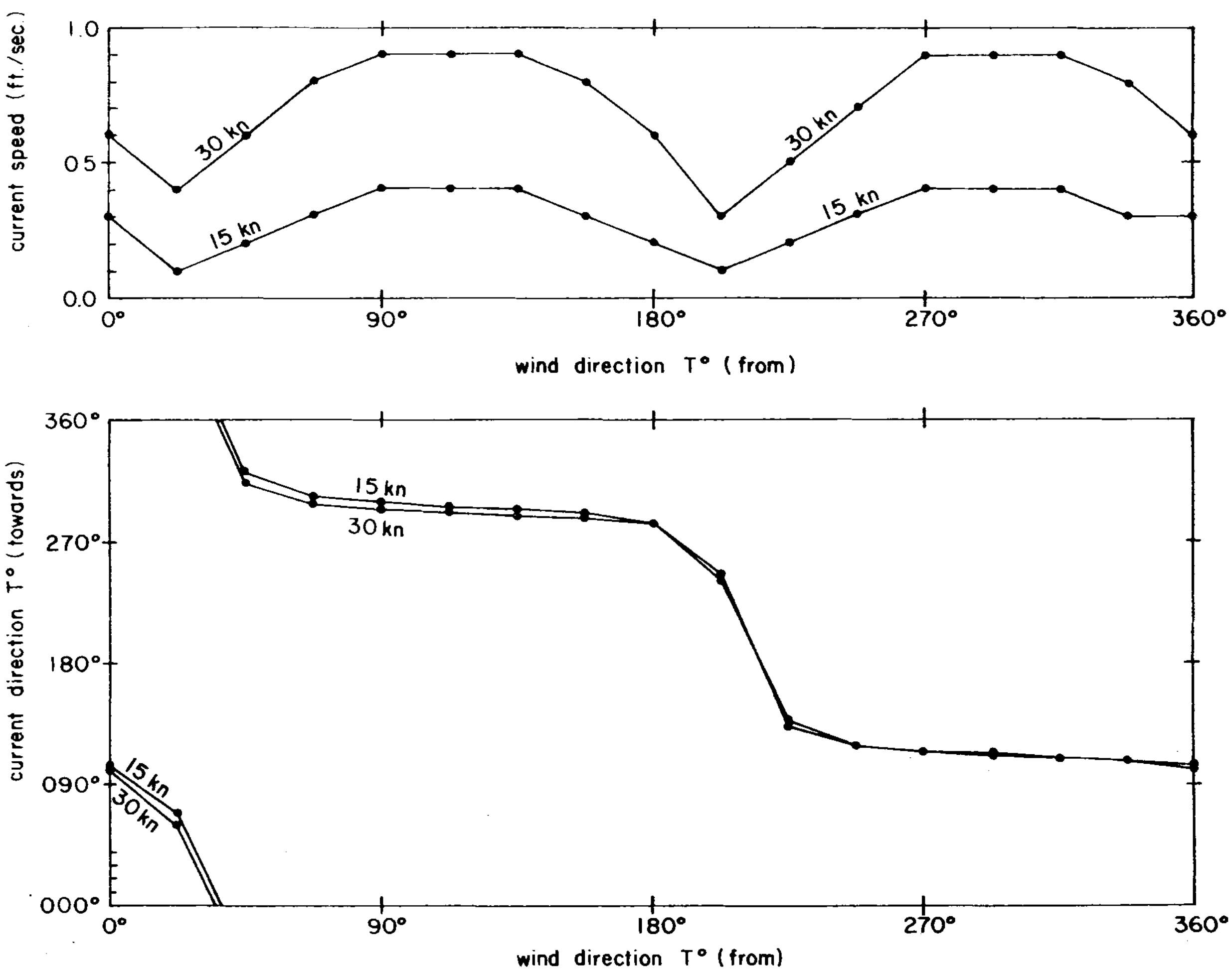


Figure A.2. Central Harrison Bay currents and directions resulting from steady winds of 24 h duration.

Trajectory Modeling

As mentioned above, real or statistically generated winds are provided to the trajectory model along with a set of current maps. A random start time within the record of 3-hourly winds is selected, and the first speed and direction are read. The nearest of the 16 sectors is then selected, and an interpolation or extrapolation is performed to obtain an estimate of the depth-mean current. To this value can, optionally, be added a wind-induced surface slick component. The spill is then moved, using the above values subject to the geometry of the region. Implicit in this approach is the assumption of negligible response time (3 hours or less) of the water column. The next wind record is then read, and the process is repeated until the particle reaches the shore or leaves the modeled region. A fresh random start time is then computed and the procedure is repeated a sufficient number of times so that a reasonable estimate of spill track distributions and shoreline hit distributions can be obtained.

Model Applicability

Of obvious concern is the general applicability of both the models--current prediction and trajectory prediction--to the problem. In open-water situations the models are limited only by tuning (selection of friction coefficient for the current model, selection of wind-drift factor and turning angle for the trajectory model). In midwinter, with full ice coverage, neither model is suitable, or in fact necessary, if one is concerned only with oil that does not go into solution.

When the pack ice edge has receded offshore for some kilometers, leaving an open extent of water, the problem can be fairly easily handled in the USGS Water Resources Division model. The ice edge is merely treated as another shore line, and a summary can be produced of the frequency with which spills produced by the trajectory model encounter each segment of this artificial shore. Grounded ice can similarly be treated, using data from satellite photos (W. Stringer) or from direct observations (P. Barnes, E. Reimnitz).

More difficult to handle is ice scattered throughout the "open"-water region. Intuitively one suspects that the open-water method may hold up to an ice concentration of, say, three- or four-tenths. Beyond this, an ice aggregation model may have to be used. Of particular interest, both practical and academic, is the subject of oil or ice movement caused by direct wind action.

Model Verification

Confidence in the overall capability of the pair of models realistically to simulate spill tracks must be estimated through verification. For the models described above, this has been achieved through comparison of progressive vector diagrams derived from current meters moored in Harrison Bay and simulated progressive vector diagrams as computed from depth-mean currents for fixed points using the trajectory model. When this was done for two current meter records, one off Atigaru Point and the other off Thetis Island, the measured and computed excursions of the progressive vector plots for two weeks of motion agreed to within 30 percent. When one considers that particle movement is accomplished by assuming that the depth-mean currents respond instantly to the wind, the agreement is impressive, and is a result of the quick response time of the water to changes in wind conditions. However, the predictions of sea level elevation by the model has not been verified.

Trajectory Results

In the computations described here, three real wind years have been used. These winds (T. Kozo, pers. comm.) are for quasi-open water periods in 1977, 1978, and 1980. A description of the winds is given in Table A.2. The approach of using real winds instead of statistically generated winds was chosen as being best suited for the scenarios on account of the need for each discipline to see visual summaries of the consequences of various wind types.

Table A.2. Wind Classification

Year	Start Date	Number of Hours	Location	Wind-Type
1977	July 24	765	Cottle Is.	Strong ENE winds: 1 week negative surge, 90% steadiness factor.
1978	July 21	1,008	Cottle Is.	Typical Easterly winds: typical average wind data for month of August (compared to 20 yr. wind average).
1980	August 1	1,308	Tolaktuvut	Strong Westerly winds: persistence in westerly direction (~ 70%) was high from August 15 to September 10.

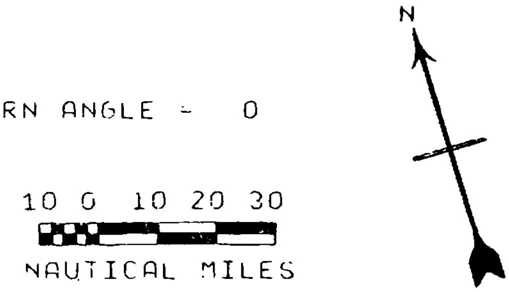
Trajectory simulations are presented for each of the three wind types. For each wind type, two computations are shown: trajectories computed under the assumption that the spill travels entirely within the water column, at a rate dictated by the depth-mean current, and trajectories that include, in addition, surface slick movement. It is felt that various disciplines may require one or the other type of information.

Since the actual tracks taken by spills will depend on the initial position of the spill, it is impractical here to cover many cases. Instead, examples will be shown for a spill originating in quasi-open water at a site some 8 km off Milne Point, at 70°39'N, 149°15'W. Six plots are shown, with 25 randomly started spills in each plot tracked for a maximum of one month.

Figures A.3, A.4, and A.5 show, respectively, simulated spills occurring at random times in the open-water months of 1977, 1978, and 1980. No surface slick movement effects have been included: the spill is assumed to move with the depth-mean current, which, following Fig. A.2, tends to be parallel to the coast. The three figures reflect the wind tendencies during the three years: easterly, typical (predominantly from the east), and westerly. Of particular interest is Fig. A.4, for typical winds. The figure shows that under those circumstances, spill transported by the water column alone will typically affect a region offshore between 18 km to the east and 93 km to the west.

Figures A.6, A.7, and A.8 again show, respectively, simulated spills occurring at random times in the open-water months of 1977, 1978, and 1980. An additional surface slick vector has been added equal to 0.03 times the wind-speed vector. Figures A.6, A.7, and A.8 have been computed assuming that the spills will stop once they reach the shore. A numerical summary is given in Table A.3, with the transit times referring to the time between the spill release and the contact with the shore.

WIND-DRIFT FACTOR = 0 X E-3, TURN ANGLE = 0



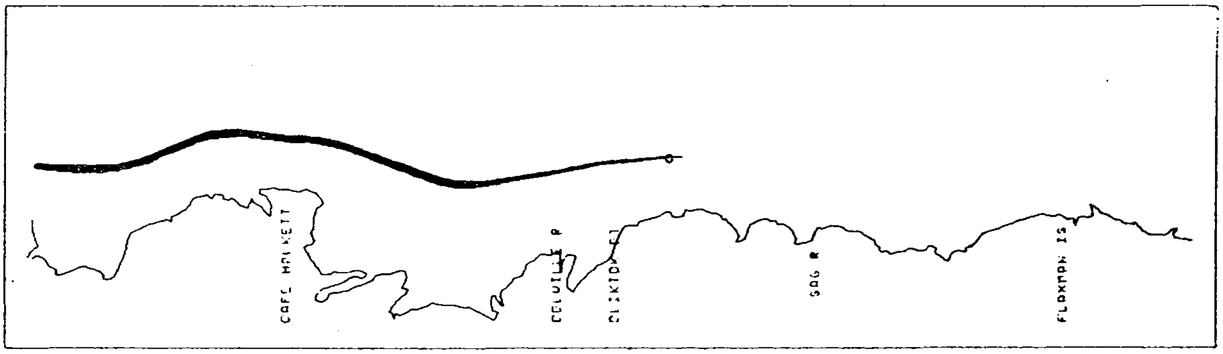


Figure A.3. Trajectories of simulated oil spills occurring at random times in the open-water months 1977.

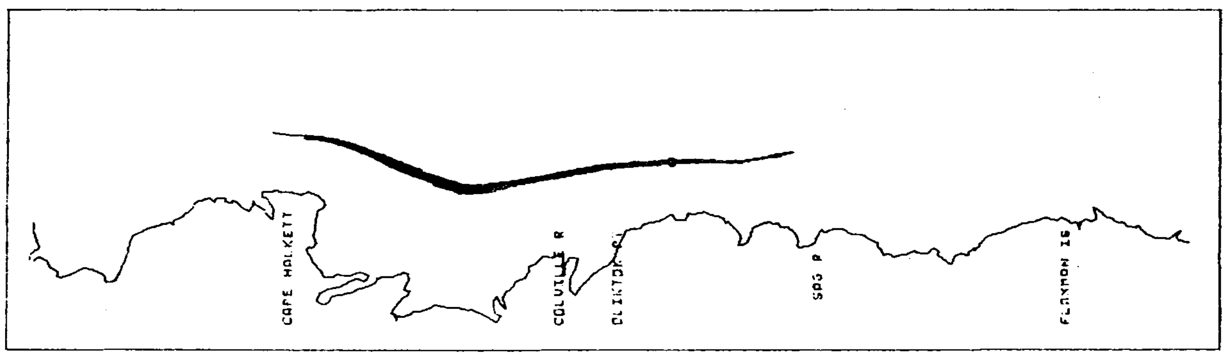


Figure A.4. Trajectories of simulated oil spills occurring at random times in the open-water months 1978.

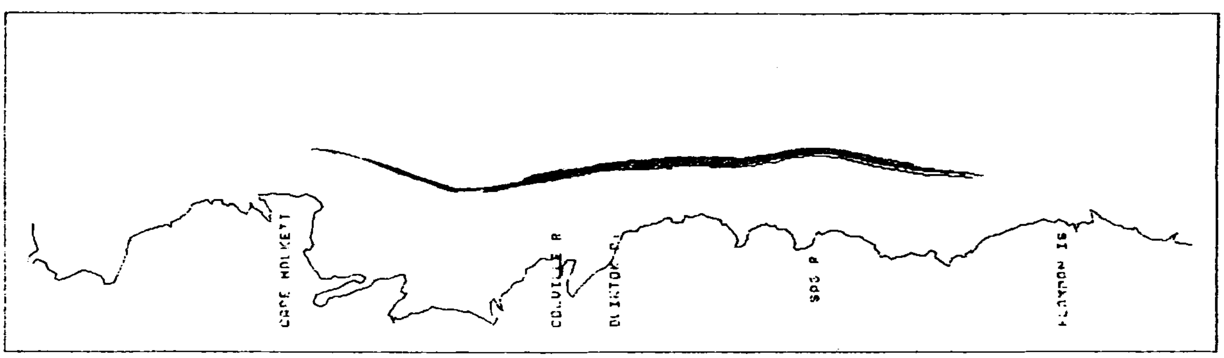


Figure A.5. Trajectories of simulated oil spills occurring at random times in the open-water months 1980.

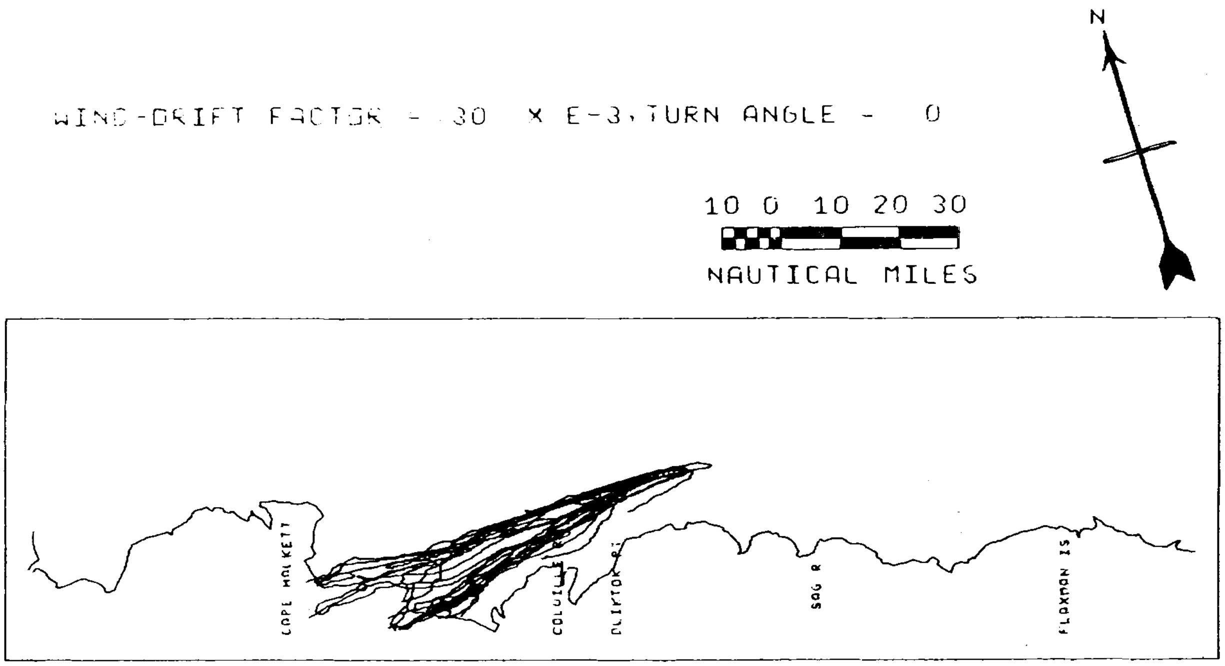


Figure A.6. Trajectories, with a surface slick vector of 0.03 times the wind-speed vector, of simulated oil spills occurring at random times in the open-water months 1977.

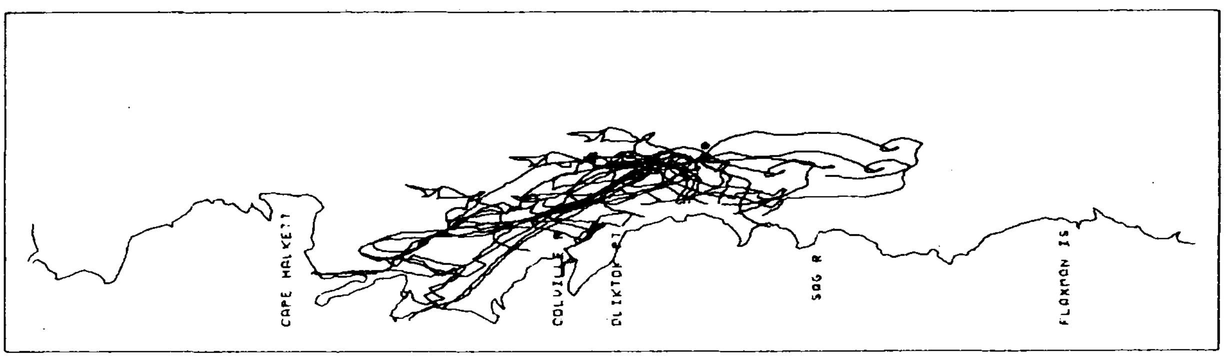


Figure A.7. Trajectories, with a surface slick vector of 0.03 times the wind-speed vector, of simulated oil spills occurring at random times in the open-water months 1978.

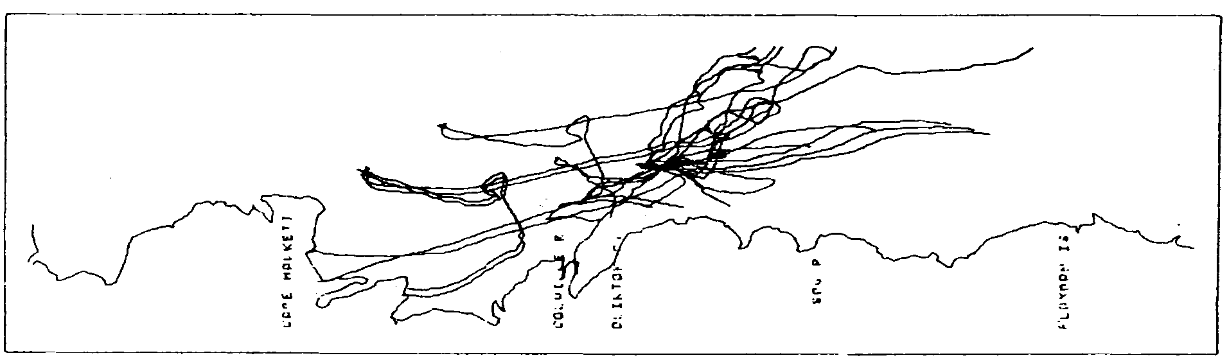


Figure A.8. Trajectories, with a surface slick vector of 0.03 times the wind-speed vector, of simulated oil spills occurring at random times in the open-water months 1980.

Table A.3. Milne Point Slick Movement Summary*

Year:	1977	1978	1980
Wind type:	Easterly storms	Typical ENE prevailing	Westerly storms
No. reaching north boundary	0	0	3
No. reaching east boundary	0	0	3
No. reaching west boundary	0	0	0
No. reaching shore or islands	25	25	19
Transit time (mean, days)	7.6	12.5	7.0
Transit time (standard deviation)	1.9	6.9	6.1

* Position: 70°39'N, 149°15'W

For the most part, the figures are self-explanatory. Strong easterly winds will cause the central and western parts of Harrison Bay to be impacted, typical winds will extend the previous impact region eastwards to the Sagavanirktok River region, and a year with a trend of offshore westerly winds will cover a region extending from Harrison Bay to the middle of Simpson Lagoon, with perhaps 25 percent of the spills going northeast toward the pack ice. Transit times (based only on 25 spills in each case) have, for the three wind conditions, means and standard deviations as shown in Table A.3.

When detailed statistics are required, a single wind record is used. For this study, the single record was obtained by concatenating the wind records for 1977, 1978, and 1980, taking one length of the 1977 wind record, five lengths of the 1978 record, and one length of the 1980 wind record. This was done so as to conform with information from T. Kozo (pers. comm.) that, based on a 20-year average, the three seasonal types of wind tend to occur, respectively, one year in 10, 7 years in 10, and 2 years in 10. When 100 spills are run using this concatenated wind field along with a wind drift factor of 0.03, the mean and standard deviations for the transit times came to 5.6 and 3.7 days, respectively, with 7 percent of the spills reaching the pack ice toward the northeast. For risk analysis, 100 spills from each of 45 possible locations have been computed.

APPENDIX B

ICE PROPERTIES

by W. F. Weeks

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ICE PROPERTIES
By W. F. Weeks

This section was prepared as a working draft for the Production Task Group of the National Petroleum Council's Committee on Arctic Oil and Gas Resources. (This material has not been considered by the National Petroleum Council and is not to be construed as a report of that Council).

Sea-Ice Structure and Composition

The structure and composition of sea ice as they affect ice properties are reviewed by Weeks and Assur (1967, 1969) and Schwarz and Weeks (1977). Briefly stated, sea ice crystals are composed of sets of plates of pure ice that contain inclusions of brine and air trapped between the plates. Regions where the plates are parallel are considered to be single crystals. The typical spacing between plates (measured normal to their plane (in the so-called c-axis direction)) is 0.4-0.9 mm, whereas a representative crystal diameter is 1-2 cm. Although the upper few centimeters of undeformed ice may show a wide range of crystal sizes and orientations, by the time the ice is roughly 20 cm thick the crystals have become oriented with their c-axes horizontal. (This orients the plates of pure ice and the entrapped brine pockets vertically.) The crystal orientation of the ice usually remains unchanged (c-axis horizontal) throughout the rest of the ice sheet, but, as the ice thickens, there is commonly a gradual increase in grain size. To summarize, typical undeformed first-year ice is largely comprised of columnar crystals composed of ice, brine, and air. These crystals are elongated in the vertical (parallel to the direction of heat flow) and, on the average, they become slightly larger near the bottom of the ice sheet.

For many years it was believed that such sea ice crystals invariably showed c-axis orientations that were random in the horizontal plane. They could be described as transversely isotropic (as properties vary in the vertical direction but are equivalent in all directions in the horizontal plane are equivalent). However, recent studies (Weeks and Gow, 1978, 1980) have revealed that most of the fast ice occurring along the northern coast of Alaska shows strong preferred c-axis alignments in the horizontal direction. The alignments appear to be controlled by the current beneath the ice, and they result in a material that is orthotropic: it shows variations in properties along three orthogonal directions. Figure B.1 is a schematic drawing showing several different aspects of the structure of such first-year ice.

Associated with variations in the freezing velocity and in the composition of the seawater being frozen are variations in the amount of salt (brine) and air entrapped in the sea ice. The amount of entrapped salt generally decreases as the ice ages. Although the mechanism is not well understood, this brine drainage gradually changes the salt content (the so-called salinity) of the ice. A schematic drawing showing representative salinity profiles for different thicknesses of first-year sea ice is given in Fig. B.2.

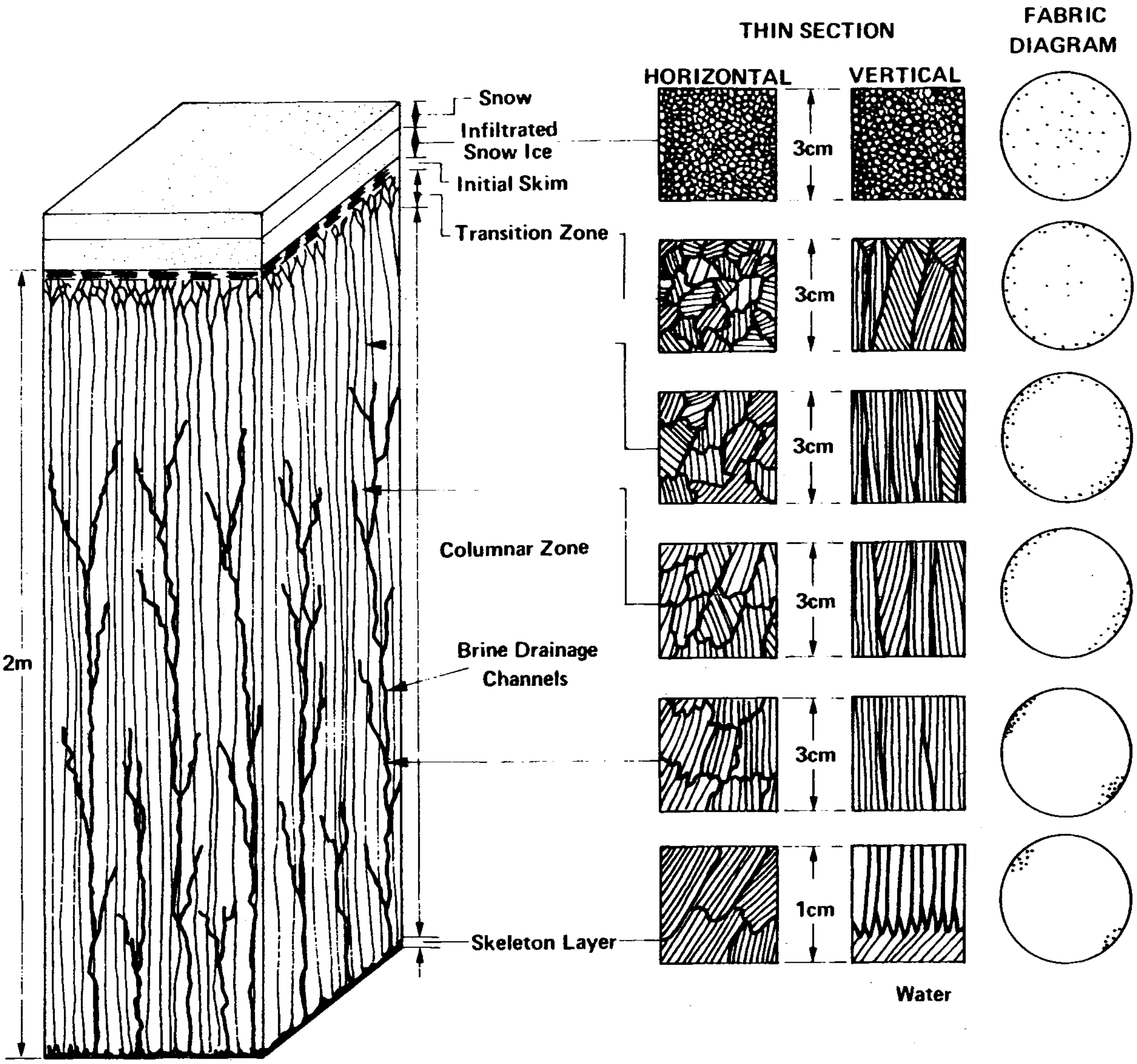

Figure B.1. Schematic drawing showing several aspects of the structure of first-year sea ice (Schwarz and Weeks, 1977).

The temperature of sea ice is variable, being largely controlled by the air temperature, the wind speed, and the snow cover. Though the relationship of these factors is complex, for many engineering purposes it is adequate to approximate the temperature distribution of sea ice by a straight line between the freezing temperature of sea water (-1.8°C) at the base of the ice sheet and the ice-surface temperature. During most of the winter the air temperature can be substituted as a conservative estimate for the sea-ice surface temperature (i.e., the air temperature is colder than the ice-surface temperature).

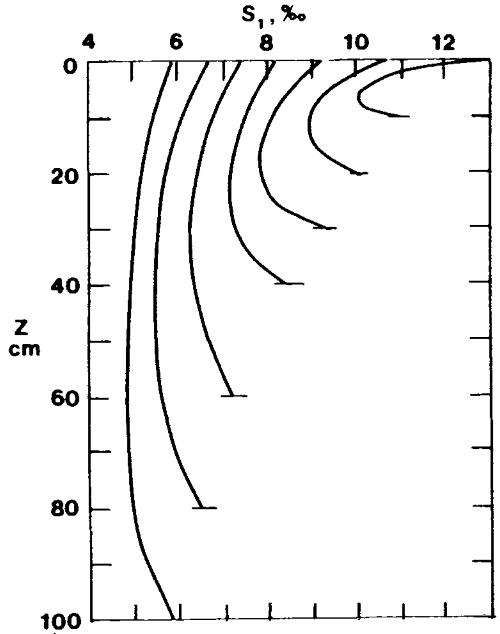

Figure B.2. Series of schematic salinity profiles for first-year ices of various thicknesses (Weeks and Assur, 1967).

The temperature and salinity of the ice are important because they control the quantity of liquid brine within the ice. Since the volume of brine increases rapidly as near-melting temperatures are reached, brine volumes are usually highest at the bottom of an ice sheet and lowest at the upper ice surface, with a nonlinear variation between. In addition, a variety of solid salts form in sea ice. The crystallization temperatures of the two most common salts are -8.7°C ($Na_2SO_4 \cdot 10H_2O$) and -22.7°C ($NaCl \cdot 2H_2O$). The effect of the presence of such solid salts on ice properties is not well understood.

The presence of liquid brine and air in sea ice greatly affects its physical properties. It is believed (Anderson and Weeks, 1958; Tabata, 1960), that the failure planes in each ice crystal largely coincide with the intercrystalline planes along which the brine and air are concentrated. This is reasonable because the fluid inclusions reduce the effective cross-sectional area of ice-to-ice bonding, causing such regions to be planes of weakness. Therefore, it is commonly assumed that the failure strength of sea ice in tension (σ_f) is given by

$$\frac{\sigma_f}{\sigma_o} = 1 - \Psi,$$

where Ψ is the plane porosity (the relative reduction in the area of the failure surface caused by the presence of the fluid inclusions) and σ_o is the so-called basic strength of sea ice (the strength of a hypothetical material containing no brine or air yet still retaining the sea-ice substructure). It is then necessary to express Ψ in terms of the geometry of the fluid inclusions. Details of these formulations were reviewed by Weeks and Assur (1967, 1969). The results suggest an equation of the general form

$$\frac{\sigma_f}{\sigma_o} = 1 - cv^k,$$

where c and k are constants whose values depend on how the geometry of the fluid inclusions change with v. In studies of strength variations, k is commonly found to equal ½ while in studies of variations in Young's modulus (E), k commonly has a value of 1. Figure B.3 (Schwarz and Weeks, 1977) is a useful and typical depiction of vertical variations in σ_f and E in 0.2-m-, 0.8-m-, and 3.0-m-thick arctic sea ice. The left portion of the figure shows the assumed temperature and salinity profiles while the right portion shows the corresponding (σ_f/σ_o) and (E/E_o) ratios. As can be seen, there are large property variations both within and between these three ice sheets. These variations do not include the added complication of a strong crystal alignment.

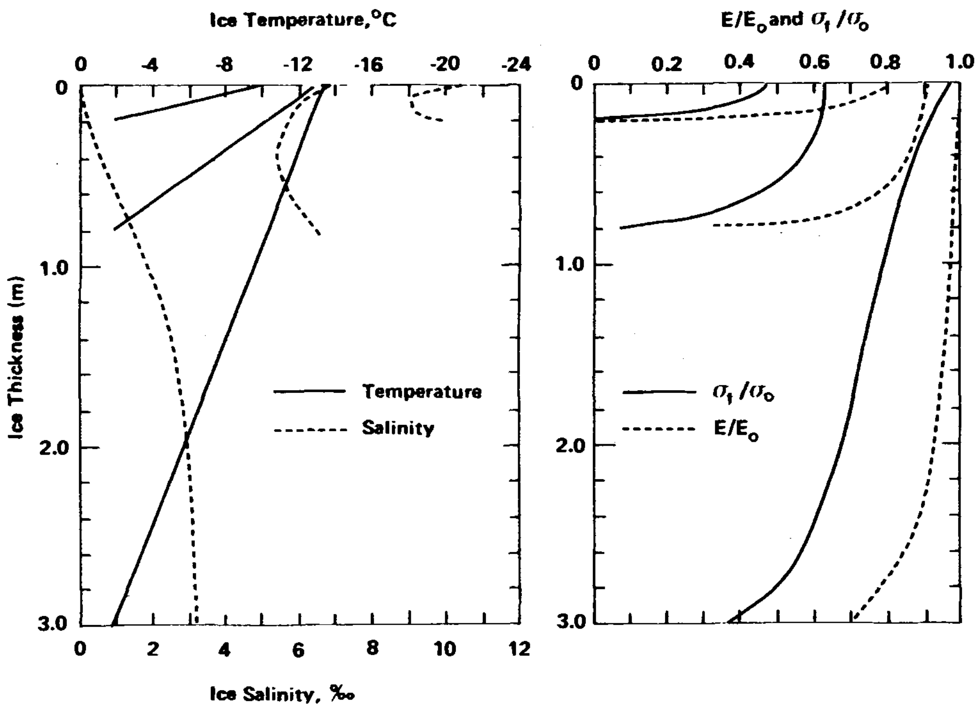

Figure B.3. Representative sea-ice temperature, salinity, E/E_o and σ_f/σ_o profiles for 0.2, 0.8, and 3.0 m thick Arctic ice on about 1 May (Schwarz and Weeks, 1977). To convert σ_f/σ_o to σ_f and E/E_o to E, multiply by 10.3×10^5 N/m^2 and by 10^{10}N/m^2 respectively based on the flexural strength determinations by Dykins (1971) and the elastic modulus measurements by Langleben and Pounder (1963).

When first-year sea ice is subjected to a period of summer melt, it undergoes a pronounced change in salinity. This is largely caused by the percolation of relatively fresh surface meltwater downward into the ice (Untersteiner, 1968). This flushing results in salinity profiles such as that given for the 3.0-m-thick ice in Fig. B.3. In the upper part of such ice floes, recrystallization, which would modify the internal structure of the ice, is possible. Ice that has survived a number of summers is composed of multiple layers of annual ice formed during successive winter periods of ice growth. Ultimately, multiyear ice reaches a thickness (~ 3-4 m) such that the thickness ablated during the summer equals the thickness grown during the winter (Maykut and Untersteiner, 1969). Although there are vast quantities of multiyear ice in the high Arctic, and multiyear ice probably composes the ice features setting the design loads for offshore structures, its properties have been insufficiently studied.

Frazil ice is formed when free-floating crystals of ice develop in the water column ahead of the normal sea-ice/seawater interface. These crystals then float upward and either congeal directly to form an ice sheet or attach themselves to the bottom of an existing ice sheet. The resulting layers of fine-grained crystals have random crystal orientations. There is little information on the properties of such ice. Until recently, frazil ice in the sea has been considered of rare occurrence except during initial ice formation, when a slush layer commonly develops if the sea surface is at all rough. However, recent work in the Weddell Sea has shown that frazil ice is very common there (S. F. Ackley and A. J. Gow, pers. comm.). At some sites, 70 percent of 4-m-thick floes were composed of frazil ice. Further field sampling will be required to determine whether there are similar occurrences in the Arctic and, if not, why not.

In summary, the main structures observed in sea ice are as follows:

A. fine-grained, equigranular ice with a random c-axis orientation,

B. medium- to coarse-grained ice with crystals elongated in the vertical direction and c-axes randomly distributed in the horizontal plane,

C. medium- to coarse-grained ice with crystals elongated in the vertical direction and the c-axes strongly aligned in the horizontal plane, and

D. multiyear ice showing a sequence of annual layers, each of which may have different structural characteristics resulting from orientation changes and/or recrystallization. (Multiyear ice has been so little studied that it is currently difficult to describe its internal characteristics.)

Although maps showing locations where different structural ice types predominate have been prepared for regions of the Siberian shelf, the data required to prepare similar maps for the Alaskan shelf are not available. It is quite possible that structures vary from year to year. Certainly the amount of initial slush ice is strongly dependent on sea conditions during freeze-up, and conditions during the formation of an ice sheet may strongly affect the development of aligned ice. Although one might suspect that aligned ice develops only in areas where the ice is fast, limited observations suggest that such ice also develops within the pack of the Beaufort Sea. More work is required to clarify our understanding of these issues.

Sea Ice Strength

Compressive Strength. The earliest simple compression tests on cylinders of sea ice were made by Butkovich (1956, 1959), who obtained median σ_c values ranging from 1,100 psi (76 x 10^5 Pa) at -5°C to roughly 1,700 psi (120 x 10^5 Pa) at -16°C from vertical cores. Average values on horizontal cores in the same temperature range varied from 300 psi (21 x 10^5 Pa) to 600 psi (42 x 10^5 Pa). These pronounced differences with changes in sample orientation are reasonable in that when a load is applied parallel to the plane of the ice sheet, both the grain boundaries and the planes of inclusions within the ice crystals are oriented so that

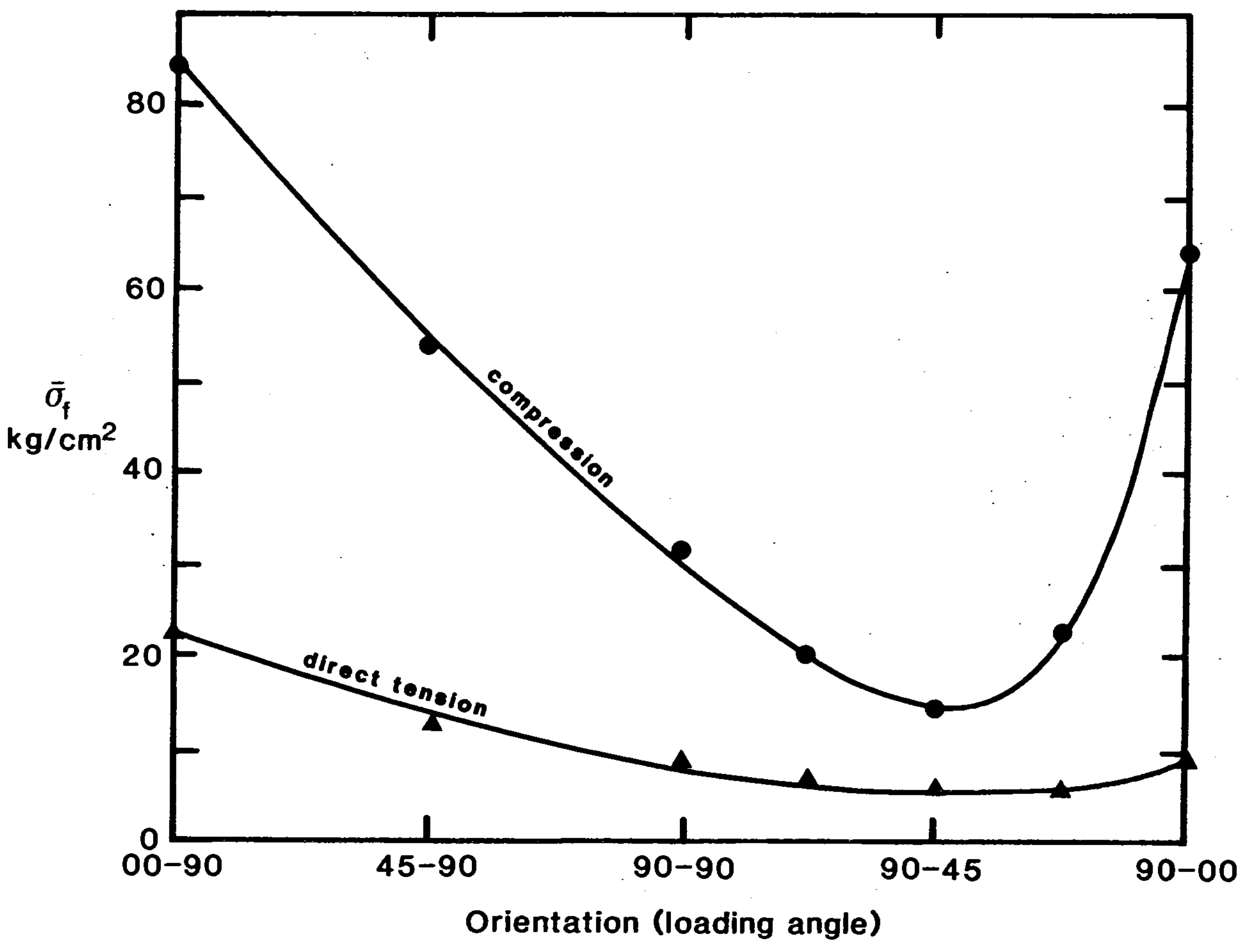

Figure B.4. Average failure strength in compression (circles) and in direct tension (triangles) vs. sample orientation: bottom ice, -10°C (Peyton, 1966).

the sample will fail readily. A similar strong orientation dependence was found by Peyton (1966), who ran tests on many samples of sea ice at various orientations and stress rates (Fig. B.4). Much of the ice used by Peyton showed strong c-axis alignment. Therefore, his samples were essentially single crystals with their c-axes oriented parallel to the plane of the ice sheet. In the loading angle notation of Fig. B.4, the first number represents the angle between the axis of the test cylinder and the vertical, and the second number represents the angle between the sample and the c-axis of the single ice crystal being tested. Note that the ratio of the strength obtained from vertical cores to that obtained from horizontal cores is 3/1, in agreement with the results of Butkovich (1959).

Peyton's results also show a strong dependence of the compressive strength on the square root of the brine volume. Unfortunately, he did not plot his observations directly, but made a series of "corrections" which make his results difficult to use. At present, insufficient work has been done to allow one to separate the influences of changes in ice temperature from changes in brine volume.

Another factor influencing σ_c is the strain rate. This effect is well known in freshwater ice. Figure B.5 shows σ_c values for Baltic Sea ice as a function of strain rate (Schwarz, 1971). A maximum occurs at a strain rate between 10^{-2} and 10^{-3} (s^{-1}) which is believed to be associated with the transition between creep-ductile and brittle failure. More recent results of Wang (1979, 1980) show a similar strain rate dependence (Fig. B.6). Other important factors shown in Wang's work are the major effects of changes in grain size, a factor not usually considered by other workers, and crystal alignment (Fig. B.7 and B.8).

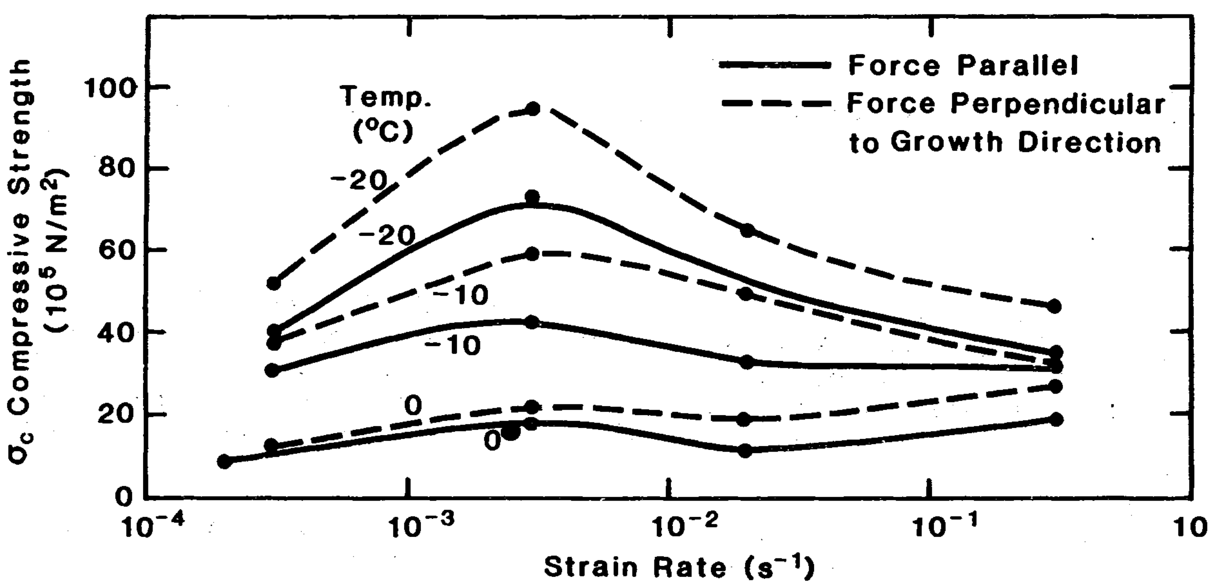

Figure B.5. Compressive strength of Baltic Sea ice as a function of strain rate, ice temperature, and orientation of the forces (Schwarz, 1971).

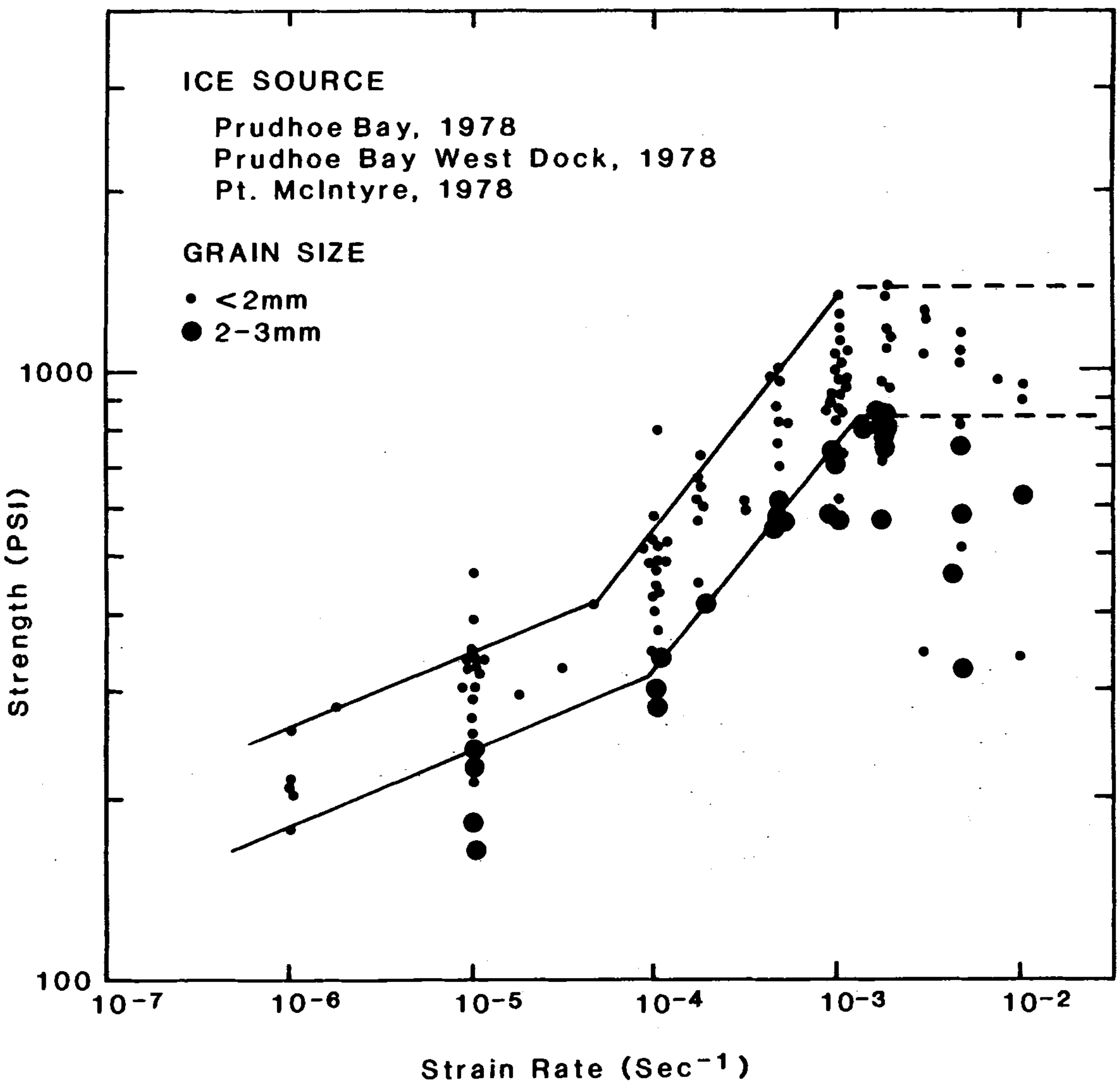

Figure B.6. Compressive strength of granular sea ice at -10°C (Wang, 1979, 1980).

A factor which in many studies is commonly ignored, is the amount of gas in the sea ice. At many locations, and particularly in older ice, the gas volume can be very important. This is shown well in Fig. B.9 which illustrates the effects of both ice density and ice temperature (Saeki et al., 1979) on σ_c values determined on sea ice from saline Lake Saroma in Hokkaido.

Although we now believe we know the more important factors (ice structure, load orientation, brine and gas volume, temperature, strain rate, grain size) that influence the compressive strength of sea ice and have a general feel for the range of strengths that might be encountered, we still cannot adequately predict the strength at which a specific type ice will fail under complex loading conditions.

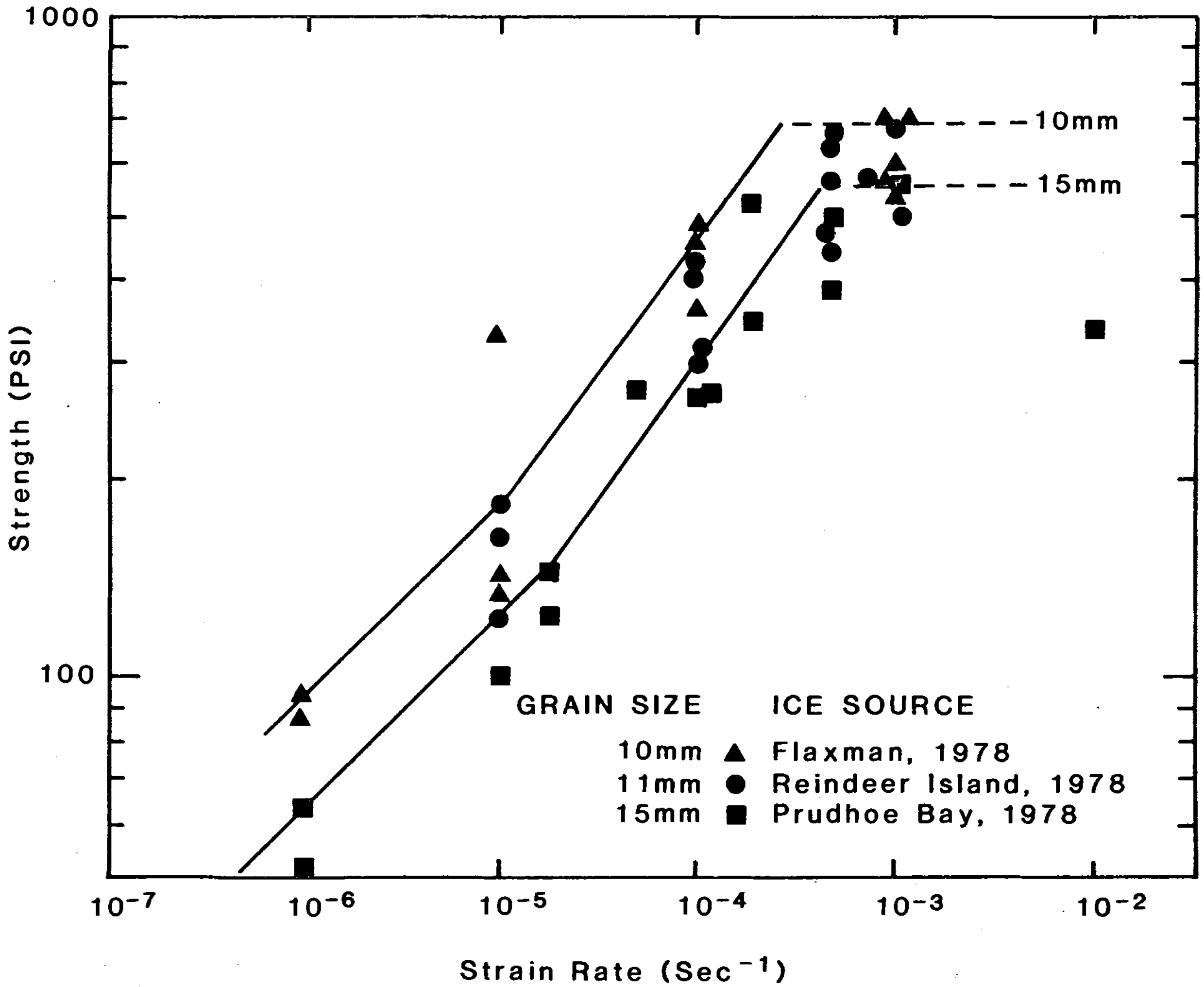

Figure B.7. Compressive strength of unoriented columnar sea ice at -10°C showing the effects of changes in grain size and strain rate (Wang, 1979, 1980).

Tensile strength. The most detailed direct tension tests on sea ice have been performed by Dykins (1967, 1970) (summarized by Katona and Vaudrey, 1973). The results from samples whose tensile axes oriented in both horizontal and vertical planes (relative to a horizontal ice sheet) are shown in Fig. B.10. The strength ratios between the horizontal and vertical orientaions range from 1/2 to 1/3.3, with the highest values always obtained from samples tested in the vertical orientation.

The combined results of Peyton (1966) and Dykins (1970) indicate that σ_t does not vary with stress rate $\dot{\sigma}$ in the $\dot{\sigma}$ range between 0.15 and 26 psi/s (1×10^3 to 1.8×10^5 Pa/s). This is in agreement with the results of carefully performed tensile tests on fine-grained bubbly freshwater ice (Hawkes and Mellor, 1972), which indicate little change (~ 25 percent) in

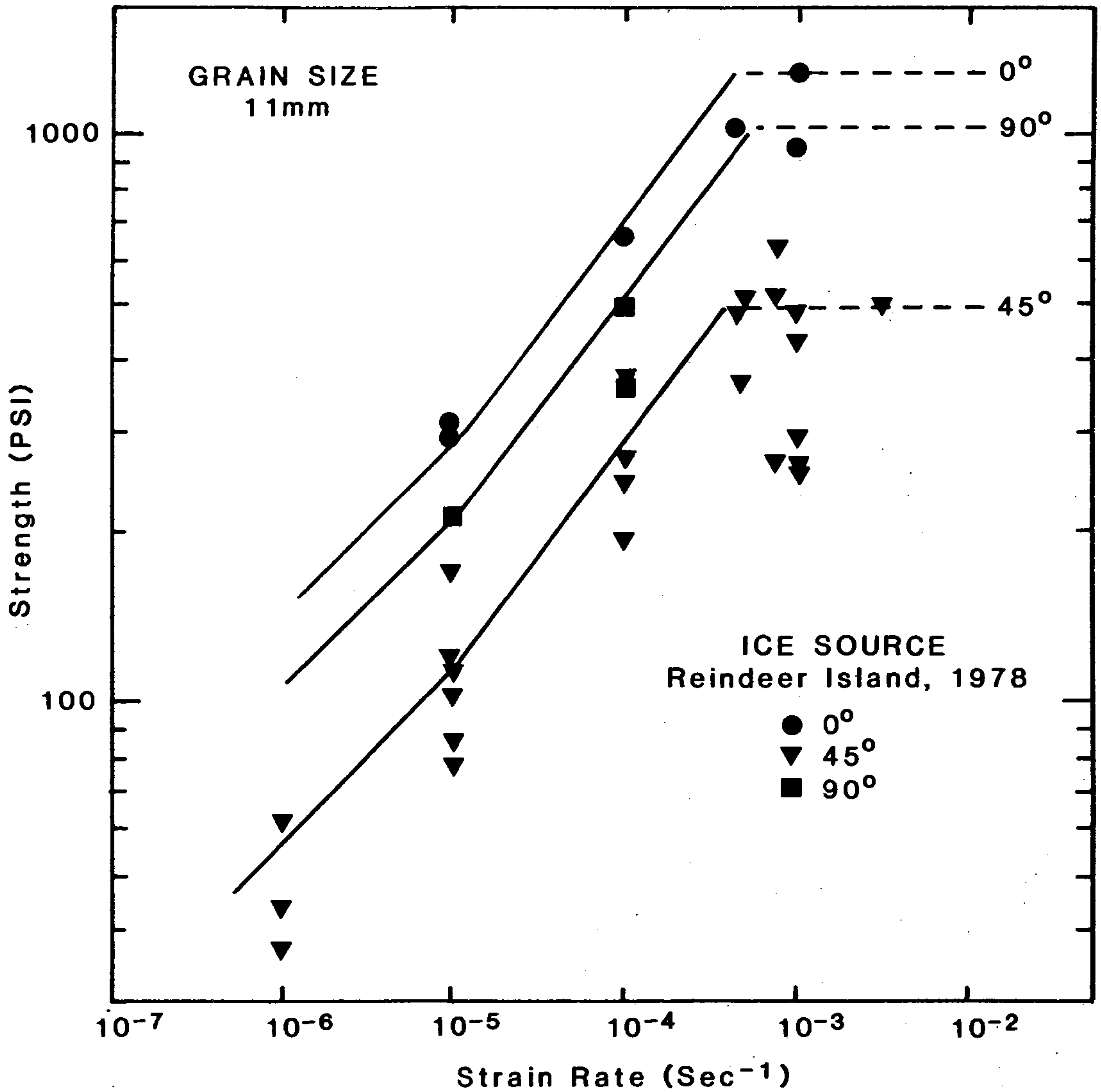

Figure B.8. Compressive strength of oriented columnar sea ice at -10°C showing the effects of changes in crystal orientation (Wang, 1980).

σ_t over 5 orders of magnitude in strain rate $\dot{\varepsilon}$. However, at $\dot{\sigma}$ values greater than 26 psi/s (1.8 x 10^5 Pa/s), Dykins observed a decrease in σ_t, with the strength dropping to 52 percent of the initial value. It is probable that this decrease results from the increased effectiveness at high strain (or stress) rates of stress concentrators (such as brine pockets and air bubbles) present within the sea-ice samples.

Many of the factors affecting the tensile strength of sea ice are presumably identical to those factors affecting its compressive strength. Yet they have been less thoroughly studied because of the difficulties in performing high-quality direct tensile tests. It is to be hoped that comparable data on tensile strength will be available soon.

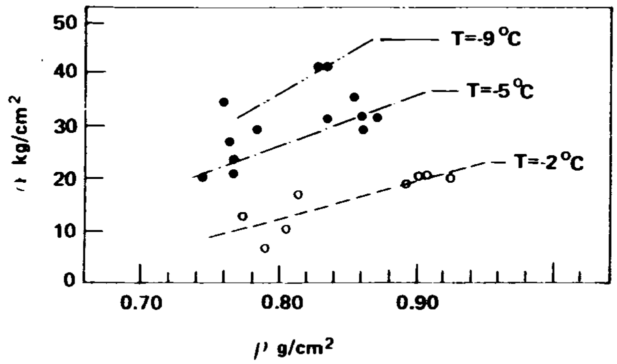

Figure B.9. Interrelations between unconfined compressive strength σ_c, ice density ρ, and ice temperature T. Samples from saline "Lake" Saroma (Saeki et al., 1979).

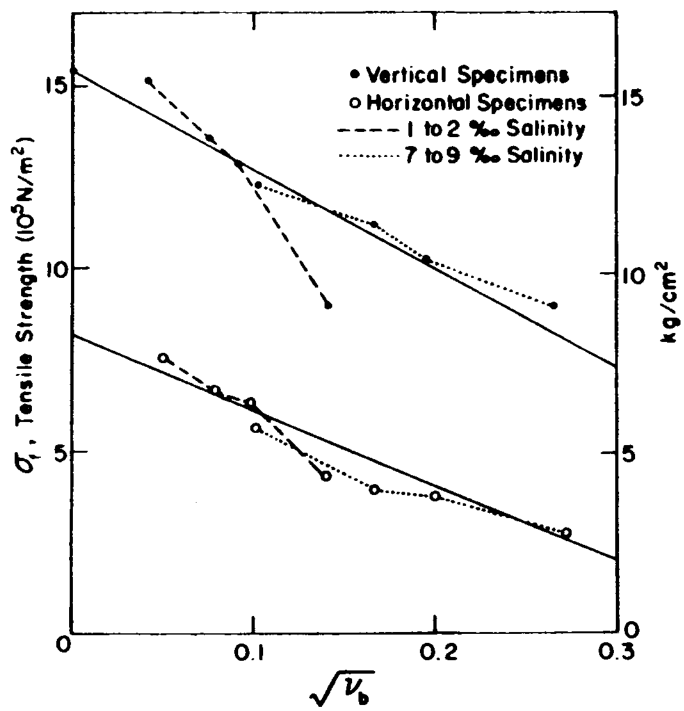

Figure B.10. Tensile strength vs. brine volume (Dykins, 1971).

Because of the difficulty in performing direct tension tests, there has been a tendency to substitute indirect tests such as the ring tensile and the brazil tests, as these tests are simple to perform in the field. These substitutions have not been successful, and their use should be avoided. The problem is that the theory upon which such tests are based usually assumes idealized material behavior that is not followed by sea ice.

Flexural strength. The flexural strength is not a basic material property but only an index strength. Nevertheless, it is useful in many applied problems and considerable data are available for sea ice. In sea ice such data are usually obtained either from cantilever beam tests or from simply-supported beam tests. In lake ice (Gow et al., 1978) it has been found that cantilever beams give values up to 50 percent less than simply supported beams, a difference believed to be the result of stress concentrations at the butt end of the cantilevers. In sea ice, such differences do not occur, presumably due to its more plastic nature.

The most extensive work on a variety of sizes of fixed-end and simply supported beams, including some beams 2.4 m thick, is that of Dykins (1971). When these results (shown in Fig. B.11) are compared with the results of in-situ cantilever tests performed by a variety of investigators, they are generally similar (similar intercepts at zero brine volume and similar slopes). The cantilever tests suggest that σ_f remains constant at $(\text{brine volumes})^{1/2} > 0.33$. Similar values have been obtained at large brine volumes in ring tensile tests and possibly in unconfined compression tests (see the discussion by Weeks and Assur, 1969). However, such trends are not apparent either in Fig. B.11 or in high-salinity ice studied in conjunction with model tests by Schwarz (1971).

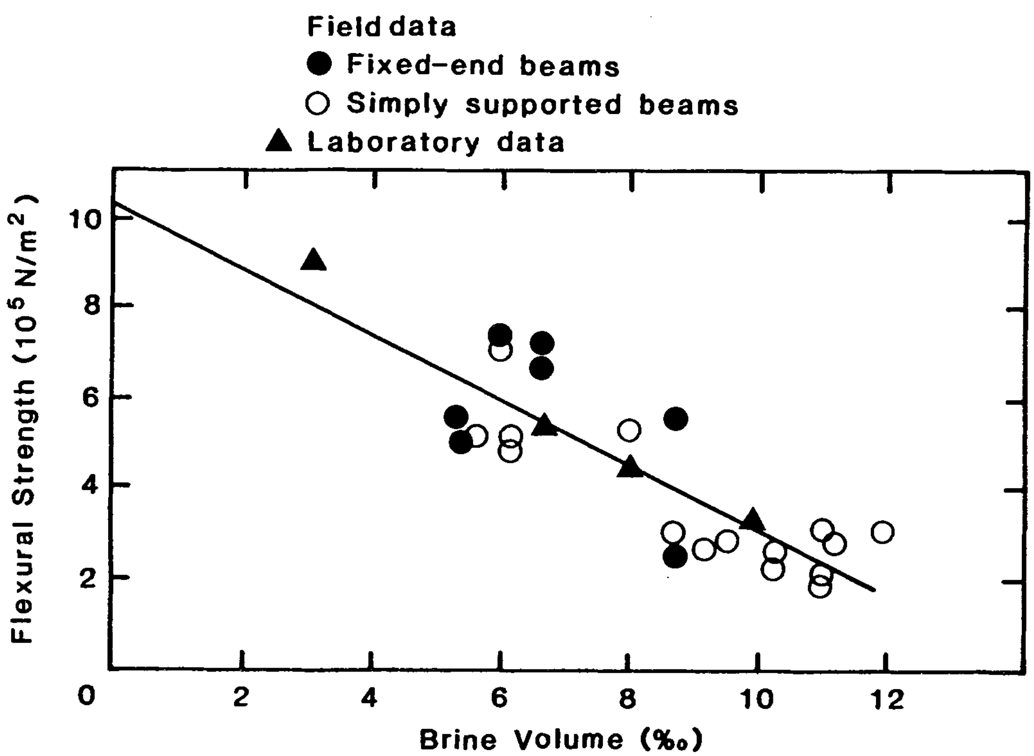

Figure B.11. Flexural strength as measured by fixed-end and simply-supported beams vs. brine volume (Dykins, 1971).

Flexural strength measurements obtained at different stress or strain rates have shown contradictory results. Tabata et al. (1967, 1975) have found that at stress rates of up to about 40 psi/s (3×10^5 Pa/s) there is a linear increase in σ_f with $\ln\dot{\sigma}$. However, results of Enkvist (1972) suggest that if corrections are made to eliminate the inertial forces associated with the displacement of water during such tests, these increases disappear and σ_f becomes essentially independent of $\dot{\sigma}$. Specific studies are needed to resolve these differences.

Shear strength. Few shear-strength tests have been reported. It is very difficult to obtain pure shear tests, and the best sets of shear tests available are those of Paige and Lee (1967) and of Dykins (1971). Many tests described as "shear" are actually the result of mixed-mode failures as in punch tests. Paige and Lee's results show similar trends with brine volume changes (Fig. B.12) as do in-situ cantilever beam tests. Also the absolute value of the shear strength is in the range of observed flexural and tensile strengths (with tension applied parallel to the growth direction). Dykins's results suggest that shear strength is not appreciably affected by changes in crystal orientation. If further experimentation supports this finding, it will affect our understanding of how ice strength is influenced by ice structure. Although shear strengths reported for lake ice are lower than those reported for sea ice, whether this is the result of structural differences or of differences in testing procedure is unknown.

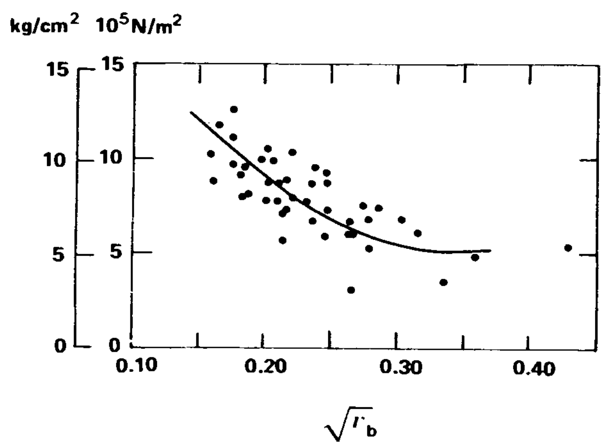

Figure B.12. Shear strength as a function of the square root of brine volume (Paige and Lee, 1967).

Fracture Toughness. The only study of the fracture toughness (K) of sea ice is that of Urabe et al. (1980), who performed 3-point bending tests on notched and unnotched specimens. The orientation of the notch tip and its specific location in the ice sheet were found to be important. K values for notch tips located in the bottom of the sea ice were greater than those obtained for notch tips on the upper side. Notches oriented with their plane normal to the side surface gave intermediate values. Also, K values appear to be independent of strain rate until strain rates greater than 10^{-3}/s are reached, when a gradual decrease in K is observed.

The scatter in K values was small. The authors claim that the flaw sizes estimated from the K values correspond well to the actual subgrain sizes observed in the sea ice. This is hard to verify from their data, as neither the exact location of the crack tip nor the distribution of subgrain sizes is given. Their finding implies that it is the grain size, not the subgrain size, that controls the failure, an idea that has as yet not been widely accepted.

Clearly more work is required before the usefulness of fracture toughness measurements can be assessed. The weakness of the test may be that fracture toughness measurements subject an extremely small volume of ice at an induced crack tip to high stresses. It is difficult to believe that such a technique would be useful in characterizing sea ice, a material in which flaws (such as brine drainage structures) having dimensions of several millimeters to even centimeters are common.

Elastic Modulus

Dynamic Measurements. Dynamic measurements of the elastic modulus E are determined either by measuring the rate of wave propagation in the ice or by exciting natural resonant frequencies of different vibration modes. The induced displacements are very small, and anelastic effects are also commonly small. Therefore, dynamic measurements of E tend to be more reproducible than typical static values.

In-situ seismic determinations of E reviewed by Weeks and Assur (1967) varied from 2.5 to 8.3 x 10^5 psi (1.7 to 5.7 x 10^9 Pa) when measured by flexural waves and from 2.5 to 13.2 x 10^5 psi (1.7 to 9.1 x 10^9 Pa) when determined by in-situ body wave velocities. This is reasonable in that flexural wave velocity is controlled by the overall properties of the ice sheet, whereas the body wave velocity is controlled by the high-velocity channel in the usually colder and stronger upper section of the ice. Pronounced changes in E are observed throughout the year. The results of Anderson (1958) plotted as a function of brine volume are shown in Fig. B.13. A pronounced decreased in E with increasing brine volume is indicated.

Most dynamic determinations of E are not from in-situ measurements but have been determined from small, reasonably homogeneous samples that have been removed from the ice sheet. A typical series of such tests (Langleben and Pounder, 1963) is shown in Fig. B.14. Elastic modulus values at zero brine volume are characteristically found to be 13 to 14.5 x 10^5 psi (9 to 10 x 10^9 Pa), in good agreement with the seismic determinations. Within the range of brine volumes studied, E decreases linearly with increasing v_b. At v_b values greater than 0.15 there is evidence that E becomes a very weak function of v_b (Slesarenko and Frolov, 1974).

Static Measurements. Static measurements of E are more variable and difficult to interpret than dynamic measurements because of the viscoelastic behavior of ice when it is subjected to significant stresses for finite periods. Nevertheless, it is these E values that are applicable to problems such as ice forces on structures. The most extensive work on the static modulus of sea ice is that of Dykins (1971), who tested small beams

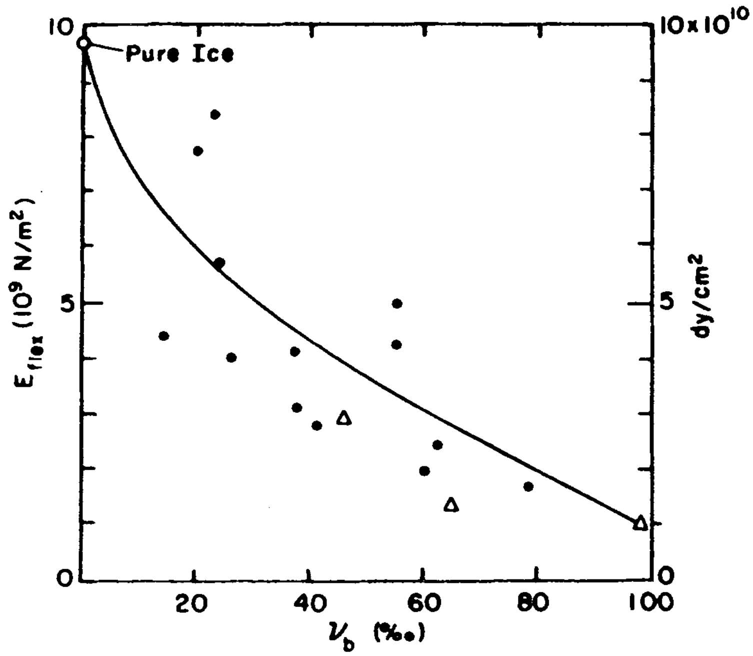

Figure B.13. Elastic modulus of sea ice as determined by seismic measurements vs. brine volume (Anderson, 1958). The three triangular points are from the static tests performed by Dykins (1971).

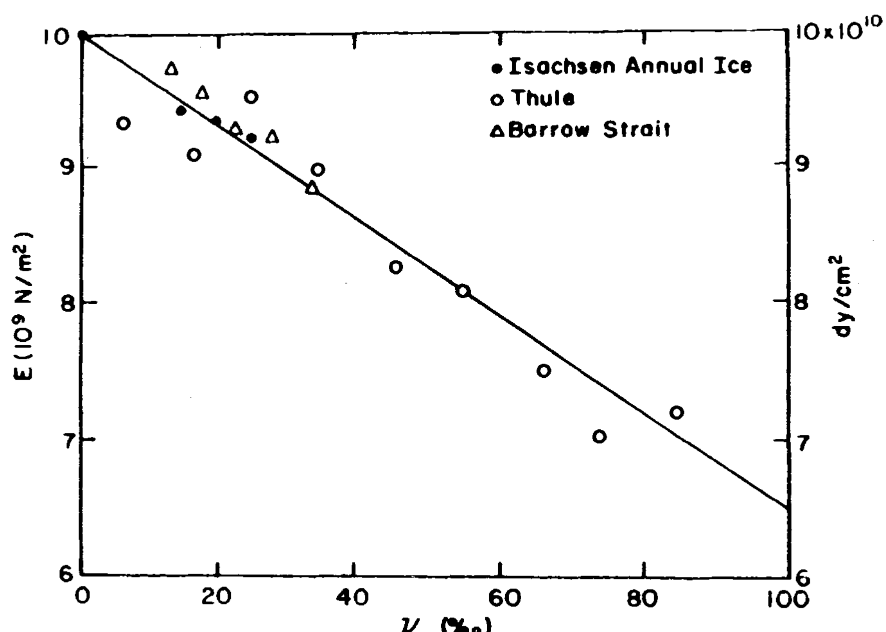

Figure B.14. Elastic modulus of cold, Arctic sea ice vs. brine volume for small specimens (Langleben and Pounder, 1963).

in bending. His stress-strain curves, which were obtained at stress rates of 38 psi/s (2.5×10^5 Pa/s), were nearly linear. The plots of E versus temperature suggest discontinuities at temperatures at which $Na_2SO_4 \cdot 10H_2O$ and $NaCl \cdot 2H_2O$ precipitate (-8.7°C and -22.8°C, respectively). However, the testing was not suffcently detailed to clearly verify this effect. When E was plotted vs. v_b, the values indicated by the triangles in Figure B.13 were obtained. It is encouraging that the values obtained by static measurements are in general agreement with the "seismic" values obtained by Anderson. Finally, Vaudrey (1977) utilized strain data from the NCEL large-beam tests to determine the apparent value of E as a function of brine volume. The resulting relation was

$$E(\text{psi}) = 10^3 \, [771 - 63.2 \, (v_b)^{\frac{1}{2}}].$$

Information on the time dependence of E in sea ice is also inadequate. The best studies of this problem have been those Tabata and his group (see references in Weeks and Assur, 1967). Their results from small beams and from in-situ cantilevers suggest that log E increases as a linear function of log $\dot{\sigma}$, approaching the dynamic value at large values of $\dot{\sigma}$. Even Tabata's highest value for E (300 psi or 2×10^6 Pa) is much lower than Dykins' or Peyton's lowest value (8.7×10^4 psi or 6×10^8 Pa). It is not known whether this large difference can be explained by differences in the test conditions (for instance, Tabata's tests were performed at very high temperatures).

Recent work by Gold and Traetteberg (1974) on the elastic modulus of columnar artificial freshwater ice has indicated that its viscoelastic behavior is complex: relaxation processes occur, one with a time constant of about one second and the other with a larger relaxation time that increases with the time of application of the load raised to the two-thirds power. This latter process predominated, with time dependence of E for times longer than 0.1 second. A decrease in E from 116×10^4 to 58×10^4 psi (8×10^9 to 4×10^9 Pa) was noted in freshwater ice; this presumably also occurs in sea ice but has not yet been observed.

Poisson's Ratio. The only data currently bearing on the variation of Poisson's ratio μ with sea ice structure and state are those in Lin'kov (1958) based on in-situ seismic observations of Cape Schmidt, Siberia. From these observations, Weeks and Assur (1967) have expressed μ as an extremely weak function of ice temperature. Presumably, the prime functional relation will prove to be between μ and $(v_b)^{\frac{1}{2}}$. The value of μ would also be expected to vary with the structural orientation of the ice and the loading conditions.

Fortunately, a detailed examination of the theoretical effects of the vertical variations of μ through a floating ice sheet on the mechanical response of the sheet (Hutter, 1975) has indicated that for most real problems it is not necessary to consider the variation of μ. In addition, studies of other materials show that μ shows only slight changes (< 10 percent) over porosity ranges up to 30 percent (Buch and Goldschmidt, 1970). Therefore, for engineering purposes μ can be considered constant with a value of 1/3.

Density. The variation of the theoretical density of air-bubble-free sea ice has been calculated by Malmgren (1927), Zubov (1945), and Anderson (1960), with values ranging from 920 to 950 kg/m^3, depending upon the temperature and salinity of the ice. Because of entrapped air in natural sea ice, actual ice densities are invariably lower than these values, with values as low as 840 kg/m^3 occasionally occurring in normal sea ice and 770 kg/m^3 in infiltrated snow ice (Weeks and Lee, 1958). Detailed ice profiles collected on the 1971 and 1972 AIDJEX stations showed average multiyear ice densities of 910 and 915 kg/m^3, respectively (Hibler et al., 1972a; Ackley et al., 1974). The data collected in 1972 indicate that the higher the freeboard of the (multiyear) ice, the lower the average ice density as given by the empirical equation

$$\rho = 194\ f + 974,$$

where ρ, the ice density, is in kg/m^3 and f, the freeboard, is in meters. For most purposes, unless highly detailed information on the actual density of a specific piece of sea ice is required (which, of course, would usually necessitate direct field measurements), 910 kg/m^3 should serve as a reasonable estimate.

Friction and Adhesion. For icebreaking by ships, it is currently believed that, in continuous-mode icebreaking, the dominant aspect of the ice resistance is related to forces associated with the buoyancy of the ice (Lewis and Edwards, 1971). These include the frictional forces between the broken ice and the hull (forces associated with the initial breaking of the ice appear to be comparatively small). Also, as discussed earlier, ice forces measured during studies of the interaction between ice and piling are as much as 50 percent higher if the ice is allowed to bond to the pile (Croasdale, 1974). In fact ice-ice and ice-metal friction and ice-metal adhesions should be considered in an analysis of almost every problem concerned with the differential motion of sea ice and structures. Therefore, the paucity of information on this subject is surprising.

Schwarz and Weeks (1977) have summarized the data on the friction coefficient between sea ice and steel available up through 1972. Many of the tests were crude, and the data can be used only to make rough estimates. The major contribution on the subject since 1972 is by Tusima and Tabata (1979). The results of this latter work indicates that

a) coefficients of kinetic friction (μ_k) between sea ice and smooth surfaces (glass, steel, PTFE) are small (0.01-0.04), whereas those between sea ice and rough surfaces (steel, painted surfaces) are higher (0.05-0.31),

b) μ_k values are relatively independent of surface pressure at surface pressure values in excess of 1 psi (5,000 Pa) (at values less than this the coefficients increase as pressure decreases),

c) μ_k values decrease with increasing sliding speed and temperature,

d) liquid brine in the ice or sea water in direct contact with the sliding surface has little effect on the friction coefficient,

e) freshwater ice shows μ_k values slightly higher than those for sea water,

f) dry snow increases μ_k values to about four times those of dry ice,

g) wet snow has similar μ_k values to those of dry, snow-free ice,

h) static friction coefficients are appreciably higher than dynamic coefficients and reach values of up to 0.7, and

i) static coefficients are relatively independent of surface pressure.

Limited information is available on the adhesion of sea ice to surfaces. This is not surprising in that even the adhesion of pure ice to clean surfaces is difficult to understand. Recent research (Stehle, 1970; Sackinger and Sackinger, 1975) indicates that in low-salinity ice adfreeze strengths increase as temperature decreases (Fig. B.15). The appreciable increase in scatter in the tests performed at -23°C over that in tests performed at higher temperatures may be attributed to the crystallization of $NaCL \cdot 2H_2O$ at -22.7°C. The effect of salinity on the adfreeze strength of ice tested at -23°C is shown in Fig. B.16. The decrease in strength with increasing salinity is presumably caused by an increase in the amount of solid salts ($NaCl \cdot 2\ H_2O$ and $Na_2SO_4 \cdot 10H_2O$) in samples tested. Further investigations into the effect of changes in the brine volume on the adfreeze strength of sea ice at warmer temperatures are needed.

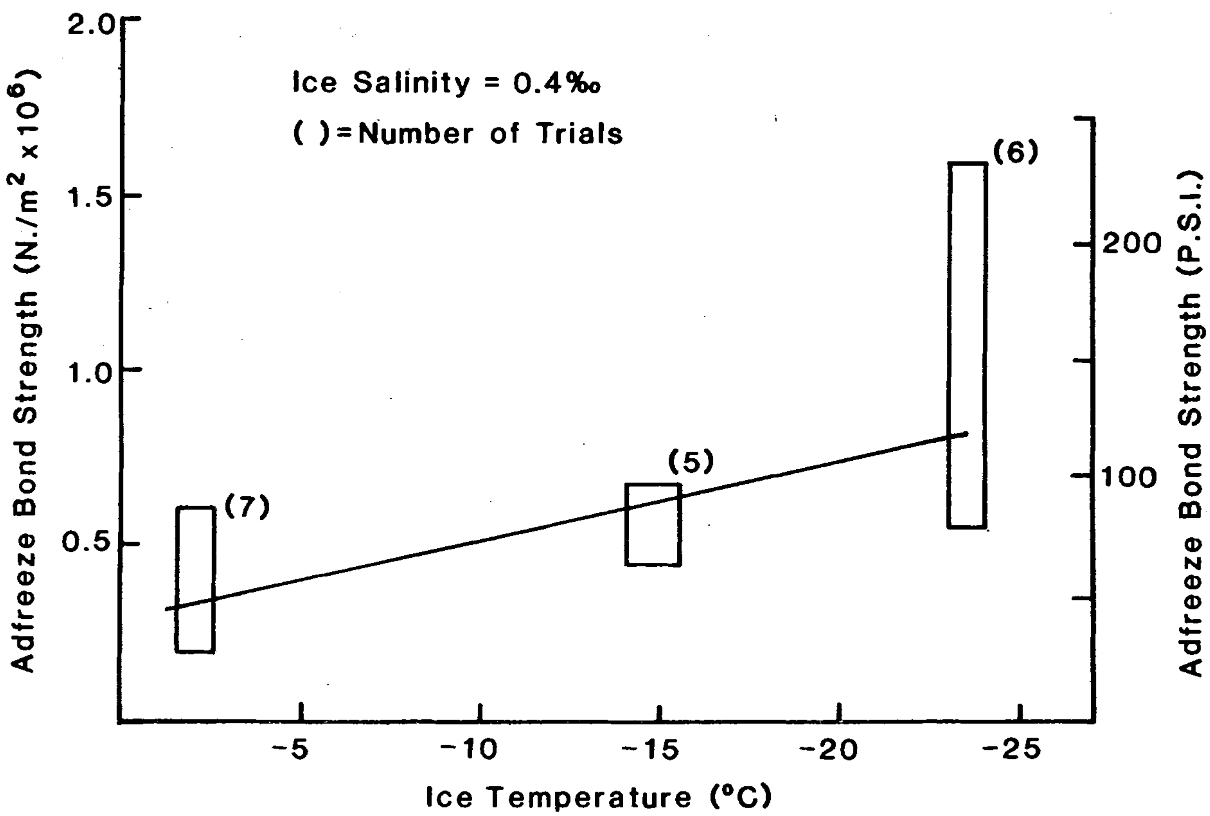

Figure B.15. Adfreeze bond of saline ice to steel as a function of temperature (Sackinger and Sackinger, 1975).

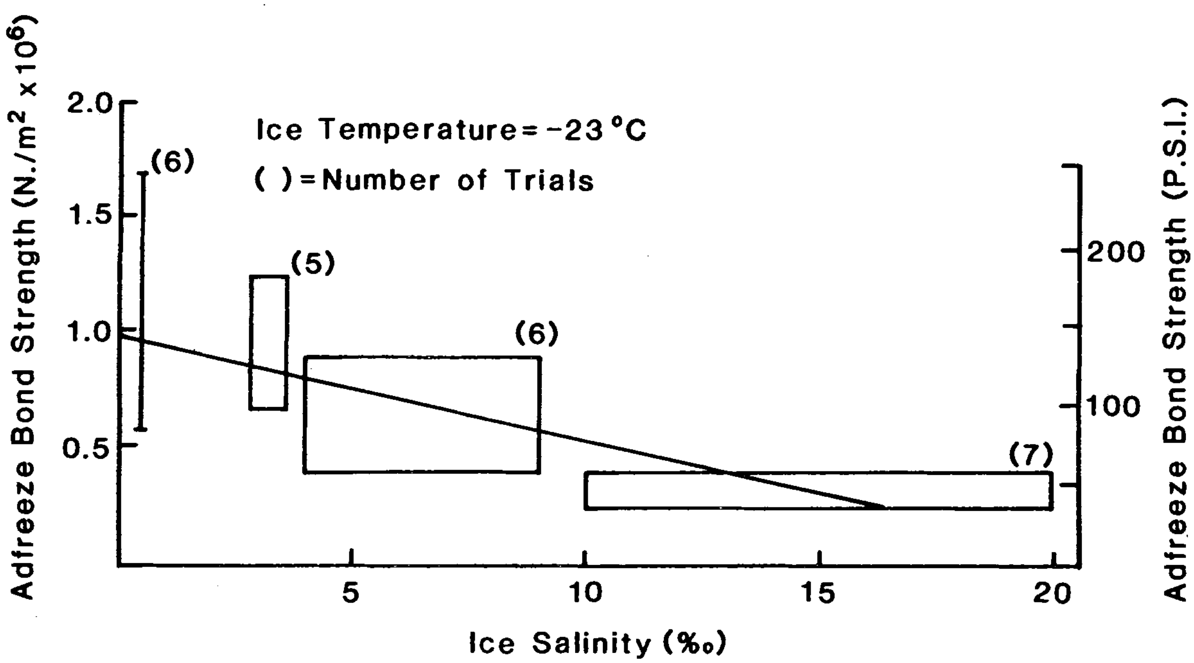

Figure B.16. Adfreeze bond of saline ice to steel as a function of salinity (Sackinger and Sackinger, 1975).

Pressure ridges

Although undeformed sea ice is important in offshore design and operations, as it comprises most of the ice (in an areal sense), the much thicker, deformed ice of ridges and rubble fields is more important, since the properties of such ice masses may determine the conditions upon which a design is based.

Properties. In most of the first-year ridges that have been studied, the packing of the broken ice blocks appears to be random. Therefore, it is reasonable to assume that most newly formed ridges have a porosity of roughly 30 percent. Field determinations of actual porosities are not available. Variations in this value will be produced primarily by the amount of snow and ground-up ice that is incorporated between the blocks. The void produced during formation of the ridge is filled immediately in the keel by sea water and filled slowly in the sail by snow . During the winter, strong interblock bonding develops slowly in ridge sails because of low ice temperatures. The degree of initial bonding in the keels probably varies appreciably with the time of formation of the ridge. Preliminary calculations show that during the winter there is sufficient cold reserve in the ice blocks to freeze an appreciable part (20-40 percent) of the initial void volume. This new ice forms most rapidly at points or areas where ice blocks touch, welding the ice blocks together. Cores generally show that although many first-year ridges contain large unfrozen cavities, most of the ice blocks do appear to be frozen together. Complete refreezing of the voids probably occurs only in the uppermost below-sea-level portion of the ridge; the thickness of the refrozen zone is equal to that of the surrounding plate ice. Ridges that are newly formed during the summer would be expected to show extremely poor bonding, particularly in the lower portions of their keels. Obviously, it is highly desirable to obtain direct measurements of the strength of such ice masses.

Our limited observations indicate that the ice in multiyear ridges is quite different. During the summer, there is appreciable ablation of the exposed portions of ridge sails. Because this ice has already experienced significant brine drainage, the meltwater is virtually fresh. It runs down and displaces the denser sea water in the keel of the ridge. In autumn, this fresh water refreezes, giving the multiyear ridge a hard, strong core with no voids (Kovacs et al., 1973; Wright et al., 1979). As can be seen in Fig. B.17, which shows temperature and salinity profiles from a ridge studied near the 1971 AIDJEX camp, the upper 10 m of ice in the 12.5-m-thick ridge has a very low brine volume (< 60 $^{\circ}/_{oo}$) and presumably is quite strong. According to reports from ships operating in ice, first-year ridges do not offer significant resistance above that required to push the large volumes of ice in the ridges out of the way. Multiyear ridges, however, are extremely difficult to break.

If a ridge is in isostatic equilibrium, the ratio of the freeboard (f) to the draft (d) can be calculated (at any point) by using the equation:

$$\frac{f}{d} = k_f \frac{(\rho_w - \rho_i)}{k_d \rho_i} ,$$

where k_f and k_d are the solidities of the above- and below-water portions of the ridge and ρ_i and ρ_w are the densities of sea ice and water. Therefore, if, soon after the ridge has formed, the solidities of the keel and the sail are similar ($k_f = k_d = 0.70$), a sail height/keel depth ratio (f/d) of 1/6.9 would exist. Even if allowance is made for subsequent ice growth in the voids of the keel by setting $k_d = 0.83$, f/d increases only to 1/5.8. Yet f/d ratios for real ridges that have been cored give an average of 1/4.9, which is very close to the average of 1/5 obtained from a study in which the laser profiles of the upper ice surface could be statistically compared with sonar profiles of the lower surface (Kozo and Diachok, 1973). More recent work suggests, however, that the relationships between the profiles of these two surfaces cannot be adequately specified by a simple proportionality constant (Wadhams, 1980). This strongly suggests that isostatic imbalance is typical in new ridges, and the ridge is partially supported by the elastic response of the surrounding ice sheet. This conclusion is borne out by observed deflections and cracking in the ice surrounding new ridges. It is this nonisostatic loading of the edges of the interacting ice sheets during ridging that causes the ice to fail. The resulting fragments are then rotated and incorporated into the developing ridge (Parmerter and Coon, 1972). The only specific observations on the thicknesses of blocks in first-year pressure ridges are from the coastal region of the Beaufort Sea north of Deadhorse (Tucker and Govoni, 1981). A number of ridges contained quite thick ice (1.6 m), and the higher ridges were generally composed of thicker ice (Fig. B.18). Such a trend was predicted by the Parmerter and Coon (1972) ridging model.

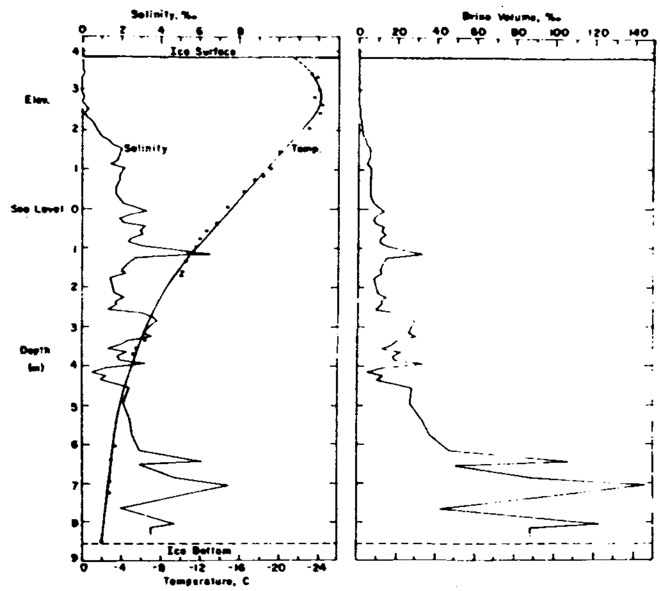

Figure B.17. Salinity, temperature, and brine volume profiles obtained by coring into a multi-year pressure ridge near the 1971 AIDJEX camp (Kovacs et al., 1973).

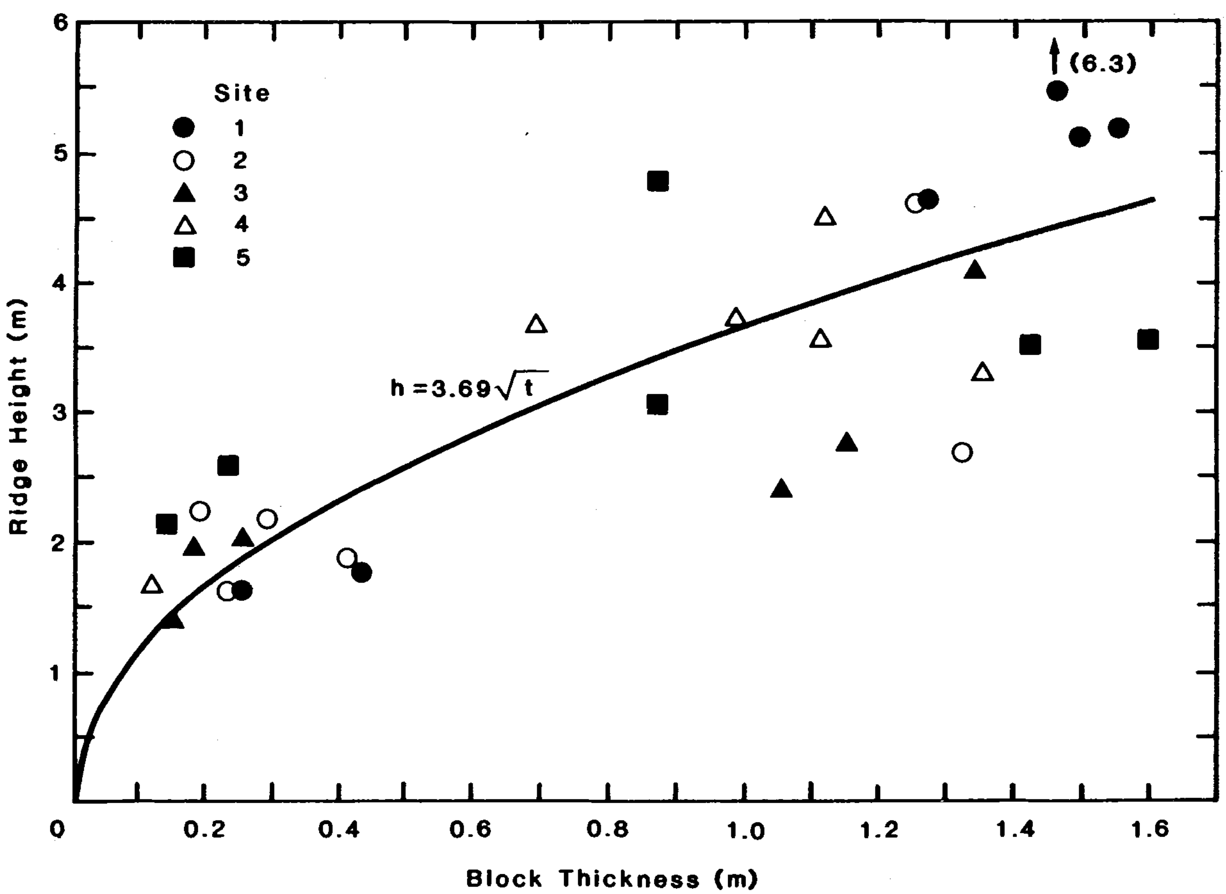

Figure B.18. Ridge height vs. block thickness (Tucker and Govoni, 1981).

Geometry. Fig. B.19 shows the distribution of the heights and depths of pressure ridge sails and keels in the Beaufort Sea as determined by Hibler et al. (1972b) and Hibler (1975). The general distributions of both sails and keels are similar in that both are negative exponentials (there are many small ridges, whereas large ridges are rare). In fitting curves to these data, two general relations have been used, one based on probability (Hibler et al., 1972b) and the other on empirical curve-fitting (Wadhams, 1976). Both give good fits to most data sets, but the equation suggested by Hibler et al., appears to underestimate the number of rare large keels. In compiling such data (usually from either laser or sonar profiles) it is common to neglect ridges smaller than some cutoff value.

To obtain a model specifying the distribution of ridges, Hibler et al. (1972b) simply assumed that ridges occurred randomly. If they do, the probability of their occurrence should be given by the Poisson distribution, which in turn implies that the spacing distribution is a negative exponential

$$P(L)dL = \mu_h \exp(-\mu_h L)\, dL,$$

where P(L)dL is the probability of two adjacent ridges of a height greater than h being separated by a distance between L and L + dL, and μ_h is the average number of ridges per unit distance. Mock et al. (1972) tested this model with good agreement, using ridge spacings obtained from photographic mosaics over the Beaufort Sea. An example of a sample of ridge spacings and the fitted theoretical distribution is shown in Fig. B.20. Wadhams and Horne (1980) have done interesting further work on keel spacing; their Beaufort Sea data show a keel shadowing effect (keels have a finite slope so that their crests cannot be closer together than a certain minimum distance) as well as an effect due to the presence of leads which interpose occasional smooth stretches of ice (or open water) into the otherwise random icefield, thereby generating an anomalous number of large keel spacings (Fig. B.21).

Orientations. To date, only one study has examined whether pressure ridges in a given area are directionally isotropic (Mock et al., 1972). The area examined was in the Beaufort Sea just northeast of Barrow. In all cases, the hypothesis that the samples came from a randomly distributed sample was rejected. However, because in all cases the degree of ridge alignment was very weak and the sample site was in a location where strong alignments might well be expected, it was concluded that the random orientation hypothesis is still a reasonable working model with which to approach ridge studies.

That ridges are nearly random in orientation does not imply that the locations where ridges usually form (i.e. the leads) are randomly oriented. Leads that are active at a given instant commonly show a high degree of preferred orientation. The same is true of pressure ridges during their formation. It is only when all existing ridges are considered, including those that have fractured and rotated as floes drift and rotate, that a random pattern is evident.

Ridge lengths. Surprisingly few observations have been made on the distribution of lengths of ridges. Those that are available have been

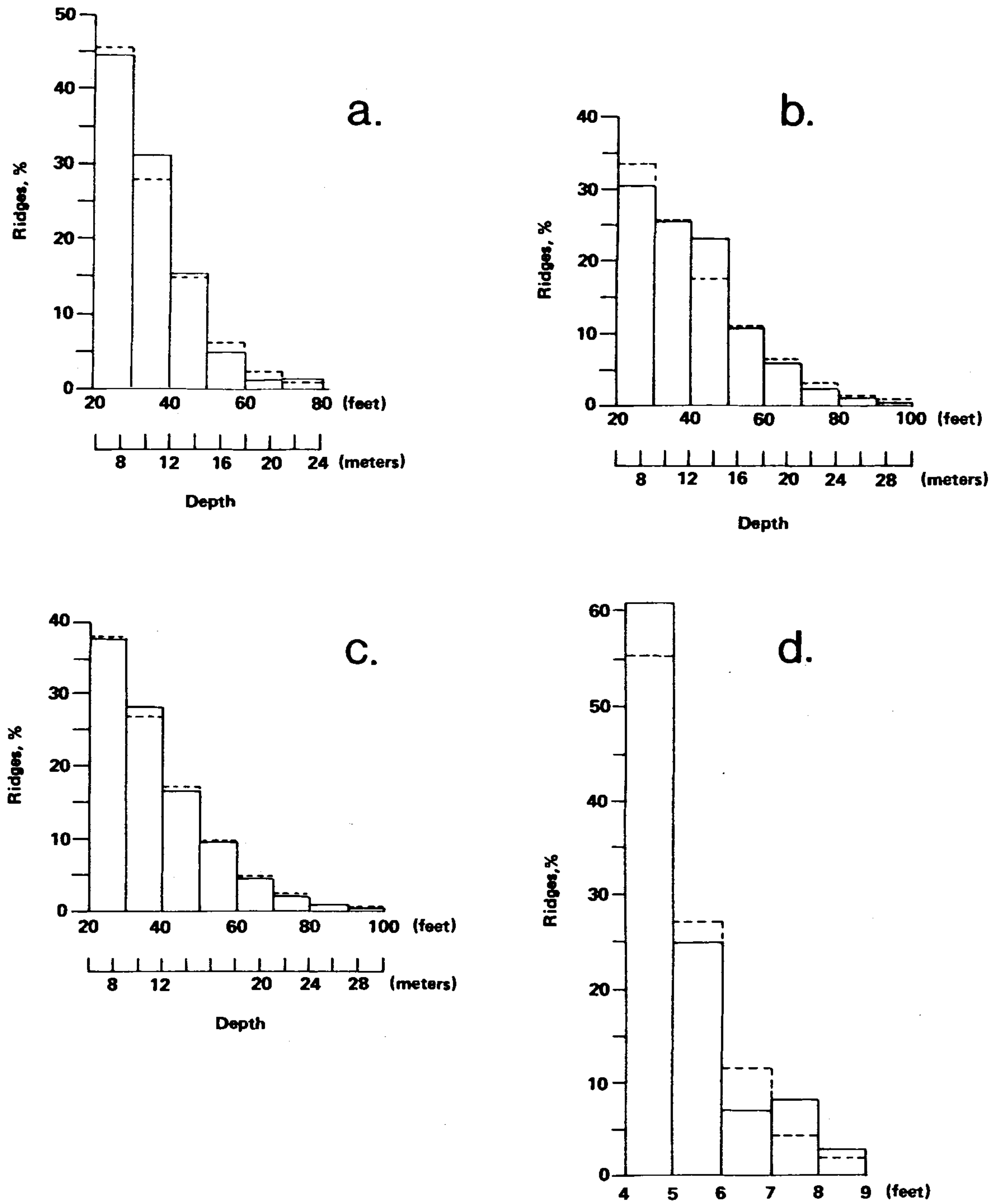

Figure B.19. Histograms of keel depths in the offshore province along the north side of the Canadian Archipelago (a-c) and ridge sails in the southern Beaufort Sea north of the US-Canadian border (d) (Hibler et al., 1972; Hibler, 1975).

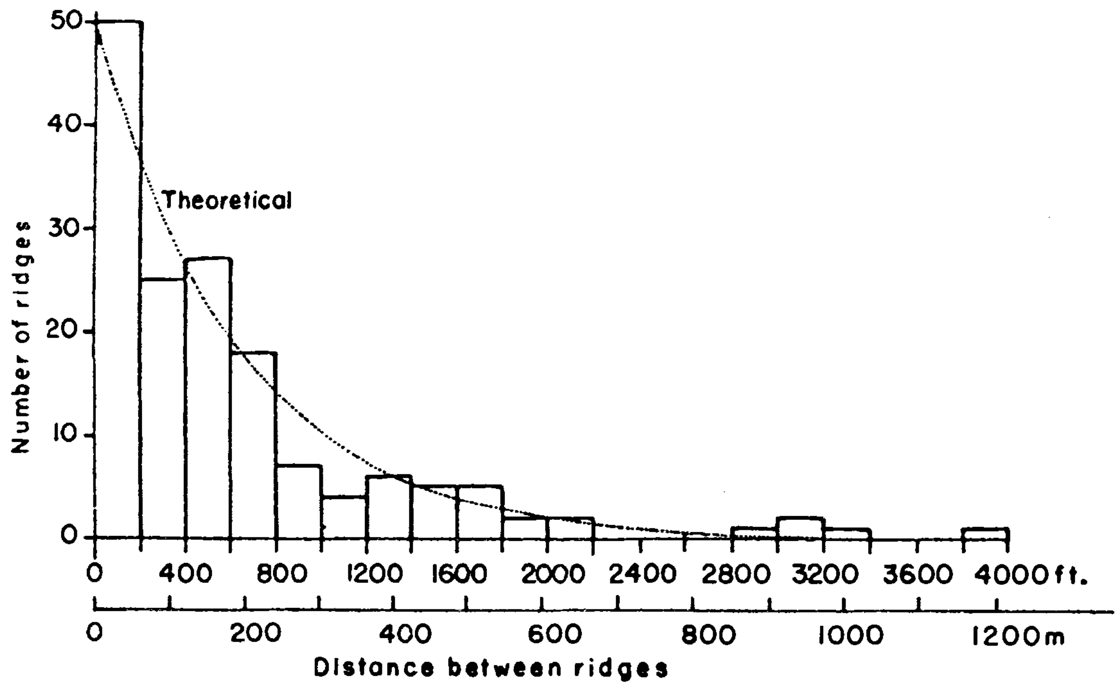

Figure B.20. Distribution of ridge spacings (for ridges higher than 0.6 m) taken from laser profile data in the Beaufort Sea. The theoretical curve is the negative exponential and is normalized so that the mean value over any category is the predicted number of ridges in the category (Hibler et al., 1972).

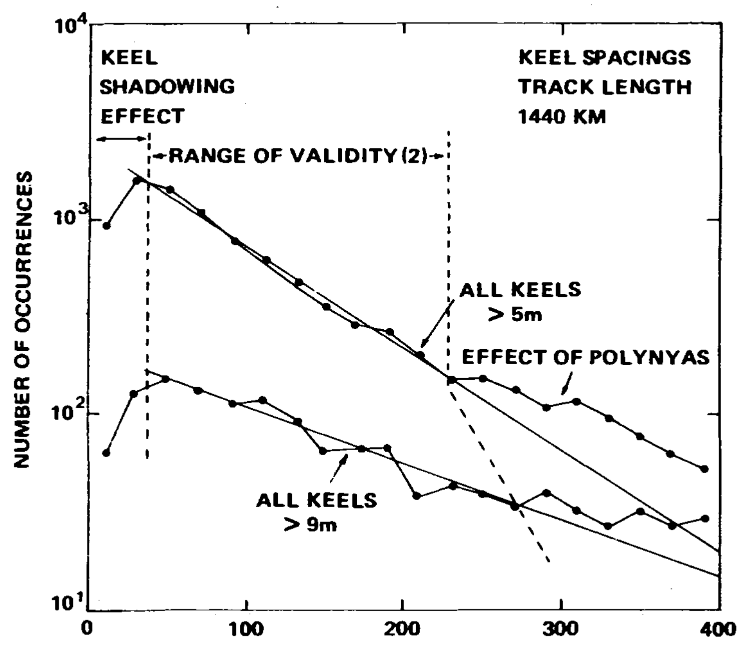

Figure B.21. Distribution of keel spacings over whole submarine track. Bin size 20 m. Results are plotted for keels deeper than 4 m and 9 m, and a straight line is fitted to the central portion of each curve (Wadhams and Horne, 1980).

collected by Hibler and Ackley (1973) and are shown in Fig. B.22. In collecting the data (from aerial photographs), only ridges higher than 1.5 m were considered, and a ridge was considered to have ended when the height dropped below 1 m and remained there for more than 100 m. The ridge length distribution is described well by a negative exponential function. This is physically reasonable, as this function can be derived by simply assuming that the holes in ridges occur randomly. Therefore, the spacings between holes, i.e., the ridge lengths, would be exponentially distributed.

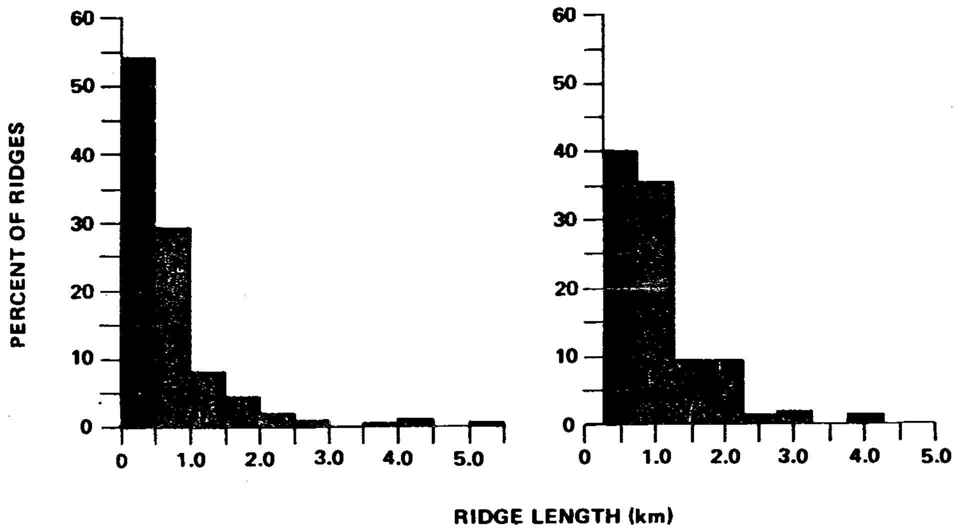

Figure B.22. Distribution of pressure ridge lengths obtained (left) near the March 1971 AIDJEX camp (75°N, 131°W) and (right) near the March-April 1972 AIDJEX camp (75°N, 145°W) in the Beaufort Sea. Total number of ridges in the samples were 180 and 307, respectively (Hibler and Ackley, 1973).

Cross-sectional geometry. Although the data are hardly adequate, there is some information on the cross-sectional geometry of ridges. Slope angles of first-year ridges studied by Weeks and Kovacs (1970) and Weeks et al. (1971) averaged 25° (sail) and 32° (keel), while values obtained by Kovacs (1972) were 24° (sail) and 36° (keel). In his studies in the Baltic, Palosuo (unpub.) obtained average values of 22° (sails) and 30° (keels). Zubov (1945) obtained angles ranging between 20° and 30°; and although it is not specified, we assume that the measurements were made on ridge sails. Wittman and Schule (1966) obtained a keel angle of 32° based on submarine sonar observations of 39 ridges in which the submarine track was most likely normal to the axes of the ridges. In spite of the wide variety of sources and techniques used to obtain the above data, the values obtained are remarkably constant. Slope angles of 25° for sails and 35° for keels of first-year ridges are reasonable estimates. It should be noted that in the grounded ridges that have been studied, the slope angle of the keel that faces the direction from which the ice was thrust was significantly larger (40-60°) than the values given above. The sail height/keel depth ratio for first-year ridges has been found to range from 1/3 to 1/9. However, most ratios are about 1/4.5 (Kovacs and Mellor, 1974).

For multiyear ridges, surface slope angles are lower, averaging about 20°; the same decrease is observed in the slopes of keels, which average roughly 30°. Sail/keel ratios show an increase to 1/3.2. As seen in Fig. B.23, this ratio is surprisingly constant (Wright et al. 1979). A geometric model for the cross section of the multiyear ridges is given by Kovacs (1972) (Fig. B.24) and has been utilized in offshore design by Karp (1980).

Ice pile-ups and ice override

The definitive work on shore ice pile-up and ride-up is that of Kovacs and Sodhi (1980) who provide extensive references to the scattered literature on the subject (worldwide). They conclude from ice-push gravel ridges, pits, and striations that can be observed on nearly all arctic beaches that the onshore movement of sea ice is common. Shore-ice pile-ups seldom occur more than 10 m from the water's edge, but they can be very large: sail heights of up to 25 m have been observed. Ice ride-ups, on the other hand, in which the whole ice sheet slides relatively unbroken over the ground surface, frequently extend 50-100 m inland. Such ride-ups can occur on both thin as well as thick sea ice. If during ride-up the advancing ice front encountered a structure, a pile-up presumably could occur against the structure. Calculations suggest that the distributed forces during such events are small (1.5-50 psi [10 - 350 x 10^3 Pa]).

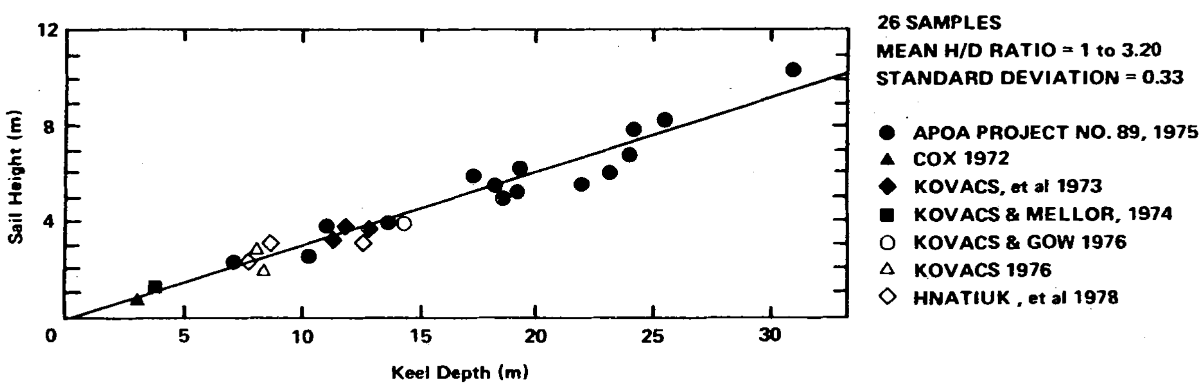

Figure B.23. Sail height vs. keel depth for 26 multi-year pressure ridges (Wright et al., 1979).

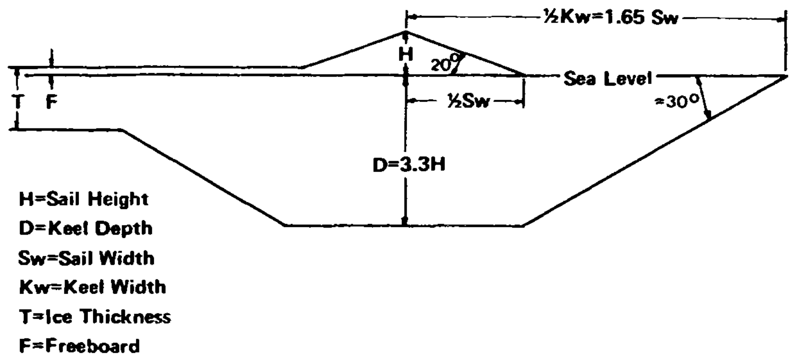

Figure B.24. Multi-year pressure ridge model (Kovacs, unpub.).

References

Ackley, S. F., W. D. Hibler, F. Kugzruk, A. Kovacs, and W. F. Weeks. 1974. Thickness and roughness variations of Arctic and multiyear sea ice, 1:109-117. In: Ocean '74, IEEE Int. Conf. Engineering in the Ocean Environment, New York.

Agerton, D. J., and J. R. Dreider. 1979. Correlation of storms and major ice movements in the nearshore Alaskan Beaufort Sea, 1:177-190. In: POAC 79. Nor. Inst. Tech., Trondheim, Norway.

Ahlnas, K., and G. Wendler. 1979. Sea ice observations by satellite in the Bering, Chukchi, and Beaufort Sea, 1:313-329. In: POAC 79. Nor. Inst. Tech., Trondheim, Norway.

Anderson, D. L. 1958. Preliminary results and review of sea ice elasticity and related studies. Trans. Eng. Inst. Canada 2:116-122.

Anderson, D. L. 1960. The physical constants of sea ice. Research 13:310-318.

Anderson, D. L., and W. F. Weeks. 1958. A theoretical analysis of sea ice strength. Trans. Amer. Geophys. Union 39:632-640.

Anonymous. 1980. Ice island count-Southern Beaufort Sea 1972-1976. A.P.O.A. Rev. 3:12-13.

Barnes, P. W., D. McDowell, and E. Reimnitz. 1978. Ice gouging characteristics: their changing patterns from 1975-1977, Beaufort Sea, Alaska. U.S. Geol. Sur. Open File Report 78-730, 42 pp.

Bercha, F. G., and D. G. Stenning. 1979. Arctic offshore deepwater ice-structure interactions, pp. 2377-2386. In: Proc. Offshore Tech. Conf., Houston, Tex. OTC 3632.

Bilello, M. 1980. Maximum thickness and subsequent decay of lake, river and fast sea ice in Canada and Alaska. USACRREL Report 80-6, 160 pp.

Brower, W. A. H. F. Diaz, A. S. Prechtel, H. W. Searby, and J. L. Wise. 1977. Climatic Atlas of the Outer Continental Shelf Waters and Coastal Regions of Alaska. Vol. 2: Bering Sea, 443 pp.; Vol. 3: Chukchi-Beaufort Sea, 409 pp. NOAA/OCSEAP, Boulder, Colo.

Buch, A., and S. Goldschmidt. 1970. Influence of porosity on elasticity moduli of sintered materials. Mat. Sci. Engng. 5:111-118.

Butkovich, T. R. 1956. Strength studies of sea ice. Snow, Ice and Permafrost Research Establishment Res. Rep. 20. 15 pp.

Butkovich, T. R. 1959. On the mechanical properties of sea ice, Thule, Greenland, 1957. Snow, Ice and Permafrost Research Establishment Res. Rep. 54. 11 pp.

Chamberlain, E. J., P. V. Sellmann, B. E. Blouin, D. M. Hopkins, and R. I. Lewellen. 1978. Engineering properties of subsea permafrost in the Prudhoe Bay region of the Beaufort Sea, pp. 629-635. In: Third Internat. Conf. Permafrost. Nat. Res. Council Canada.

Clukey, E. C., H. Nelson, and J. E. Newby. 1978. Geotechnical properties of northern Bering Sea sediment, U.S. Geol. Sur. Open File Report 78-408, 47 pp.

Coachman, L. K., K. Aagaard, and R. B Tripp. 1975. Bering Strait: The Regional Physical Oceanography. Univ. Wash. Press. Seattle, Wash.

Cox, G. F. N., and W. S. Dehn. 1981. Summer ice conditions in the Prudhoe Bay area, 1953-75, 2:799-808. In: B. Michael (ed.), POAC 81, Quebec, P.Q.

Croasdale, K. R. 1974. Crushing strength of Arctic ice, pp. 377-398. In: J. C. Reed and J. E. Sater (eds.), The coast and shelf of the Beaufort Sea. Arctic Inst. N. Am., Arlington, Va.

Deily, F. H. 1979. Aerial reconnaissance and subsea profiling of sea ice in the Bering Sea, 1:207-219. In: POAC 79. Nor. Inst. Tech., Trondheim, Norway.

Dunbar, M., and W. Wittmann. 1963. Some features of ice movement in the Arctic Basin, pp. 90-108. In: Proceedings Arctic Basin Symposium 1962. Arctic Inst. N. Am.

Dykins, J. E. 1967. Tensile properties of sea ice grown in a confined system, pp. 523-537. In: Physics of Snow and Ice. Inst. of Low Temperature Sci., Hokkaido Univ.

Dykins, J. E. 1970. Ice engineering: tensile properties of sea ice grown in a confined system. Naval Civil Engr. Lab. Tech. Rep. R689. 56 pp.

Dykins, J. E. 1971. Ice engineering: Material properties of saline ice for a limited range of conditions. Naval Civil Engr. Lab. Tech. Rep. R720. 95 pp.

Enkvist, E. 1972. On the ice resistance encountered by ships operating in the continuous mode of icebreaking. Swedish Acad. Eng. Sci. Finland, Rep. 24, 181 pp.

Gardiner, J. V., T. L. Vallier, and W. E. Dean. 1979. Sedimentology and geochemistry of surface sediments and the distribution of faults and potentially unstable sediments, St. George Basin region of the Outer Continental Shelf, Southern Bering Sea. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Final Rep. Phy. 2:181-271.

Gold, L. W., and A. Traetteberg. 1974. Young's modulus of ice and ice engineering problems. In: Second Symposium on Application of Solid Mechanics, June 1974. Fac. Engng., McMaster Univ., Hamilton, Ont.

Gow, A. J., H. T. Ueda, and J. A Richard. 1978. Flexural strength of ice on temperate lakes--comparative tests of large cantilever and simply supported beams. USA CRREL Rep. 78-09, 14 pp.

Hanson, A. M. 1980. Critique of Chukchi-Beaufort Sea climatic atlas. Arctic Alpine Res. 12:385-89.

Hawkes, I., and M. Mellor. 1972. Deformation and fracture of ice under uniaxial stress. J. Glaciol., 11:103-131.

Heideman, J. C. 1979. Oceanographic design criteria. In "Technical Seminar on Alaskan Beaufort Sea Gravel Island Design." EXXON Company, USA, Houston, Tex.

Hibler, W. D. 1975. Statistical variations in Arctic sea ice ridging and deformation rates. Proc. Soc. Naval Arch. Mar. Eng. Symposium on Ice Breaking and Related Technology, Montreal, 9-11 April 1975.

Hibler, W. D., and S. F. Ackley. 1973. A sea ice terrain model and its application to surface vehicle trafficability. CRREL Rep. 314. 21 pp.

Hibler, W. D., S. F. Ackley, W. F. Weeks, and A. Kovacs. 1972a. Top and bottom roughness of a multiyear ice floe. Int. Assoc. Hydraulic Res. Symposium on Ice and its Action on Hydraulic Structures, Leningrad.

Hibler, W. D., W. F. Weeks, and S. J. Mock. 1972b. Statistical aspects of sea ice ridge distributions. J. of Geophys. Res. 77:5954-5970.

Hutter, K. 1975. Floating sea ice plates and the significance of the dependence of the Poisson ratio on brine volume. Proc. Roy. Soc., Lond. A. 343:85-108.

Karp, L. B. 1980. Concept development of a concrete structure founded in the ice-stressed Chukchi Sea: A case of ice/structure interaction in an offshore arctic region. Dept. Civil Engng., Univ. Calif., Berkeley, Calif.

Katona, M. G., and K. D. Vaudrey. 1973. Ice engineering: summary of elastic properties research and introduction to visoelastic and non-linear analysis of saline ice. Naval Civil Eng. Lab. Tech. Rep. R797. 67 pp.

Kovacs, A. 1972. On the structure of pressured sea ice, pp. 276-295. In: T. Karlsson (ed.), Sea Ice, Proceedings on an International Conference. Nat. Res. Council, Reykjavik, Iceland.

Kovacs, A., and M. Mellor. 1974. Sea ice morphology and ice as a geologic agent in the southern Beaufort Sea, pp. 113-161. In: J. C. Reed and J. E. Sater (eds.), The coast and shelf of the Beaufort Sea, Arctic Inst. N. Am., Arlington, Va.

Kovacs, A., and D. Sodhi. 1980. Shore ice pile-up and ride-up: Field observations, models, theoretical analyses. Cold Regions Sci. Tech. 2:209-88.

Kovacs, A., W. F. Weeks, S. F. Ackley, and W. D. Hibler. 1973. Structure of a multiyear pressure ridge. Arctic 26:22-31.

Kozo, T. L., and O. I. Diachok. 1973. Spatial variability of topside and bottomside ice roughness and its relevance to underside acoustic reflection loss. AIDJEX Bull. 19:113-121.

Langleben, M. P., and E. R. Pounder. 1963. Elastic parameters of sea ice, pp. 69-78. In: W. D. Kingery (ed.), Ice and snow: Processes, properties, and applications. MIT Press, Cambridge, Mass.

Lewis, C. F. M. 1977. The frequency and magnitude of drift ice groundings from ice-scour tracks in the Canadian Beaufort Sea, 1:567-576. In: POAC 77. St. John's, Nfld.

Lewis, J. W., and R. Y. Edwards. 1971. Methods for predicting icebreaking and ice resistance characteristics of icebreakers. Trans. Soc. Naval Arch. Mar. Eng. 78:213-49.

Lin'kov, E. M. 1958. Study of the elastic properties of an ice cover in the Arctic. Vestnik Leningradskogo Univ. 13(4):17-22 (text in Russian with English summary).

Malmgren, F. 1927. On the properties of sea ice. Scientific results of the Norwegian North Pole Expedition with the "Maud", 1918-1925, 1(5):1-67.

Marine Board. 1981. Research Needs in Sea Ice Mechanics. Mar. Bd. Assembly of Eng., Nat. Res. Council/Nat. Acad. Sci.

Matthews, J. B. 1981. Observations of under-ice circulation in a shallow lagoon in the Alaskan Beaufort Sea. Ocean Manag. 6:223-234.

Maykut, G., and N. Untersteiner. 1969. Numerical prediction of the thermodynamic responses of Arctic sea ice to environmental changes. RAND Corporation (RM-6093-PK), Santa Monica, Calif.

McNutt, L. 1981. Ice conditions in the eastern Bering Sea from NOAA and LANDSAT imagery: winter conditions 1974, 1976, 1977, 1979. NOAA Tech. Memo. ERL PMEL-24, 179 pp.

Mock, S. J., A. D. Hartwell, and W. D. Hibler. 1972. Spatial aspects of pressure ridge statistics. J. Geophys. Res. 77:5945-5953.

Muench, R. D., and K. Ahlnas. 1976. Ice movement and distribution in the Bering Sea from March to June 1974. J. Geophys. Res. 81:4467-4476.

Paige, R. A., and C. W. Lee. 1967. Preliminary studies on sea ice in McMurdo Sound, Antarctica, during "Deep Freeze 65". J. Glaciol. 6:515-528.

Parmerter, R. R., and M. D. Coon. 1972. A model of pressure ridge formation in sea ice. J. Geophys. Res. 77:6565-6575.

Pease, C. H. 1981. Eastern Bering Sea ice processes. Monthly Weather Rev. 108 (12).

Peyton, H. R. 1966. Sea ice strength. Geophys. Inst., Univ. Alaska, Rep. UAG-182, Fairbanks, Alaska.

Reimnitz, E., and P. W. Barnes. 1974. Sea ice as a geologic agent on the Beaufort Sea shelf of Alaska, pp. 301-351. In J. C. Reed and J. E. Sater (eds.), The Coast and Shelf of the Beaufort Sea". Arctic Inst. N. Am., Arlington, Va.

Reimnitz, E., and D. K. Maurer. 1978. Storm surges in the Alaskan Beaufort Sea. USGS Open-File Rep. 78-593, 26 pp.

Reimnitz, E., L. J. Toimil, and P. W. Barnes. 1977. Arctic continental shelf processes and morphology relative to sea ice zonation. AIDJEX Bull. 36:15-64.

Sackinger, W. M., and P. A. Sackinger. 1975. Shear strength of the adfreeze bond of sea ice to structures, pp. 607-614. In: POAC 75, St. Johns, Nfld.

Saeki, H., T. Nomura, and A. Ozaki. 1979. Experimental study on the testing methods of strength and mechanical properties for sea ice, 1:135-149. In: IAHR Symposium on Ice Problems, Lulea, Sweden.

Schwarz, J. 1971. The pressure of floating ice-fields on piles, pp. 373-385. In: IAHR Symposium on Ice Problems, Hanover, N. H.

Schwarz, J., and W. F. Weeks. 1977. Engineering properties of sea ice. J. Glaciol. 19:499-531.

Selkregg, L. L. (ed.). 1975. Alaska Regional Profiles. University of Alaska, Arctic Environmental and Data Information Center, Anchorage. Vol. II: Arctic Region, 218 pp.; Vol. V: Northwest Region, 265 pp.; Vol. VI: Yukon Region, 346 pp.

Sellman, P.V., and E. J. Chamberlain. 1979. Permafrost beneath the Beaufort Sea: Near Prudhoe Bay, Alaska, pp. 1481-1488. In: 11th Annual Offshore Technology Conference, Houston, Tex. (OTC 3527).

Sellmann, P. V., E. J. Chamberlain, A. Delaney, and K. G. Neave. 1980. Delineation and engineering characteristics of permafrost beneath the Beaufort Sea. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP. Ann. Rep. 4:125-157.

Shapiro, L. H. 1975. A preliminary study of ridging in landfast ice at Barrow, Alaska, using radar data, 1:417-425. In: POAC 75. Inst. Mar. Sci., Univ. Alaska, Fairbanks, Alaska.

Shapiro, L. H., and J. J. Burns. 1975. Satellite observations of sea ice movement in the Bering Strait region, pp. 379-386. In: G. Weller and S. A. Bowling (eds.), Climate of the Arctic. Geophys. Inst. Univ. Alaska, Fairbanks, Alaska.

Sharma, G. D. 1979. The Alaskan Shelf. Springer-Verlag, New York.

Slesarenko, Yu. Ye., and A. D. Frolov. 1974. Comparison of elasticity and strength characteristics of salt-water ice, 2:85-97. In: IAHR Symposium: Ice and its action of hydraulic structures, Leningrad.

Stehle, N. S. 1970. Adfreezing strength of ice. In: Proc. IAHR Ice Symposium, Reykjavik, Iceland. paper 5.3.

Stringer, W. J. 1978. Morphology of Beaufort, Chukchi and Bering Seas Nearshore Ice Conditions by Means of Satellite and Aerial Remote Sensing. Geophys. Inst., Univ. Alaska, Vol. I, 218 pp., Vol. II, 576 pp.

Tabata, T. 1960. Studies on mechanical properties of sea ice. V. Measurement of flexural strength. Low Temp. Sci., Ser. A. 19:187-201.

Tabata, T. 1967. Strength of the mechanical properties of sea ice, X--the flexural strength of small sea ice beams, 1:481-497. In: Physics of Snow and Ice. Inst. Low Temp. Sci., Hokkaido Univ.

Tabata, T., K. Fujino, and M. Aota. 1967. Studies of the mechanical properties of sea ice: The flexural strength of sea ice in situ, 1:539-550. In: Physics of Snow and Ice, Inst. Low Temp. Sci., Hokkaido Univ.

Tabata, T., Y. Suzuki, and M. Aota. 1975. Ice study in the Gulf of Bothnia II-Measurements of flexural strength. Low Temp. Sci., Ser. A., 33:199-206.

Toimil, L. 1979. Ice gouge characteristics in the Alaskan Chukchi Sea, 2:863-876. In: Civil engineering in the oceans IV. San Francisco.

Thor, D. R., and H. Nelson. 1979. A summary of interacting surficial geologic processes and potential geologic hazards in the Norton Sound Basin, Northern Bering Sea, pp. 377-385. In: Proc. Offshore Tech. Conf., Houston, Tex. (OTC 3400).

Thor, D. R., and A. Nelson. 1981. Ice gouging on the subarctic Bering shelf, 1:279-291. In: D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources. NOAA/OMPA, Seattle, Wash.

Tucker, W. B., and J. Govoni. 1981. Morphological investigations of first-year sea ice pressured ridge sails. Cold Regions Sci. Tech. (in press).

Tucker, W. B., W. F. Weeks, and M. Frank. 1979. Sea ice ridging over the Alaskan continental shelf. J. Geophys. Res., 84:4885-4897.

Tucker, W. B., W. F. Weeks, A. Kovacs, and A. J. Gow. 1980. Nearshore ice motion at Prudhoe Bay, Alaska, pp. 261-272. In: R. S. Pritchard, (ed.), Sea Ice Processes and Models. Univ. Wash. Press. Seattle, Wash.

Tusima, K., and T. Tabata. 1979. Friction measurements of sea ice on flat plates of metals, plastics, coatings, 1:741-755. In: POAC 79, Trondheim, Norway.

Untersteiner, N. 1968. Natural desalination and equilibrium salinity profile of perennial sea ice. J. Geophys. Res., 73:1251-1257.

Urabe, N., T. Isawasaki, and A. Yoshitake. 1980. Fracture toughness of sea ice. Cold Regions Sci. Tech. 3:29-37.

Vaudrey, K. D. 1977. Ice engineering-study of related properties of floating sea-ice sheets and summary of elastic and viscoelastic analysis. U.S. Navy Civil Engng. Lab. Rep. TR-850. 81 pp.

Wadhams, P. 1976. Sea ice topography in the Beaufort Sea and its effect on oil containment. AIDJEX Bull. 33:1-52.

Wadhams, P. 1980. A comparison of sonar and laser profiles along corresponding tracks in the Arctic Ocean, pp. 283-299. In: R. S. Pritchard (ed.), Sea ice processes and models, Univ. Wash. Press, Seattle, Wash.

Wadhams, P., and R. J. Horne. 1980. An analysis of ice profiles obtained by submarine sonar in the Beaufort Sea. J. Glaciol. 25:401-24.

Wang, Y. S. 1979. Sea ice properties. In: Technical seminar on Alaskan Beaufort Sea gravel island design, EXXON Co., USA, Houston, Tex.

Wang, Y. S. 1980. Crystallographic studies and strength tests of field ice in the Alaskan Beaufort Sea, pp. 651-665. In: POAC 79, Trondheim, Norway.

Weeks, W. F., and A. Assur. 1967. The mechanical properties of sea ice. USA CRREL Cold Regions Science and Engineering IIC3.

Weeks, W. F., and A. Assur. 1969. Fracture of lake and sea ice. USA CRREL Res. Rep. 269.

Weeks, W. F., P. W. Barnes, D. Rearic, and E. Reimnitz. 1981. Statistical aspects of ice gouging on the Alaskan Shelf of the Beaufort Sea. USA CRREL Report (in press).

Weeks, W. F., and A. J. Gow. 1978. Preferred crystal orientation in the fast ice along the margins of the Arctic Ocean. J. Geophys. Res. 83:5105-5121.

Weeks, W. F., and A. J. Gow. 1980. Crystal alignments in the fast ice of Arctic Alaska. J. Geophy. Res. 85:1137-1146.

Weeks, W. F., and A. Kovacs. 1970. The morphology and physical properties of pressure ridges, Barrow, Alaska, April 1969. In: Int. Assoc. Hydraulic Res. Symposium on Ice and Its Action on Hydraulic Structures, Reykjavik, Iceland, paper 3.9.

Weeks, W. F., A. Kovacs, and W. D. Hibler. 1971. Pressure ridge characteristics in the arctic coastal environment, 1:152-183. In: Proc. First International Conference on Port and Ocean Engineering under Arctic Conditions, Tech. Univ. Trondheim, Norway.

Weeks, W. F., and O. S. Lee. 1958. Observations on the physical properties of sea ice at Hopedale, Labrador. Arctic 11:134-155.

Weeks, W. F., W. B. Tucker, M. Frank, and S. Fungcharoen. 1980. Characterization of surface roughness and floe geometry of the sea ice over the continental shelves of the Beaufort and Chukchi Seas, pp. 300-312. In: R. S. Pritchard, (ed.), Sea ice processes and models, Univ. Wash. Press. Seattle, Wash.

Wheeler, J. D. 1979. Sea ice statistics. In: Technical Seminar on Alaskan Beaufort Sea Gravel Island Design. EXXON Company, USA, Houston, Tex.

Wittmann, W. I., and J. J. Schule. 1966. Comments on the mass budget of Arctic pack ice, pp. 217-246. In: J. O. Fletcher, (ed.), Proc. Symposium on Arctic Heat Budget and Atmospheric Circulation, RAND (RM-5233-NSF).

Wright, B., J. Hnatiuk, and A. Kovacs. 1979. Multiyear pressure ridges in the Canadian Beaufort Sea, 1:107-126. In: Proc. POAC 79, Trondheim, Norway.

Zubov, N. N. 1945. Arctic Ice. Izdatel'stvo Glavesmorputi, Moscow (in Russian).

APPENDIX C

SEASONAL ICE MORPHOLOGY MAPS

By W. J. Stringer

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C.1 EXPLANATION OF LATE FALL TO EARLY WINTER ICE MORPHOLOGY MAP (FIG. C.1)

The following maps have been prepared with attached explanatory notes and comments to provide a background of the average behavior of the ice in the Harrison Bay region at the different times of year. Extremely unlikely events are not shown on these maps.

The zones defined on this map are used to describe the formation of near-shore ice during late fall and early winter. These zones are all within what becomes, by the end of the period covered by this map, the fast-ice region (Region I) as defined by the shoreward limit of the zone of flaw leads (the dashed line).

Zone Ia

By the end of early winter, this zone contains relatively undeformed fast ice which has traditionally been used as a transportation route. This zone has been divided into two subzones according to the presence or absence of islands to the seaward side which tend to protect the ice and cause it to be even less deformed. These subzones could be subdivided even further by the limits of what later becomes the bottomfast zone (2 meters). That has not been done here because this aspect of ice morphology has no obvious effect on ice behavior during this period. (Furthermore, ice does not grow to its full thickness until April).

Subzone Ia1. This subzone lies shoreward of barrier islands. Ice often forms here in late October. At this time, thin sheets of newly formed ice can be seen detached from shore and drifting around. Some rafting is apparent. However, ice within this subzone does form relatively early and becomes the smoothest sea ice found within any zone. Although local deformations may take place, vast expanses of very smooth ice may also be formed. Large cracks, presumably resulting from thermal contraction, can form in this zone. Ridging is almost totally absent.

Subzone Ia2. Ice forms here early in the ice season in thin sheets attached to shore. This ice is apparently easily detached and is often transported away. Eventually, stable ice does form, and the extent of its small-scale roughness depends a great deal on the conditions responsible for the final ice cover. However, large-scale ridges do not form within this zone (and actually are used to define its seaward limit).

Zone Ic

This zone forms after Zone Ia. (Zone Ib is a special case and will be described later.) It contains concentrations of large ridges which begin forming in early December. All the ridges become stable and are presumably bottomfast. The zone has been subdivided into two subzones which surround Zone Ib.

Subzone Ic1. Ice forms here relatively early in December and covers water depths between 10 and 14 m. This subzone is defined by the location of ridges marking the seaward limit of Subzone Ia2. These ridges begin forming around the 10-m isobath and build seaward, each strengthening the

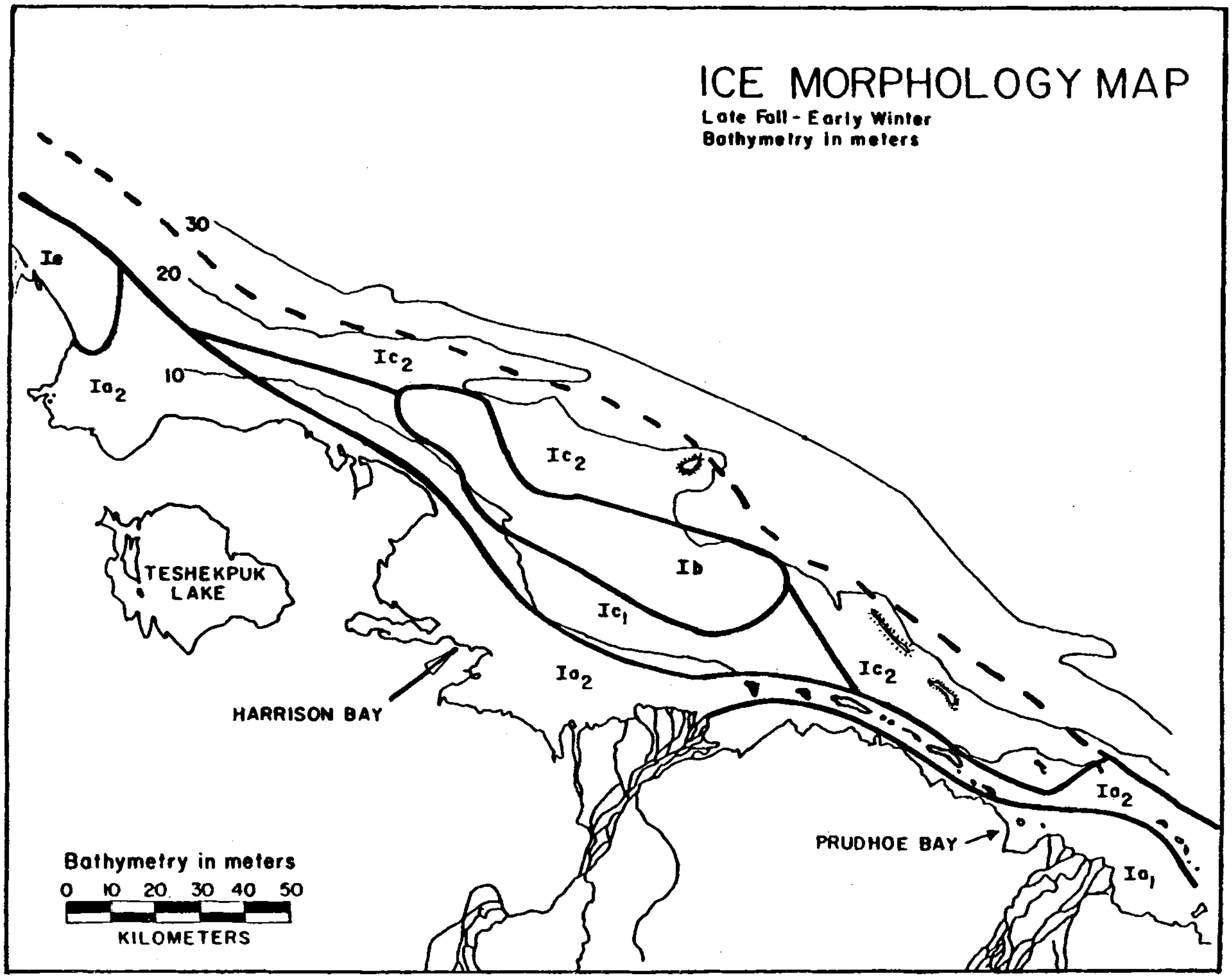

Figure C.1. Late fall - early winter ice morphology map (Stringer, 1981).

ice for the formation of ridges farther seaward. This subzone is not well defined every year. Some years only minor ridging occurs.

Subzone Ic2. This is the site of major ridging and hummocking between mid-December and mid-January. Massive ridges and extensive hummock fields form, and all become part of the stable fast ice. Many of the ridges are long and sinuous (shear ridges). In addition, some of the large hummock fields tend to recur each year, forming on the shoals shown on this map adjacent to the 20-m isobath.

Zone Ib

This is a zone of relatively undeformed ice surrounded by the Ic subzones. The following mechanism is postulated for its formation: In early December, ridges begin forming around the 10-m isobath, usually as a result of pack ice driven from the east. With time, the ridges form at increasing depths, building seaward throughout Zone Ic. When the depth of ridge formation reaches 14 m, ridges and hummock fields begin building on the shoals located near the eastern end of Subzone Ic2. This buildup brings the westward passage of ice through Harrison Bay to an abrupt halt, ending the construction of ridges there at about the 14-m isobath and defining subzone Ic1. The line of shoals causes the zone of ridging to be deflected around the middle of Harrison Bay, forming a zone where shear ridging does not take place, Zone Ib. Thus, this zone forms in the "shadow" of the shoals identified on this map. It can contain relatively rough ice--essentially the pack ice which was located there when the deflection of ridging took place. Often large pans with rims of piled ice can be found surrounded by relatively flat ice--presumably areas of water when the pack ice motion stopped. Occasionally, rather dirty pans can be found frozen into this zone.

Zone Ie

This is an area of nearshore fast ice with some major ridges. As it is largely out of the area of discussion, it will not be considered further.

C.2 EXPLANATION ON LOCATIONS OF MAJOR RIDGES 1973-1977 (FIG C.2)

Shown here are the major ridges and hummock fields observed on LANDSAT imagery between 1973 and 1977. Each year's data are denoted by their own symbol. Hummock fields are denoted by concentric groupings of that year's symbol. Also shown is the 20-m isobath.

In the Harrison Bay area are three zones of ridging.

A. An inner zone, located in water depths around 10 m. The ridges found here form early in the year when the ice is relatively thin. Later, major ridging takes place farther seaward. These ridges are grounded.

B. A middle zone, located near the 20-m isobath. The ridges found here generally define the seaward boundary of the stable portion of the fast ice between January and June (although on occasion a considerable extent of "attached" fast ice can extend even tens of kilometers seaward of these ridges). These ridges are generally grounded. However, ridges on the seaward side of this zone have been observed to be carried away during dynamic ice events.

C. An outer zone, located in water depths significantly greater than 20 m. The ridges found here are very likely not grounded. They form as pack ice is driven past floating "attached" fast ice. Clearly, these ridges can be transported away when flaw leads occur shoreward.

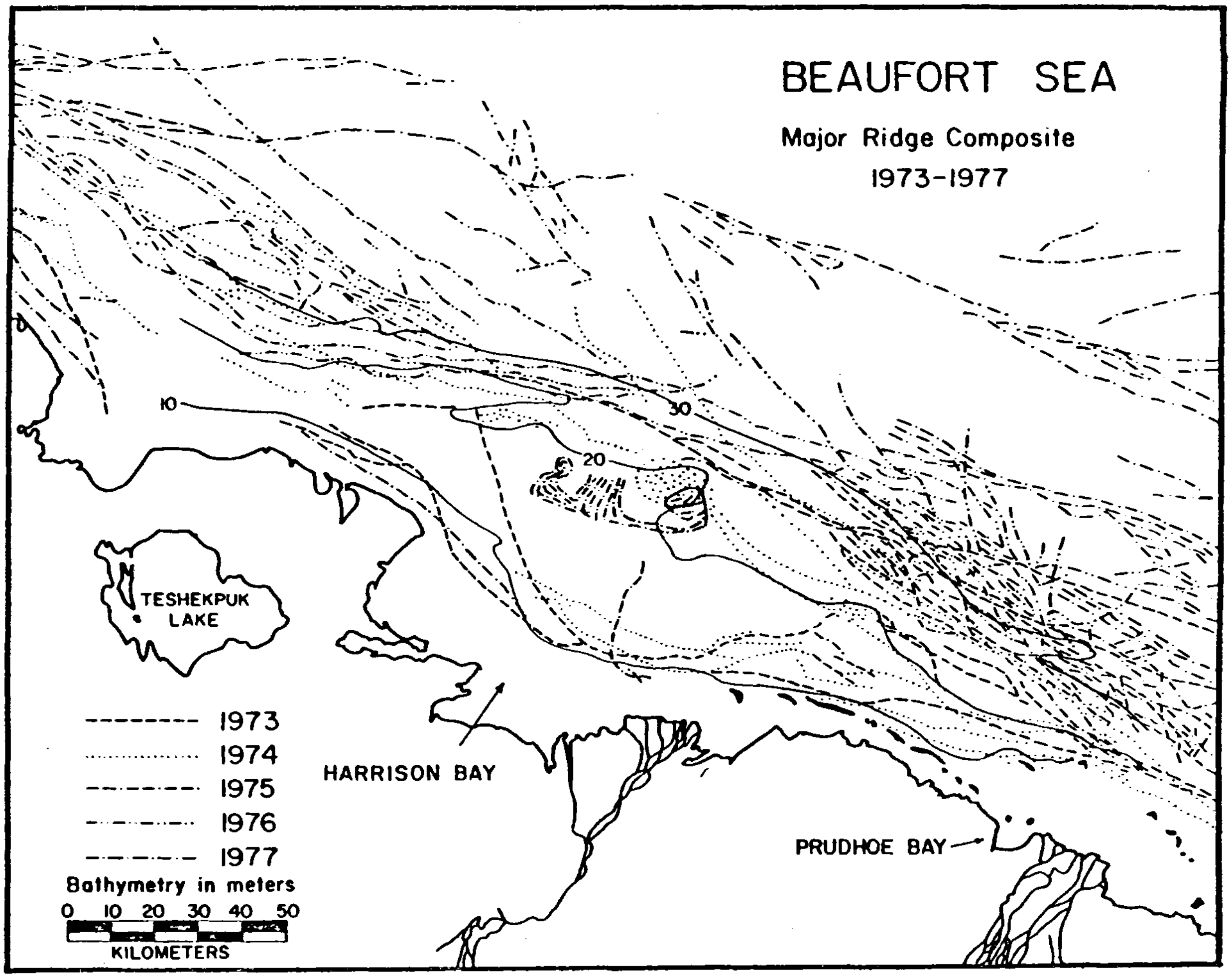

Figure C.2. Locations of Major Ridges 1973-1977 (Stringer, 1981).

In addition, a zone of hummock fields lies just shoreward of the 20-m isobath. In general, these hummock fields coincide with the locations of shoals just landward of the 20-m isobath. Apparently, during some years, piled ice accumulates on these shoals after or about the same time that the inner ridge zone forms but before the middle zone forms.

C.3 EXPLANATION ON THE EDGE OF FAST ICE MAP (FIG C.3)

This map shows the edges of fast ice recorded between February and June, 1973-1977. The edge of fast ice can nearly always be easily identified on LANDSAT imagery. The boundary generally falls within one of three categories:

A. <u>Flaw lead</u>. A flaw lead appears as a black line or band against the white background of the snowcovered ice. The flaw lead occurs when the ice fails under tension and parts.

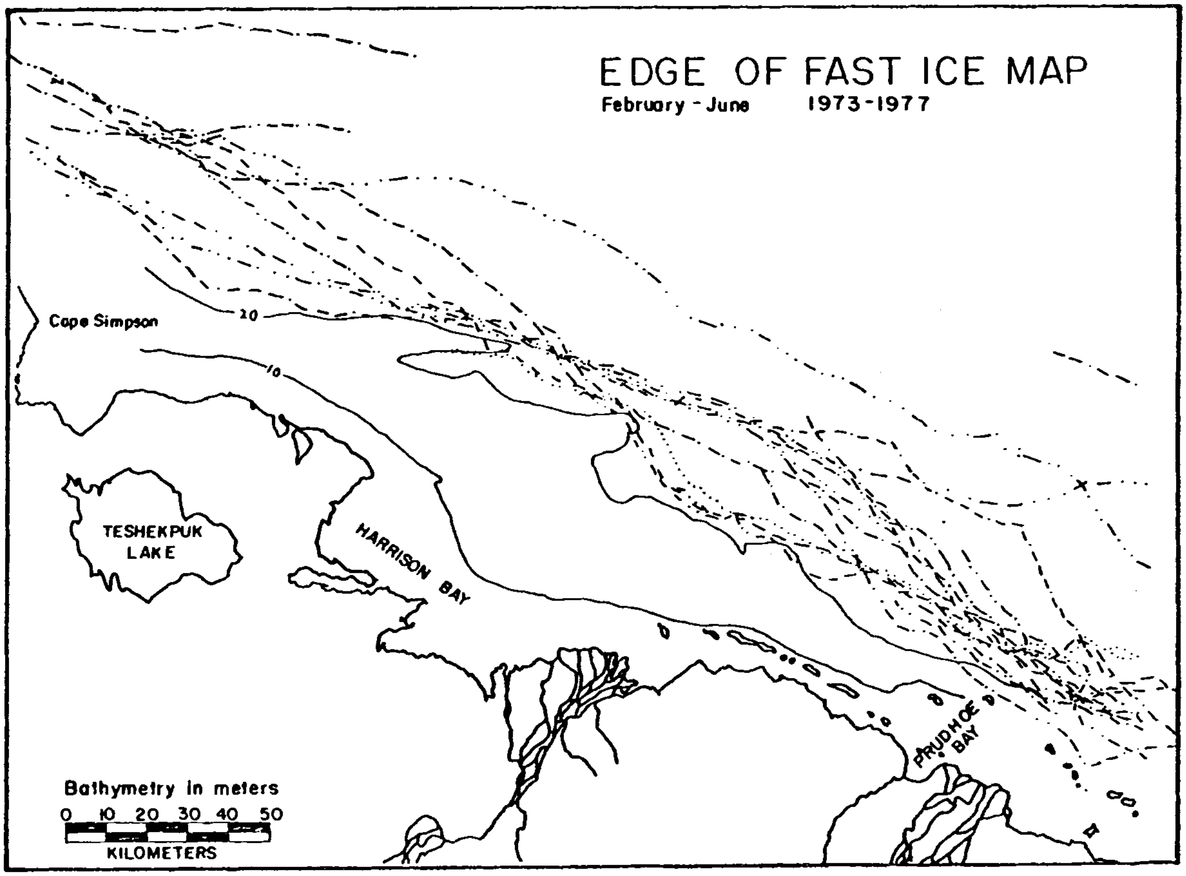

Figure C.3. Edge of fast ice map (Stringer, 1981).

B. Line of failure. If the ice fails under compression, obviously a flaw lead is not created. Generally the line of failure is somewhat irregular, and, depending on the degree of compression and magnitude of tangential forces, it is composed of shear ridges and short leads and polynyas. Seaward, cracks and leads generally appear, whereas landward, the fast ice does not fail. The line of failure often appears as a grey line punctuated by leads and polynyas, with cracks and leads radiating seaward.

C. Zone of shear stress. At times, particularly when the fast ice extends far beyond the grounded ridges, shear stress can build until crack patterns occur, but complete failure does not take place. The shearing forces cause a characteristic pattern of parallel cracks at approximately 30° to the ultimate line of failure. Ice which has been stressed to this degree is not considered fast ice, and the edge of fast ice is drawn shoreward of these locations. In the absence of additional shear, the leads created may simply freeze over. When this occurs, the edge of fast ice is drawn to the seaward.

An attempt was made to detect a systematic seasonal advance or retreat of the average edge of fast ice which would indicate a strengthening (or weakening) of the fast ice sheet. No consistent behavior was found although there is a general trend seaward until March-April and shoreward thereafter.

The edges of fast ice drawn here do not mean that the boundary between fast ice and pack ice is always located within the envelope of edges drawn here. On some occasions, the edge of fast ice has been observed considerably farther seaward than the study area. However, when the ice failed following these occasions, the line of failure was one of the lines shown here. Hence, it could be concluded that the occasional extensive advance of the fast ice occurred as a result of the absence of stress within the ice under freezing conditions rather than a general strengthening of the ice.

The edge-of-fast-ice maps defines the seaward edge of stable fast ice between February and June. Clearly, the farther landward one progresses through the envelope of observed ice edges shown here, the more stable is the fast ice. Conversely, as one passes farther seaward through the envelope of flaw leads, the greater the chance of encountering pack ice.

C.4 EXPLANATION OF EARLY WINTER TO LATE SPRING ICE MORPHOLOGY MAP (FIG C.4)

This map is divided into three major regions:

I. <u>The stable fast-ice region</u>: After the end of January, the ice in this zone is shorefast and stable with a very low probability of failure.

II. <u>Flaw-lead region</u>: This zone is defined by the statistical envelope of flaw leads. The ice within this zone is alternately fast ice or pack ice during this season.

III. <u>Pack-ice region</u>: Flaw leads are generally inshore of this zone, and the ice here can be considered to be pack ice.

Ice within Region I is static during this season. The dynamics of this zone were described in terms of the Late Fall-Early Winter Morphology Map. The nature of ice in the subzones of Zone I will be described as they are generally found during this time.

Region I

<u>Zone Ia</u> consists of two subzones. The presence of barrier islands on the seaward side of subzone Ia1 causes the ice here to be even smoother and more stable than that within Ia2. However, this entire zone has traditionally been used as a transportation route. Another distinction has not been indicated on this map: As winter progresses the ice grows to depths of 2 m or more. As a result, by April most of the ice within the 2-m isobath is bottomfast.

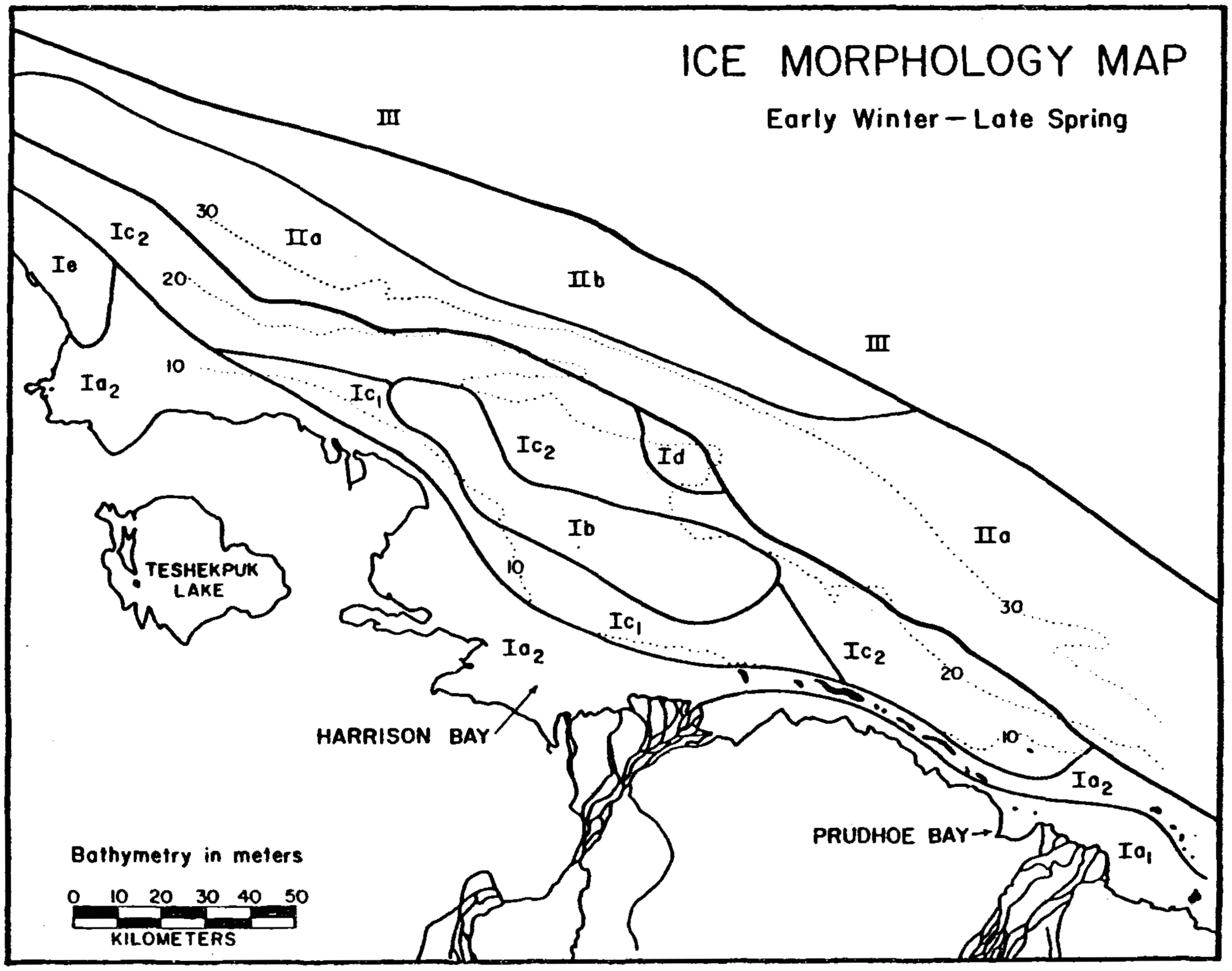

Figure C.4. Early winter - late spring ice morphology map (Stringer, 1981).

Zone Ib is an island of floating fast ice generally overlying waters 14-18 m deep; it may be rough or smooth but does not contain large grounded-ridge systems.

Zone Ic contains most of the major ridges and hummock fields in the stable fast-ice zone. Its inshore boundary generally coincides with the 10-m isobath and is defined by the shoreward edge of the envelope of large grounded ridges. Its seaward boundary is defined by the observed shoreward limit of the envelope of flaw leads between February and July. Subzone Ic1 develops earlier than Ic2 and is smoother. Subzone Ic2 contains long, sinuous, grounded shear ridges and hummock fields.

Zones Id are locations of persistent large, hummock fields grounded on shoals.

Zone Ie is a zone of nearshore ice within the 10-m isobath which contains some grounded ridges.

Region II

Ice within Region II is highly dynamic and could appropriately be called a "shear zone" because shearing often takes place here, frequently to the point of failing the ice. This zone has been defined by the envelope of flaw leads. Because of these leads, this is also a region of major ridging from February through June. Unlike the ridges in Zone Ic2, these ridges are not generally well grounded and more readily broken up and transported. Based on ridge density this region has been divided into two zones. Zone IIB contains significantly fewer ridges than IIa.

Ice within Region III is generally pack ice during the period concerned here, although occasionally it can become fast for up to a few weeks.

C.5 ICE HAZARDS

This discussion refers to the zones defined on the Mid-winter to Late Spring Ice Morphology Map, and covers the period October 1 through July 1.

Override and ride-up

This hazard increases with the thickness of the ice. It appears that long-range internal ice forces are required for significant displacements. The morphology and geographic configuration of ice in the various zones indicate that override and ride-up could damage man-made structures during the following periods:

Zone	Period	Relative Hazard
Ia1	10/1 - 12/1	Very low: long-range forces not likely to build up because of barrier islands.
Ia2	10/1 - 12/1	Low: ice does not become very thick before grounded ridges form to seaward.
Ic1	10/1 - 12/15	Moderate: ice subject to motion when moderately thick (1 m).
Ib	10/1 - 1/1	Significant: ice subject to motion when moderately thick (1 m).
Ic2	10/1 - 2/1	Great: ice grows to significant thickness (1 m) when still mobile.
Id	10/1 - 1/1	Great: ice normally piles in hummock fields when at moderate thickness (1 m).
IIa	10/1 - 7/1	Very great: ice grows to maximum thickness (2 m) and is subject to motion at any time.

Zone	Period	Relative Hazard
IIb	10/1 - 1/1	Great: ice grows to maximum thickness (2 m) and is subject to motion at any time.
III	10/1 - 7/1	Extremely large: ice grows to maximum thickness and is subject to motion throughout the ice season.

Large-draft ice features

By far the greatest hazards in this category are tabular icebergs adrift in the Arctic Ocean. The danger is largely a function of water depth modified by the presence of firmly grounded barrier ridges. The next-largest deep-draft features are free-floating first-year ridges followed by multiyear ice (which here we take to include stamukhi). The following table gives the dates by zone when each of these features could be a problem during the period October 1 through July 1. Generally the formation of stable fast ice in a zone eliminates this hazard from a particular zone, while the water depth determines the range of potential hazards to which the zone is subject.

Zone	Tabular iceberg (draft 25 m)	Iceberg fragments (draft 14 m, 25 m)	Floating first-year ridges	Multiyear ice	Maximum draft (m)
Ia1	----	----	----	----	5
Ia2	----	----	----	10/1-12/1	10
Ib	----	10/1-1/1	10/1-1/1	10/1-1/1	20
Ic1	----	10/1-12/15	10/1-12/15	10/1-12/15	14
Ic2	----	10/1-2/1	10/1-2/1	10/1-2/1	22
Id	----	----	10/1-12/1	10/1-2/1	14
Ie	----	----	----	----	----
IIa, b	10/1-7/1	10/1-7/1	10/1-7/1	10/1-7/1	30
III	10/1-7/1	10/1-7/1	10/1-7/1	10/1-7/1	Arctic Ocean ice features not draft-limited by bathymetry

C.6 TRANSPORT OF SPILLED PETROLEUM

This discussion refers to the zones defined on the Mid-winter to Late Spring Ice Morphology Map and covers the period October 1 through July 1.

It deals only with large-scale ice morphology (open water, freezing conditions, ridge formation) and not under-ice currents, surface winds, and brine-channel drainage.

Region I

Zones Ia and Ie. Between October and early December petroleum spilled within this zone could encounter a wide variety of conditions ranging from open water to a closed canopy. Furthermore, ice conditions could quickly change following introduction of petroleum --even to include the advection of contaminated ice away from the shore. However, it is most likely that spilled petroleum would be incorporated in the newly-forming ice by rafting, local piling, and encapsulation.

After early December, the ice tends to remain stable and maintain a closed canopy. The major exceptions are tidal cracks at the boundary between bottomfast ice and floating fast ice and thermal tension cracks (which can become pronounced in subzone Ia1). Petroleum spilled on top of the ice canopy or originating under the ice would tend to remain where spilled except near the aforementioned cracks.

Beginning in May, this zone is subject to riverine flooding, followed by melting of ice near shore. Since this could follow brine-channel drainage and introduction of petroleum to the ice surface, transport by surface flooding or introduction into recently melted leads and polynyas could take place between May and July.

Zone Ib. Ice in this zone is highly mobile between October 1 and late December. It often consists of unconsolidated floes and open water under freezing conditions. Spilled Petroleum could be transported either in open water or in newly formed ice. The petroleum would most likely become highly incorporated within the ice.

From mid-December until late June, the ice remains stable fast ice. Petroleum spilled either on or under the ice would tend to remain where it had been spilled.

In mid-June, melt ponds start to develop, and at least local horizontal transport and vertical migration of petroleum from one side of the ice barrier to the other are possible.

Zone Ic1. Ice within this zone is highly mobile and subject to ridging and hummocking between October and mid-December. Petroleum introduced then could be transported a considerable distance either in open water or in newly formed ice. The petroleum could also be incorporated into newly formed ice which is hummocked and ridged.

Zones Ic2 and Id. This zone is the most seaward of the stable fast-ice zones. Ice here is stable after late January. Before then, spilled petroleum could encounter conditions ranging from open water through freezing ice to ridging ice nearly a meter thick. Transport to remote sites or incorporation within ice that is subsequently piled into massive shear ridges is likely.

After late January, this zone becomes stable fast ice. Petroleum introduced then would tend to remain on the side of the ice canopy where it originated. Many deep underwater pockets in the ice could catch and retain the petroleum.

This zone tends to persist the longest of the stable fast ice--usually well into July.

Region II

Zones IIa and IIb. Ice in these zones remains highly mobile until January or February. Before that time conditions are similar to those described for Zones Ic2 and Id during the period October to mid-January.

After mid-January this zone is the site alternately of fast ice and of recurring flaw leads followed by shear ridging. A petroleum spill between January and July could encounter fast ice which would remain in place as long as six to eight weeks or a porous network of floes and leads. The probability of encountering broken ice increases seaward across these zones, and with time after mid-April. By mid-May, these zones largely contain mobile pack ice. Petroleum spilled during this period has an increasing chance of being incorporated into ridges and transported with ice. This chance also increases seaward across these zones. Ice is normally transported westward at about 1 km/d between February and April.

Region III

Usually this region contains pack ice the entire winter season. However, on some occasions fast ice extends into this zone, and much of the time large expanses of continuous ice are found. Petroleum spilled in this zone would be incorporated into the pack ice and join in its generally westward drift.

APPENDIX D

ISSUE ANALYSIS
by D. Redburn

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ISSUE ANALYSIS
By D. Redburn

[ed. note: The following section on drilling wastes was contributed by Doug Redburn of the Alaska Department of Environmental Conservation, Juneau, after the April Synthesis Meeting. The author is centrally involved in the regulatory and management issues he discusses in this section.]

Issue VIII. Disposal and Drilling Wastes

The regulation of the disposal of drilling wastes (muds, cuttings, and formation waters) in Arctic waters has evolved in recent years in response to selected studies in the Beaufort Sea and literature reviews covering the entire United States continental shelf. Drilling muds, and cuttings, on the one hand, and formation waters, on the other, are two entirely different categories of waste and have been regulated accordingly.

Drilling Muds and Cuttings

Discussion. The issue of environmentally acceptable disposal practices for drilling mud and cuttings in the Beaufort Sea is recognized during both the exploratory and development phases of oil and gas operations. As with produced waters, the regulatory decision on discharge has been principally based on the following criteria: 1) local oceanographic circulation patterns, 2) depth of water, 3) sensitivity of the receiving water biota, 4) volume of discharge, 5) rate of input, and 6) relative toxicity of the drilling mud formulation as specified on the product label. The composition (and hence, the relative toxicity) of drilling mud is variable within certain limits since the mud makeup is altered as a function of drilling depth. All muds are primarily composed of inert constituents (e.g., barite and bentonite clays) plus a variable suite of additives such as ferro-chrome lignosulfate. The chemical composition of drilling muds used in the Reindeer Island stratigraphic test well is documented in the Reindeer Island stratigraphic study (Northern Technical Services, 1981).

Past and current drilling mud disposal methods for the nearshore Beaufort have included both above ice and under ice disposal of non oil-based muds, reinjection down the well bore, and disposal at approved upland sites. These practices in state waters are subject to case-by-case review by the Department of Environmental Conservation through issuance of a wastewater disposal permit; EPA regulates discharges in Federal waters.

Offshore disposal of drilling muds free of hydrocarbon contamination during the exploratory phase has been permitted for experimental purposes to objectively evaluate the short-and long-term effects of mud disposal on selected fish and invertebrates, and to develop a long-range policy for their disposal.

Sohio Alaska Petroleum Company contracted Northern Technical Services to conduct several such studies, specifically at Reindeer Island and surrounding areas during the winter of 1979-1980 and during the winter of 1980-1981 in the Sagavanirktok River Delta and at Challenge Island (Northern Technical Services, 1981). Only the results and conclusions of the Reindeer Island study are summarized as the later study results are not yet available. The following selective conclusions were drawn from the Reindeer Island study:

A. Above ice disposal delays release of the effluent until the later stages of breakup when the receiving waters are naturally turbid. At that time, the effluent is released slowly thus helping to ensure maximum dilution and dispersion.

B. Additional above ice dispersion can be achieved prior to sea ice breakup if the above ice disposal site can be located nearshore in areas of river flooding.

C. Freshwater drilling muds readily flocculate upon discharge into seawater. These flocculants are loosely deposited on the seafloor during winter and can be resuspended with the slightest agitation.

D. Ninety-six hour LC_{50} values obtained from bioassay testing (concentration of drilling effluent that produces mortalities in 50 percent of the test organisms in four days) ranged from 4 percent to greater than 70 percent by volume. Fish were among the most sensitive organisms tested while invertebrates included both sensitive and relatively resistant species.

E. While not statistically definitive, trace metal analyses suggest that most heavy metal concentrations in organisms subjected to both 96-hour and several-month exposures to drilling effluents are within the high natural range of these metals in unexposed organisms. Cadmium showed some potential for accumulation in exposed amphipods.

F. Physical modeling of below ice discharge and in-situ tests show concentrations of drilling effluents at the seafloor to be approximately 25 percent or less of the lowest 96-hour LC_{50} value determined by acute toxicity tests.

G. Based upon random replicate bottom sampling at the test disposal and control sites, it is concluded that over several months there were not detectable changes in benthic fauna that were attributable to the test disposal of drilling effluents when statistically compared to control populations.

H. In-situ exposure to discharged drilling fluids had no apparent effect on species of clams used in three-month tray experiments, although this conclusion cannot be statistically validated due to the small number of samples.

I. Simulated above ice disposal of drilling fluid has no effect on diatom assemblages that developed during the summer.

Whereas the results of this single-well exploratory study suggest acute (lethal) short-term effects of drilling fluids to adult organisms characteristic of the Beaufort Sea, these are unlikely, except in the immediate vicinity of the discharge, sublethal and long-term (greater than one year) effects of multiple well dumps in a shallow fixed area (e.g., development drilling phase) on bottom organisms are still unknown and have not been tested to date. Available short-term laboratory toxicity tests and direct field examination suggest a hypothesis that the major and very localized detrimental effects from drilling mud and cutting disposal result from physical smothering of bottom dwelling organisms, with little field documentation of chemically related toxic effects (Northern Technical Services, 1981).

Recommendations (drilling muds and cuttings). The drilling stipulation for the Joint Federal-State Lease Sale area is not an absolute restriction; rather, it requires case-by-case evaluation by appropriate Federal and state managers.

> "Discharge of drilling muds and cuttings into marine water is prohibited, except that the Supervisor [Director] may approve discharge (a) in tracts greater than 10 meters of water on a case-by-case basis and (b) in tracts of less than 10 meters of water on a case-by-case basis if effluents are shown to be non-toxic and can be adequately dispersed."

Recent studies suggest few acute effects, yet a continuation of case-by-case evaluation of mud disposal in water less than 10 meters deep is warranted pending evaluation of results of current above ice disposal studies. Should these studies, which cover a range of ice conditions and geographic locations, uphold the hypothesis of few to no acute effects, then permits should be issued for well sites with analogous physical properties (ice thickness and cracking, depth of water, and river influence) and similar biological populations. Areas of unique, untested conditions will likely require additional monitoring. Carefully placed above-ice disposal is preferred over under-ice disposal to maximize mud and cutting dispersal. Mud disposal in deep water should be addressed more liberally than for shallow water environments.

Exclusion areas in the lease province could include under-ice discharges close to the Fish Creek and Coville River Deltas in winter which could introduce pollutants or highly saline water into channels or winter pools under ice which, in turn, could affect overwintering fish. The area behind Thetis Island, an Oldsquaw molting area, should not be subjected to under-ice discharges because of the importance of the benthic invertebrates as food for these birds.

Within areas inundated by the Colville River spring flood, disposal of drilling muds in confined pits on the ice is considered a safe alternative to land disposal in pits on the tundra, particularly in coastal areas where pits are not previously established. On-ice disposal is a viable alternative in most cases and should be considered on a site-specific basis consistent with the criteria mentioned above. This disposal method is receiving the most study.

Case-by-case evaluation should be mandatory for multiple-well dumps at a fixed location over several years (e.g., development drilling) until a data base addressing possible long-term (greater than one year) low-level effects on benthos and demersal fish is established. Selected development drilling sites should be monitored for this purpose prior to full-scale permitting of all wells.

Whenever possible, oil-free drilling cuttings should be incorporated into artificial islands. In the open and exposed environment of Harrison Bay, local accumulations of cuttings from two or three wells per site should have no ill effect on the environment, and should soon be dispersed by natural processes. In all cases, the formation of oil slicks from cuttings must be avoided and oil-contaminated cuttings and muds must be disposed of onshore.

Disposal of Produced Waters (oil field brines)

Discussion. As there are currently no offshore producing oil fields, disposal of produced waters from offshore facilities in the Beaufort Sea has not yet occurred. Current operating practice with regard to produced water disposal from onshore producing fields in Prudhoe Bay is by subsurface reinjection to shallow strata. As a secondary recovery method, treated seawater and produced water will continue to be injected into subsurface oil reservoirs as an integral part of the Prudhoe Bay waterflood project and Exxon's Duck Island visit. Produced water chemical composition in Prudhoe Bay has not been analyzed for all compounds in the State of Alaska's water quality standards of EPA's priority pollutant list. The current safe standards for hydrocarbons establishes a 10 mg/ℓ (ppb) limit in receiving waters after dilution. Although effluent concentrations are variable, depending on the specific oil reservoir, produced waters are often high in heavy metals and devoid of oxygen and contain before dilution relatively high and variable dissolved volatile aromatic hydrocarbon concentrations of up to about 50 parts per million (AMOCO, 1981). Relatively high concentrations of volatile aromatics (up to 8 mg/ℓ) and dissolved nonvolatile hydrocarbons ($\sim$ 300 mg/ℓ) have been determined for produced water from the Shell Oil Company productions treatment facilities in Cook Inlet and offshore platforms in the Gulf of Mexico (Lysyj, 1981a) and while it is expected these will vary in composition from those in the Prudhoe Bay area, the generic components will likely be similar. The Department, through an interagency agreement with EPA, is attempting to obtain funds to analyze the chemistry of Prudhoe Bay produced waters.

The proper disposal of these hydrocarbon-contaminated wastes is a major water quality issue during the production phase and has been addressed through a stipulation of the Joint Federal/State Beaufort Sea Lease Sale which prohibits surface discharge in depths less than 10 meters. Subsurface reinjection from onshore producing oil and gas wells has been routinely permitted below the depth of any groundwater horizon of drinking water quality.

The economics of reinjection in offshore waters are often not as desirable as for onshore wells and consequently, the method of disposal of wastes in offshore areas is a more controversial issue. Reinjection of water to maintain field pressure and enhance recovery of oil is generally considered to be economically desirable after several years of field development, as production rate drops and the volume of water brought to the surface becomes proportionally much greater than the amount of oil. The optimal timing of reinjection or "waterflooding" will vary as a function of the specific oil reservoir. At the present stage of field production for Prudhoe Bay, volumes of water are comparatively low with respect to oil (State of Alaska, 1981). Variables which moderate biological effects include the particular flushing and circulation characteristics of the marine waters in question, depth of water, volume and rate of pollutant input, concentration of suspended organic material, bacterial degradation, and identified uses and biological sensitivities in the local area.

The long-term marine environmental effects of continuous produced water disposal on benthic organisms and the chemical composition of sediments in shallow water embayments (approximately 2 to 10 meters) has been comprehensively addressed in selected oil producing areas outside Alaska (Armstrong et al., 1979). Trinity Bay, Texas in the Gulf of Mexico, the site of a major study of produced water effluents, is physically similar to the nearshore Beaufort Sea in depth, in its predominantly wind mixed circulation in summer and in the seasonally high suspended organic load. Highlights of the study include the following facts which are relevant to the Beaufort Sea:

A. Individual and total aromatic hydrocarbons in oil field produced waters, receiving waters, and sediments were quantified and correlated to the health of the benthic infaunal community at varying distances from the discharge point.

B. Significant levels of aromatic hydrocarbons (greater than 11 ppm total aromatics) and total hydrocarbons (greater than 25 ppm) exist in Gulf of Mexico produced water effluents from Trinity Bay platforms.

C. Selected polynuclear aromatic hydrocarbons concentrate in sediments. Collectively, the di-, tri-, and tetra-methylnaphtalenes were four orders of magnitude more concentrated in sediments than in the overlying water column. The naphthalenes persisted for extended periods of time in the sediments and high concentrations were correlated statistically to lower numbers of bottom organisms.

D. The number of individuals and species of benthic organisms were severaly depressed within 150 meters of the outfall and were negatively affected up to 400 meters from the platform.

E. Polluted sediments can be resuspended and deposited outside the area of effluent discharge in shallow, wind-mixed bays, thus enlarging the areal extent of polluted sediment.

These findings have several important implications for disposal policy regarding produced waters in the shallow, nearshore Beaufort Sea. First, the Texas study was conducted in a shallow (2.5 meters average depth), wind-mixed, lower salinity organic rich embayment. Analogous features characterize the lagoonal environments of the coastal Beaufort Sea.

Aside from temperature effects, physical comparisons can be drawn between the Trinity Bay and Beaufort Sea environments. These would not be so apparent for the deeper waters of Cook Inlet or the Gulf of Alaska.

The study supports laboratory and other field results reported in the literature which point to the adverse effects of low levels of water-soluble oil components on benthic organisms chronically exposed over long periods of time (Farrell, 1974; Leppäkoski and Lindstrom, 1978; Shaw et al., 1981). The four order of magnitude increase in sediment naphthalenes over concentrations in the bottom water and the documented deleterious effects on the benthic infauna suggest that hydrocarbons are adsorbing onto organic particles and being deposited. Levels of aromatic hydrocarbons in water, therefore, do not provide a complete picture by themselves, and indeed, may be deceiving. Water sampling must be accompanied by sediment monitoring.

The current Department petroleum hydrocarbon criterion established a 10 mg/ℓ upper limit on total aromatic hydrocarbons in receiving waters and states that there shall be no concentrations of hydrocarbons in the sediments which cause deleterious effects to aquatic life. The Trinity Bay study shows both an excess of 10 mg/ℓ total aromatics some distance from the platform and also documents deleterious effects (reduced numbers of benthic individuals and species) a considerable distance (greater than 300 meters) from the discharge point. The movement of polluted sediments out of the originally affected area represents an additional concern.

Recommendations (produced waters). The hydrocarbon and heavy metal composition of produced waters from offshore Beaufort Sea fields is not presently known. Ranges in concentration of volatile and nonvolatile aromatic hydrocarbons bracketed through analyses of Cook Inlet and Gulf of Mexico produced waters (Lysyj, 1981b) provide useful data in making projections. Additionally, the chemical compositions of onshore Prudhoe Bay produced waters will be documented during the summer of 1981 (Lysyj, pers. comm.).

Studies of Cook Inlet and Gulf of Mexico offshore platform and shore-based treatment technology indicate that while current methods are effective in removing suspended free oil, they are inefficient in reducing the concentration of dissolved aromatic hydrocarbons (Lysyj, 1981b). It is this class of compounds on which the State's hydrocarbon water quality standard is based due to toxic properties. Alyeska Pipeline Service Company is currently studying the feasibility of alternative treatment technologies for their ballast water effluents, including performance and cost effectiveness.

Until routine treatment technology is sufficiently upgraded to remove water soluble hydrocarbon fractions from produced water and the potential for partitioning of hydrocarbons to bottom sediments in shallow water is reduced, a policy of subsurface reinjections appears warranted for the nearshore Beaufort Sea (less than 10 meters depth). Exxon Corporation, in producing the shallow offshore Duck Island Unit, plans to reinject their effluent to enhance secondary recovery and reduce pollution potential (M. A. Jones, pers. comm.). Far offshore areas in Harrison Bay (greater than 10 meters depth) warrant a case-by-case look at direct marine disposal. This depth-dependent policy was also adopted for the adjacent joint lease sale area. The likelihood of hydrocarbon concentrations in sediments approaching adverse levels for bottom invertebrates, after adsorption and settling processes, is much reduced in these offshore regions. Possible avoidance behavior of fish and mammals to low levels of water-soluble hydrocarbons encountered in the lease area has not been addressed in the text. Permitting of disposal in deeper Federal waters should be accompanied by a monitoring program designed to quantify hydrocarbon concentrations in sediment and tissue burdens for selected benthic infaunal and demersal fish species.

References

Amoco. 1981. Aromatic hydrocarbon content in effluents from offshore platforms. Discharge monitoring report (DMR) to Environmental Protection Ageny.

Armstrong, H. W., K. Fucik, J. W. Anderson, and J. W. Anderson and J. M. Neff. 1979. Effects of oilfield brine effluent on sediment and benthic organisms in Trinity Bay, Texas, 2:55-69. In: Marine Environmental Research, Applied Science Publishers. England.

Farrell, D. 1974. Benthic communities in the vicinity of producing oil wells in Timbalier Bay, Louisiana. GURC/OEZ:14-95.

Leppäkoski, E. J., and L. S. Lindstrom. 1978. Recovery of benthic macrofauna from chronic pollution in the sea area off a refinery plant, southwest Finland. J. Fish. Res. Bd. Can 35:766-775.

Lysyj, I. 1981a. Chemical composition of produced water in selected offshore oil and gas extraction operations. Rockwell International, EPA contract No. 68-03-2648. 56 pp.

Lysyj, I. 1981b. Treatment effectiveness: Oil tanker ballast water facility. Rockwell International. Newbury Park, California. EPA report (in press).

Northern Technical Services. 1981a. Beaufort Sea drilling effluent disposal study. SOHIO Alaska Petroleum Company. 327 pp.

Northern Technical Services. 1981b. Progress report on above-ice disposal tests. Sag Delta 7 and 8 and Challenge Island wells, Beaufort Sea, Alaska. SOHIO Alaska Petroleum Company. 25 pp.

Shaw, D. G., L. E. Clement, D. J. McIntosh, and M. S. Stekoll. 1981. Some effects of petroleum on nearshore Alaskan marine organisms. EPA Report No. 600/S3-81-018. 4 pp.

State of Alaska. 1981. Report of the Oil and Gas Conservation Commission. Alaska individual well production for January, 1981.

APPENDIX E

List of Attendees
BEAUFORT SEA SYNTHESIS MEETING
Chena Hot Springs Resort, Fairbanks
21-23 April, 1981

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