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FOSSIL ENERGY

A REVIEW OF TECHNOLOGY FOR ARCTIC OFFSHORE OIL AND GAS RECOVERY

Volume 1. Second Edition

By
William M. Sackinger

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University of Alaska
Geophysical Institute
Fairbanks, Alaska

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A Review of Technology for Arctic Offshore Oil and Gas Recovery

by

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Volume I

TABLE OF CONTENTS

PREFACE

This technical background briefing document is the first step in the preparation of a plan for the development of the technology needed for Arctic offshore oil and gas recovery. Sponsored by the Department of Energy, this report is to be followed by a small workshop which will prepare a specific engineering research plan.

The terms of reference applied in this planning process include both exploration and production of offshore petroleum resources in those waters of the Bering, Chukchi, and Beaufort Seas that are covered with ice for any part of the year. A ten-year time frame is suggested, with production initiated in 1990-1992, although a shorter time frame is possible if sufficient resources are available. The intent is to have adequate technology available; other considerations certainly enter into the decision-making process as applied to lease sale, exploration, and production decisions. However, it is important to have the best technology available, and to establish quantitative confidence levels for technical performance, as an aid in decision-making as well as in the optimal execution of any production plans.

Some of the technological frontiers are the subject of current industry research; some frontiers are the responsibility of government agencies, such as the U.S. Geological Survey, the U.S. Coast Guard, and others; and some technological frontiers are not being advanced. Once these areas are identified, existing activities can be encouraged, and additional resources can be allocated to important technical topics that have been neglected.

One might ask whether industry can or will execute all of the research identified in the plan. Some items mentioned in the summary are beyond the traditional scope of industry (e.g. satellites for ice forecasting, ice-breaker operations, earthquake detection). Other research subjects involve very large financial commitments, which industry may be unwilling to make in advance of a lease sale; these subjects may require more years for research than is normally allowed between exploration and production. Extremely large commitments often must follow a substantial discovery, and again insufficient time may be available for optimum technological solutions. Generally speaking, the objectives of providing petroleum to the American public at the lowest cost, more quickly, in the largest total quantity, and with an appropriate degree of environmental safety, do not result in the same research plan as would be derived from objectives oriented toward maximum return on industry owner's equity. Although technical objectives will be similar, differences in timing and scale are to be expected.

This report only contains brief discussions of environmental assessment of the Arctic outer continental shelf, monitoring of offshore operations during production, and cleanup of oil spills. Although these topics involve technology applications in the Arctic offshore and deserve to be advanced, time did not permit adequate review of them in detail. When one makes a survey of this breadth, there must be a compromise with respect to the breadth and depth of each specialty explored. Technical specialists may consult the bibliographies in Appendix E for further details. Constructive comments on the material discussed in this report are most welcome, and should be directed to the author, who takes sole responsibility for the material herein.

June 6, 1980

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Note for the Second Edition: The constructive comments of G. Weller, J. Prince, K. Croasdale, W. F. Weeks, and J. Kreider were most helpful, and are sincerely appreciated.

EXECUTIVE SUMMARY

This technical background briefing report is the first step in the preparation of a plan for engineering research oriented toward Arctic offshore oil and gas recovery.

A five-year leasing schedule for the ice-prone waters of the Arctic offshore has been illustrated in Figure E-1, which also shows the projected dates of the lease sale for each area. In Figure E-2, the estimated peak production rates for these areas are given, based on Department of Interior estimates (April 1980). There is considerable uncertainty for all these production estimates, since no exploratory drilling has yet taken place.

In view of the world petroleum situation since 1973, the probability of successful exploration and production from some areas of the Arctic offshore, at some time in the foreseeable future, is very high. Whenever and wherever that occurs, it will be in the public interest to bring to bear the best technology, to minimize risk, quantify cost and time factors, and maximize the quantity of petroleum delivered to the American consumer.

The flow chart in Figure E-3 relates the special Arctic factors, such as ice and permafrost, to the normal petroleum production sequence. Although the following text goes into much more detail, some highlights can be drawn from the chart and from the technical review.

1) In many Arctic offshore locations the movement of sea ice causes major lateral forces on offshore structures, which are much greater than wave forces. In such locations, new design procedures are required, and the structures must be very rugged.

2) Spray ice buildup on structures, ships and aircraft will be considerable, and must be prevented or accommodated with special designs.

3) The time available for summer exploratory drilling, and for deployment of permanent production structures, is limited by the return of the pack ice. This time may be extended by ice-breaking vessels in some cases.

4) During production, icebreaking workboats will service the offshore platforms in most areas throughout the year; winter ice roads will be used near the coast in Beaufort and Chukchi Sea Access to offshore platforms may be made difficult by ice rubble.

5) Transportation of petroleum by icebreaking tankers from offshore tanker loading points is a highly probable situation, except in the Alaskan Beaufort. This is a consequence of the lack of ice-free deepwater ports on the Bering and Chukchi coasts, the technical problems of ice scour and subsea permafrost as hazards to seafloor pipelines in the Chukchi Sea, and the high cost and time for completion of a land pipeline to an ice-free port on the Gulf of Alaska.

6) Arctic pipelines must contend with permafrost, which is prone to thaw near a warm buried pipeline, causing loss of support, or which forms ice lenses around a cold buried pipeline, causing upward frost heave. Both of these mechanical changes are non-uniform and can often lead to rupture of the pipe. Instrumentation is needed to detect these subtle changes of the pipe before rupture occurs.

Other technological frontiers are identified in the final section of this report. All of the subjects mentioned there should be advanced, to extract Arctic offshore oil and gas in an optimized and economic manner. Fortunately, the required technology is within reach. With the coordinated efforts of industry and government, and the allocation of sufficient resources in a timely manner, all of these technical advances can be accomplished in the decade ahead.

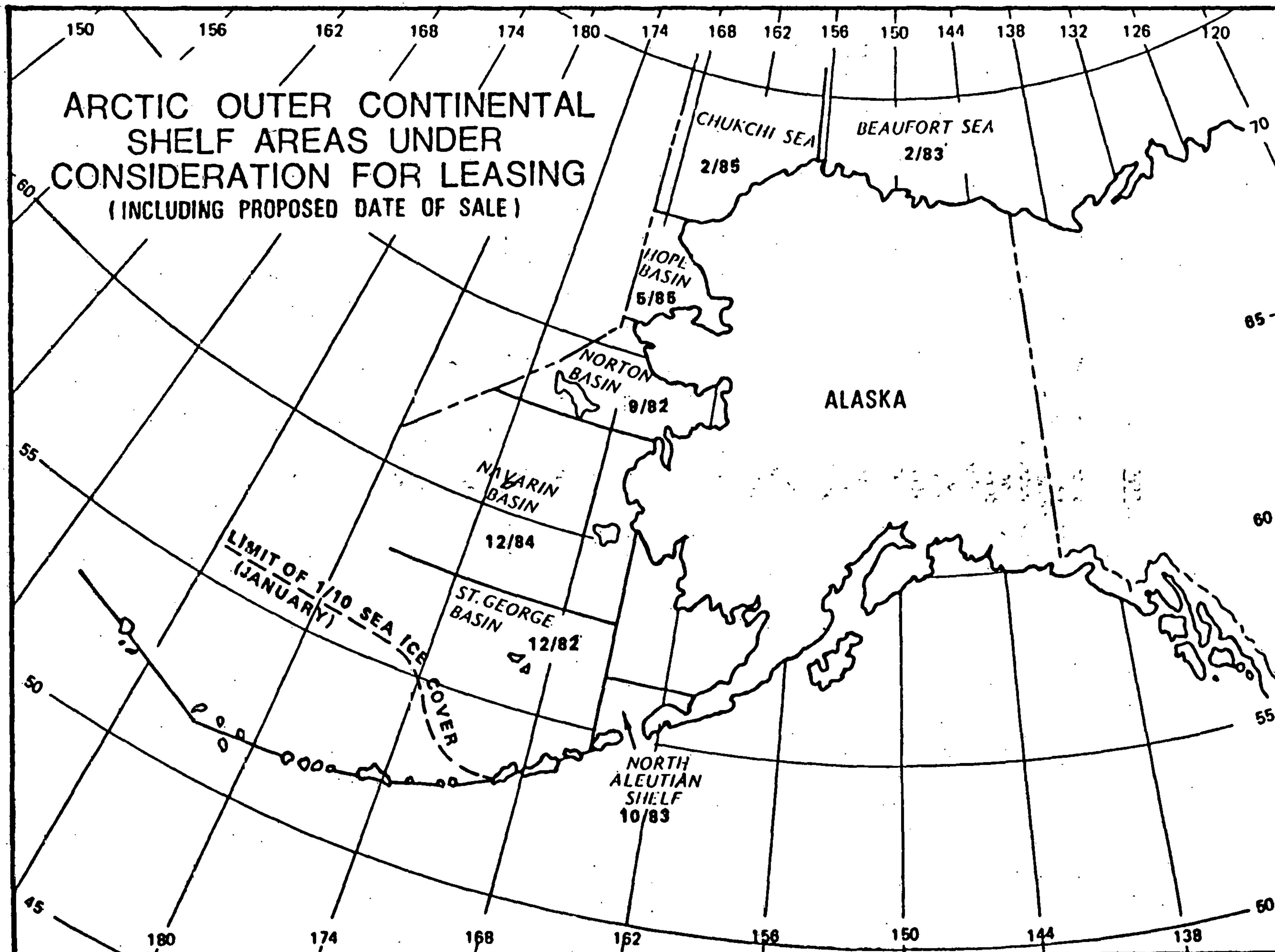


FIGURE E-1

ADAPTED FROM U.S. DEPARTMENT OF THE INTERIOR, APRIL 1980

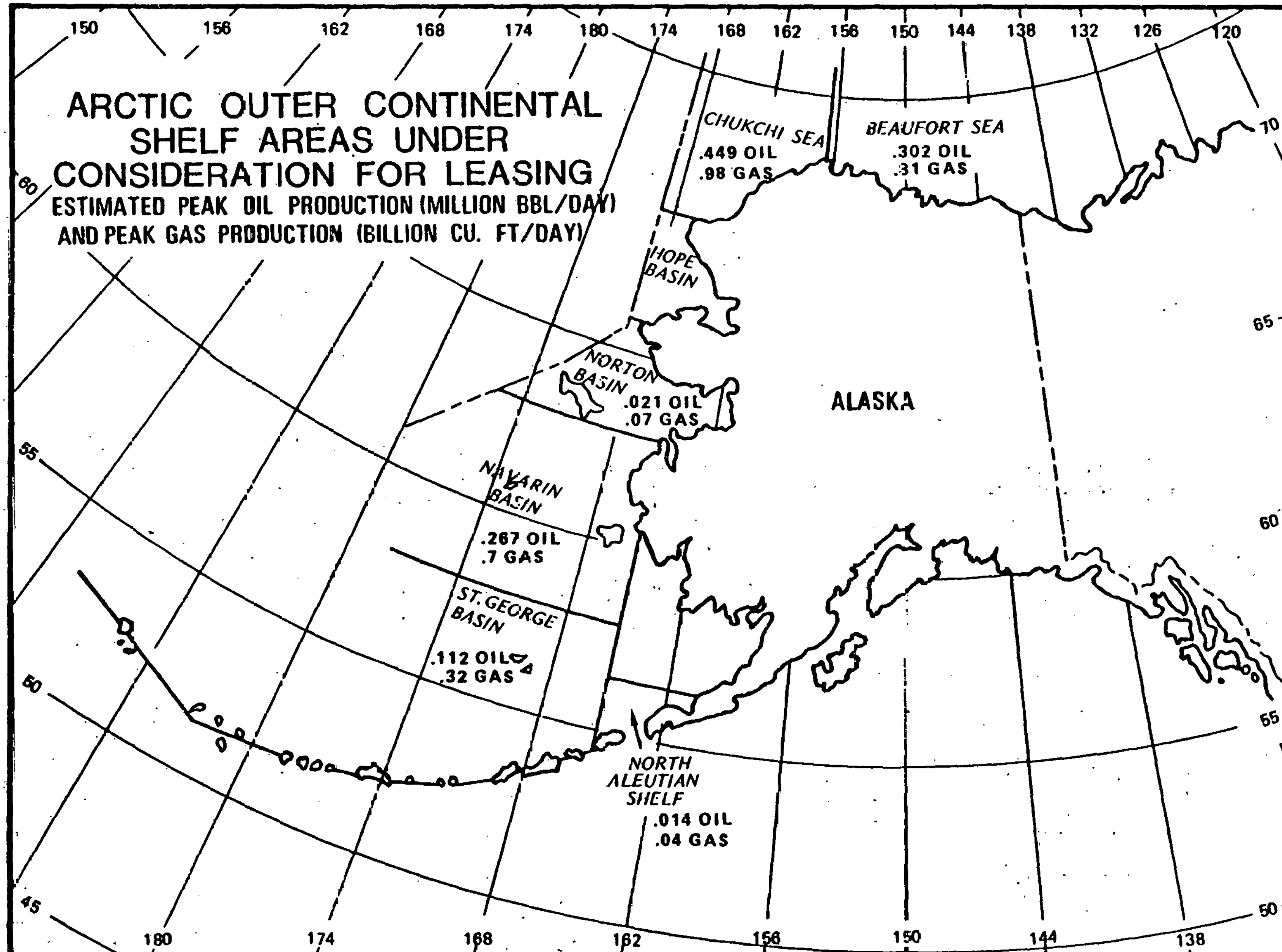


FIGURE E-2   ADAPTED FROM U.S. DEPARTMENT OF THE INTERIOR, APRIL 1980

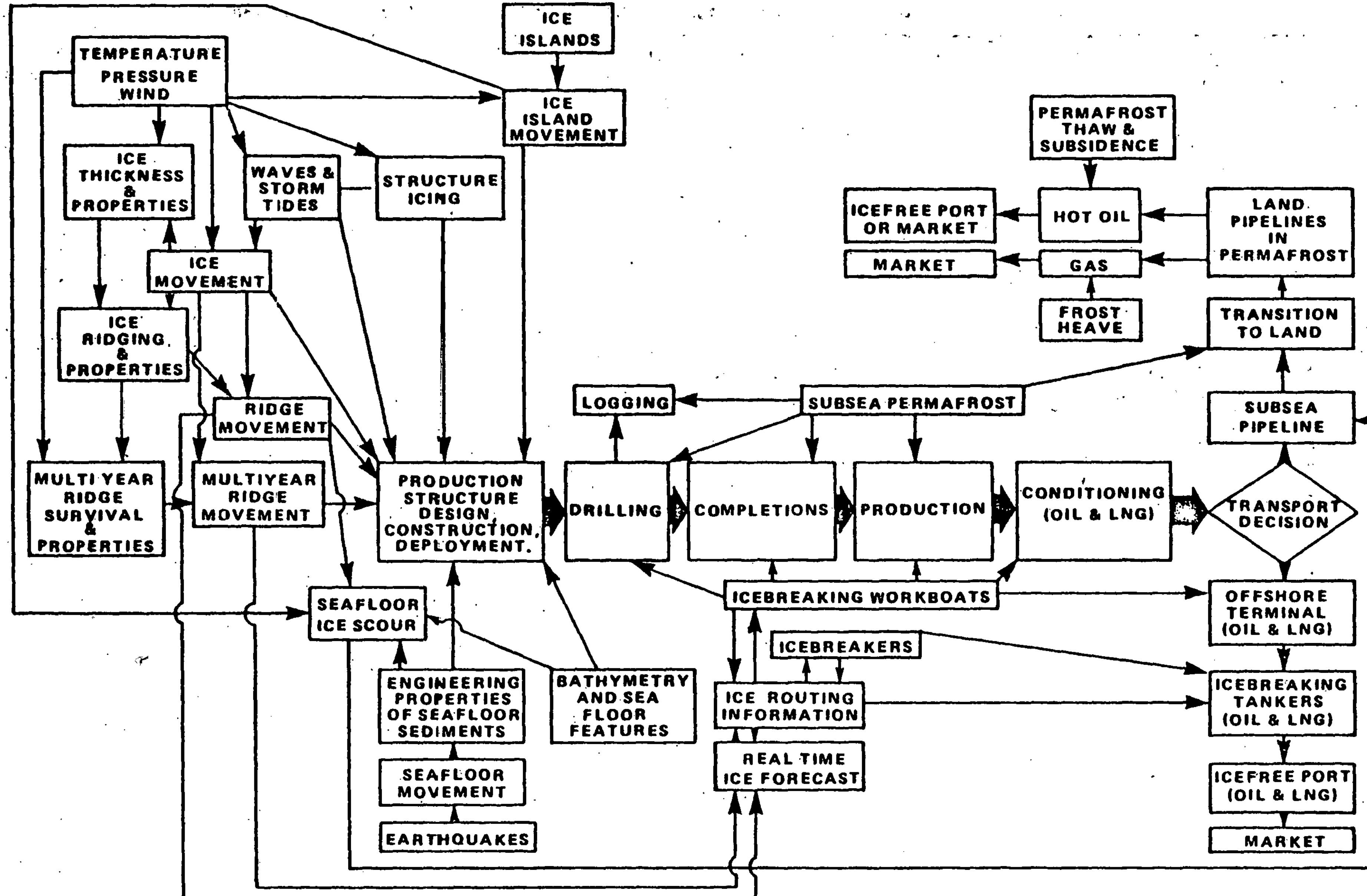
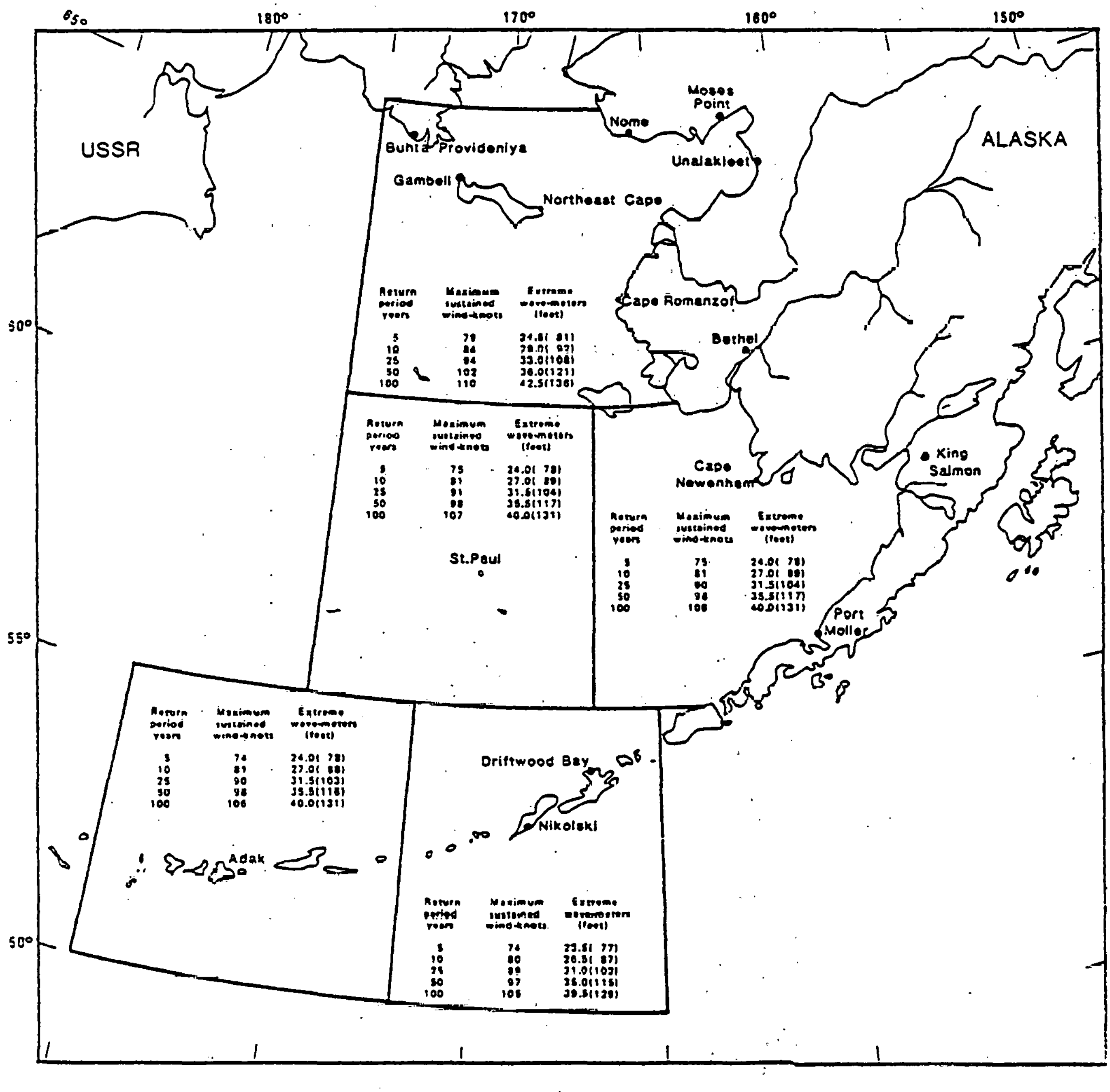


FIGURE E-3: MAJOR TECHNICAL FACTORS RELATED TO ARCTIC OFFSHORE OIL AND GAS RECOVERY

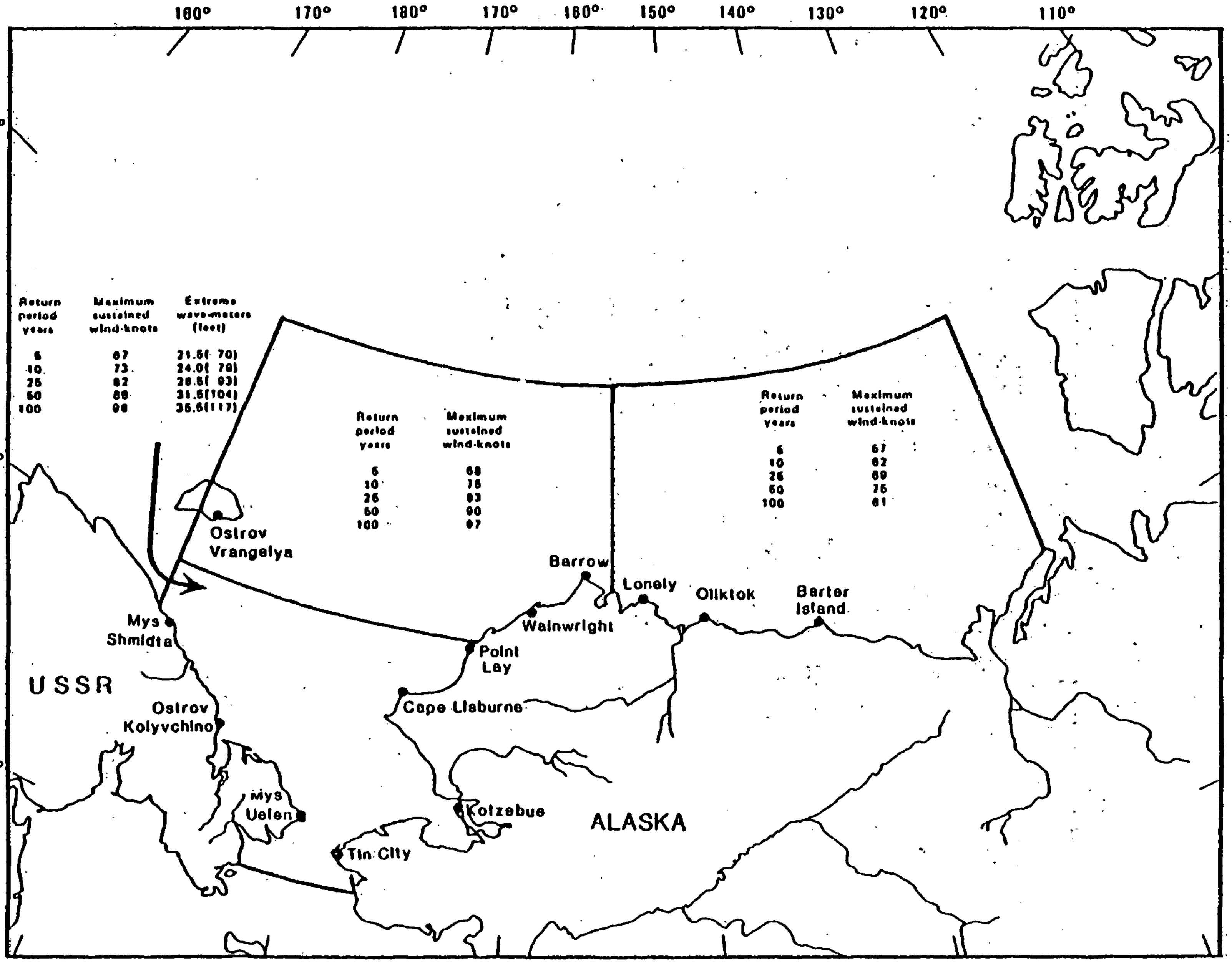
NATURAL FORCES

WINDS AND WAVES

In the Arctic offshore region, the forces of winds, waves, and sea ice are very large and are interrelated. Since high winds and long fetch cause high wave heights, as well as direct loading of offshore structures, it is important to review the 100-year return period values for maximum sustained (1-minute) wind speed given in the literature.[1] For the Bering Sea, Figure 1 shows how the region has been divided into five parts, for purposes of calculation, and the applicable values for wind and also wave height[2] are given in Figure 1. The wave heights are calculated,[1] based upon the work of Thom,[3,4] and do not include the possibility that the wind fetch and wave height are reduced by the possible presence of ice cover. The location of floating, drifting pack ice is so strongly affected by the storm conditions in turn, that the complete interactive description of ice movement during these conditions is still the subject of research, to be discussed below. Certainly, however, prudence would require the assumption that the 100-year storm may arrive when ice cover is absent. However, the data in Figure 1 may be misleading even if used for design purposes for summer loading by winds and waves. The summer period of open water is of brief duration in the Chukchi and Beaufort Seas, as is discussed below, but the same Climatic Atlas[1] provides similar predictions for three regions there,[5] as shown in Figure 2. The fact that the extreme wave height predictions[5] should be disregarded in the Beaufort and northern Chukchi seas, because ice cover reduction of wave fetch was not included, was pointed out by Heideman[6]. A good review of existing oceanographic data for the Beaufort Sea has been given by Heideman,[6] who also had access to two proprietary storm hindcast studies carried out by Intersea Research Corp.[7,8] The hind-cast approach is outlined in his paper,[6] and his results (including the effect of ice cover) for the Beaufort Sea are presented in Figure 3 for a hypothetical site in 30 foot water depth near Prudhoe Bay. For a 100-year return period, he predicts that a storm surge of 6.3 feet is accompanied by a maximum wave height of 27 feet, very nearly that of a breaking wave at that depth.[9] It appears



1. Extreme wind and wave conditions for the Bering Sea (from Ref. 1). *(These extreme waves may be excessively high -- Author's Note).*



2. Extreme wind and wave conditions for Chukchi and Beaufort Seas (from Ref. 1).
(These extreme waves may be excessively high -- Author's Note.)

OCEANOGRAPHIC DESIGN CRITERIA, ALASKAN BEAUFORT SEA, 30 FT DEPTH INSIDE BARRIER ISLANDS

RETURN PERIOD (YRS)	STORM SURGE (FT)	STORM MEAN WATER DEPTH* (FT)	CURRENT SPEED** (FT/SEC)	SIG. WAVE HEIGHT (FT)	SIG. WAVE PERIOD (SEC)	MAX. WAVE HEIGHT (FT)	MAX. CREST HEIGHT (FT)
25	4.4	35	3.4	12***	7***	22	17
100	6.3	37	4.4	14	7	27	22

*INCLUDES 0.7 FT ASTRONOMICAL TIDE BUT EXCLUDES WAVE SET-UP.

**RESULTANT CURRENT, NEGLECTING SMALL COMPONENT DUE TO ASTRONOMICAL TIDE; APPROXIMATELY IN THE SAME DIRECTION AS WAVES.

***SIGNIFICANT WAVE HEIGHT AND PERIOD FOR A 10-YEAR RETURN PERIOD WOULD BE ABOUT 10 FT AND 6 SEC.

3. Estimate of oceanographic environmental exposure, Alaskan Beaufort Sea, 30 ft. depth inside barrier island (from Heideman, Ref. 6)

that a similar hindcast approach would be appropriate for the Chukchi Sea, (Figure 2), making use of known information about ice cover during the severe historical storms. Hindcast studies in the Bering Sea, which include the effect of ice cover, would also be useful. The 100-year return period values for wind and wave loading on offshore structures are important, but the sea ice forces are also very significant, and should be considered carefully. Since the natural oceanographic forces cause sea ice movement, these movements are discussed below. Knowledge of waves and currents is important for construction planning and for design against erosion and scouring. All of the natural forces should be considered, first in relation to a fixed structure, and then as they affect marine transportation.

ICE

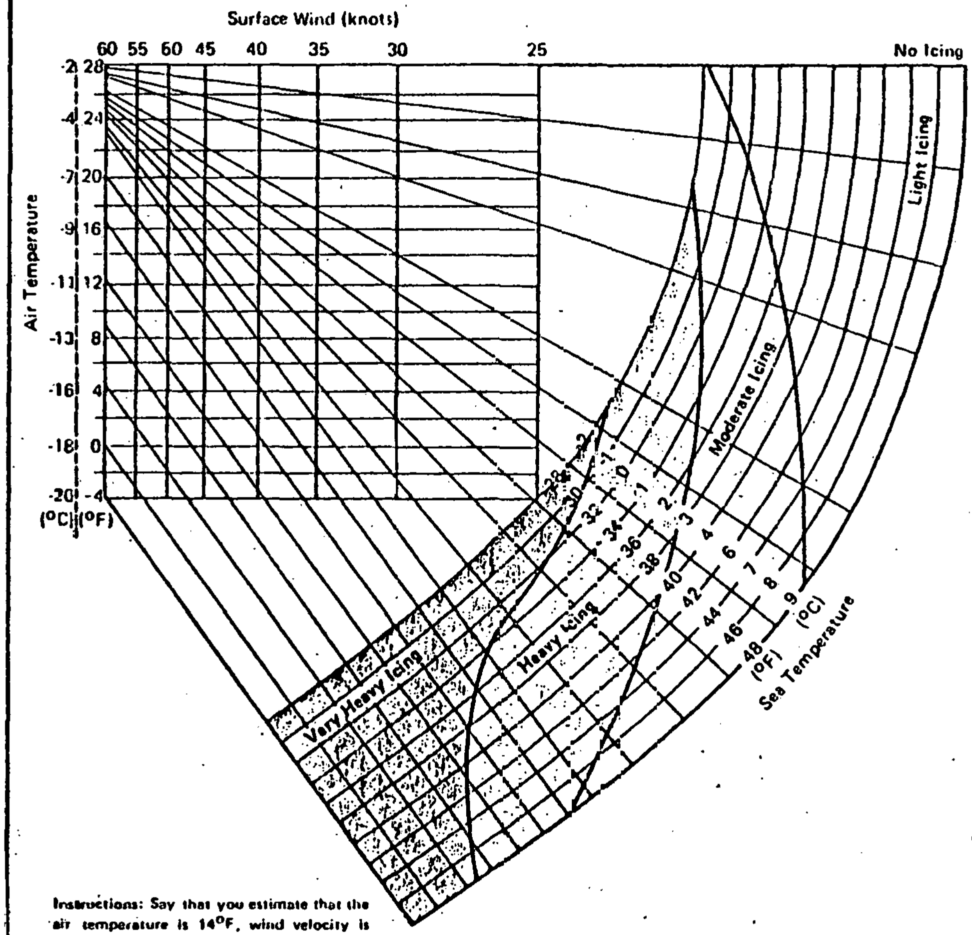
Ice accretion on ships and structures can be a serious hazard. Smaller ships, such as those used for resupply of offshore platforms, are susceptible to wave wash, heavy spray, and freezing rain, which can greatly increase the vessel's weight and elevate the center of gravity. Very large gravity loads can be imposed upon fixed offshore platforms subject to ice accretion. The most common and most rapid ice accretion occurs with freezing sea spray, when sea surface temperatures are below +5°C, and air temperatures are below -2°C. The National Weather Service uses the nomograph shown in Figure 4 for forecasting spray ice accumulation.[10] As an example, consider the January condition in the Bering Sea. In Figure 5, the sea surface temperature extremes[11] are shown. In Area B 10% of the observations were below +1°C. Using St. Paul as an example,[12] a wind speed of 22 to 33 knots, combined with an air temperature of less than -13°C, occurs 2% of the time, from Figure 6. Using these conditions for the nomograph of Figure 4, one expects heavy icing, 2.6 inches to 5.7 inches in 24 hours.

Under freezing conditions, frazil ice particles are floating in the upper parts of the water column, mixed by wave action. As large waves break against offshore structures, the frazil ice adheres to the structures. Buildup of ice on structure areas washed by wave action can be

Superstructure Icing

Ice accretion is a complex process that depends on sea conditions, atmospheric conditions, and the ship's size and behavior. Icing can be caused by heavy sea spray, freezing rain, or fog. It can mean no more than slippery decks on large merchant vessels since they often pass quickly through icing conditions and experience less wave wash in rough seas because of their high freeboard. At other times, even large vessels may experience problems. Smaller ships with relatively lower freeboard, such as fishing vessels, small merchant ships, and coast guard cutters, are susceptible to wave wash in rough seas. Icing can greatly increase a vessel's weight and elevate the center of gravity, making it top heavy. Ice may increase the sail area and heeling moment due to wind action, and trim can be changed because of nonuniform ice distribution. Icing also hampers steerability and lowers ship speed. Similar, potentially dangerous stresses can occur on oil-drilling and other stationary platforms.

Freezing spray is the most common and dangerous form of icing. It can occur when the air temperature falls below the freezing temperature of sea water (usually about -2°C) and when sea surface temperatures are below about 5°C. If the air temperature falls below about -18°C, wind-induced spray may freeze before striking the ship and not adhere. The lower the temperature and the stronger the wind, the more rapidly ice accumulates. Freezing spray may deposit thick layers of ice on rigging or on deck areas, rapidly increasing the vessel's weight, which can cause it to sink.



Instructions: Say that you estimate that the air temperature is 14°F, wind velocity is 30 knots, and the sea temperature is 32°F. Enter the nomograph on the 14°F line. Follow this line to the 30 knot wind velocity line. From the intersection of the two lines, follow the diagonal line to the appropriate water temperature line. At the intersection read off the icing category—in this case, heavy icing.

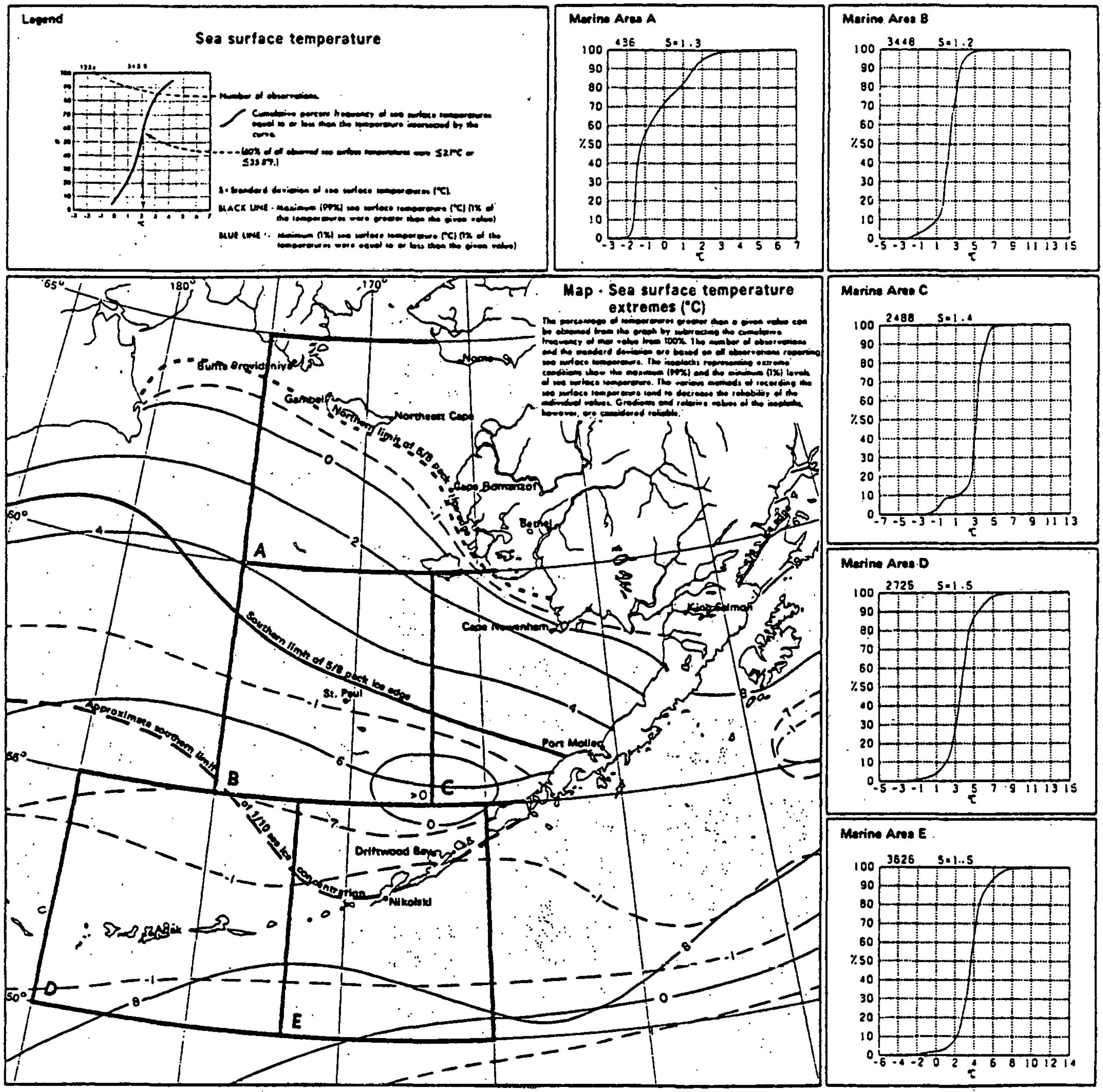
The icing categories used by the NWS are:

Category	Accumulation
Light	0.4" to 1.4" in 24 hours
Moderate	1.4" to 2.6" in 24 hours
Heavy	2.6" to 6.7" in 24 hours
Very Heavy	6.7" + in 24 hours

Adapted from: Comiskey, A. 1976. Vessel Icing-Know When to Expect It. *Alaska Seas and Coasts*, University of Alaska, Alaska Sea Grant Program. 4(5): pp. 6-7.

Nomograph for forecasting spray ice accumulation

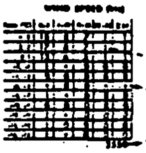
4. Nomograph for forecasting spray ice accumulation (adapted from Ref. 1).



5. Sea surface temperature extremes in January, Bering Sea, (from Ref. 1).

Legend

Air temperature/wind speed



Percent frequency of simultaneous occurrence of specified temperature (°C) and wind speed (knots).

(1% of all observations reported temperature 3-2°C simultaneously with wind speed of 22-33 kts.)

Indicates <.5% but >0.

Number of observations.

Map - Air temperature extremes (°C)

BLACK LINE - Maximum (99%) air temperature (1% of temperatures were greater than the given value)

BLUE LINE - Minimum (1%) air temperature (1% of temperatures were equal to or less than the given value)

The graph can be used to determine the extent of human discomfort from the combined effects of extreme heat or cold and winds or to estimate the likelihood of superstructure icing. Icing potential increases as the air temperature drops below freezing and the winds increase above 10 knots (12 mph) and may become quite severe with temperatures equal to or less than -9°C (16°F) and winds equal to or greater than 34 knots (39 mph).

Buhta Provideniya

WIND SPEED (KTS)

TEMP (°C)	0-3	4-10	11-21	22-33	≥ 34
6.7	0	•	•	0	0
4.5	0	•	•	•	0
2.3	•	•	•	•	0
0.1	•	1	2	•	•
-2.-1	1	3	4	1	•
-4.-3	1	3	3	•	•
-6.-5	1	2	3	•	0
-8.-7	1	2	3	1	•
-10.-9	1	2	3	1	•
-12.-11	2	1	3	2	•
≤-13	20	13	12	3	1

2387

Gambell

WIND SPEED (KTS)

TEMP (°C)	0-3	4-10	11-21	22-33	≥ 34
0.1	0	0	•	1	•
-2.-1	•	2	4	2	•
-4.-3	1	3	5	3	•
-6.-5	•	2	3	2	1
-8.-7	•	1	3	2	•
-10.-9	0	•	2	2	1
-12.-11	0	1	2	4	1
-14.-13	•	1	3	3	1
-16.-15	•	1	3	4	•
-18.-17	•	•	2	5	1
≤-19	1	5	11	9	2

1237

Northeast Cape

WIND SPEED (KTS)

TEMP (°C)	0-3	4-10	11-21	22-33	≥ 34
2.3	0	•	•	1	•
0.1	•	•	1	2	•
-2.-1	•	1	3	2	•
-4.-3	1	1	3	1	•
-6.-5	1	2	3	•	•
-8.-7	1	2	3	1	•
-10.-9	1	1	3	1	•
-12.-11	1	2	4	•	•
-14.-13	2	3	3	1	•
-16.-15	1	1	3	1	•
≤-17	14	14	10	2	•

2960

Nome

WIND SPEED (KTS)

TEMP (°C)	0-3	4-10	11-21	22-33	≥ 34
6.7	0	0	0	•	0
4.5	0	0	•	•	0
2.3	0	•	1	•	0
0.1	•	1	2	•	•
-2.-1	•	1	3	1	•
-4.-3	•	2	4	1	•
-6.-5	1	2	2	1	•
-8.-7	1	2	3	1	•
-10.-9	1	2	2	1	•
-12.-11	1	2	3	1	•
≤-13	21	20	12	3	•

7423

Moses Point

WIND SPEED (KTS)

TEMP (°C)	0-3	4-10	11-21	22-33	≥ 34
4.5	0	•	0	0	0
2.3	•	•	•	0	0
0.1	•	1	1	•	•
-2.-1	•	1	2	1	•
-4.-3	•	2	2	•	0
-6.-5	1	2	2	•	•
-8.-7	1	2	3	•	0
-10.-9	1	1	2	•	•
-12.-11	1	2	4	1	0
-14.-13	1	2	5	1	0
≤-15	11	19	19	7	•

4402

Unalakleet

WIND SPEED (KTS)

TEMP (°C)	0-3	4-10	11-21	22-33	≥ 34
8.9	0	•	0	0	0
6.7	0	0	•	•	0
4.5	0	•	•	•	0
2.3	0	•	1	•	0
0.1	0	•	1	•	0
-2.-1	•	1	3	1	•
-4.-3	•	1	2	1	•
-6.-5	•	1	2	1	•
-8.-7	•	1	2	2	•
-10.-9	•	1	3	2	•
≤-11	9	27	21	12	1

5253

Cape Romanzof

WIND SPEED (KTS)

TEMP (°C)	0-3	4-10	11-21	22-33	≥ 34
8.9	•	•	•	0	0
6.7	•	•	1	•	0
4.5	•	•	1	0	0
2.3	•	1	2	•	0
0.1	•	1	4	1	•
-2.-1	1	2	6	2	•
-4.-3	2	2	4	2	•
-6.-5	1	1	2	1	•
-8.-7	2	2	3	1	•
-10.-9	2	1	1	1	•
≤-11	10	8	14	12	3

3346

Bethel

WIND SPEED (KTS)

TEMP (°C)	0-3	4-10	11-21	22-33	≥ 34
8.9	0	0	•	0	0
6.7	0	0	•	0	0
4.5	0	•	1	•	0
2.3	•	1	2	•	•
0.1	•	2	2	•	•
-2.-1	•	3	3	1	•
-4.-3	•	2	2	•	0
-6.-5	•	1	1	•	0
-8.-7	1	2	1	•	0
-10.-9	•	2	1	•	•
≤-11	8	27	30	3	•

5692

Cape Newenham

WIND SPEED (KTS)

TEMP (°C)	0-3	4-10	11-21	22-33	≥ 34
10.11	0	0	0	•	0
8.9	0	•	•	•	•
6.7	0	•	1	1	•
4.5	•	•	1	1	•
2.3	•	1	4	3	•
0.1	1	3	6	1	•
-2.-1	2	4	6	2	•
-4.-3	3	3	3	1	•
-6.-5	2	1	1	1	•
-8.-7	3	2	2	1	•
≤-9	15	12	10	2	•

3601

King Salmon

WIND SPEED (KTS)

TEMP (°C)	0-3	4-10	11-21	22-33	≥ 34
12.13	0	•	0	0	0
10.11	0	0	0	0	0
8.9	0	•	•	•	0
6.7	0	•	1	•	•
4.5	•	1	1	1	•
2.3	•	2	4	2	•
0.1	•	3	3	1	•
-2.-1	1	4	3	1	•
-4.-3	1	4	2	•	0
-6.-5	1	3	1	•	0
≤-7	17	28	15	2	•

6438

St. Paul

WIND SPEED (KTS)

TEMP (°C)	0-3	4-10	11-21	22-33	≥ 34
6.7	0	0	0	•	•
4.5	0	•	1	1	•
2.3	•	3	12	7	1
0.1	1	4	9	5	1
-2.-1	1	3	6	4	1
-4.-3	•	2	4	2	•
-6.-5	1	1	2	1	•
-8.-7	•	2	4	3	•
-10.-9	•	1	3	2	•
-12.-11	•	1	3	2	•
≤-13	•	1	2	2	•

4339

Port Moller

WIND SPEED (KTS)

TEMP (°C)	0-3	4-10	11-21	22-33	≥ 34
12.13	0	•	0	0	0
10.11	0	•	•	0	0
8.9	•	1	1	•	0
6.7	1	2	1	•	0
4.5	1	2	1	0	0
2.3	2	5	4	1	•
0.1	3	6	3	1	0
-2.-1	7	12	3	•	0
-4.-3	4	8	1	•	0
-6.-5	2	3	2	0	0
≤-7	2	13	8	1	0

2190

Driftwood Bay

WIND SPEED (KTS)

TEMP (°C)	0-3	4-10	11-21	22-33	≥ 34
10.11	•	•	•	0	0
8.9	•	1	1	•	0
6.7	1	3	3	•	0
4.5	1	3	3	•	•
2.3	2	6	5	1	•
0.1	6	9	5	•	•
-2.-1	6	13	6	•	0
-4.-3	2	6	3	•	0
-6.-5	1	2	2	•	0
-8.-7	1	2	2	•	0
≤-9	•	1	3	•	0

2305

January

6. Percent frequency of simultaneous occurrence of specified temperature and wind speed for selected Bering Sea locations (from Ref. 1).

much more rapid than the spray buildup process described by the nomograph of Figure 4. In both cases, however, it is clear that many inches of ice accretion are possible. Designs must accurately assess this additional load and take it into consideration, or, alternatively, methods to prevent ice adhesion must be included in any designs for the Arctic offshore. Special surface coatings such as PTFE may be considered,[13] and waste heat may be utilized in certain circumstances.[13] Moreover, the surfaces of structures and ships must be resistant to pack ice gouging, as will be described below.

SEA ICE

The features of sea ice which initially are recognized as being hazardous to offshore structures and to marine transport vessels are its location, movement, thickness, and physical properties. These factors vary considerably from one basin to another, with time of year, and from year to year. It should be kept in mind that offshore structures may be of the artificial gravel island variety, appropriate for shallow water, or of the steel or concrete variety as used in deep water elsewhere in the world. Ice loading is a major consideration for both, if they are located in the Arctic.

Regardless of the choice of structure, it must be put in place. It is obviously far easier to do so during a period of ice-free open water, for most structures; (one exception is that gravel islands can be constructed by trucking fill over the shorefast ice and dumping through a hole in the ice, during winter). Ice movement is a statistically varying quantity, and it is possible to develop statistics on the time available for construction purposes during the open-water summer season. A summary of a study of this sort for the Beaufort Sea from Cape Halkett to Camden Bay has been given by Wheeler.[14] As an example of the information needed, Figure 7 defines nomenclature[14] for summer-ice statistics, and Figure 8 gives a summary of the results of the study.[14] In the first column of Figure 8, the probability of open water in a particular year is 91.3%. However, open water is subject to pack ice invasions; the probability of no invasions is 23.8%; of just one invas-

NOMENCLATURE FOR SUMMER-ICE STATISTICS

1.	Breakup	First occurrence of less than 8 oktas cover
2.	First Open Water	First occurrence of the oktas of ice cover in which the operation can be conducted
3.	Last Open Water	Last occurrence of the oktas of ice cover in which the operation can be conducted
4.	Freeze-up	The first of two consecutive weeks of 8-okta cover, following breakup
5.	Continuous Open Water	Expected duration of an open-water period
6.	Maximum Continuous Open Water	Expected duration of the longest open water period in a year
7.	Total Open Water	Expected sum of all open water periods in a year
8.	Gross Open-Water Season	Time between first and last occurrence of open water
9.	Invasion	Ice coverage in excess of open water that is preceded and followed by open water
10.	Global Maximum Cover	The maximum ice cover (oktas) that occurred during an invasion in 23 years
11.	Percent Multiyear at Max	The expected percentage of the ice cover that is multiyear during any invasion
12.	Expected Max Oktas	The expected maximum ice cover during an invasion
13.	Expected Date of Max	The expected date of the invasion that has the maximum ice cover
14.	Area Percent of Floes	The expected areal percentage of floes in the stated size ranges at the peak of an invasion
15.	Large-floe Invasion	An invasion having one or more oktas coverage by floes with diameter greater than the stated value

7. Nomenclature for summer sea ice statistics (from Wheeler, Ref. 14.)

Summer Ice Statistics

Operational Ice Tolerance (oktas)	0-1	2	4
Breakup	Jul 12	Jul 12	Jul 12
Std. Dev. (Days)	8.	8.	8.
First Open Water	Jul 30	Jul 24	Jul 18
Std. Dev. (Days)	14.	10.	9.
Last Open Water	Sep 22	Sep 22	Sep 28
Std. Dev. (Days)	14.	10.	9.
Freeze-up	Oct 4	Oct 4	Oct 4
Std. Dev. (Days)	9.	9.	9.
Open Water			
Probability it Occurs	0.913	1.0	1.0
Expected Duration			
Continuous OW	20.6	32.5	49.4
Std. Dev.	23.9	29.1	30.7
Max Continuous OW	33.1	54.0	67.3
Std. Dev.	29.4	24.9	18.6
Total (Days)	46.0	62.1	73.0
Std. Dev.	25.1	19.9	15.2
Gross OW Season	61.1	70.7	77.0
Std. Dev.	21.3	16.2	15.4
Invasions			
Probability, Given Open Water			
Of None	0.238	0.392	0.609
One	0.381	0.391	0.304
Two	0.286	0.130	0.087
Three	0.048	0.087	0.0
Four	0.048	0.0	0.0
Expected Duration (Days)			
First	13.5	9.9	8.7
Std. Dev.	10.8	6.9	6.1
Second	6.8	8.4	6.0
Std. Dev.	2.1	3.3	0.0
Third	12.0	9.0	0.0
Std. Dev.	8.5	4.2	0.0
Fourth	6.0	0.0	0.0
Std. Dev.	0.0	0.0	0.0
Expected Time			
First	Aug 11	Aug 11	Aug 5
Std. Dev.	18.4	22.3	25.1
Second	Aug 29	Aug 23	Aug 5
Std. Dev.	14.5	16.6	4.2
Third	Sep 10	Sep 10	None
Std. Dev.	12.7	8.5	0.0
Fourth	Sep 16	None	None
Std. Dev.	0.0	0.0	0.0
Global Max Cover	7.0	7.0	7.0
Percent MYR at Max	48.1	35.4	28.4
Std. Dev.	42.3	36.2	26.4
Expected Max Oktas	3.8	4.9	6.0
Std. Dev.	2.1	1.6	0.9
Expected Date of Max	Aug 17	Aug 11	Aug 11
Std. Dev. (Days)	22.	21.	24.
Area Percent of Floes			
.Lt. 65 Ft.	45.0	35.5	28.5
Std. Dev.	32.7	16.2	20.7
65-1600 Ft.	49.8	56.3	49.5
Std. Dev.	31.1	18.6	22.5
.Gt. 1600 Ft.	5.2	8.2	21.9
Std. Dev.	15.4	17.3	26.0
Large-floe Invasions (1600 Ft. Floes)			
Probability, Given Open Water			
Of None	0.762	0.739	0.696
One	0.238	0.261	0.261
Two	0.0	0.0	0.043

8. Summer ice statistics, Alaskan Beaufort Sea (from Wheeler, Ref. 14).

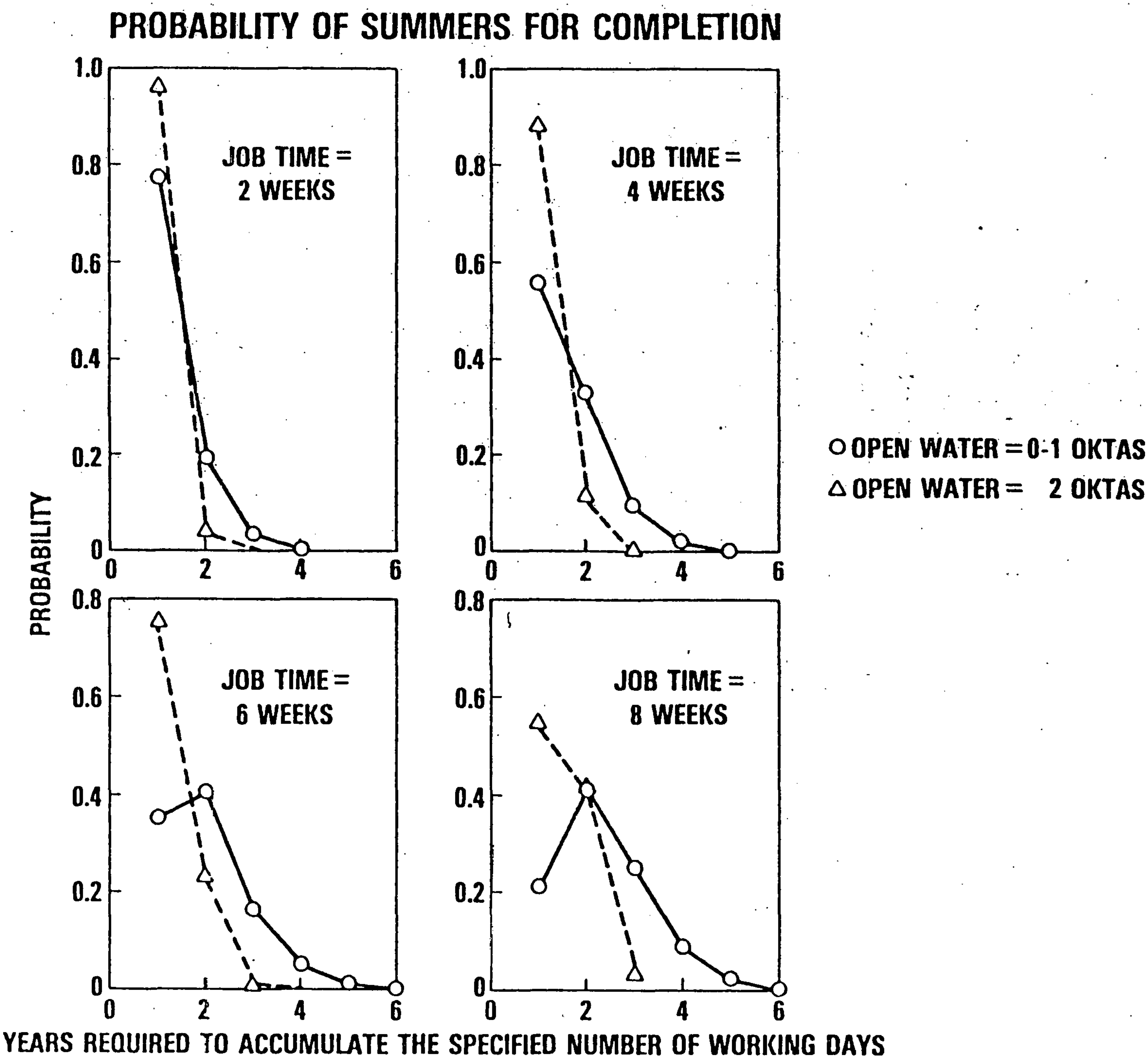
sion is 38.1%; of two invasions, is 28.6%, and of three or more, is 9.6%. The first column also gives the expected duration of these invasions.[14] Wheeler[14] has used these to calculate the probability for job completions, as shown in Figure 9. Such results quantify the risks related to ice intrusion during open water periods, and can be combined with the statistics of open-water conditions (waves, storm surges, winds) to give the optimum time and the likelihood of success of a specific structure installation event. A similar set of statistics is being developed for Chukchi and Bering Sea lease sale areas by Sea Ice Consultants, Inc., as an AOGA project.

Ideally, for safe design of an operational offshore structure, the maximum ice force to be expected should be known. Typically, structures are designed for environmental forces and structural loads which have a small but finite probability of occurrence. The return interval of 100 years has been commonly used for offshore structures which are to have an anticipated useful life of 20 years. Whether this is adequate in a particular case, considering the risks of capital assets, human life and economic value of adjacent marine resources in a philosophical matter, but is it possible to use return intervals of as high as 1000 years if necessary. The primary technical matter is the establishment of the statistical base, from which probabilities (or return intervals) are estimated with confidence.

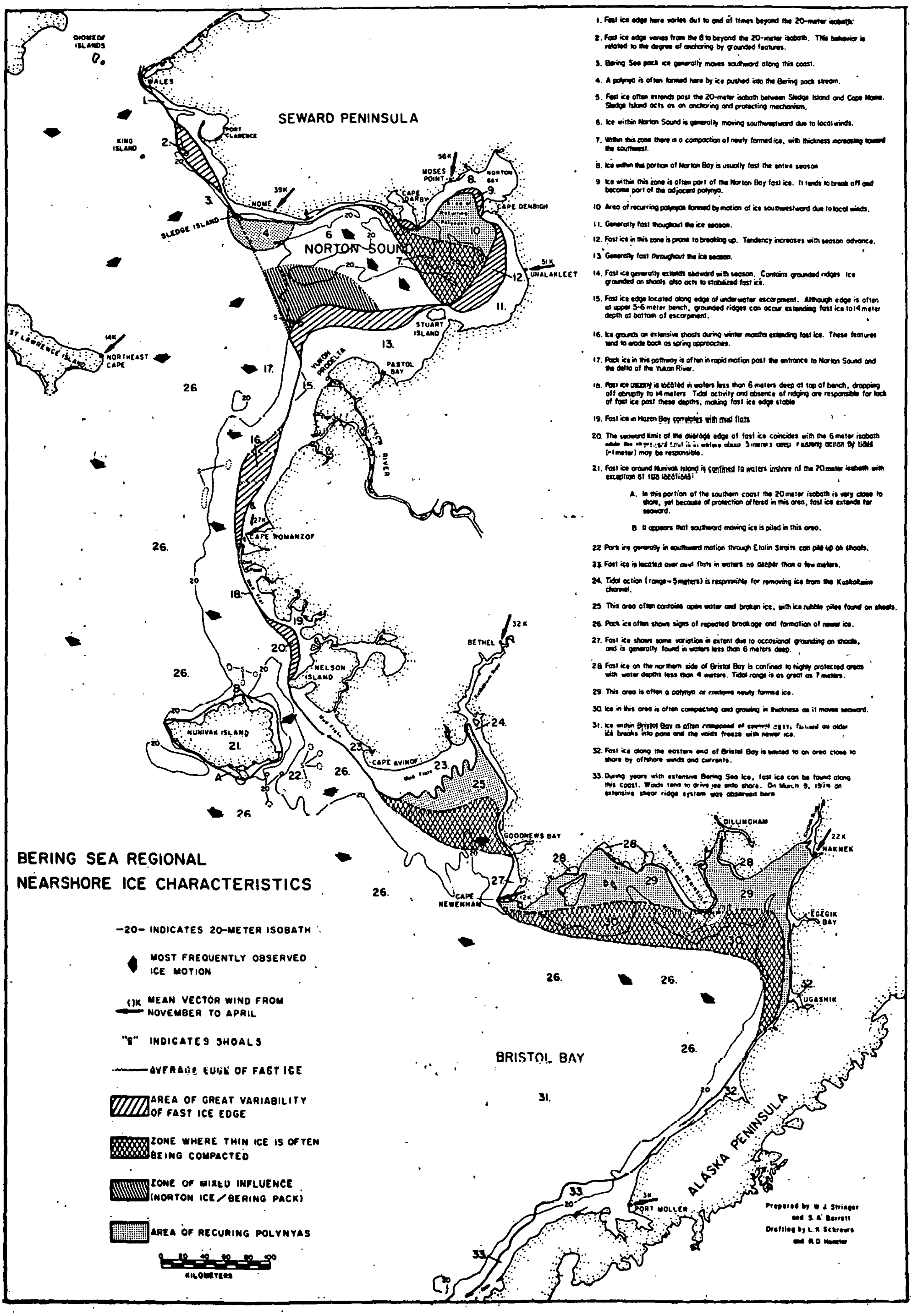
At least three different times of year can be conceptually considered, on the basis of distinct differences in ice loading conditions.

First, in the late winter, in the Beaufort and Chukchi Seas (and the landfast ice regions of the Bering Sea, Figure 10) the annual ice may be up to 6 feet thick, relative continuous and immobile. This "land fast ice" may move from zero to 335 feet or more during the winter depending on location.[14,15] In the winter, the upper part of the ice sheet is cold and strong in most locations.

Secondly, in contrast, during summer breakup the ice is warm, weak, discontinuous, and highly mobile. A third notable condition is during summer or fall, when the intrusion of the pack ice edge (in Chukchi and Beaufort Seas only) may involve the impact of a multi-year pressure ridge against a structure. These formidable multi-year ridges have



9. Probability for completion of an installation project in summer in the Alaskan Beaufort Sea (from Wheeler, Ref. 14).



10. Bering Sea regional nearshore ice characteristics (after Stringer and Barrett, c.f. for example Ref. 70).

experienced several years of melting and refreezing, and are as much as 137 feet thick.[16] They are free of voids,[16] and are of low salinity and great strength.

For a site in 190 feet of water in the Canadian Beaufort Sea, Bercha and Stenning[17] have estimated the 100-year return period multi-year ridge to be 115 feet deep, 398 feet wide, 500 feet long, embedded in an ice sheet 15 feet thick. For structures in deeper water, and for ships, multi-year ridges represent the most severe sea ice hazard.

However, embedded within the pack ice are ice islands, (which would be called tabular icebergs in the Labrador Sea). These are shelf ice fragments originating on Ellesmere Island which are carried by the pack ice around the Arctic basin. They are of fresh ice, very strong, and with a thickness which depends upon the extent of melting which they have experienced. Thicknesses greater than 150 feet are possible. Bercha and Stenning[17] have estimated the largest ice island hazard at their Canadian Beaufort site to be 7.14 miles in diameter, 164 feet thick, and having a velocity of 1.25 knots. Such ice islands move with the ice pack, and are found only in the Beaufort and Chukchi Seas. At a given site, they occur very infrequently, but the probability in a given region remains to be established. They could perhaps be tracked, and in a production situation, active countermeasures might be used (i.e., they might be destroyed).

In the Bering Sea, the pack ice outside of the landfast zone moves considerably throughout the winter, and in that respect resembles conditions of ice breakup in the Beaufort and Chukchi Seas. Ridges of annual ice, with heights of up to 23 feet,[18] have been observed in the Bering Sea. Using Kovacs'findings,[19-20] the keel depth of a first-year ridge is approximately 4 to 5 times the ridge height, suggesting that annual ice ridges in the Northern Bering Sea with thickness of as much as 115 feet may occasionally be encountered. This may appear to be implausible, but further field observations can quantify such details. Annual ice ridges have many voids, and are held together by both adhesion of the ice blocks and by a layer of refrozen ice near the water line.[21-23] In some instances, however, ice rafting during the ridge formation process can lead to consolidated ice thicknesses of as much as 20 feet.[23] It should be pointed out that most ridge sectioning upon which this is based has been done in the Beaufort Sea of Alaska[23] and Canada,[21,22] and also in the Gulf of Bothnia,[24,25] between Finland and Sweden; only one report of annual ice ridge sectioning in the ice of the Bering Sea has yet been published.[26]

Clearly, offshore structures and also icebreaker transport will encounter much more formidable ice forces in the Chukchi and Beaufort Sea, due to the multi-year ridges and ice islands. However, the mode of interaction of the ice with a structure has a great effect upon the lateral loading, as will be discussed below.

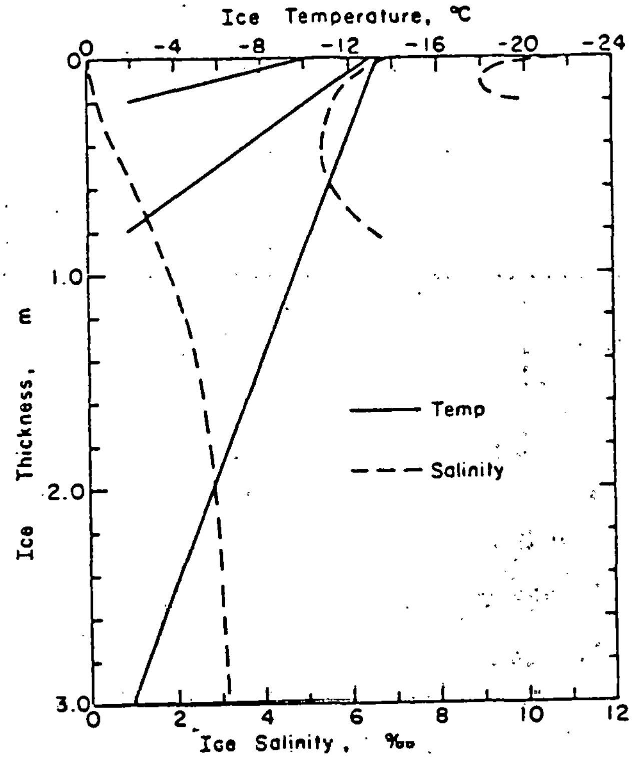
ICE-STRUCTURE INTERACTION

Three approaches have been used to investigate this problem area. Theoretical calculations have been made; model tests have been carried out; and certain full-scale measurements on structures have been completed. Attempts to relate all of these approaches have met with only partial success. To appreciate some of the reasons for this lack of quantitative agreement, it is worthwhile to consider the variables which enter into the ice/structure interaction in a full-scale situation.

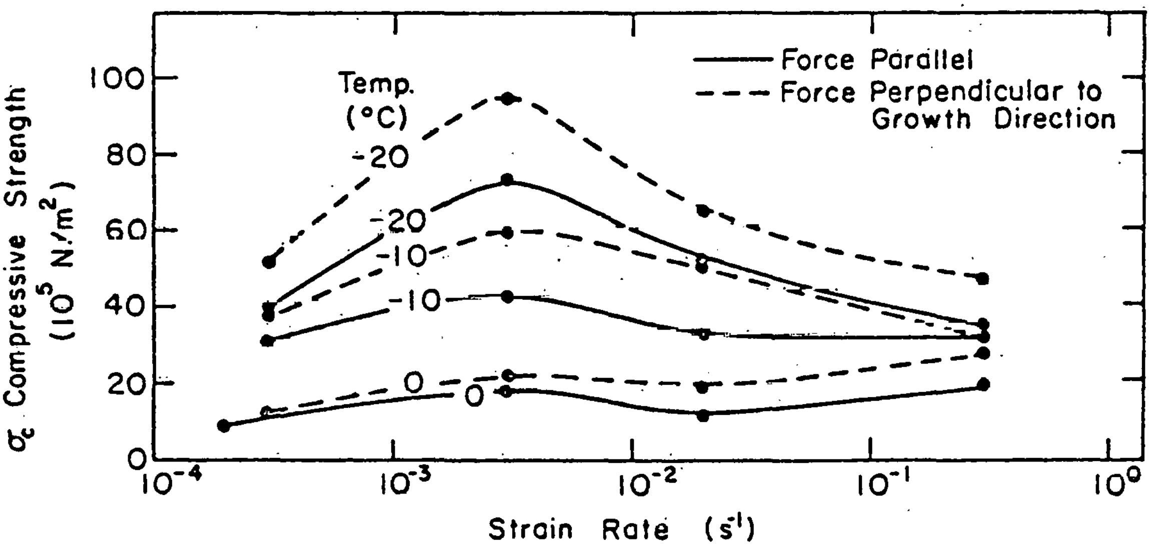
The ice itself, adjacent to the structure, is not a homogeneous, isotropic material of uniform thickness, but rather has a thickness which depends upon the location of snow drifts on the upper surface. Deep snow drifts cause a reduction in ice growth, because of their low thermal conduction. The ice thickness (in the absence of ridging) can vary by as much as 25% of the mean thickness, based upon late winter measurements.[27-29] Moreover, early in the winter, wind-driven thin ice moves against structures forming ice rubble which may not necessarily clear itself away from structures located in shallow water. Model tests by Prodanovic[30] have indicated that ice rubble acts as a Mohr-Coulomb material. The variation in thickness of the annual and multi-year ice ridges is an additional major parameter.

The engineering properties of sea ice depend upon salinity, temperature and crystal orientation. An excellent review of these properties has been given by Schwarz and Weeks.[31] Temperature and salinity vary with thickness through the ice sheet; a representative set of curves, adapted from Schwarz and Weeks,[31] is given in Figure 11. Compressive strength would be important for the case of an ice sheet moving against a vertical structural surface. In Figure 12, compressive strength as measured for small samples is presented as a function of strain rate, temperature, and orientation of the force.[31,32] Additional data taken at constant loading rates has been obtained by Shapiro.[116] For purposes of structural design, one may note that the strongest sea ice is at the lowest salinity and temperature. The strength is about 20% higher when compressed in the horizontal direction rather than in the vertical direction.[31] The compressive strength also depends upon strain rate, with maximum strength at a strain rate of about 3 x 10^{-3}sec^{-1}. This is associated with the transition between creep-ductile and brittle failure, and has been noted also in tests of fresh-water ice.[32] More recent results of Wang[33] show a similar strain rate dependence. In Figure 13-16, taken from Wang's paper, the compressive strength of sea ice at -10°C is plotted versus strain rate for granular, unoriented columnar, and oriented columnar sea ice. Granular ice is normally found near the top of a thick ice sheet, below which is found unoriented columnar ice, and finally oriented columnar ice is found in the lower part of the ice sheet. As Figure 16 shows, there is a variation of compressive strength from 1300 p.s.i. to 500 p.s.i. as the angle between the applied load and the c-axis varies from 0° to 45°, indicating that oriented sea ice is strongly anisotropic. Significantly different properties have been observed in large-scale tests, suggesting that natural cracks in large samples may be important.[21]

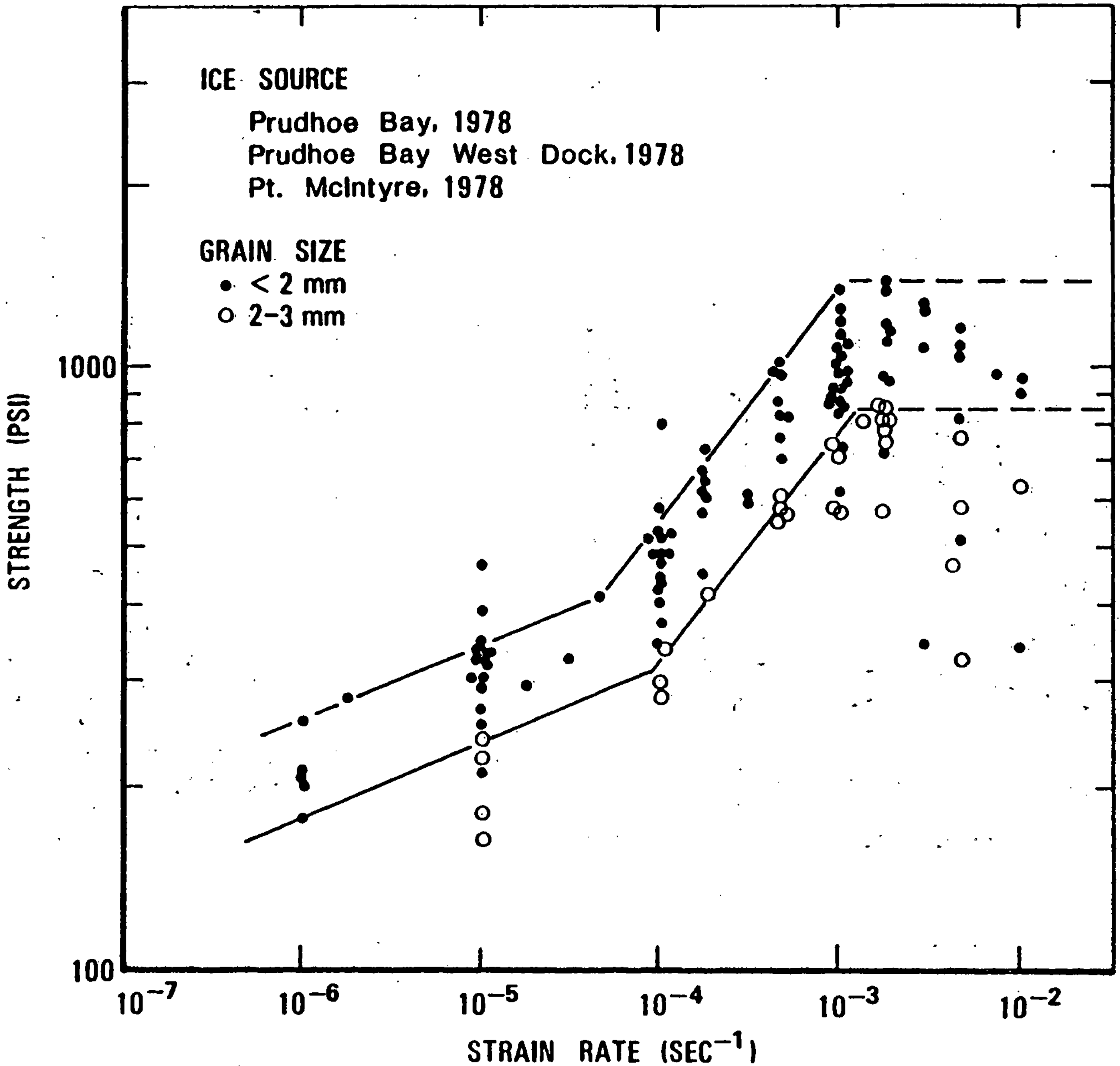
As will be discussed below, one way to reduce lateral loading is to provide an inclined structure surface, so that ice fails by flexure and buckling against it. Flexural strength has normally been measured by either simply-supported beam tests or cantilever beam tests. Cantilever tests have the advantage that they can be performed in the field without the occurrence of excessive brine drainage. Some results have been



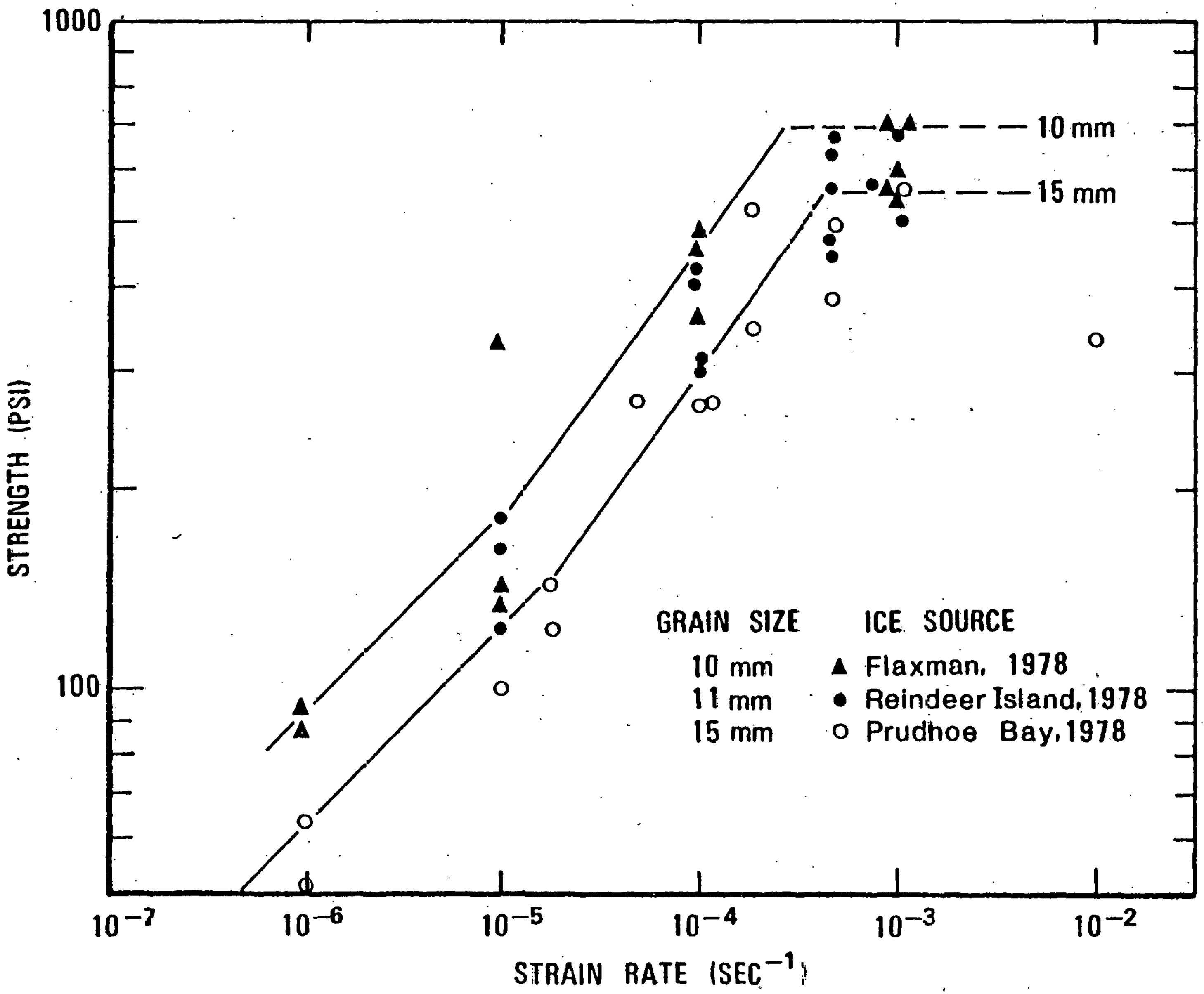
11. Representative annual sea ice temperature and salinity profiles on about 1 May for 0.2, 0.8 and 3.0 meter thickness (from Schwarz and Weeks, Ref. 31).



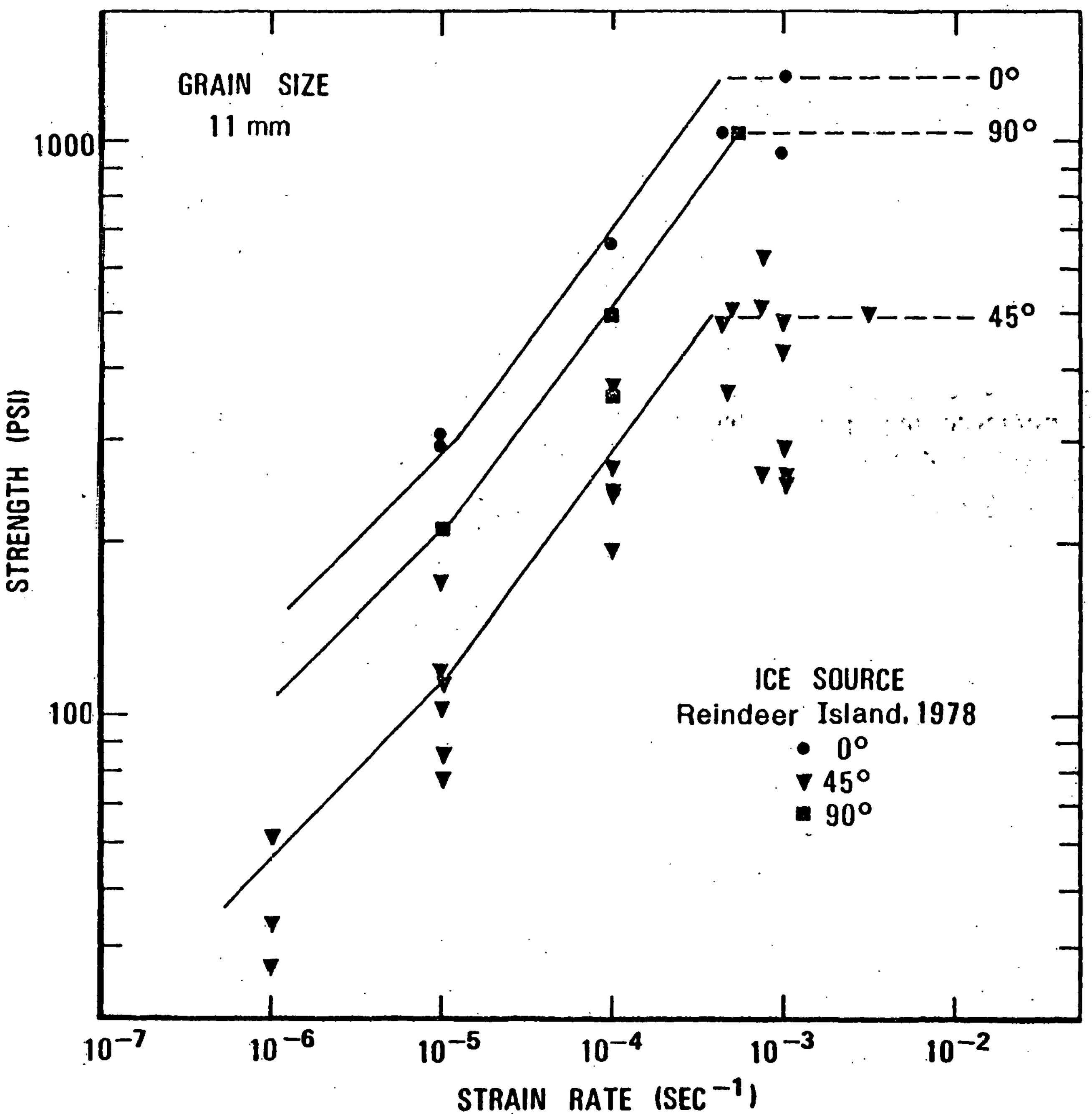
12. Compressive strength of Baltic Sea ice as a function of strain rate, ice temperature, and orientation of the force (from Schwarz and Weeks, Ref. 31).



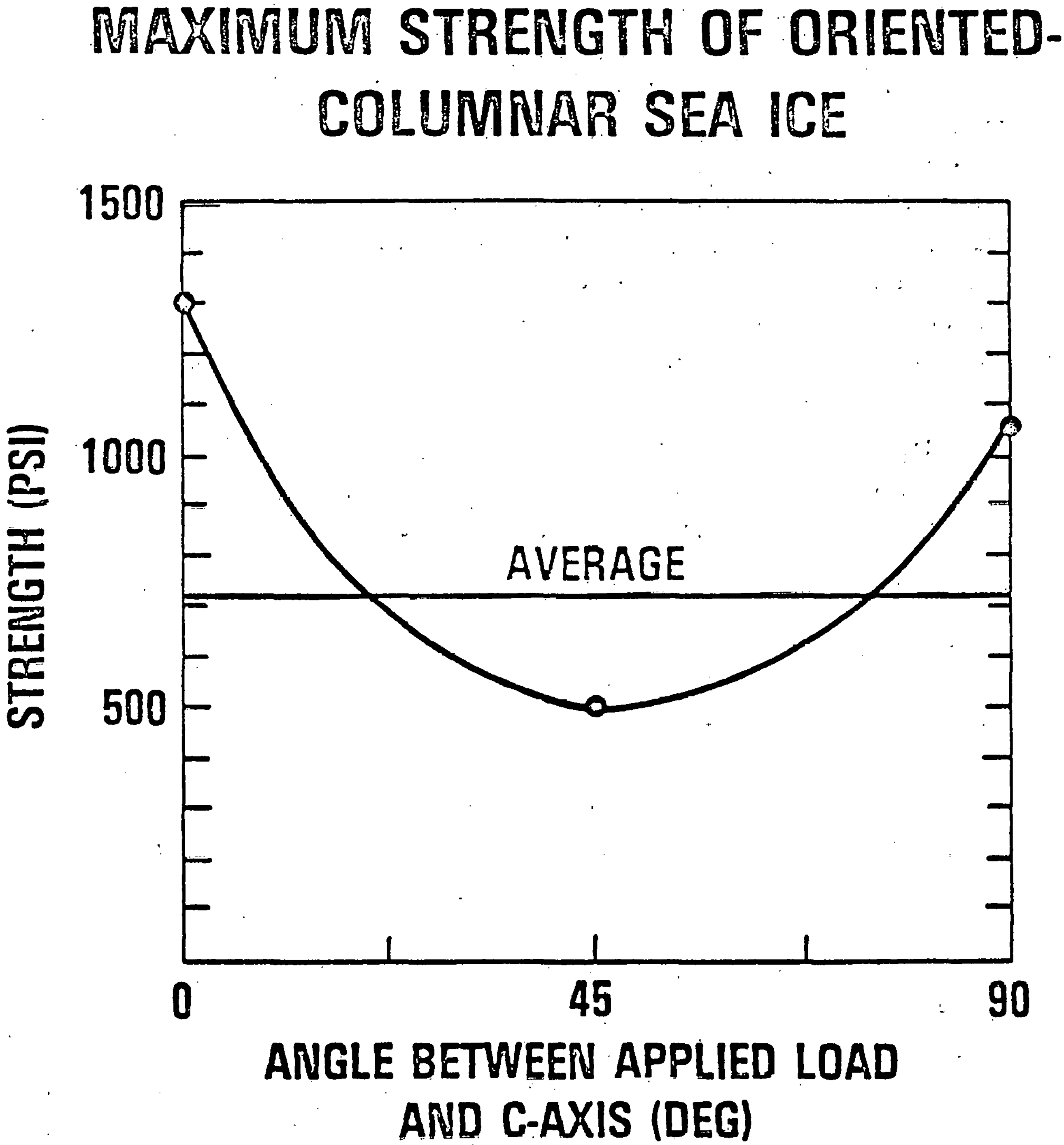
13. Compressive strength of granular annual sea ice at -10°C (adapted from Wang, Ref. 33).



14. Compressive strength of unoriented columnar annual sea ice at -10°C (adapted From Wang, Ref. 33).



15. Compressive strength of oriented columnar annual sea ice at -10°C (adapted from Wang, Ref. 33).



16. Maximum compressive strength of oriented columnar annual sea ice at -10°C as a function of sample orientation (adapted from Wang, Ref. 33).

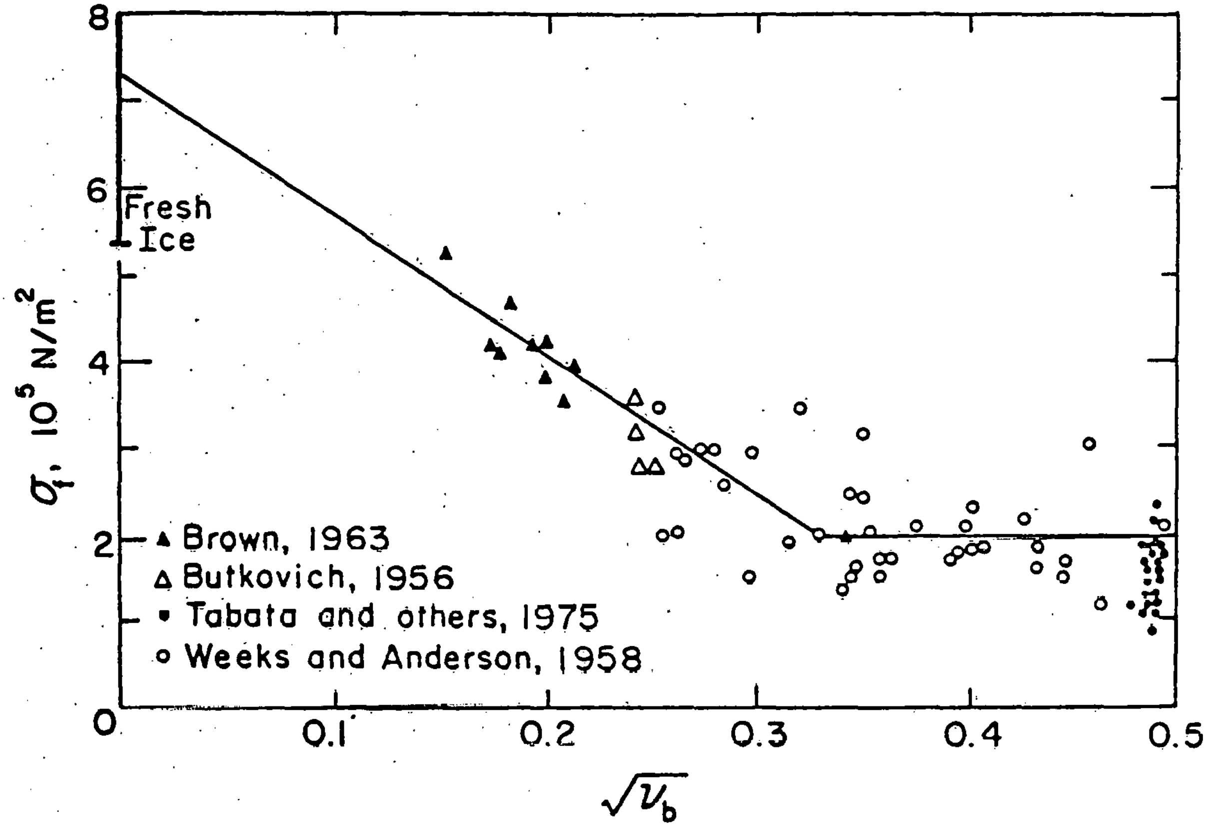
summarized[31] and are plotted in Figure 17. The interpretation of such results, and indeed the calculation of flexural response for anisotropic ice sheets with temperature and salinity variations, is perhaps possible through the application of Hutter's theory,[34] but much additional work remains to be done if this is to be accomplished.

Considering the complex properties of sea ice sheets described above, it is clear that the model approach in an ice tank cannot hope to scale all of the properties of the ice sheet. If anisotropy, temperature and salinity gradients are neglected, some success in scaling of bulk properties is possible, but simultaneous scaling of the frictional forces at the interface remains a formidable task.

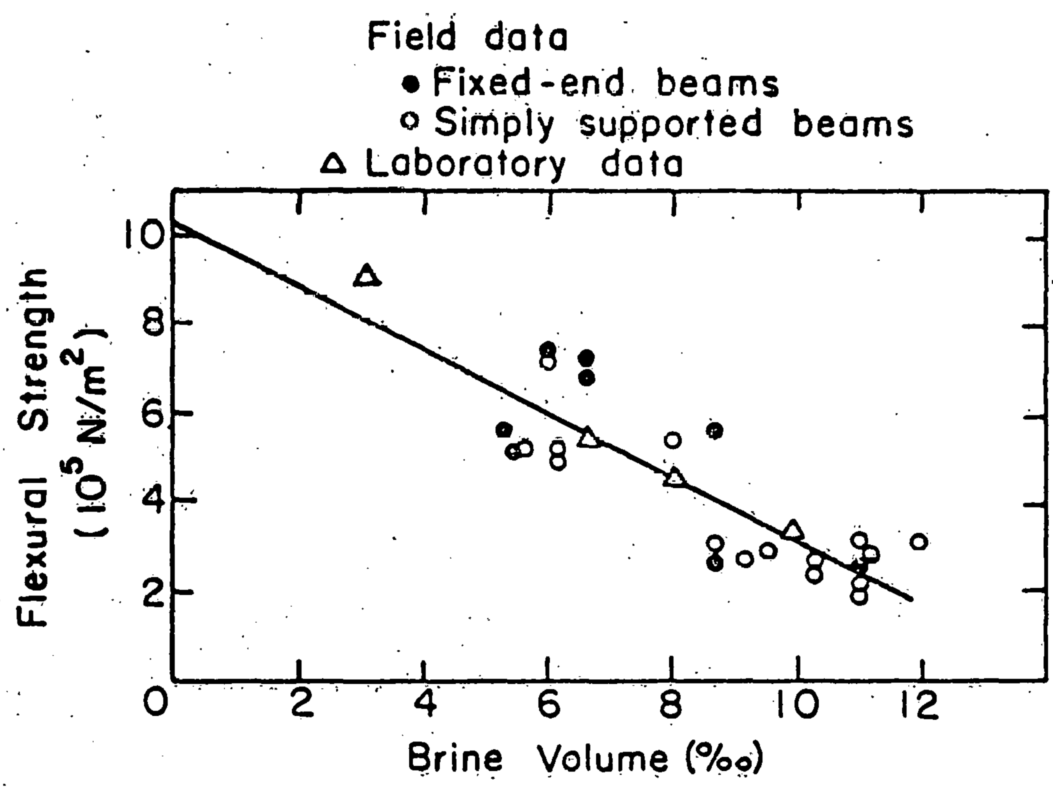
Researchers are now attempting to relate scale model tests to analytical models and to full-scale field test results, to establish empirical rules of correspondence which might be used in future structure model tests.

A typical design calculation procedure for a gravel island is given by Ralston,[21] who makes assumptions about the island boundary, the failure mode, the ice type, thickness, salinity, temperature and the strain rate. The strain rate is a particularly important parameter, as shown in Figures 13-16.

Observations of the boundary between the ice sheet and both natural and artificial islands have revealed that the ice in the boundary region is usually quite complex. There is at least one tide crack, and often several. Snow has formed deep drifts at the boundary, because of the height difference between the island and the ice sheet. This retards the rate of ice formation, warms the ice sheet, and provides a gravity load which often puts the water line above the ice sheet, causing sea water to come up through the tide crack. High winds in early winter often move the thin sea ice a great deal, leading to the fracturing and buildup of ice rubble piles at the boundary of the island.[35] Clearly, a realistic model of this complex situation is extremely difficult. This author's observations of several situations in which an ice sheet was pushing against an artificial island have indicated that initial closure of the tide crack was followed by a tendency of the ice sheet to buckle upward at the tide crack; of course, purely compressive failure modes



17. Flexural strength of annual sea ice versus square root of brine volume (a) and versus salinity (b) (from Schwarz and Weeks, Ref. 31).



are theoretically possible. Ralston[21] has therefore conservatively assumed that failure occurs in compression, for a cold (-10°C) thick (7 ft.) ice sheet composed of granular sea ice (upper 5 feet) and columnar ice (lower 2 feet).

The relationship between the ice sheet movement rate and the effective strain rate at the region of failure is difficult to establish in full scale in the field. However, the strain rate is an important parameter, as shown in Figures 13-16. Small-scale laboratory tests have been made by Michel and Toussaint,[35] in which rectangular indentors of widths from 6.3 mm to 203.2 mm were used. They found the relationship

$$\dot{\varepsilon} = \frac{V}{4b}$$

to hold, where $\dot{\varepsilon}$ is the equivalent uniaxial strain rate in sec-1, V is the rate of indentation, and b is the width of the indentor. Larger scale indentor tests in the field have been reported by Croasdale et al,[37] for a flat indentor of width 0.75 m and height 1.0 m; (ice thickness ranged from 18 cm to 99 cm during the tests). Their results also show the strain rate dependence associated with the transition from ductile to brittle behavior. The formula given by Michel and Toussaint[36] has been used with modification by Ralston[21] in a design calculation for a gravel island of 500 ft diameter.

Ice crushing loads against a vertical pier have been calculated based upon the early formula of Korzhavin,[38]

$$p = Imk\sigma$$

where p is the ice pressure, I is the indentation factor, m is the shape factor, k is the contact factor and σ is an (undefined) compressive strength of the ice. The usefulness of this equation is limited unless one knows the appropriate values of I, m, k, and σ; much of the engineering research in recent years has revolved around the determination of these values. Empirically, I = 1 for a wide structure and about 2.5 for a narrow structure. Moreover, k = 1 for perfect contact, and m = 1.0 for a flat face; m = 0.9 for a round face. The value of σ depends upon strain rate, as discussed above.

For a wide structure, such as a gravel island, Ralston[21] has modified the above equation to give the force F on an island as

$$F = kI\sigma bt$$

where t is the ice thickness, b is the diameter of the island, and the other symbols are defined above. As the ice sheet moves against the island, the load may be expected to vary irregularly with time, and this equation expresses the first peak load, which corresponds to a condition where the contact factor k is a maximum (k=1). A plastic limit analysis has been used to find an upper bound of I = 3 in columnar ice and I = 1.2 in granular ice.[39]

Ralston advocates the use of a factor 2 (rather than the factor 4, as in Michel and Toussaint)[36] in the denominator of the equation relating strain rate to ice sheet velocity.[21] However, he makes use of the average ice movement rate of 8 ft/hr., associated with a 100-year return period, as derived by Wheeler.[14] Wheeler's paper indicates that ice sheet position information was sampled every ten minutes. It appears possible that the movement recorded between two adjacent sampling times may have occurred in an extremely brief time interval, conceivably of the order of a few seconds, and in such a case that strain rates calculated on the basis of an average over a ten-minute sampling interval could be as much as 100 times too low. Until some ice movement data is taken with a short sample time interval, and the results analyzed together with existing data, the ice movement rate used by Wheeler for so-called "landfast" ice should be regarded only as a first estimate. Using the 8 ft/hr average rate, Ralston[21] calculates a strain rate of 2×10^{-6} sec^{-1}, and an island loading of 340 kips/ft. of island diameter. The use of defensive techniques, such as cutting slots in the ice sheet, was assumed by Ralston to offer a reduction in the contact factor to an estimated value of k = 0.8, giving an estimated load for an exploration island (with defense) at 270 kips/ft. of diameter. This example calculation contains several assumptions, and should serve only as a starting point for more refined calculations.

It should be mentioned that an attempt to allow for ice rubble accumulation, as an alternative design condition, has also been discussed.[21] The major unknown in that instance is the degree to which the ice rubble has grounded on the seafloor adjacent to the island, and the resulting additional resistance to ice sheet pressure which it provides. Counterbalancing that effect is the fact that the diameter of the rubble pile is greater than that of the island, leading to greater total forces. In practice, rubble piles grow on their outer periphery, as the ice fails in flexure or in shear, and in some instances the ice stress observed between grounded ridges and land is low even when ridges are building.[40] It is this author's opinion that in most instances the presence of grounded ice ridges or rubble provides a net protective effect for an island; experiments are currently in progress to attempt to verify this.[41] Kry[113] has suggested that simultaneous failure does not occur across the entire island diameter, so that the total load is less. Even submerged shoals collect ice rubble which offers sufficient lateral resistance to cause the growth of additional ridges and rubble. These calculations will be used in discussions about offshore structure loads below.

OFFSHORE STRUCTURE DESIGN

The only fixed offshore structures in the Beaufort Sea which have been designed and constructed to date are artifical islands. Many islands, in water depths up to 60 feet, have been built in the Canadian Beaufort Sea.[117] A design example has been presented recently[42,43] by Prodanovic. A representative well-graded sandy gravel available at Prudhoe Bay has a typical unit weight of 115 pounds per cubic foot (pcf) above water level and 65 pcf buoyant weight below water level. For trucked unfrozen gravel, the strength is expressed by the internal friction angle of 34°, with 32° friction angle for dredged fill and 30° for granular subsea soil. Alternatively, the subsea soil is assumed to have an undrained shear strength of 1000 pounds per square foot. For a fill island, the resistance R_f is given by[42]

$$R_f = (\rho_1 V_2 + \rho_2 V_2)\ \frac{\tan\phi}{\gamma_{mf}}$$

where ρ_1 and ρ_2 are unit weights above and below the waterline, respectively, V_1 is the fill volume above water level, V_2 is the fill volume between water level and shearing plane, ϕ is the angle of internal friction, and γ_{mf} is the granular material factor (taken to be 1.2). For the case of cohesive soil, the resistance is taken to be[42]

$$R_c = A\ \frac{c}{\gamma_{mc}}$$

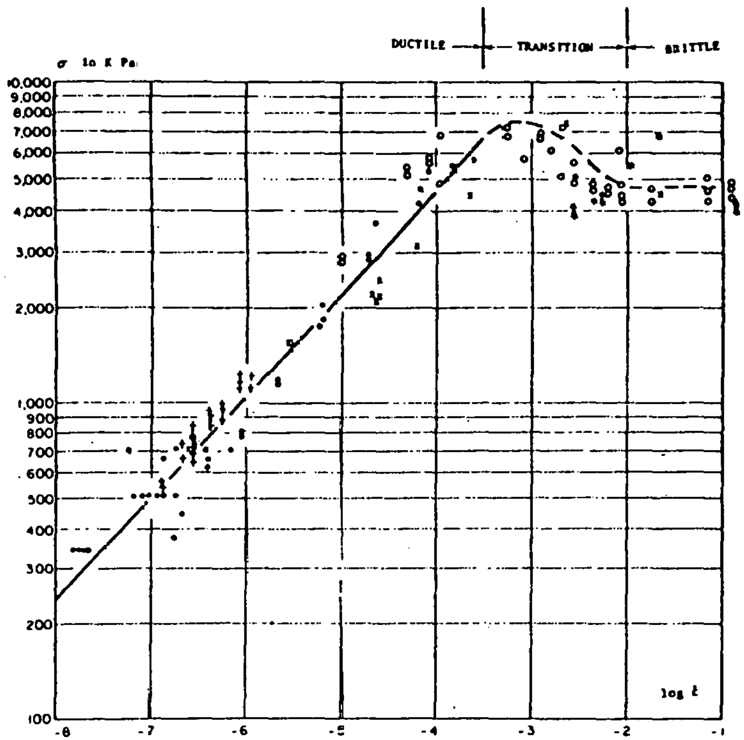
where A is the shearing surface area, c is the soil cohesion, and γ_{mc} is the cohesive material factor (taken to be 1.4). This design example was presented to illustrate one procedure for island design; the numerical values would likely be different for different locations.

Additional complexity is introduced by the advance of the freezing front into the island after it's formation, the rejection of brines downward during that process, and the properties of the resulting frozen saline granular fill. A sequence of alternate annual freeze/thaw cycles could transport fresh water from snow melt into the island, resulting in a rather complex layered island structure. There are a number of such problems related to artificial islands which remain to be examined in detail, prehaps by using a finite element computational approach together with a detailed set of field observations.

Island freeboard is determined by both oceanographic and ice load criteria. Storm surges, wave setup, and astronomical tide set a minimum for island freeboard. However, application of the ice load criteria may result in higher freeboard. In the example of Prodanovic,[43] this is the case, and the design freeboard of 11 feet includes a safety margin of 56%; island shearing resistance exceeds the 100-year estimated ice load by this margin. Wave runup depends upon island beach slope,[44] and appropriate beach protection for production islands should include not only sufficient height to prevent overtopping, but also large aggregate or some armor layer to prevent wave erosion. Moreover, during large ice movements, such as those occurring during breakup and freezeup, fragmented ice cover can move and pile up on the beaches of artificial islands, forming piles as high as 22 m at or near the beach. An extensive review of all published observations of such pilups has been given by Kovacs and Sodhi.[45,46] While such pileups are of little consequence if they are confined to the beach, it is necessary to design the beach profile so that ice sheet breakup and pileup does occur at the island edge. The four techniques for this as described by Jahns[47] are: 1) a rough beach with a high sliding resistance; 2) a steep bluff at the top of the beach to cause jamming; 3) an eight-foot high berm to trigger pile-up; 4) a buffer zone behind the berm where ice can accumulate without interfering with operations. A discussion of these techniques for production islands is given by Jahns,[47] and certainly a great deal more observation of ice pileup would assist in the synthesis of appropriate specific beach profiles. Ice sheets can ride up shallow beaches and travel on the order of 100 meters inland,[44] but this can be converted into pileup with appropriate sharp beach profiles.[47] Clever innovation in beach design might reduce ice rideup and pileup to a predictable location and extent, but more research is needed.

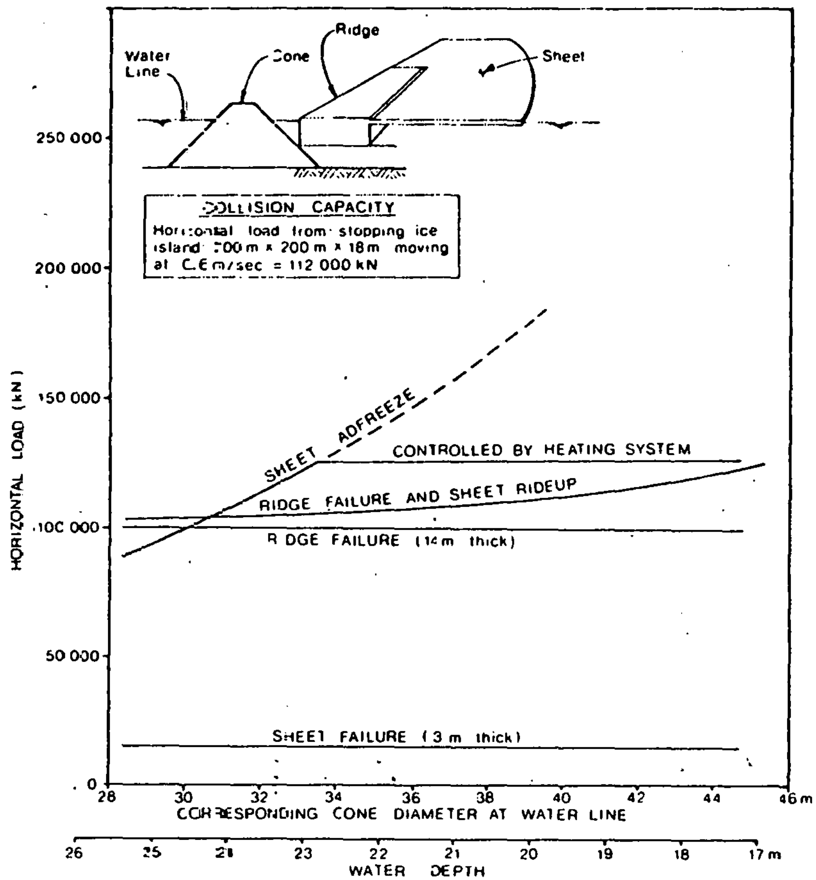
The probability of encountering multi-year ice should be evaluated when designing production islands. For the Beaufort Sea, (and presumably for the northern Chukchi Sea), Bercha and Stenning's[17] estimate of a maximum multi-year ridge thickness of 115 feet (based on 100-year return period) means that in most water depths (less than 115 feet) the island may encounter ice of thickness equal to the water depth. Multi-year ice is low-salinity ice at a temperature close to 0°C. If one uses the small-scale data summarized by Michel and Toussaint,[36] Figure 18, and if compressive failure is assumed, extremely large calculated forces result. Hence attention is given to the flexural mode of failure when one is considering practical production structures resistant to multi-year ridges in deeper water. The ideas behind such designs are discussed below.

In many bridge piers emplaced in ice-infested rivers, the upstream faces are made in the shape of inclined wedges. The maximum force predicted by Korzhavin's formula[38] is reduced, and Tryde[48] has suggested a reduction factor C_f, which depends upon the geometry and the ice



Universal curve for uniaxial crushing and indentation of S_2 ice at −10°C: ○—— Michel and Paradis (1976), uniaxial; ○- - - Carter and Michel (1972), uniaxial; † Frederking and Gold (1975), indentation; • Hirayama and others (1974), indentation; × present study, indentation.

18. Universal curve for strength in uniaxial crushing and indentation of fresh water ice at -10°C (from Michel and Toussaint, Ref. 36).



HORIZONTAL ICE LOADS

45° CONE

19. Estimate of horizontal ice load against a 45° conical offshore structure (from Jazrawi, Ref. 52).

properties. Other early work by Tryde[49] considered the forces on a sloping plane. A more elaborate theory has recently been developed in a thesis by Sørenson.[50] He recognizes that the initial region of contact between the ice sheet and the sloping structure leads to a crushing failure, and only after the local crushing contact region is large enough to provide sufficient lifting force is it possible to produce a bending failure at some distance from the ice sheet/structure boundary. Because of his assumption that the ice sheet is of uniform thickness, we will not repeat his results here; the interested reader can refer to his thesis.[50] It should be pointed out that the cross-section of a multi-year ridge is approximately trapezoidal,[51] both below and above the water line, and the details of interaction of a multi-year ridge with a sloping (circular) structure are quite different than in Sørenson's model.

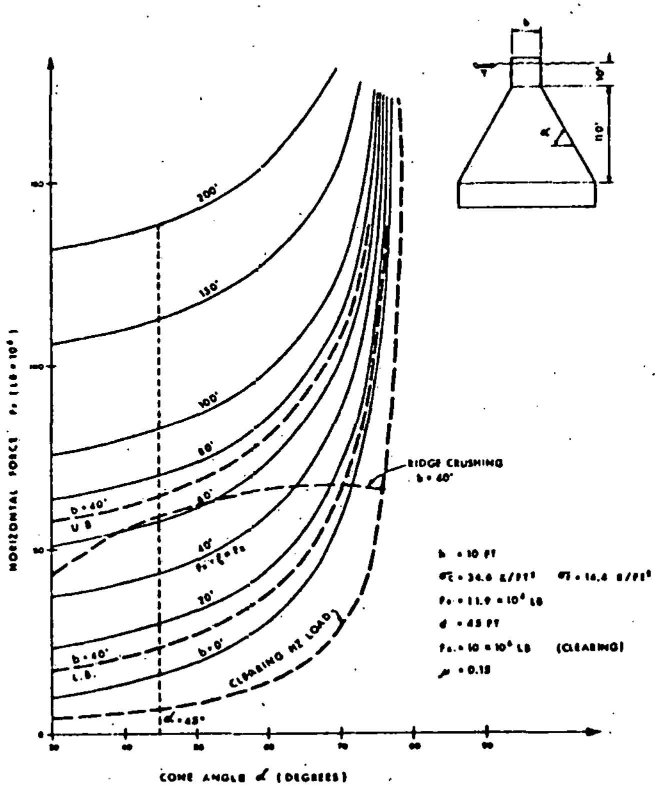
A preliminary design of a conical structure with a 45° angle, for water depths up to 41 meters in the Canadian Beaufort Sea, has been described by Jazrawi and Khanna.[52] Horizontal loads due to wave forces were established by a 1/90 scale model test, and the maximum horizontal wave force was expected to be 64,500 kN., corresponding to a 10 meter wave with 9 sec. period, in 41 meter water depth. In Figure 19, they have given the horizontal load due to an impact of a 14 meter thick multi-year ice ridge, which they calculate to be 100,000 kN. Also in Figure 19 is an estimate of the horizontal load from the impact of an ice island of dimensions 200 m x 200 m x 18 m, moving at a velocity of 0.6 m/sec. Such an ice island is only a fragment, but they estimate a horizontal load of 112,000 kN. for this event. Clearly, their calculations show that ice forces are dominant in the design of conical structures for the Beaufort and Chukchi Seas.

The discoveries in the Canadian Beaufort Sea have lead to the publication of another conical structure design,[52] for water depths of 150 ft to 250 ft. Stenning and Schumann have described a gravity structure with a conical section beneath the waterline to break ridges in flexure, a cylindrical section piercing the waterline to fail sheet ice in the crushing mode, and prevent ride-up and adfreeze. An ice island event was considered unlikely, but provision was made for such an event by means of disconnecting the superstructure from the base near the seafloor. They expected a maximum keel depth of 150 ft. for ice islands in the Canadian Beaufort Sea region of interest, and with the assumption of 200 ft. water depth, they designed the base section to be only 50 ft. high, so that an ice island would clear it without damage. For water depths shallower than 150 ft., they suggest other platform concepts as being more economic. Their maximum ice load was for a ridge 115 feet thick, frozen into a 10 ft. thick multi-year ice sheet. A companion paper by Bercha and Stenning[17] outlines the analysis of the interaction of such an ice ridge with the conical structure. For a 45° cone, topped with a 50 ft. diameter cylindrical section, his curves (Figure 20) predict a maximum horizontal load of 100,000 kips. A very detailed analysis has obviously been made by Bercha, and it will be very interesting to review his assumptions, procedures, and results when they are completely published. He does mention the scale effect, related to the fact that for very wide structures, failure is likely to occur sequentially along the interface, rather than simultaneously, and that total loads would be reduced. Further study is needed to quantify this reduction factor.

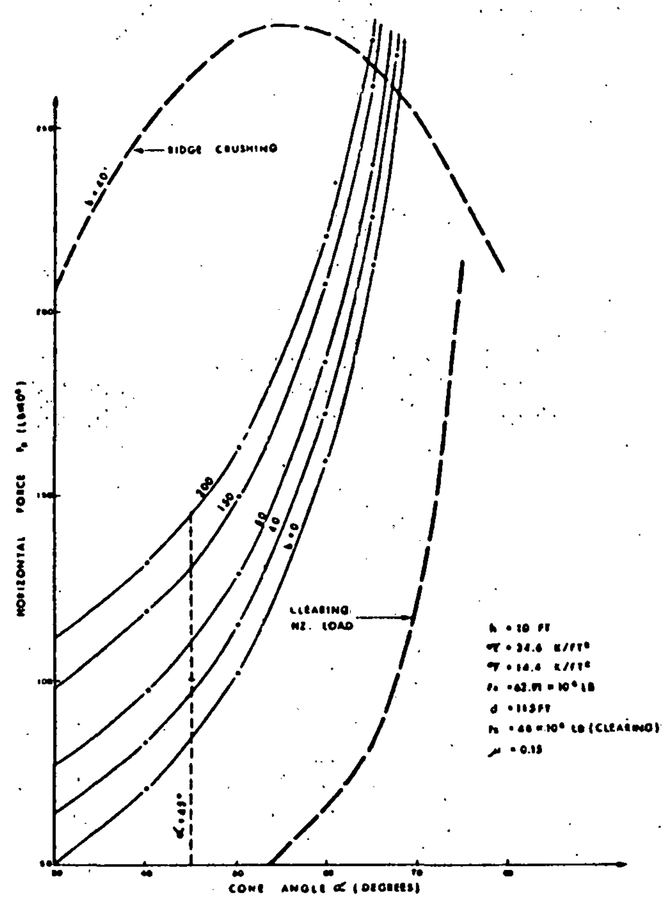
Another study of a conical offshore structure concept has been made by Pearce and Strickland,[54] but no detailed results are given. Tests on conical structures have been made at the Esso Resources Canada ice test basin, at a relatively large structure size (10 ft. diameter).

A wide variety of novel conceptual designs for Arctic structures have been proposed, including an ice-cutting rotating monopod. A review of earlier concepts has been given by Strain.[55] Generally, the lack of acceptance of novel designs in the past few years can be attributed to the feelings throughout industry that a passive (rather than active) defense against ice forces is more reliable, and that traditional design techniques are more reliable. Of course, reliability issues and cost issues are inextricably intertwined, in the development stages as well as in the operational phases.

It should be pointed out that the ice conditions in the Canadian Arctic Islands, and the drilling methods there, as described by Strain,[55] are different from those applicable in the Alaskan Arctic.



Monocone-design ridge interaction.



Monocone-maximum ridge interaction.

20. Estimate of horizontal ice loads against conical structures due to multi-year ice ridge movement (from Bercha, F. G. and Stenning, D. G., "Arctic Offshore Deepwater Ice-Structure Interactions", Proc. Offshore Technology Conf., Houston, (1979), pp. 2377-2386 (OTC-3632), (Ref. 17).

Water depth between the Canadian Islands is typically 500 ft. or greater, the multi-year ice is restrained in its movement by the islands, and it is practical to drill from a thickened ice sheet without experiencing so much lateral movement that the marine riser exceeds allowed deflection. There is no comparable situation in the Alaska Arctic.

Based upon published calculations[1] (which should be refined further), the wind and wave conditions in some parts of the Bering Sea are as severe as in any other part of the world subject to offshore oil and gas development. A large literature has been developed which gives extremely sophisticated tools to the offshore structure designer. The guidelines for structure design have been set by Det Norske Veritas, Lloyds Register of Shipping, and the American Bureau of Shipping. The U.S. Geological Survey Arctic Operating Orders apply in the regions considered here, and are given in Appendix A. The most detailed set of design guidelines are those of Det Norske Veritas,[56] which are reproduced in Appendix B. The variety of detail which must be taken into account in a structure verification program is illustrated there. The U.S. Geological Survey Conservation Division has recently initiated a structure verification program as well.[115] The ice conditions in the Bering Sea do represent additional loading, and are worthy of such special considerations.

Production structures for the Bering Sea need only contend with annual ice sheets, and first-year ice ridges. Although such ridges may be thick, they are not consolidated, and presumably have much lower strength than multi-year ridges. Consolidated rafted annual ice more than 10 m thick has been reported near St. Lawrence Island, however.[118] The necessity for a conical shape is no longer obvious, although it may be desirable. The ice movement in the Bering Sea is often of the order of 30 cm/sec, and ice fragment accumulation upon or around a structure could be substantial. Moreover, for structure diameters of 10-20 meters, and an ice velocity of 30 cm/sec, use of the strain rate relationship of Michel and Toussaint[36] provides a strain rate in the range associated with maximum values of crushing strength of ice. Assuming granular ice, and a temperature of -10°C, a compressive strength of the order of 1100 p.s.i is obtained from Wang's curves[33] (Figure 13). The approach of Ralston[21] may be extended to this case, with a contact factor of 0.6, and an indentation factor of 1.2. If the ice is 5 feet thick (4 feet of competent ice), a horizontal load of the order of 450 kips/ft of diameter results. The load on a cylindrical monopod of diameter 5.8 meters would be about 8600 kips. This should only be taken as an approximate indication of lateral load, to indicate that ice loading may be significant in the Bering Sea because of the high strain rate associated with ice failure against the structure. Much more data, particularly at temperatures near 0°C, needs to be obtained on Bering Sea pack ice morphology, mechanical properties, and movements before these values can be established with confidence.

Two large-scale test structures have been built in recent years in waters subject to moving annual sea ice sheets. One, in the Finnish waters of the Gulf of Bothnia,[57] is located in a water depth of 12 meters, and is subjected to a maximum ice sheet thickness of 0.9 meters, with ridges of 3 meter height and 12 meter keel depth. A cylindrical monopod of 5.8 meter diameter penetrates the water line. A conical base is attached, and the transition from cone to cylinder takes place 4 meters below the waterline. This lighthouse structure was erected in 1975 using prestressed concrete, at a cost of 5 million Finnmarks. The fundamental resonant frequency is in the range 2.8 Hz to 3.2 Hz. This artifical structure replaced an earlier structure which failed because of fatigue caused by ice-induced vibrations.[58]

These Finnish structures have been subject to dynamic analysis by Maattanen,[59] and it should be recognized that the ice loading is dynamic, leading to periodic structure and foundation loading. Any artificial steel or concrete structure designed for ice-covered waters should be subject to dynamic analysis. Existing finite-element computer programs have been applied to offshore structures, but the nature of the ice forcing function, and the properties of the structure foundation and adjacent seabed under cyclic loading, remain to be determined and integrated into such dynamic computerized analysis.

The KEMI I Finnish lighthouse described above is instrumented to measure ice forces and structural response. It has four accelerometers, four vertical rods to measure bending deformation, and 30 pressure transducers along its outer surface to measure local ice pressures and pressure ridge loading distributions against the structure. Two telemetry systems transmit data to a receiving station on the shore, where data is recorded and analyzed. Limited results are just becoming available;[60] the quantity of data obtained depends to a large extent upon the degree of ice movement in a given year.

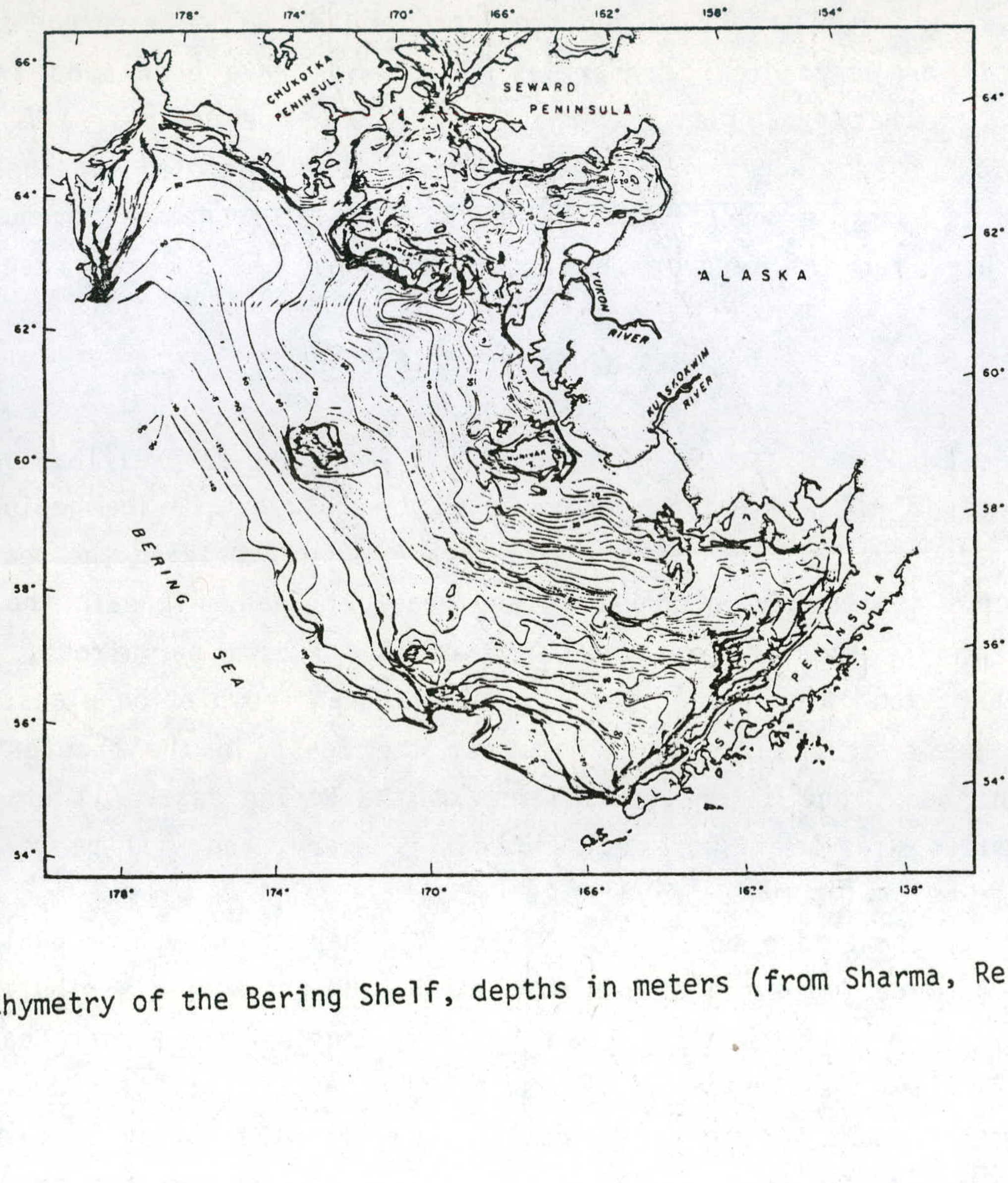
A test structure was constructed in the Sea of Okhotsk, about 600 meters offshore near Mombetsu, Hokkaido, Japan, in 1975, by Mitsui Shipbuilding and Engineering Co., Ltd. Under the sponsorship of Mitsui and also the Japan National Oil Corp., this effort's purpose was to develop a design for operation in ice-covered waters. Few results have been published, but Tabata and Nohguchi[61] have reported that the lateral load oscillated between 90 tons and 30 tons, with a period of about 20 seconds. After about ten such cycles, the ice failed in a different manner and the force dropped to the 10 tons to 30 tons range, still oscillating. The resonant frequency of the tower was about 15 Hz. Two seasons of data with a cylindrical tower were taken, and at least two seasons of data with a conical tower have also been taken.[62] Additional laboratory tests have been performed on the adfreeze bond of sea ice to offshore structures.[62] The current research phase involves the loads imposed upon the structure by ice ridges.[62,63] Data from this structure, when it becomes available, will be of great interest to those involved in the design of offshore structures for the Bering Sea. At this time, however, it is not clear whether a sufficiently diverse and large number of transducers were installed on the Mombetsu tower in 1975 to answer the significant design-related questions which remain. Test results in such an experiment are invariably limited by ice conditions presented by nature.

It is the opinion of many engineers involved in Arctic design that it would be quite useful to construct a carefully-instrumented test structure in a representative ice-covered Arctic region in order to answer many of the unknown questions which remain. The validity of Korzhavin's expression is in question, for compliant structures that are excited by ice movement. For cases where it can be used, the appropriate values of contact factor and indentation factor, for full scale structures, remain to be determined experimentally. Ice compressive strength varies with depth through the ice sheet, and the appropriate values for strength are open to question. Some thought should be given to the kinetic friction conditions at the structure interface. If a structure does vibrate, it may enhance the ice-fracturing capability of the structure. Finite element formulation of the ice-structure interaction problem should be considered. Very few measurements of physical and mechanical properties of sea ice have been made in the field, in the Bering Sea and the Chukchi and Hope Basins. If these gaps in our knowledge are filled, and carefully assembled together, it should be possible to optimize the design of safe, economical production structures for the recovery of Arctic offshore oil and gas reserves.

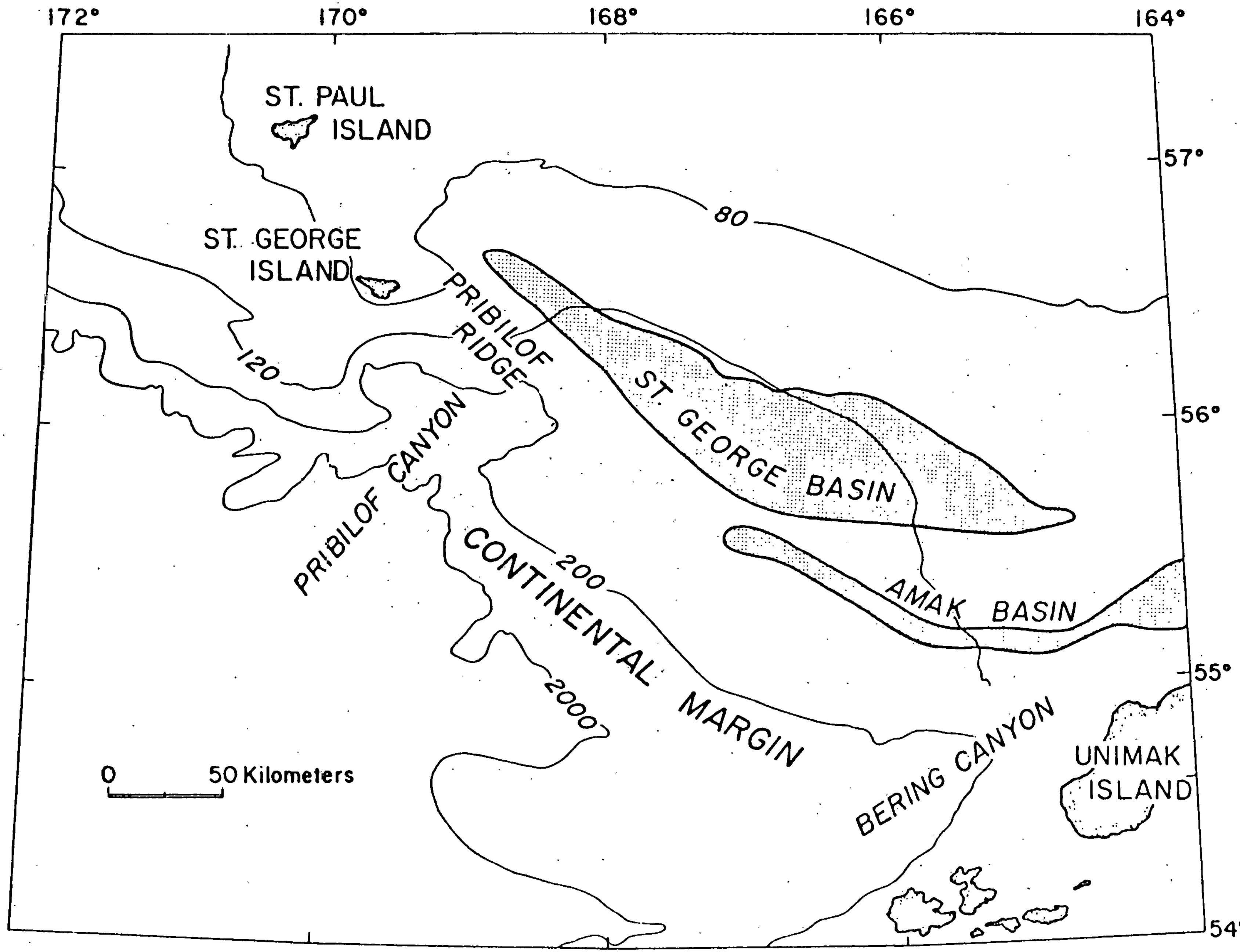
SUBSEA GEOTECHNICAL HAZARDS

Seafloor conditions vary considerably among the several lease areas included in the current Arctic OCS lease schedule. Marine geologists have made great strides in the past decade, characterizing the seafloor sediments in the Bering, Chukchi, and Beaufort Seas. Beneath the seafloor in the Beaufort and Chukchi Seas lies subsea permafrost, which must be taken into consideration in drilling and completion plans. Ice ridge keels scour the sea floor near the coast in the Beaufort and Chukchi Seas, and in shallower parts of the Bering Sea. All of these conditions affect offshore oil and gas recovery, and will be reviewed briefly below.

A comprehensive book by G. D. Sharma[64] has recently been published which provides much useful information on sediment size distribution in the Arctic offshore areas. First, one may consider the Bering Sea, and specifically the Norton, St. George, and Navarin basins. From the bathymetry chart[65] given by Sharma (Figure 21), the Norton Basin water depths are in the range 20-30 meters, the St. George Basin water depths are 100-140 meters, (see Figure 22),[66] and the Navarin Basin is a large basin in water depths of 100-200 meters. Although the Bristol Basin is



21. Bathymetry of the Bering Shelf, depths in meters (from Sharma, Ref. 64).



22. Location and bathymetry of St. George Basin, depths in meters (from Gardiner, Vallier, and Dean, Ref. 71).

not presently scheduled for oil exploration, the probability of oil reserves is appreciable there, and the water depths are in the range of 50 meters.

The sediments in Norton Sound are high in silts, as shown in Figures 23-27, taken from Sharma's work.[64] The Yukon river discharges some 88 to 100 million metric tons per year into Norton Sound.[64] The U.S. Geological Survey, as part of the OCS Environmental Assessment Program, has conducted detailed studies of this area, and a summary of their results has been presented by Thor and Nelson.[65] They have indicated that gas-charged sediments and sediment susceptible to liquefaction by cyclic-wave loading are two potentially unstable conditions found in Norton Sound. A large acoustic anomaly, probably a gas accumulator, has been located some 30-40 km south of Nome. This is about 9 km in diameter and 100 m below the sediment surface. Vibracorer penetration rates were three times faster in such regions of gas-charged sediment, and gas bubble trains emanating from the sea floor have been observed. They warn that "any artificial structures penetrating the large gas accumulation at 100 m...... may provide direct avenues for uncontrolled gas migration to the seafloor."[65] According to their studies, the nearsurface gas may be temporarily trapped by a 1-2 m layer of impermeable Holocene mud, but during storm conditions, the sealevel setup, seiches, and storm waves cause rapid changes in porewater pressures, sediment liquefaction, gas venting, sediment craters, and depressions which would challenge the stability of gravity foundations for offshore structures. The shear strength of the sediment is reduced and is locally variable because of the gas and organic content.[65,66,67] Obviously, the Norton Basin presents a serious challenge in geotechnical design for permanent offshore structures. Fortunately, according to Hopkins,[68] the likelihood of encountering permafrost in submerged areas of the northern Bering Sea is very low. The most likely regions for possible relict permafrost are narrow nearshore belts a few hundred feet wide between the Koyuk River and Cape Denbigh, between St. Michael and Apoon Pass, and between Kwikloak Pass and Cape Romanzof. Field measurements by Harrison and Osterkamp are currently in progress to confirm this prediction; no subsea permafrost has yet been found. The sediments

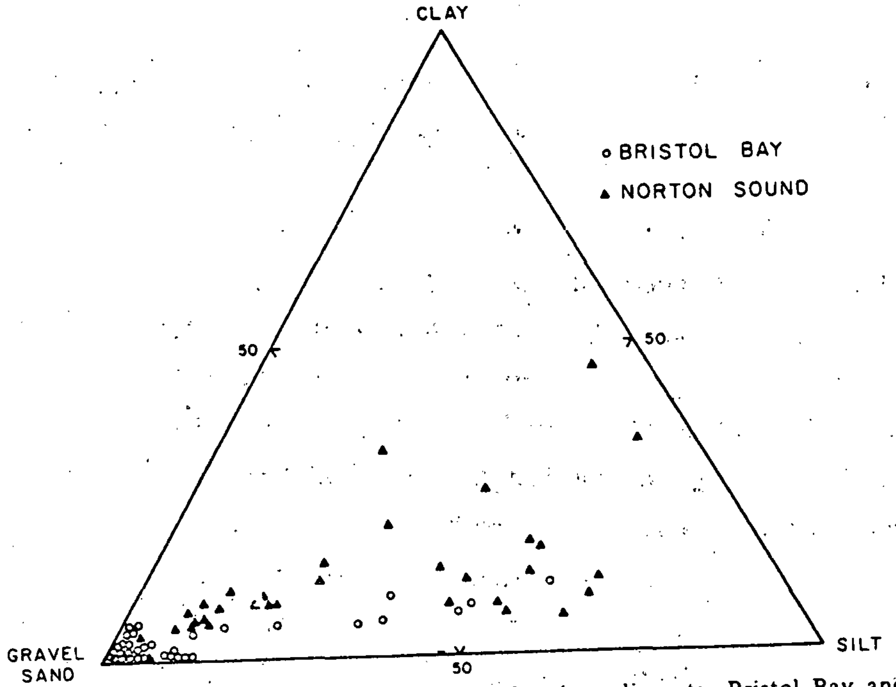


Figure Percent gravel-sand, silt, and clay in sediments, Bristol Bay and Norton Sound.

23. Percent gravel-sand, silt, and clay in sediments, Bristol Bay and Norton Sound (after Sharma, Ref. 64).

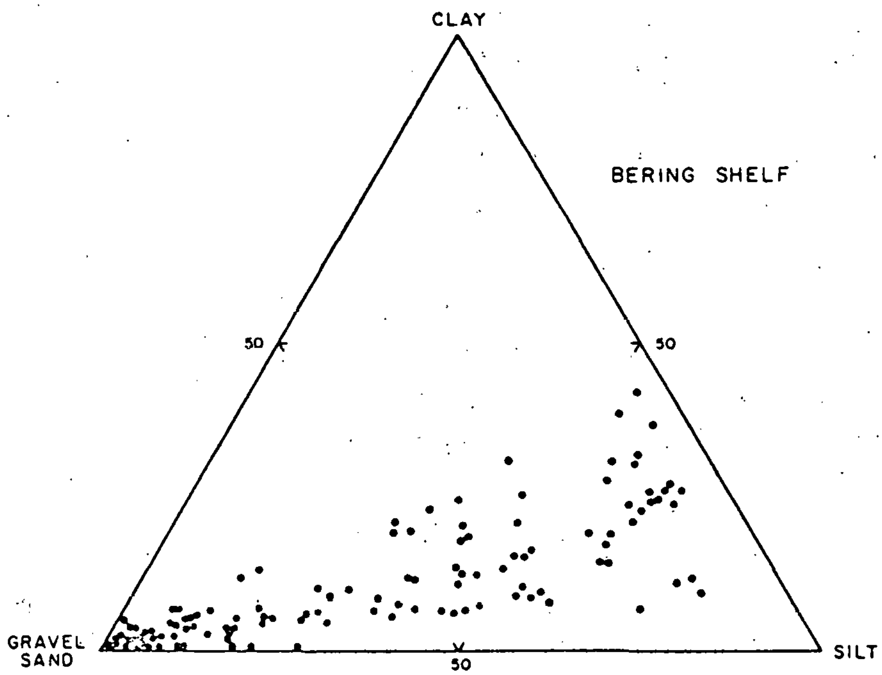
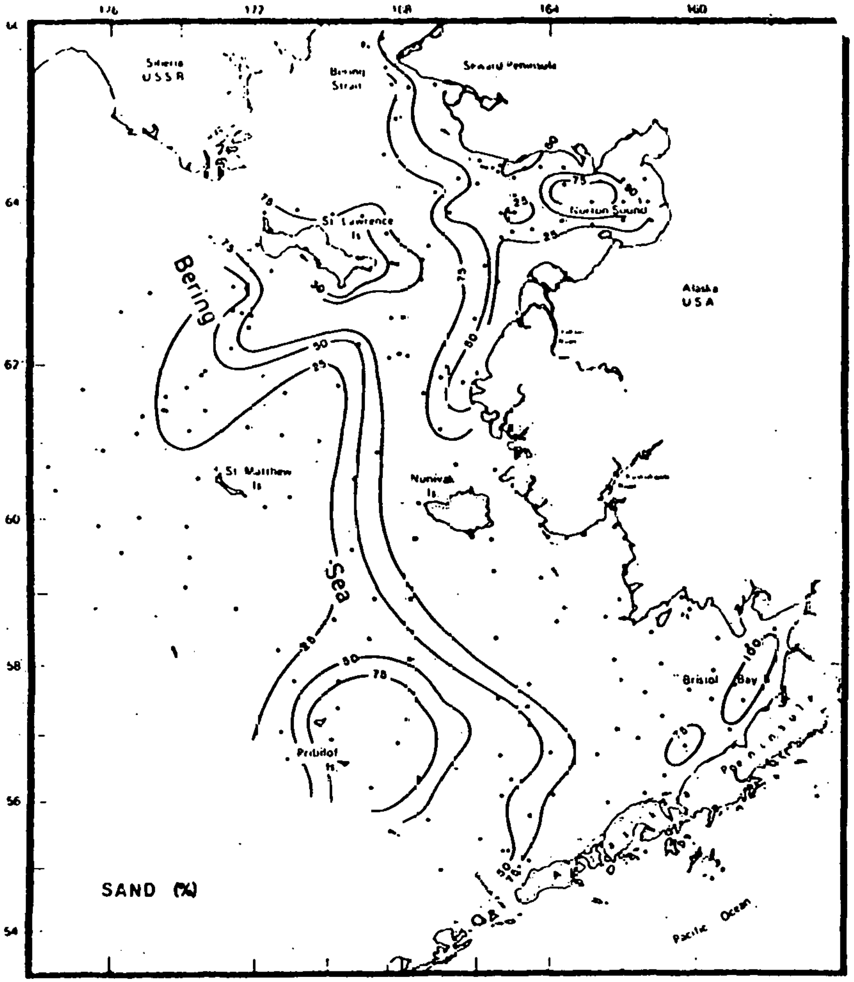
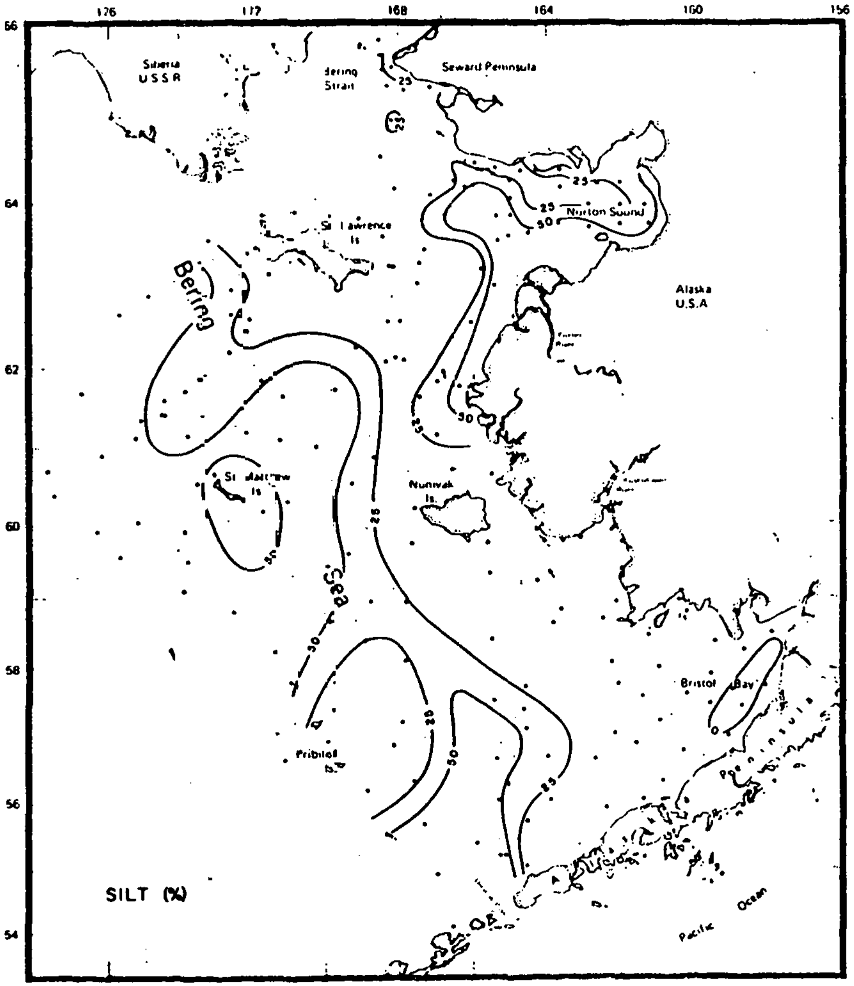


Figure Percent gravel-sand, silt, and clay in sediments, Bering Shelf.

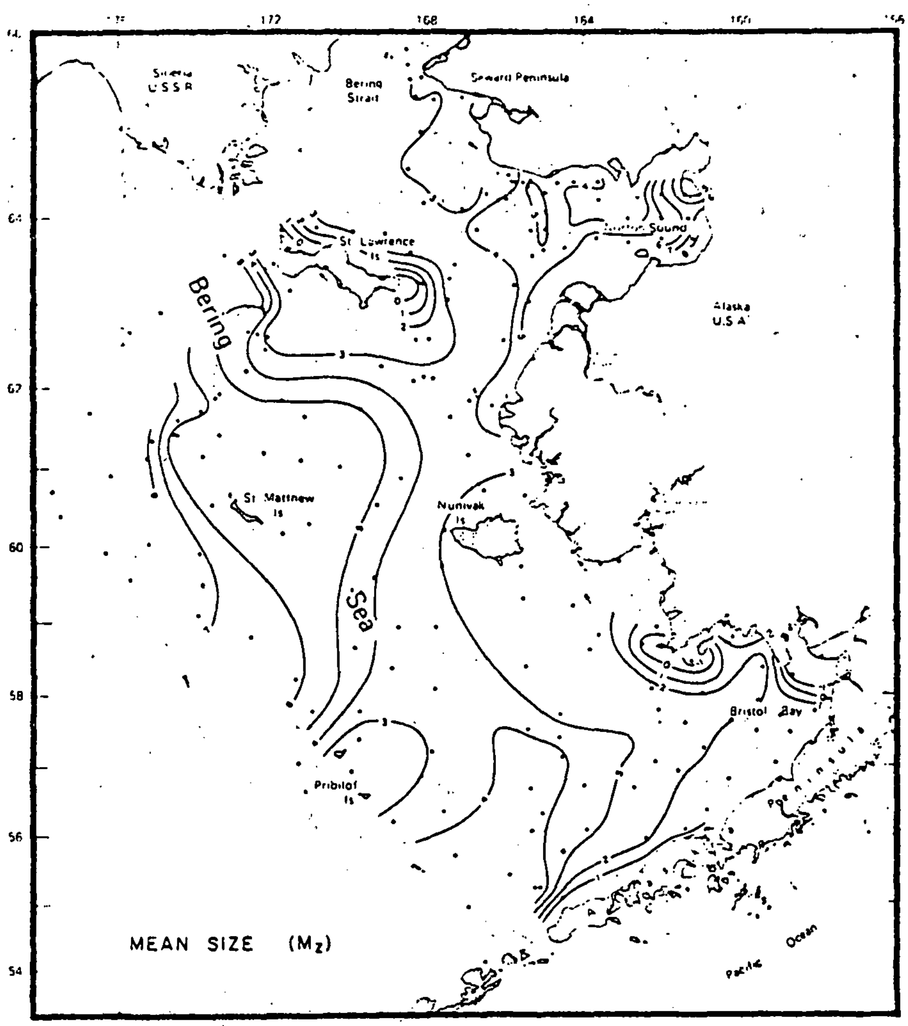
24. Percent gravel-sand, silt, and clay in sediments, Bering Shelf (after Sharma, Ref. 64).



25. Weight percent sand in sediments, Bering Shelf (after Sharma, Ref. 64).



26. Weight percent silt in sediments, Bering Shelf after (Sharma, Ref. 64).



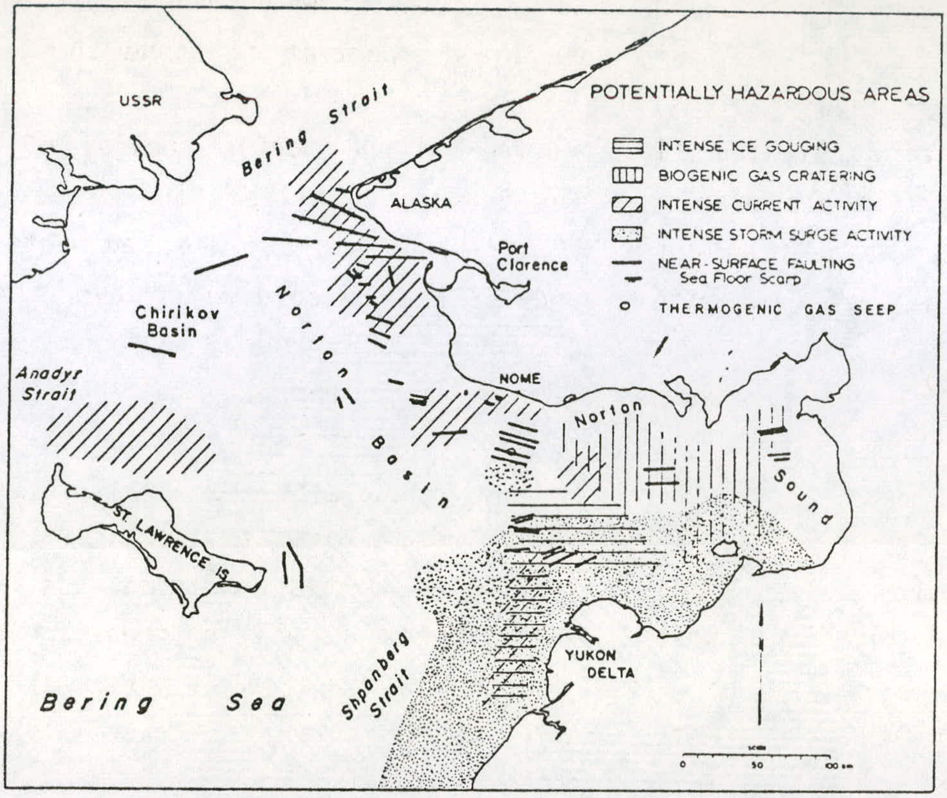
27. Sediment size mean distribution, Bering Shelf (after Sharma, Ref. 64).

of Norton Sound are subject to ice scour by ridge keels, and the region subject to scour is shown in Figure 28. Scour marks are a maximum of 1 meter deep, and are most numerous in the shear ice zone near the boundary of the shorefast ice.[68-70] Such ice scour is a very important consideration for the design of offshore pipelines, and presumably the water depth at which it occurs can be used as an indicator for the thickness of annual sea ice ridge keels which may frequently be expected in a given location. In Figure 28, the known nearsurface faulting is also indicated, and this hazard is important in connection with the choice of drilling sites.

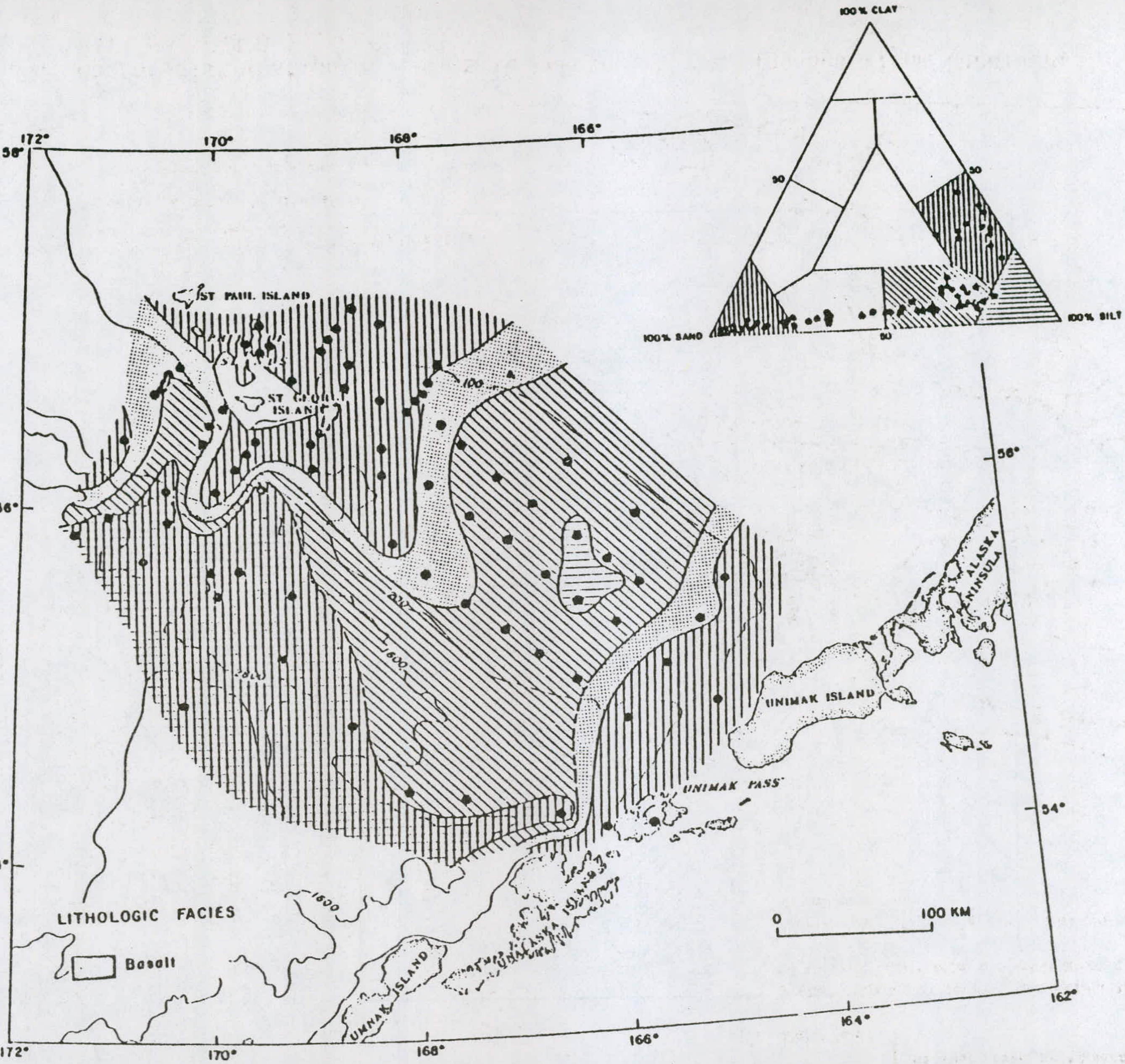
A very detailed field survey of the marine geology of the St. George Basin has been given by Gardiner, Vallier, and Dean.[71] Their results, shown in Figure 29, indicate that surface sediments in the lease sale area are mainly sandy silts located directly over the basin. Analysis of the gaseous hydrocarbons in the sediments did not show any excessive concentrations, which could cause sediment instabilities. Acoustic records did show anomalies at depths of 200 m - 300 m, which are assumed to be gas, but their data suggests that these gases do not leak to the surface. Their initial research was not specifically oriented towards geotechnical engineering properties determinations, however, and some additional work in these directions will be needed. They have also given a map of known faults in the area (Figure 30). Seismic hazards are significant, in their opinion, and they have given a map of epicenters for the entire southern Aleutian region of the Bering Sea (Figure 31). They suggest that seismic events can trigger unstable sediments on the continental slope and walls of submarine canyons; the rather gradual gross bathymetry shown in Figure 22 suggests that this may not be a serious problem in most of the lease sale area of the St. George Basin, with possible very local exceptions.

The very limited data on seafloor sediments for the Navarin Basin suggests that they are fine, (Figure 27), but more detailed surveys remain to be completed and geotechnical investigations should also be done.

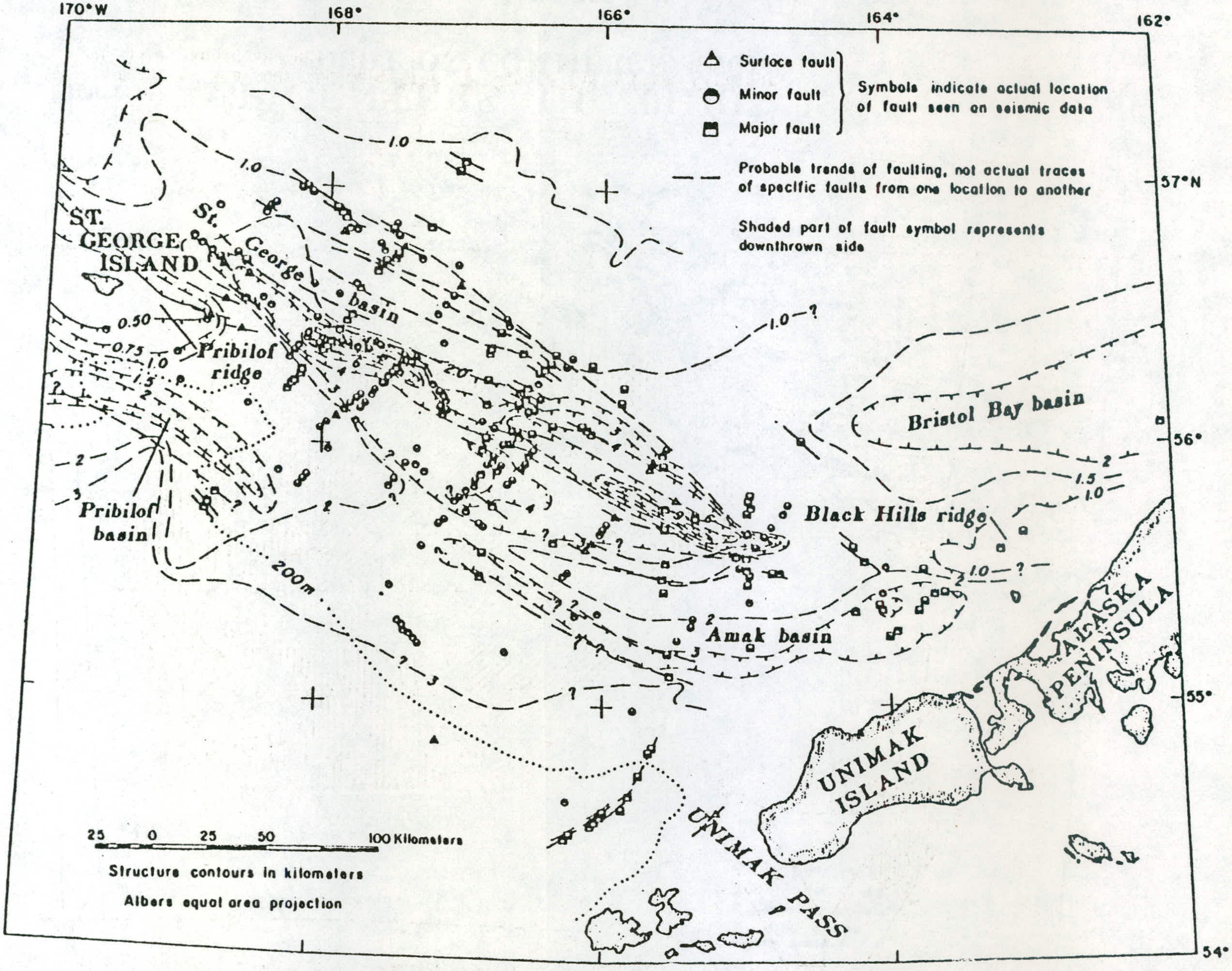
The Chukchi Sea is presently scheduled for two lease sales; one, in the vicinity of Kotzebue Sound, is the Hope Basin; the other is termed



28. Summary of potentially hazardous areas of Northern Bering Sea (from Thor and Nelson, Ref. 66)



29. Details of seafloor sediments for St. George Basin (from Gardiner, Vallier, and Dean, Ref. 71).



30. Map of distribution of faults in the southern Bering Sea (from Gardiner, Vallier, and Dean, Ref. 71).

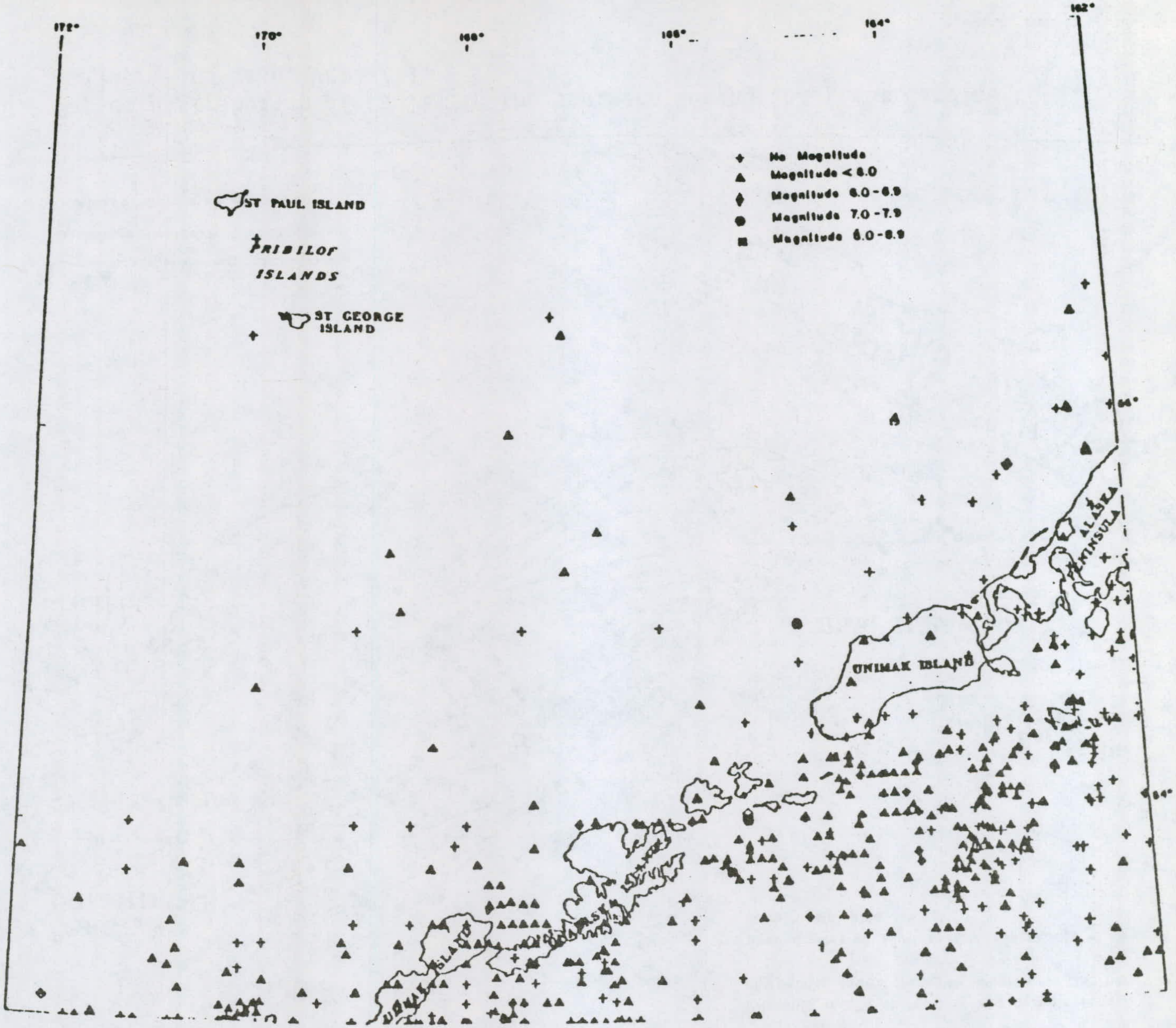
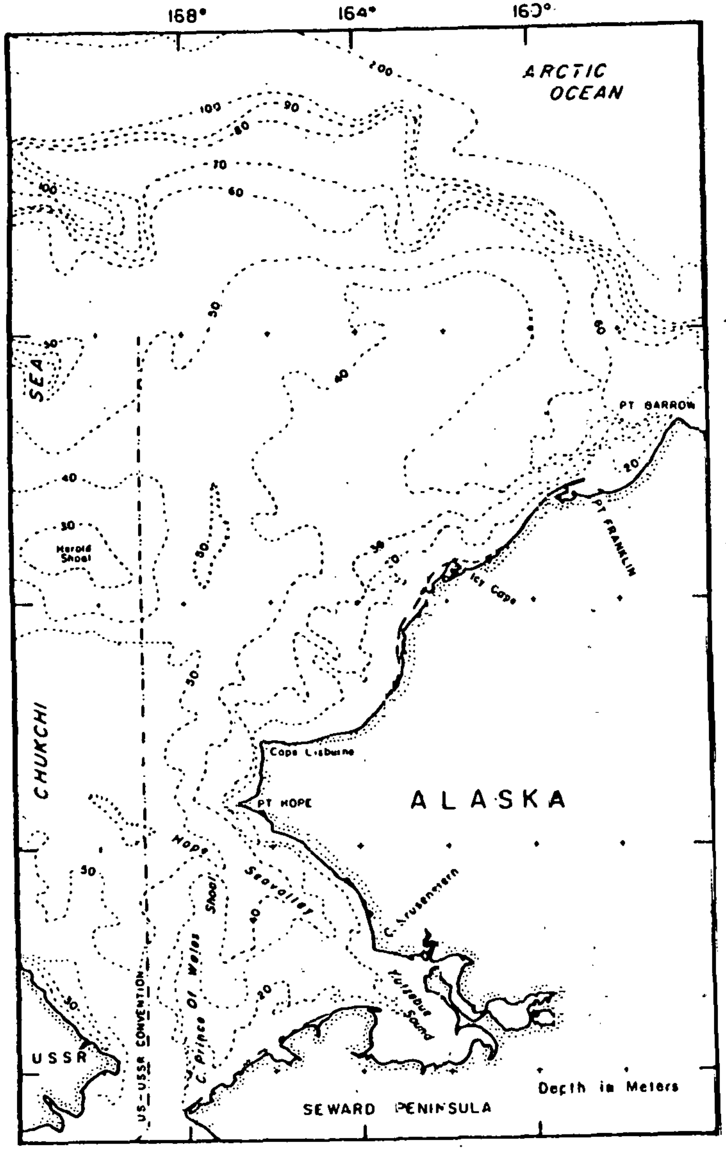


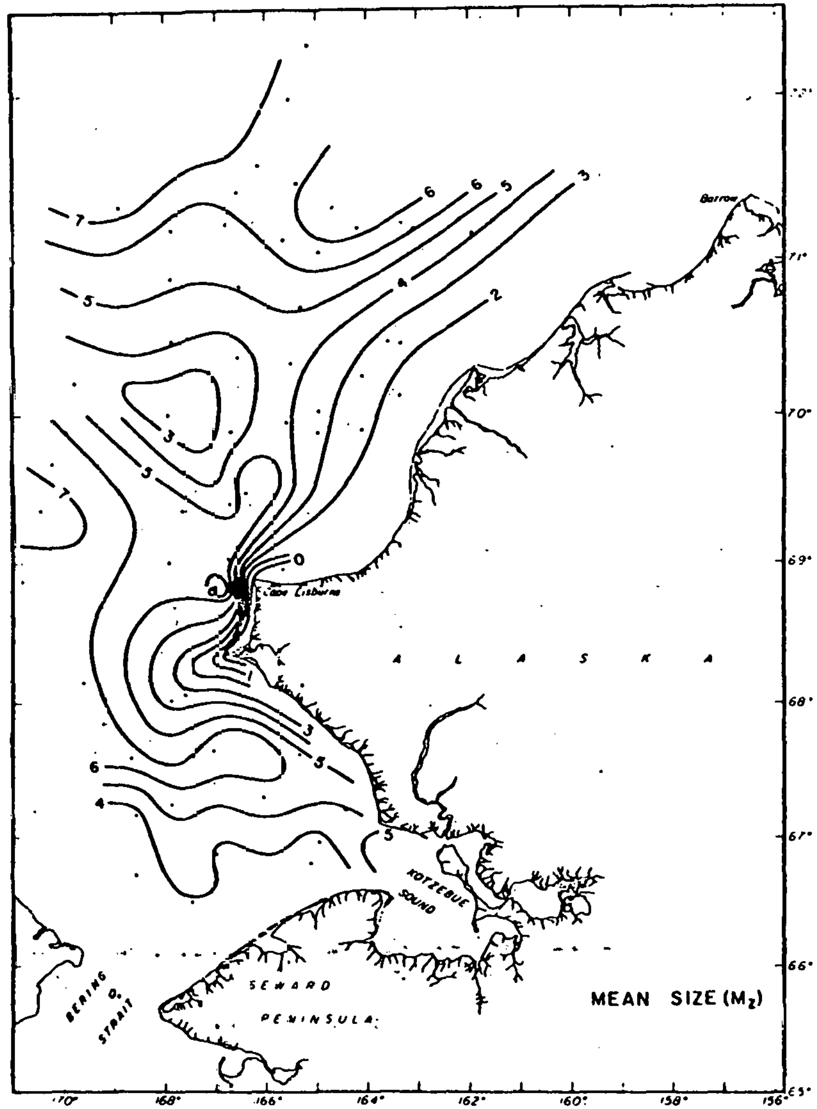
Figure 31 EPICENTERS UP THRU 1964
(DEPT. OF COMMERCE, 1970)

(from Gardiner, Vallier, and Dean, Ref. 71).

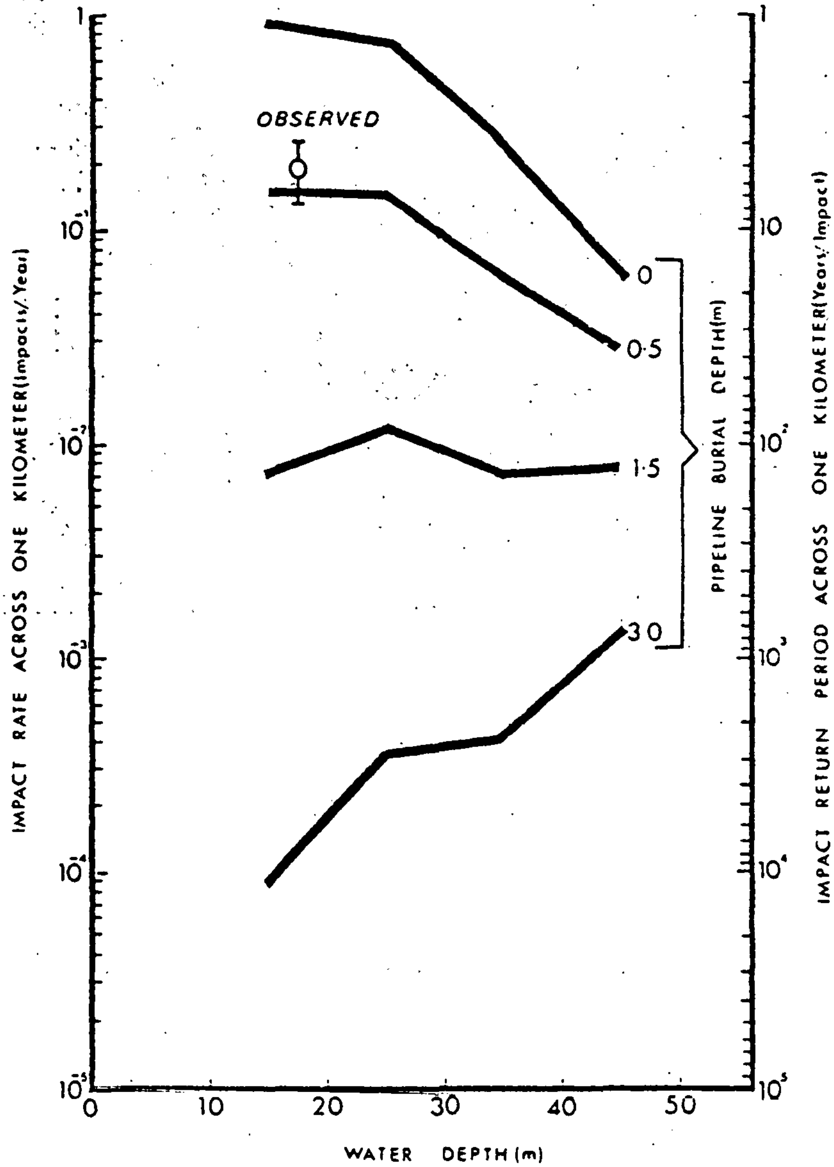
the Chukchi Basin, and is a much larger area between Cape Lisburne and Point Barrow. A flat and featureless bathymetry is typical in both areas, with water depths in the 20 m - 40 m range; a notable exception is the Hope Sea Valley, which penetrates towards Kotzebue Sound, just south of Point Hope (Figure 32). In the Hope Basin, sand is typical near the shore, with finer sediments farther offshore (Figure 33). Dense sediment plumes are found in Kotzebue Sound itself, at the mouths of the Kobuk and Noatak Rivers. The geotechnical engineering reconnaissance of both the Hope Basin and the Chukchi Sea remains to be completed. A very likely hazard is subsea permafrost. In the Chukchi Sea, seafloor gouging by the keels of multi-year pressure ridges and ice islands is likely. Detailed side-scan sonar surveys of scour tracks remain to be done in these areas. A model for iceberg scouring has been given by Chari,[72] which might be adapted to predict scouring in the Chukchi Sea. Data presented by Lewis[73] on ice scours in the Canadian Beaufort Sea has shown that the seafloor is virtually saturated with ice-scour tracks in water depths from 15 m to 40 m. This depth range corresponds to the Hope Basin and the Chukchi Shelf, which, although ice conditions are different, may also be subject to ice scour; field data on scours remains to be taken. Scour depths reported by Lewis[73] on the average range from 0.5 m to 1.0 m, but maximum depths range at least to 6 m below the seafloor. Some very rare scours are even up to 10 m deep.[73] The ability to predict extreme penetration depths for ice keels is essential from a subsea pipeline engineering standpoint, and Lewis[73] has discussed this in some detail. It is important to differentiate between areas of active scour and relict scour, in this connection. Lewis[73] has resolved this, and as an example of his results, Figure 34 depicts the impact return period across one kilometer of pipeline length as a function of water depth, for several burial depths from 0 to 3 m. A great deal of data acquisition and analysis remains to be done in the Chukchi Sea before similar statistics are available for production subsea pipeline designs there. One alternative which has been proposed for the Beaufort Sea is to elevate pipelines on gravel causeways, avoiding subsea pipelines entirely, and making ice scour less important.



32. Bathymetry of the eastern Chukchi Shelf, depth in meters (from Sharma, Ref. 64).



33. Sediment mean size distribution, eastern Chukchi Shelf (from Sharma, Ref. 64).

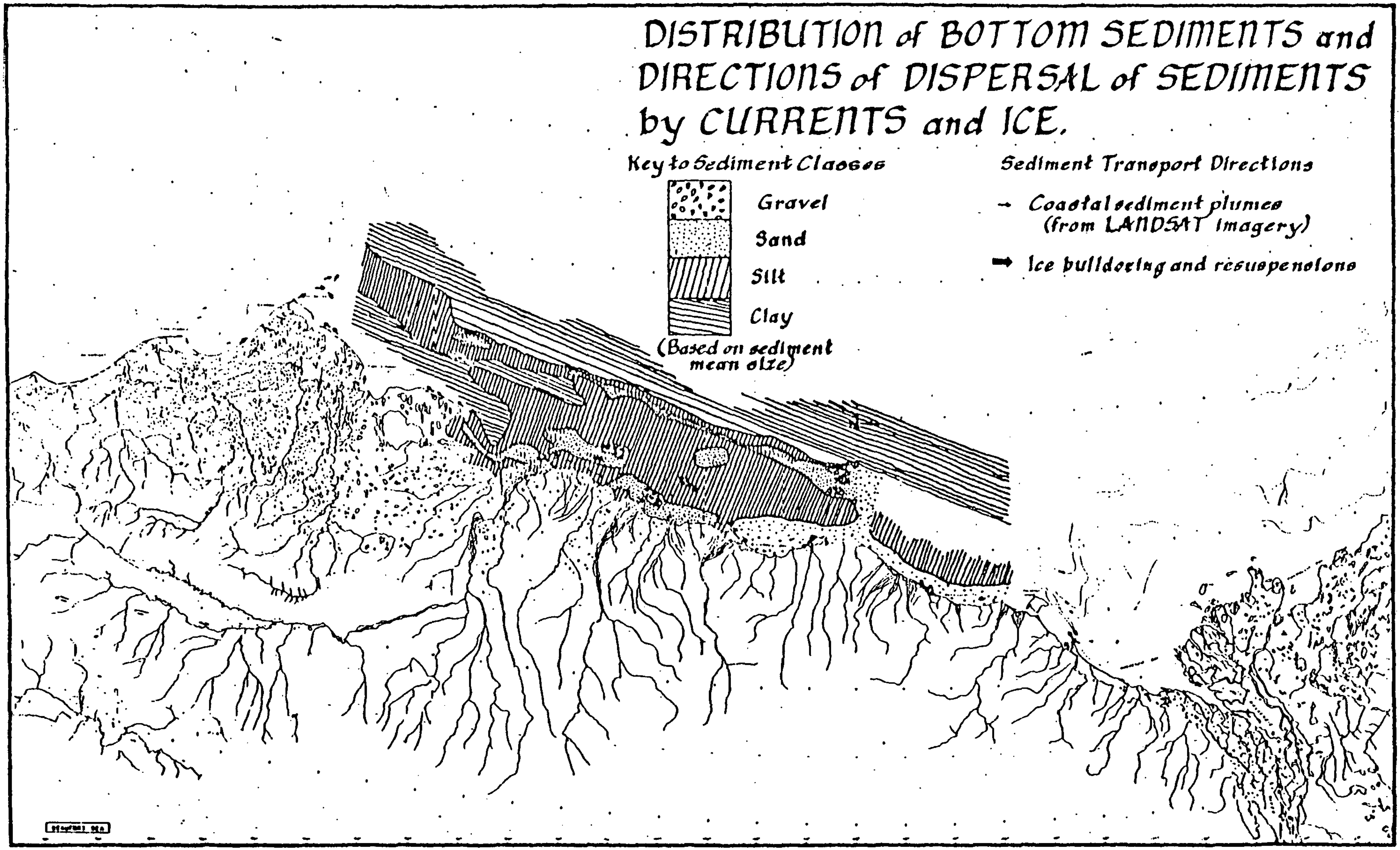


34. Theoretical ice keel impact rates and return periods for a 1 km section of a pipeline placed at various depths relative to the seafloor. Values are plotted vs. water depth for the Beaufort Sea Continental Shelf, Canada, (after Lewis, Ref. 73).

For Chukchi Sea reservoirs in 20 m to 40 m water depth, such methods are clearly impractical because of the tremendous quantity and cost of fill required for a long causeway into deeper water. Methods for deep burial or for armoring buried subsea pipelines should be reviewed, and system design alternatives such as offshore loading terminals should be considered.

In the Beaufort Sea near Prudhoe Bay, an intensive marine geological program has been underway for nearly a decade. A summary of all of the findings up to 1977 has been presented in the Beaufort Sea Synthesis Report, prepared by the OCS program.[74] The Final Environmental Impact Statement[75] contains similar information for the area of the lease sale of December 1979. The bottom sediments are reasonably well-mapped, as shown in Figure 35. The lease sale area scheduled for February 1983 extends west of the 1979 sale area, and has mainly clay and silt, from Figure 35. Specific geotechnical sampling in the area of the 1979 Beaufort Sea sale has been completed,[75] but a great deal more remains to be done to characterize the engineering properties of the sediments for the 1983 Beaufort Sale region.

It is generally recognized[74] that subsea permafrost is found along the entire Beaufort Coast, and it is very likely to be found along the Chukchi coast as well. It is a relict feature in most areas, and is degrading as a result of the intrusion of seawater upon the coastline. The processes of thermal conduction and saline water convective transport are combined in various proportions[74] to cause the melting of ground ice and other relict terrestrial permafrost features beneath the seafloor. This oversimplified picture of subsea permafrost thaw is accompanied by the fact that such thaw is followed by mechanical subsidence. In locations where the ice-bonded subsea soil is close to the surface, any foundation preparation activity, or any heat transmitted from foundations to the seafloor, could cause thaw and subsidence, and possibly eventually challenge the stability of the foundation. Generally, researchers have found that the top of the ice-bonded permafrost is near the surface of the sea floor close to the shoreline, in shallow (0-4m) water, and also in areas which are overlain with consolidated fine-grain sediments, such as clay, which retard the



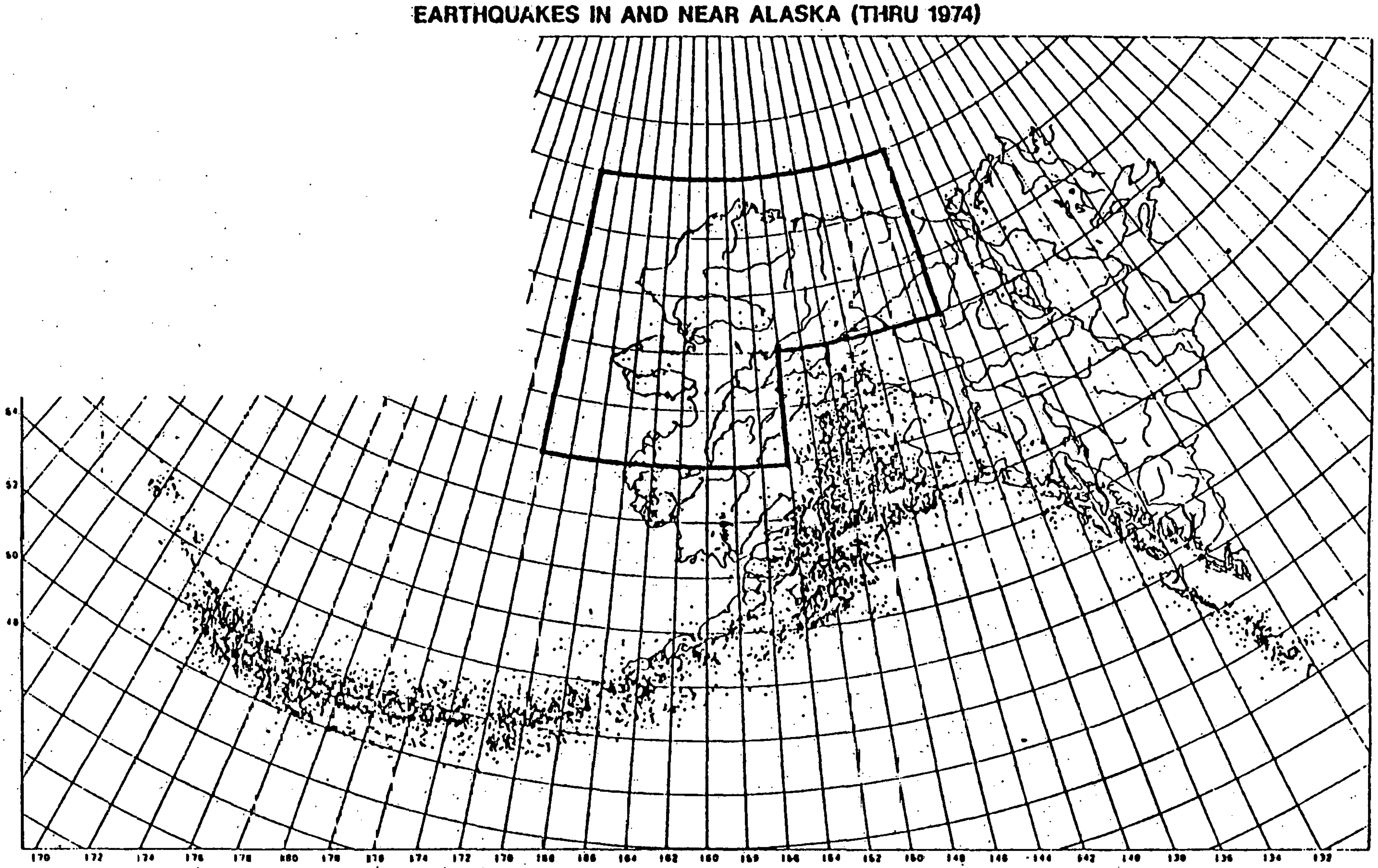
35. Distribution of bottom sediments in the Alaskan Beaufort Sea., (after Barnes and Reimnitz, quoted in Ref. 74).

penetration of seawater into the sediments. Even if the subsea permafrost is quite far below the sea floor, however, Goodman[77] has pointed out that adjacent production wells which penetrate the permafrost could have thaw/subsidence zones which overlap and coalesce after a number of years of production. The composite casing/thawed soil system will develop strains during subsidence which must be kept within the allowable design limits of the casing systems chosen. If wells in a cluster are shut-in after drilling or after a brief production period, freezeback will proceed slowly around each well, and the resulting confining pressure on the casing must be kept below those pressures which cause casing collapse. The combined thermal and mechanical analysis of such a problem, using a finite-element computer approach, remains to be published. The more elementary problem of a single production well thaw/subsidence has been solved and published, however.[78]

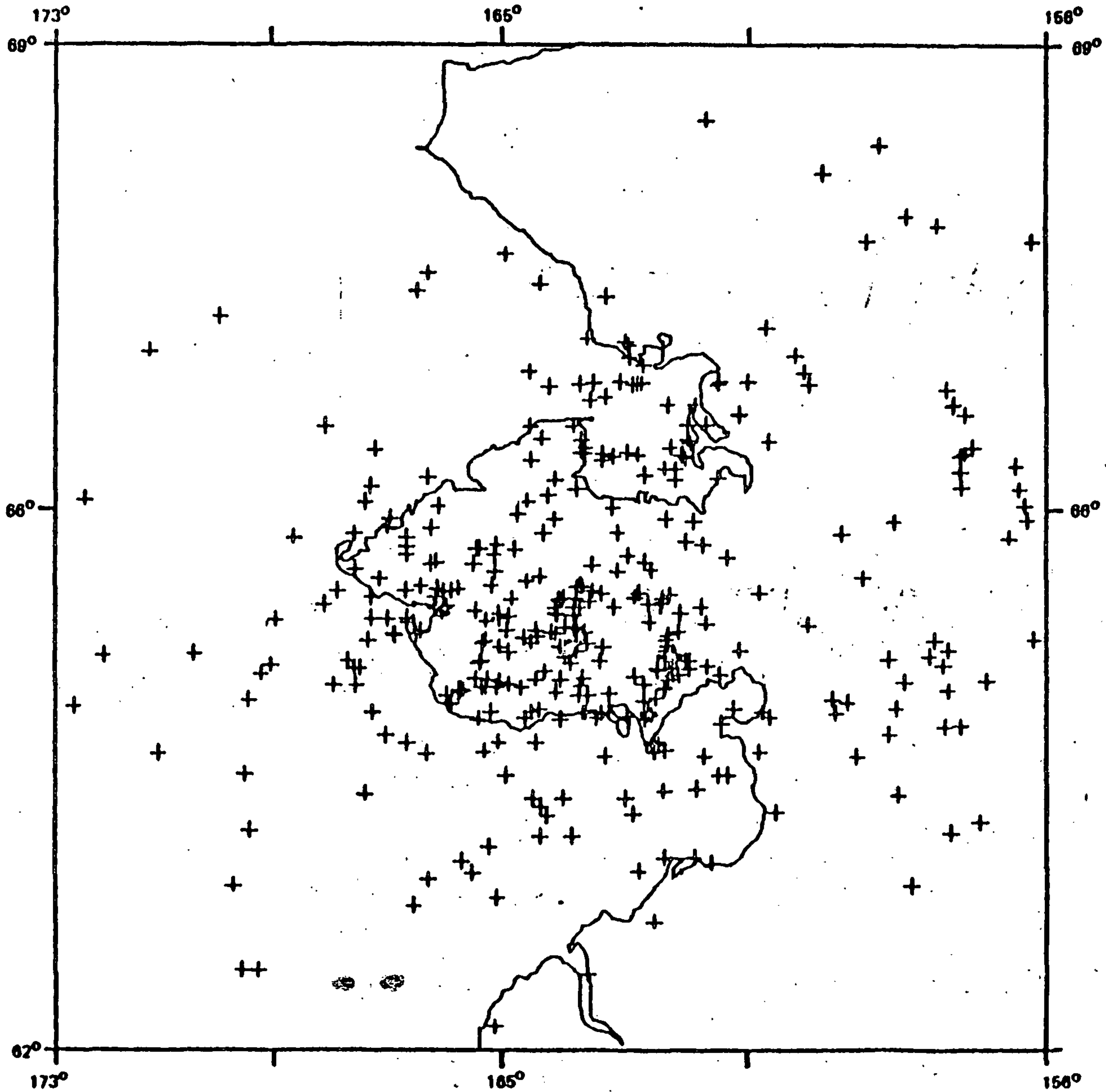
Ice scour has been extensively documented for the Beaufort Sea of Alaska by Barnes and Reimnitz.[79-81] Vibracores have been taken along the Beaufort Shelf to establish stratigraphy. Many of the dynamic geological processes in the Arctic marine environment have been established and geotechnical engineering properties of unbonded sediments have been determined for the Prudhoe Bay vicinity by Sellmann et al.[82-85] However, engineering properties of ice-bonded sediments remain to be determined, and more field measurements of engineering parameters of seafloor thawed sediments for the remainder of the Beaufort and Chukchi Seas should be made as well.

Once the engineering parameters of subsea soils in the Arctic offshore have been determined, the accumulated geotechnical knowledge which has been obtained in other offshore areas, such as the Gulf of Mexico and the North Sea, can be applied. Phenomena such as vortex shedding around pipelines, sediment slope instability, cyclical loading, and shear strengths as applied to specific foundation designs can be predicted.

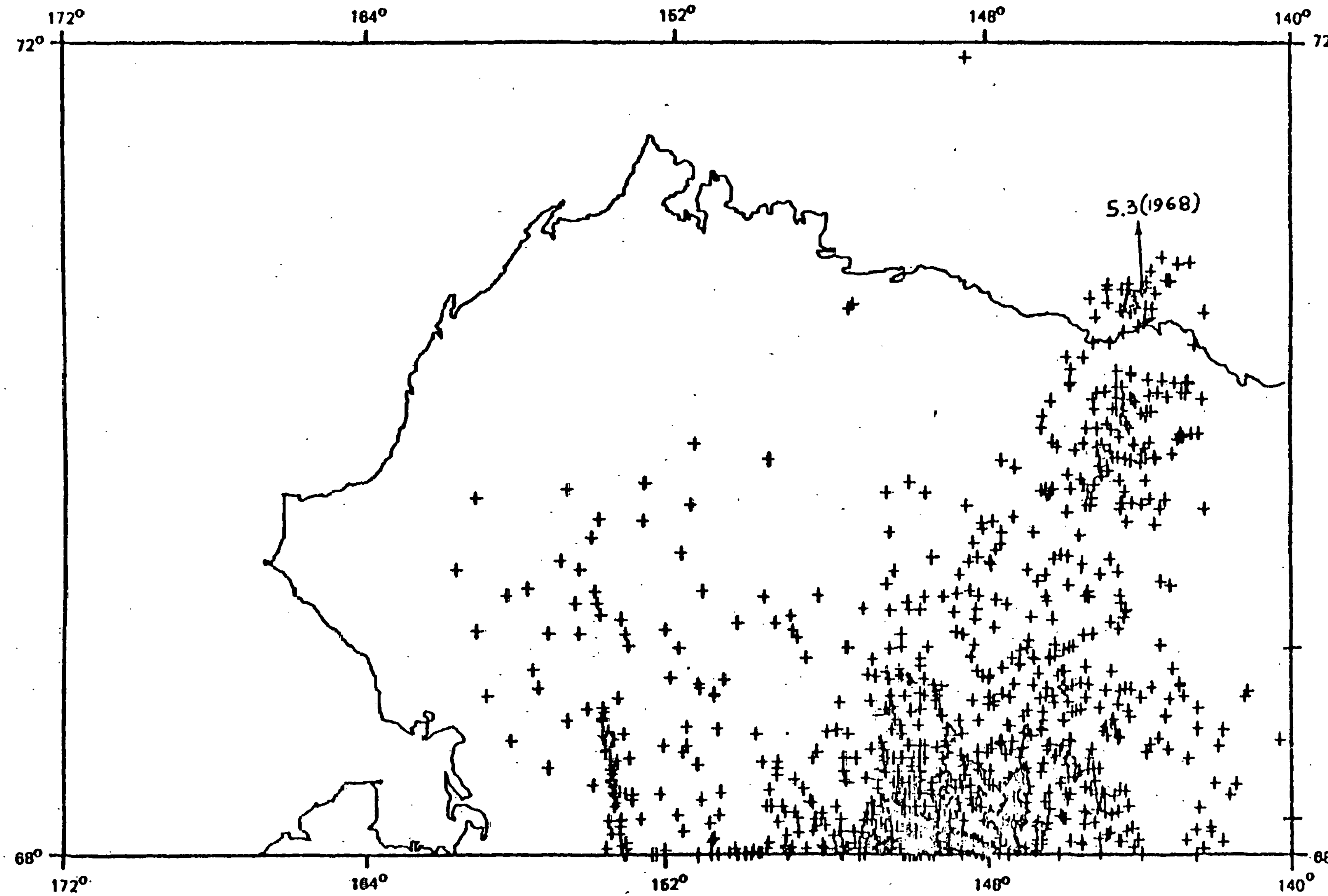
The dynamic response of specific structure/foundation designs may also be evaluated once the seismic excitation for a given area is known. The existing seismic network in northern and western Alaska has shown[86] that Norton Sound, Hope Basin, and the eastern Beaufort Sea are regions of moderately high seismicity; the present data shows little activity in the Navarin Basin,[86] St. George Basin,[87] and Chukchi Sea.[86] However, it has been pointed out by Davies[87] that the instrumentation on the Pribilofs, adjacent to the St. George Basin, has limitations, and that the seismic activity may be greater there. Earthquakes of magnitude greater than 4.0 on the Richter scale, detected by the world network, are shown in Figure 36, for all of Alaska. The more intense activity of the Norton and Hope Basins are indicated[86] in Figure 37, and the Beaufort and Chukchi Sea seismic events are in Figure 38.[86] There is an instrumentation gap in the Navarin Basin, and also from Point Hope to Point. Barrow, along the Chukchi Sea. The complicated faults in the latter offshore region may be active; a dense seismic network to assess this question remains to be deployed. Possible seafloor fault movements could threaten the integrity of buried pipelines, so more dense seismic coverage would be useful. Finally, it should be emphasized that no relationships have yet been experimentally established between seismic events and local seafloor accelerations and displacements in the Arctic offshore areas of the Bering, Chukchi, and Beaufort Seas. This data is very important in structural dynamic analyses, and requires sophisticated seafloor instrumentation in representative offshore locations. Once that data is available, structure designers can proceed with vibration analyses using known techniques.[88-91]



36. Earthquakes in and near Alaska (thru 1974) (from Biswas, Ref. 86).



37. Earthquake epicenter locations for Seward Peninsula region, 1977 and 1978, (from Biswas, Ref. 86).



38. Earthquake epicenter locations for Northern Alaska region, 1968 to 1978 (from Biswas, Ref 86).

TRANSPORTATION OF ARCTIC OFFSHORE OIL AND GAS

SUBSEA PIPELINES

For situations in which both oil and gas are to be produced, conventional practice is to pipe both products to the adjacent landfall and provide for separation, limited processing, and transport there. However, the Arctic coast of Alaska is not free of ice for the entire year, and furthermore a pipeline system from western Alaska to an ice-free port on the Gulf of Alaska would be very long and expensive. Such an approach would perhaps be justified if very large reserves were found. A much more realistic situation is that many smaller reservoirs will be found in succession. The extraction of oil from many ordinary offshore reservoirs can begin more quickly and be economically justified at lower threshold reserves if a marine transportation system (in this case, ice-breaking tankers) is used.[114] However, very few natural deep water harbors exist along the coast of the Bering, Chukchi, and Beaufort Seas of Alaska. In fact, the Bering Strait bathymetry is in the 40 meter range, implying that only vessels of modest (20 meter) draft are likely to be used. Even with 20 meter draft, natural harbors are rare, and would be expected to be congested with ridged shorefast ice for a large part of the winter. The hazards to subsea pipelines posed by fishing trawls would be present in the Bering Sea, just as have been experienced in the North Sea. Pipeline burial to a depth of 1-2 meters, plus reinforced concrete armor around the pipe, has provided a workable solution for this type of natural hazard in the North Sea. The additional hazard which should be noted is the possibility of ice scour. If the water depth is in the 20 m - 40 m range, such as in the Norton Basin, annual ice keels may scour the seafloor. However, observed scour marks are of the order of 1 meter deep, suggesting that the unconsolidated annual ridge keels do not have sufficient strength to gouge much deeper. It appears that a 1-2 m burial, perhaps combined with reinforced concrete armor, would protect a submarine pipe from such ice scour. Pipelines may cross faults, and if they are surficial and active some hazards might be encountered. In parts of the Norton Basin, submarine pipelines may be poorly supported by the gas-charged fine sediments, and differential settlement perhaps could occur, which may lead to pipeline buckling. It is possible that a pipeline may avoid such sediments, or it is possible that special pipeline burial and buoyancy might be used to overcome this difficulty. There is room for innovative subsea pipeline design in the Norton Basin.

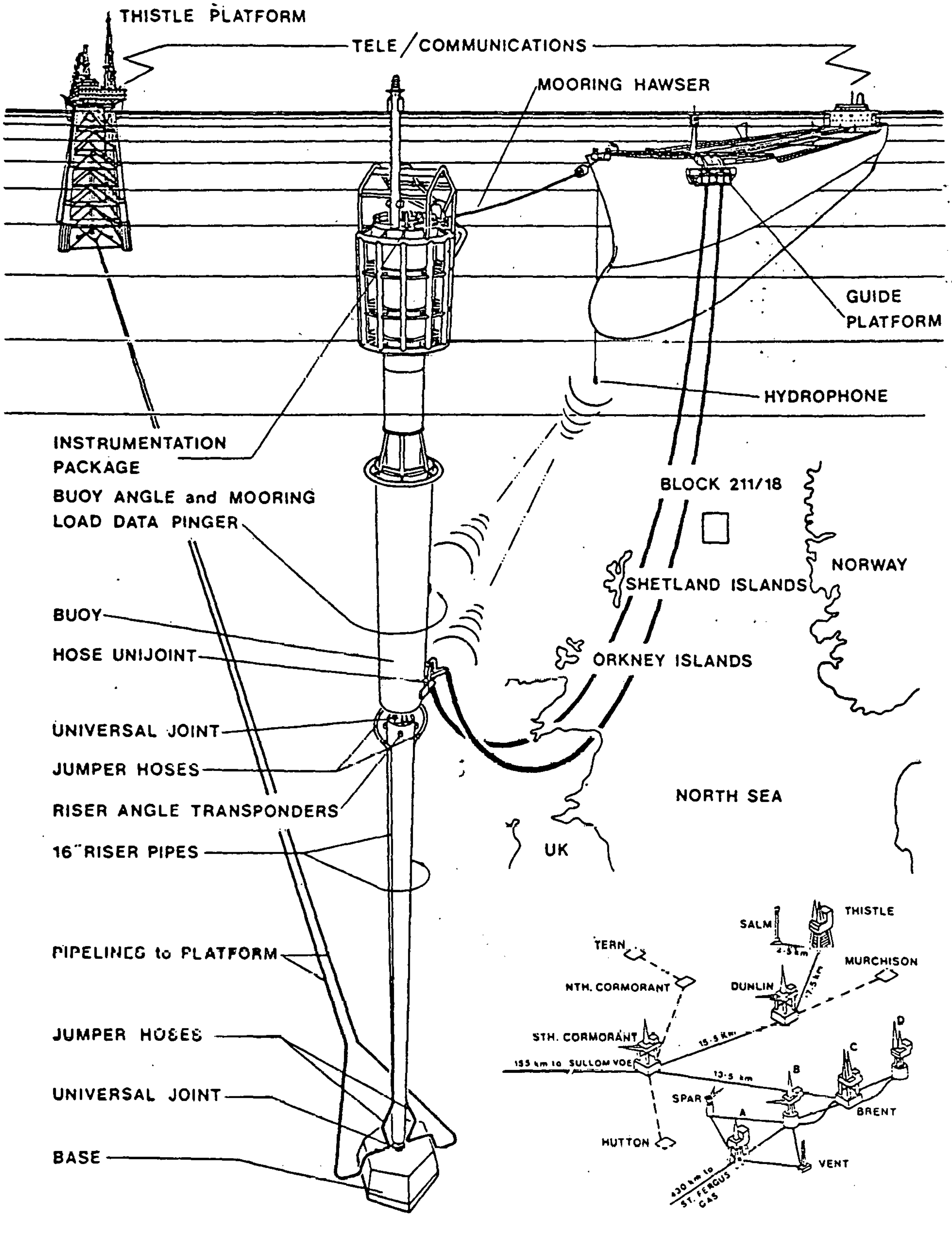
In the Hope Basin, the Chukchi Sea, and the Beaufort Sea, subsea permafrost is widespread. Warm subsea oil pipelines will transfer heat to the surrounding sediments, and if the ice-bonded permafrost is within - conservatively - 10 meters of the seafloor, there is the possibility of the heat from the pipeline causing thaw of the ice-bonded sediments, and possible subsidence if they have a high ice content. These conditions exist at the shoreline, and also in some recently inundated offshore bars and regions of consolidated clays. However, in other locations, particularly where coarse sediments offer the possibility of thermal convection cooling of the buried warm pipe, the rate of thaw would perhaps not be accelerated by the presence of the pipe. There is a need for a computer model which includes heat, mass and salt transfer, and phase changes, to provide some insight into this question. The major design question of the transition from offshore to land (elevated) conditions should also be considered. Elevation on a short causeway, or removal of beach permafrost and burial in coarse backfill, are two possibilities which have been mentioned. Regardless of the region, once a landfall is reached, the pipeline is subject to potential Arctic problems associated with permafrost, such as thaw/subsidence or frost heave; this category of Arctic hazard will be discussed in a separate section below.

OFFSHORE TERMINALS IN THE ARCTIC

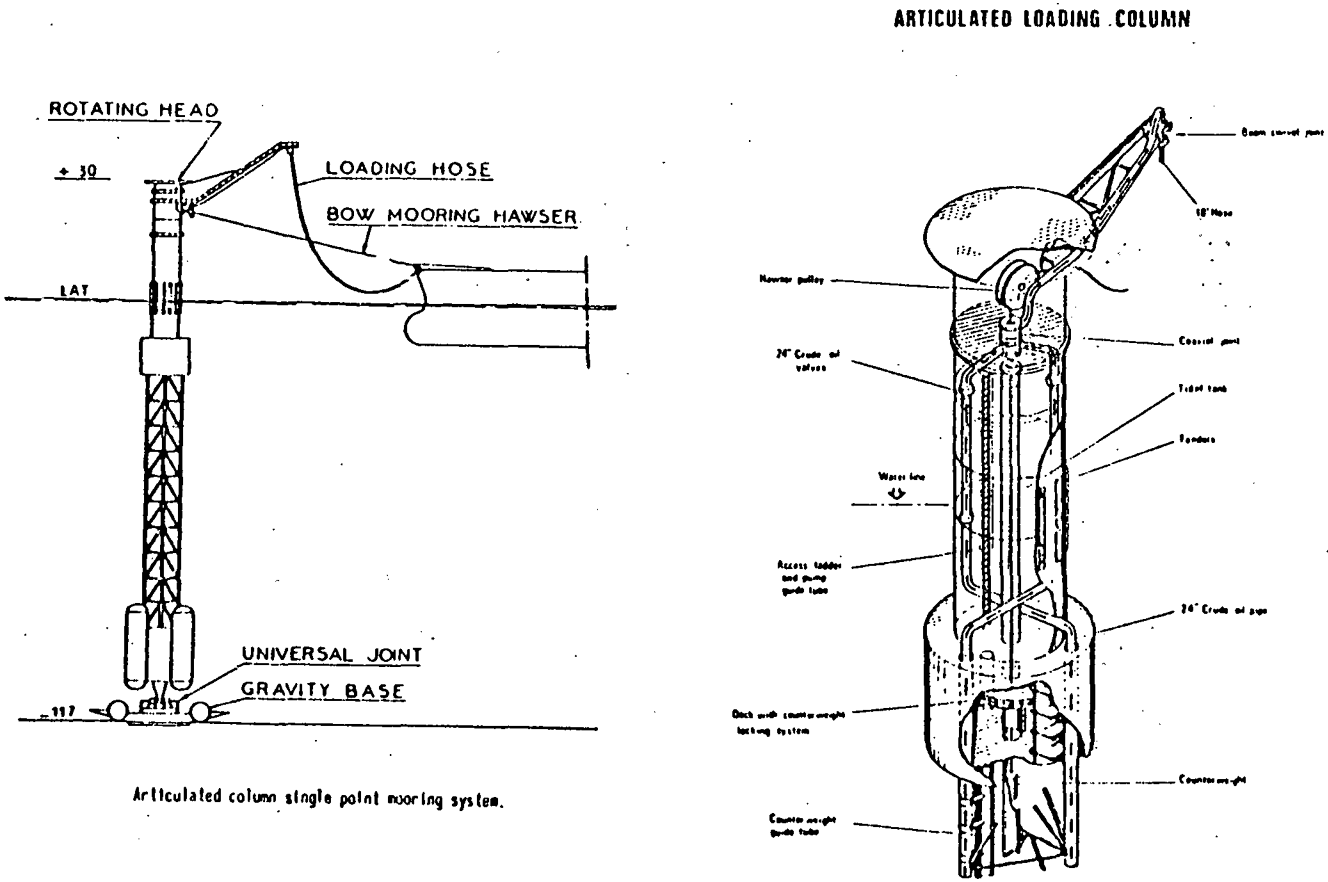
The scarcity of harbors in the Arctic offshore naturally leads to the consideration of offshore terminals for loading tankers. Several natural forces should be taken into consideration. High winds and waves can prevent terminal loading operations during open water conditions.

The statistics of such extreme conditions should be determined, but the technology of offshore loading in the North Sea has progressed to the point where (in the Thistle Field)[92] a maximum wave height of 7 m at 9 sec. period, a 50 knot windspeed, and a peak hawser force of 200 tonnes has been certified by Lloyds Register. Oil transfer time in 1978 for this single anchor leg mooring system ranged from 80% of the time in August to about 40% in November, depending primarily on weather conditions. Three 100,000 dwt tankers were used, with platform storage limits of 70,000 bbls. and projected production at 180,000 bbls/day. The system is illustrated in Figure 39. An articulated oil loading column has been used at the Beryl Field,[93] as shown in Figure 40. This has been used up to 8-9 meters wave height and winds of Force 9. The articulated column concept[93] dates back to 1963, and has reached the operational stage successfully. The 99.4% efficiency of the Beryl SPM is due to the large (900,000 bbl) storage capacity of the Beryl Central Platform, which allows oil production and storage in times of extremely adverse weather. The use of yoke moored tankers for storage at SPM locations is quite widespread,[94] as shown in Figure 41. These floating storage and transfer vessels can also incorporate processing, delivering processed crude, LPG, and fuel gas. Maximum wave heights to 85 ft. and wind speeds to 87 mph have been provided for,[94] as shown in Figure 42.

None of these techniques have been used in ice-infested seas, but the extension of such techniques to the Arctic deserves some consideration. Ice reinforcement of moored tankers would be necessary, and will be discussed below in connection with ice-reinforced transport vessels. High mooring forces would be required. At Beryl, a maximum hawser tension of 102 metric tonnes was registered for a 4-meter wave height and an average wind of 37 knots. The natural drift velocity of the ice sheet may be taken to be of the order of 30 cm/sec.; brittle compressive failure is likely to be involved in such cases. A mooring load in drifting ice remains to be determined, but may be even larger than the breaking strength used in the mooring design for the LOOP deepwater port design for VLCC tankers offshore of Louisiana.[96] Mooring design innovations are likely to be needed for tankers during loading operations. One fundamental design principle for offshore fixed struc-



39. Offshore oil loading terminal in the North Sea (from Millar et al., Ref. 92).



40. Articulated column single point mooring terminal (from Hays et al, Ref. 93).

TABLE 1

PERMANENT FLOATING STORAGE FACILITIES (IN USE OR USED AT ONE TIME)
(NON-YOKE TYPE)

NO.	OPERATOR	COUNTRY	LOCATION (FIELD)	CAPACITY MBBL.	MOORING METHOD STORAGE TANKER		YEAR	DESIGNER STORAGE SPM
1	Shell	Qatar	Halul	285	CALM	(1)	1964	IHC Gusto
2	Gulf	Nigeria	Escravos	386	Spread	(2)	1965	—— . ——
3	Continental	Dubai	Fateh	295 + 350	Spread	(3)	1966	—— . ——
4	Ipac	Iran	Cyrus	300	Spread	(2)	1967	—— . ——
5	Kerr McGee	USA	Gulf of Mexico	110	CALM	(2)	1967	McDermott
6	Shell/BP	Nigeria	Forcados	825	CALM	(1)	1969	SBM
7	Texaco	Nigeria	Pennington	370	Spread	(2)	1970	—— . ——
8	Ipac	Iran	Cyrus	1000	CALM		1970	SBM
9	Arco	Indonesia	Ardjuna	1000	CALM		1972	Imodco
10	Iiapco	Indonesia	Cinta	1000	CALM		1972	Imodco
11	Aramco	Saudi Arabia	Zuluf	1800	CALM	(1)	1973	SBM
12	Shell	Spain	Amposta	500	CALM		1973	SBM
13	CFP	Abu Dhabi	Abu El Bu Koosh	700	CALM		1974	SBM
14	Arco	Indonesia	Ardjuna	1000(same as 9)	CALM		1974	SBM
15	Crescent	Sharjah	Mubarek	800	Spread		1974	—— ——
16	Shell/Exxon	U.K.	Brent	300	SPAR		1975	IHC Gusto
17	Texaco	Nigeria	North Apoi	370(same as 7)	CALM		1975	SBM
18	CFP	Indonesia	Bekapai	700	CALM		1975	SBM
19	Exxon	Malaysia	Tembungo	600	SALM		1975	Sofec
20	Gulf	Zaire	Mibale	500	CALM		1976	Imodco
21	ONGC	India	Bombay High	700	CALM		1976	SBM
22	CFP	Indonesia	Handil	750	CALM		1977	SBM
23	SNEA	Cameroon	Kole	750	Spread		1977	—— . ——
24	Agripetco	Ghana	Gulf of Guinea	550	SALM		1978	Sofec

(1) Mooring now used for export function.
(2) No longer in service.
(3) One of the two vessels in service at present.

TABLE 2

FLOATING STORAGE FACILITIES - FILLING STATION CONCEPT
(INSTALLED OR ON ORDER)

NO.	OPERATOR	COUNTRY	LOCATION (FIELD)	TANKER CAPACITY MBBL.	MOORING METHOD STORAGE TANKER	YEAR INSTALLED (INSTALLATION EXPECTED)	DESIGNER STORAGE SPM
1	Phillips	Norway	Ekofisk	300	CALM	1971	SBM
2	Phillips	Norway	Ekofisk	300	CALM	1971	SBM
3	Gulf	Denmark	Danfield	400	CALM	1973	SBM
4	Shell/Exxon	U.K.	Auk	300	ELSBM	1975	IHC Gusto
5	Hamilton	U.K.	Argyll	300	CALM	1975	SBM
6	Amoco	U.K.	Montrose	700	CALM	1976	SBM
7	Amoco	U.K.	Montrose	700	CALM	1976	SBM
8	Burmah	U.K.	Thistle	550	SALM	1977	SBM
9	Petrobras	Brazil	Enchova	350	CALM	1979	SBM
10	BP	U.K.	Buchan	550	CALM	(1979)	Imodco
11	Petrobras	Brazil	Garoupa	550	CALM	Standby	Imodco
12	Shell/Exxon	U.K.	Brent	600	CALM	Standby	SBM

TABLE 3

RIGID-YOKE MOORINGS INSTALLED OR ON ORDER

NO.	YEAR INSTALLED (INSTALLATION EXPECTED)	COUNTRY	OWNER	FIELD	TYPE	DESIGNER	TANKER SIZE	PRODUCTS (HYDROCARBONS)
1	1974	Tunisia	SNPA	Ashtart	SBS	SBM	70,000	Processed Crude
2	1975	Indonesia	Cities Service	Poleng	SBS	SBM	70,000	Processed Crude
3	1976	Indonesia	Atlantic Richfield	Ardjuna	SBS	SBM	66,000	LPG and Fuel Gas
4	1977	Spain	Shell	Castellon	SALS	SBM	58,000	Live Crude
5	1978	Malaysia	Exxon	Pulai	SALS	SBM	167,000	Processed Crude
6	1979	Indonesia	Conoco	Udang	SBS	SBM	102,000	Processed Crude
7	1979	Philippines	Cities Service	South Nido	SBS	SBM	70,000	Processed Crude
8	1979	Brazil	Petrobras	Garoupa	Yoke Tower	CBI	54,000	Live and Processed Crude
9	(1979)	United Arab Emirates	Amerada Hess	Arzanah	SBS	SBM	252,000	Processed Crude
10	(1979)	Tunisia	SNPA	Ashtart	SBS	SBM	135,000	Processed Crude
11	(1979)	Italy	AGIP	Nilde	SALS	SBM	80,000	Live Crude
12	(1980)	Dubai	Conoco	Fateh	Yoke CALM	Imodco	126,000	Processed Crude
13	(1980)	U.K.	Shell/Exxon	Fulmar	Yoke Tower	EPRCO	210,000	Processed Crude
14	(N/A)	United States	Exxon	Santa Barbara	Yoke SALM	Imodco	50,000	Fuel Gas and Processed Crude

41. Moored tanker oil storage installation statistics (from Smulders and Remery, Ref. 94).

TABLE 4

RIGID-YOKE MOORINGS - SITE CONDITIONS

NO.	FIELD	TANKER SIZE (DWT)	WATER DEPTH (FT)	WAVE HEIGHT (FT)	WIND SPEED (MPH)	CURRENT (KNOTS)
1	Ashtart	70,000	220	41	78	2.5
2	Poleng	70,000	180	27	81	3
3	Ardjuna	66,000	140	27	81	3.5
4	Castellon	58,000	389	52	76	2.5
5	Pulai	167,000	220	44	94	2.5
6	Udang	102,000	305	39	69	2.9
7	South Nido	70,000	200	40	75	2
8	Garoupa	54,000	400	51	84	3.5
9	Arzanah	252,000	107	25	82	3
10	Ashtart	135,000	220	41	78	2.5
11	Nilde	80,000	312	60	101	2.3
12	Fateh	126,000	130	36	69	3.5
13	Fulmar	210,000	269	85	87	2.4
14	Santa Barbara	50,000	490	41	75	2

42. Rigid-yoke moorings-site conditions (from Smudlers and Remery, Ref. 94).

tures in ice-covered waters is that the ice forces increase as the cross-sectional structure area presented to the ice sheet increases. In view of this, it seems appropriate to consider oil storage at the platform in tanks on the seafloor, as is common practice with North Sea gravity structures such as CONDEEP.[97] With such a scheme, the only structures which penetrate the waterline are the loading buoy and the transport tanker itself. The design of the loading buoy may be articulated; it may include subsea guys, borrowing from the guyed tower concept; to minimize ice forces it should have a small cross-sectional area presented to the ice sheet.

The tolerance of an articulated loading column to angular displacements permits the ice fracture to be in the flexural mode rather than in the compressive failure mode, resulting in lower lateral forces. Clearly, such an offshore loading terminal would require extensive conceptual and detailed design, model testing, and field tests, but at this point in time there seems to be no reason why such an offshore loading concept could not be developed for the deeper waters of the Arctic Alaskan Shelf.

An alternative approach is to construct wide and extremely robust structures, relying upon the strength provided by the large amount of structure material. This is analagous to the design concept of the artificial island. Near the shoreline, oil storage on land may also be considered. An artificial harbor has also been considered by Dome Petroleum Ltd.[114]

In water depths of 20 meters or less, the ice fracturing around the structure would very likely build ridges which become grounded and stay in place, presenting an obstacle to the arrival and loading of ice-breaking tankers. The buildup of ice ridges around fixed structures could also impede resupply traffic. The Norton Basin, with its shallow bathymetry, would face this problem. The Beaufort Sea is shallow as well, but since there is already a transport method available (the Trans-Alaska pipeline), marine transport is not needed. For the Hope Basin and the Chukchi Sea, as well as the Norton, St. George, and Navarin Basins, marine transport is likely to be a cost-competitive mode of petroleum extraction, and should be thoroughly investigated. It should be mentioned that fixed (non-articulated) single-point loading structures may be appropriate as well, and that direct loading from a specially-designed offshore production platform may be technically feasible in some medium-depth locations such as the St. George and Navarin Basins.

ICE-CLASS TANKERS IN THE ARCTIC OFFSHORE

The voyages of the Manhattan in 1969 demonstrated that ice-reinforced tankers could successfully traverse the annual ice of the Northwest Passage. The economics of tanker operation, plus the technological uncertainties of an offshore deepwater loading terminal in the Beaufort Sea, and other factors as perceived ten years ago, led to the decision to construct the trans-Alaska pipeline. Several recent proposals for tanker transport through the Northwest Passage have been made.[98] The Department of Energy discussion of alternatives to the Northern Tier pipeline contained such a proposal; Seatrain lines proposed a marine transport system to the Department of Energy; Dome Petroleum has proposed a fleet of Canadian Class 7 icebreaking tankers to service its proposed Beaufort Sea production; Globtik has proposed such a system; and Newport News Shipbuilding has also studied such a system. Conceptual designs for such large projects have often been prepared, but the technical and economic difficulties inherent in such systems often remain obscure. The most serious set of proposals have been consistently presented and refined by Dome Petroleum Company[99] which has made several very promising discoveries in the waters of the Canadian Beaufort Sea (90 ft to 190 ft depth). A major Canadian governmental commitment has already been made to indirectly support the exploration for oil and gas in the Beaufort Sea, and it can be expected that the discovery of sufficient reserves there will prompt the emplacement of a production and transportation system.[114] The proportionally higher cost of the offshore production structure suggests that the lower cost marine transport of oil will be used rather than a long pipeline.

For the United States, however, the icebreakers and icebreaking tankers required in the Bering Sea would be Canadian Class 3 to 5, depending on location. This type of ship is operational in many parts of the world. The U.S.A. has two new icebreakers potentially capable of routine operation in even more severe conditions, the Polar Star and the Polar Sea. The Finnish and Swedish icebreaker fleet is made up of vessels capable of operating in annual ice in the Baltic, which is of lower salinity and higher strength than Bering Sea ice. Their fleet includes several ice-strengthened tankers. The largest fleet of ice-breakers and ice-reinforced vessels is operated by the U.S.S.R. on their Northern Sea Route. There are three nuclear-powered ships (Lenin, Arktika, and Sibir'), which are capable of transiting annual ice and thin multi-year ice. A photograph of the Lenin, the first nuclear icebreaker, is shown in Figure 43. The table given by Armstrong[100] (Figure 44) gives the details of the Soviet icebreaker fleet. In addition, there are many ice-reinforced cargo vessels, as shown in Figure 45, a total of 287 ships in all. In August 1977, the Arktika (a class 7) sailed to the North Pole, covering 3,852 nautical miles in 14 days at an average speed of 11.5 knots. (The decision to make this voyage was based upon real-time ice reconnaissance which showed an open lead - a huge polynia - extending to the Pole). The newest icebreaker, Sibir', is shown in Figure 46 leading a convoy in annual ice in the Kara Sea. Armstrong reports that the Sibir' was completely stopped by a heavy multi-year ice floe in the East Siberian Sea; she mounted the floe, failed to break it, heeled over 20°, and finally slid backwards into the water.[100] For the Bering Sea, it appears that self-powered icebreaking tankers in the 100,000 dwt class could readily be used to transport oil and LNG. For the Hope Basin and Chukchi Sea, icebreaker support would probably be needed for some of the winter months, and two icebreakers are more than twice as useful as one.[100] The route for these icebreaking tankers would presumably be to the U.S. west coast, since the transit of the Northwest Passage in the winter would be more demanding. The Soviet fleet is operational from March to January on the Northern Sea Route, and year-around operation could be designed into any marine oil transport system for the Bering and Chukchi Seas. The eco-

43. Soviet nuclear icebreaker Lenin, in annual sea ice (from The Two Poles, by Gennady Koposov, Planeta Publishers, 1975).

Table 1

Soviet icebreakers used on the northern sea route, in service 1978.

Ship	Where built	When completed	Power shp	Displacement tonnes	
Arktika	USSR	1975	75,000	23,400	nuclear
Sibir'	USSR	1977	75,000	23,400	nuclear
Lenin	USSR	1959	44,000	16,000	nuclear
Yermak	Finland	1974	36,000	20,240	
Admiral Makarov	Finland	1975	36,000	20,240	
Krasin	Finland	1976	36,000	20,240	
Moskva	Finland	1960	22,000	13,290	
Leningrad	Finland	1961	22,000	13,290	
Kiyev	Finland	1965	22,000	13,290	
Murmansk	Finland	1968	22,000	13,290	
Vladivostok	Finland	1969	22,000	13,290	
Kapitan Sorokin	Finland	1977	22,000	14,900	shallow-draught
Kapitan Nikolayev	Finland	1978	22,000	14,900	shallow-draught
Kapitan Belousov	Finland	1954	10,500	5,360	
Kapitan Voronin	Finland	1955	10,500	5,360	
Kapitan Melekhov	Finland	1956	10,500	5,360	
Vasiliy Pronchishchev (ex Ledokol-1)	USSR	1961	5,400	2,500	
Afanasiy Nikitin (ex Ledokol-2)	USSR	1962	5,400	2,500	
Khariton Laptev (ex Ledokol-3)	USSR	Before 1963	5,400	2,500	
Vasiliy Poyarkov (ex Ledokol-4)	USSR	1963	5,400	2,500	
Yerofey Khabarov (ex Ledokol-5)	USSR	1963	5,400	2,500	
Ivan Kruzenshtern (ex Ledokol 6)	USSR	1964	5,400	2,500	
Vladimir Rusanov (ex Ledokol-7)	USSR	1964	5,400	2,500	
Semen Chelyuskin (ex Ledokol-8)	USSR	1964	5,400	2,500	
Yuriy Lisyanskiy (ex Ledokol-9)	USSR	1965	5,400	2,500	
Petr Pakhtusov	USSR	1966	under 5,000		
Georgiy Sedov	USSR	1967	under 5,000		
Fedor Litke	USSR	1970	5,400?		
Semen Dezhnev	USSR	1971	5,400?		
Ivan Moskvitin	USSR	1971	5,400?		
Otto Schmidt	USSR	1978	5,400	3,650	
		On Order			
2 Sorokin-class	Finland	1980-81	22,000	14,900	shallow-draught

Source: Polar Record and Inter-Nord, passim, based on Soviet press reports.

44. Soviet icebreakers in service in 1978 (from Armstrong, Ref. 100).

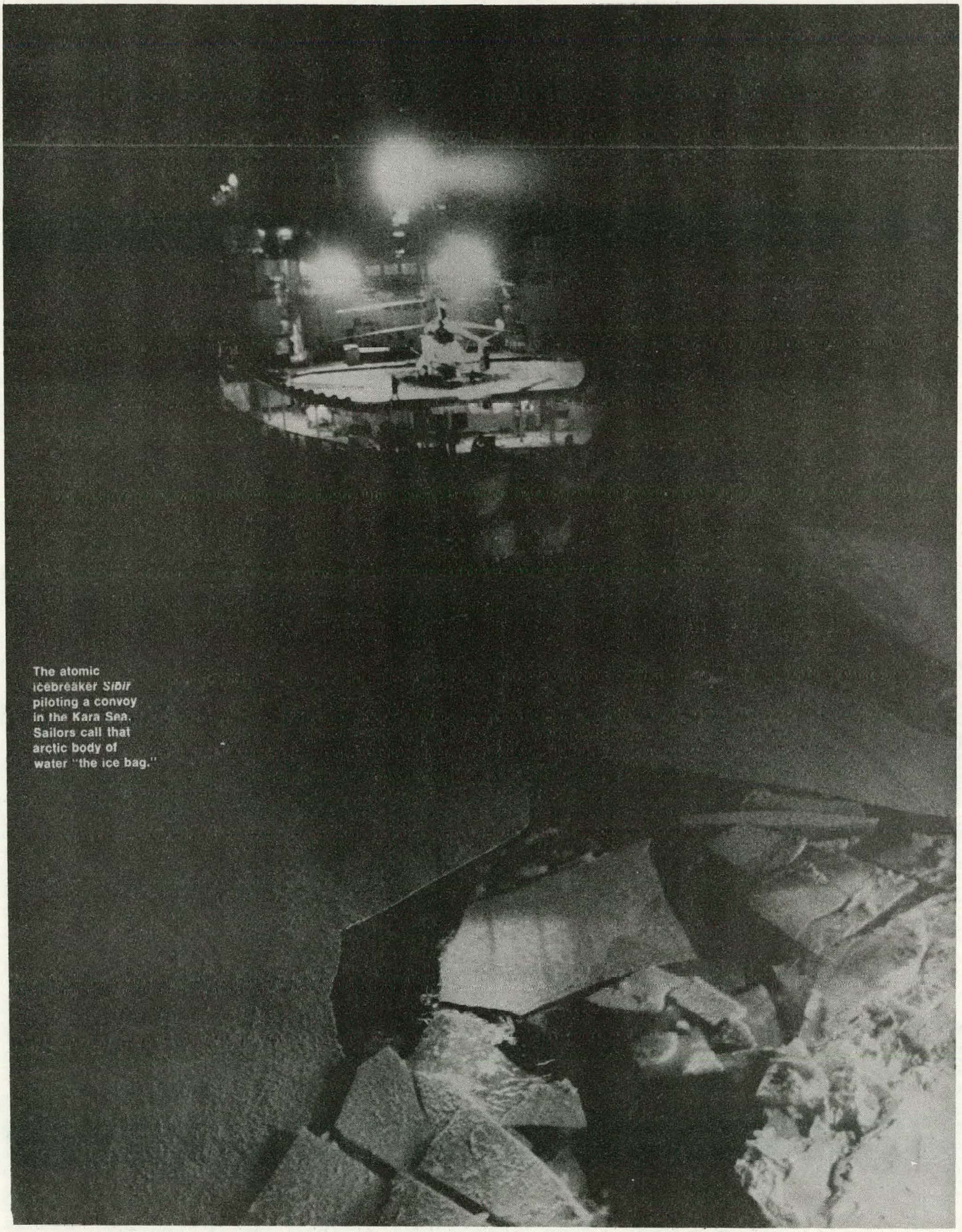
Table 2

Sea-going self-propelled ships of over 100 GRT on the Soviet register in 1977, cleared for sailing on the northern sea route

Ship Types	Dwt tonnage	% built in USSR	Place of Registration: White & Barents Seas	Far East	Baltic Sea	Black Sea	Caspian Sea	Lena River	Unat-tached	TOTAL
Icebreakers	354-6,147	52							30	30
Specially strength-ened freighters (ULA) - chiefly dry cargo	310-9,280	81	5	13	2	1				21
Timber ships	4,454-6,780	50	12	7	7					26
Tankers	17,200	0		9	1					10
Passenger ships	2,427	100		5						5
Dry cargo	7,430	0	1							1
Tugs & salvage vessels	71-605	46	10	47	24	40	17	2	3	143
Sealers & fishing boats	790-1,139	0	12	17						29
Container ships	6,270	100		3	2	1				6
Hydrographic & expedition ships	190-4,220	7	8		2				6	16
TOTAL		43	48	101	38	42	17	2	39	287

Source: *Registrovaya kniga morskikh sudov SSSR 1976-77* (Leningrad, 1976), and *Prilozheniya (Supplements)* 1-3, 1977

45. Soviet ice-reinforced cargo vessels, icebreakers, and hydrographic ships, 1977 (from Armstrong, Ref. 100).



46. Soviet nuclear icebreaker Sibir', leading a convoy in annual sea ice in the Kara Sea (from Soviet Life, March 1980).

nomics of trans-shipment into VLCC's at a deepwater port in the Aleutians should be examined. The draft of the vessels for the Norton Sound and Chukchi Sea service should be as shallow as possible.

There are many aspects of polar marine technology which should be advanced, as such a system is contemplated. A recent report of the Marine Board, National Academy of Sciences,[101] lists several areas. Ship icing defense, ice navigation training, ice movement studies, ice mechanics, communications, remote sensing, and system studies were among those recommended.[101]

The design of icebreakers has advanced in recent years,[102-103] but further improvements (while not structurally necessary from a safety standpoint) would lead to significant cost savings in fuel consumed over the life of an icebreaking tanker fleet. Active icebreaker design groups in Finland, West Germany, Canada, U.S.S.R., U.S.A., and Japan are involved in research and model studies. Because of its obvious importance, research on icebreakers, icebreaking tankers and service vessels has been recommended by the MS-9 Panel of S.N.A.M.E. Details will not be discussed here, but some of the ice-related factors entering into icebreaker design will be mentioned.

The dynamic friction between the icebreaker and the ice sheet is important, since it reduces the power available for forward motion. Icebreakers often traverse snow-covered ice sheets, and should be coated with materials having high abrasion resistance as well as a low dynamic friction coefficient with the snow and the ice. Breakage of the ice sheet obviously depends upon mechanical properties of ice in the regime of rapid loading rates and flexural failure. Stress concentrations at the contact interface between ship and ice sheet deserve more attention. Ice fragments sliding beneath the hull offer considerable resistance to ship motion, and interfere with efficient operation of the ship's propulsion screws. Recent tests of Dome Petroleum's new icebreaking workboat Kigoriak have shown that special water flooding at the bow can reduce friction, that a spoon-shaped bow promotes flexural failure of the ice, and that a slightly wider bow section reduces frictional drag along the sides of the ship.

Of course, if open water regions or non-ridged regions can be located ahead of the ships on a real-time basis, and the interpreted information or imagery transmitted to the captain along with an accurate short-term ice movement forecast, great savings could result. To obtain imagery over a large area, useful for a ship routing plan for 12-24 hours, implies either satellite surveillance or other high-altitude surveillance. Fog and clouds are almost always present, meaning that an active microwave system such as side-looking airborne radar (SLAR) or synthetic aperture radar (SAR) must be used. The SEASAT satellite had SAR capability and very good ice pictures were obtained.[104] The L-band SAR imaged a 100 km swath at a resolution of 25 meters on the ground, over a path length of about 4,200 km, within view of a receiving station such as the one at Fairbanks, Alaska. The data rate was 110 megabits/second, and the orbital tracks converged at latitude 72°N, producing overlapping frequent coverage of some Arctic offshore areas.[104] The possibility of obtaining ice position and velocity vectors thus existed, but unfortunately SEASAT-1 failed on October 10, 1978, and the next one is scheduled for launch after 1985. The high data rates are related to the massive number of picture elements per swath. The information must be optically correlated, or correlated by digital processors; to accomplish this in a near-real-time mode is a heroic task in electronic system engineering. Some on-board processing is possible; to transmit data to the bridge of a ship in near-real-time would still take a very wide-band satellite communications link. The proposed ICEX satellite[105] experiment will approach this capability, according to its recent report. Operational use of satellite SAR data in near-real-time is possible, however, and within the next decade will probably occur. A numerical model for the prediction of ice motion could theoretically be operated in a near-real-time mode with real-time imaging as its input data. However, the models presently used for research purposes, such as the AIDJEX model, do not lend themselves to real-time operation, nor do they have appropriate boundary conditions. With sufficient time and resources, such sophisticated tools conceivably could be put to use in a predictive near-real-time mode, however.

A major use of the numerical models for pack ice motion, such as the AIDJEX model, is in the prediction of transport of spilled oil. The probability of an offshore oil spill remains finite, because of human error, and the movement, fate, and effects of an oil spill is one of the major concerns of the Outer Continental Shelf Environmental Assessment Program (OCSEAP) of the Department of Interior. This program began in Alaska in 1975, and has produced many useful results, some of which have been specifically referred to above. Of course, the transport of spilled oil in moving pack ice is of major interest to the U.S. Coast Guard, which is charged with the mission of oil spill containment and cleanup. An industry oil spill organization, Alaskan Beaufort Sea Oil Spill Response Body (ABSORB) has also been established, and is conducting research. From the discussion above on ice movement, it is apparent that oil spill cleanup in moving ice presents a major engineering challenge at this time, but a full discussion of that topic is beyond the scope of this report. Innovative designs and field tests will be required.

Central to the safe operation of offshore structures and loading terminals in ice-infested waters is the capability of surface transport in small vessels, for logistics, resupply, human transport, and assistance in loading operations. Tugboats and workboats are suitable in open water, but must be ice-reinforced for winter use. A high power-to-displacement ratio is a typical requirement for both tugs and icebreakers, so only ice-reinforcement of tugs is likely to be required. Poor visibility and ship icing is inevitable, so special superstructure design and precise electronic navigation (satellite navigation, for example) will be required, along with the usual radar. Hovercraft have been suggested for over-the-ice transport; apparently, the spray icing problem has been overcome in Canadian industry trials. Another craft capable of traversing a mix of water and ice cover has been developed by Mitsui; it floats upon two parallel counter-rotating flotation cylinders, with spiral flutes on the cylinders providing for forward motion. Other design ideas may offer promise for stable surface transport, and should be considered. Because of high winds, turbulence, and ice conditions, helicopter access to offshore operations will be limited oftentimes by inclement weather. Special navigation and de-icing equipment on helicopters can be used to improve this situation. Helicopters must be sheltered from spray icing when not in use.

Some spectacular offshore failures in the North Sea, such as the Ekofisk marine riser problem, can be attributed to marine corrosion. Special corrosion conditions in cold oceans are associated with high dissolved oxygen levels, stress-corrosion fatigue, and inadequate cathodic protection. A massive research program is underway in the U.K. and Norway to overcome these problems, and it is important in Arctic development in Alaska to keep abreast of such progress. It also may be necessary to specifically address ice-related corrosion problems in cathodic protection which are not characteristic of the North Sea, such as the effectiveness of cathodic protection on structures surrounded by ice.

LAND PIPELINES

The option of transport by subsea pipeline and land pipeline must be considered, and indeed the existing trans-Alaska oil pipeline and the proposed Alaska Highway Natural Gas pipeline bear witness to their advantages in the case of large, proven reservoirs. From a technical standpoint, the major obstacle for such pipelines is permafrost.

In the case of the hot oil pipeline, the escape of heat can cause thaw of the surrounding soil in which the line is buried. If the soil is ice-rich, this leads to subsidence of the soil supporting the line. Differential subsidence can cause excessive stresses and failure of the pipe by buckling, for example. To avoid this, approximately half of the line length (about 400 miles) was elevated on stable supporting piles. Nevertheless, in some regions of pipe burial where widely-spaced drill holes showed thaw-stable soils, there are thaw-unstable soils beneath the pipe which are thawing slowing. Two pipe failures were reported in the summer of 1979. If a rapid, unambiguous, continuous subsurface remote sensing survey with high resolution could have been made between drillholes along the pipeline right-of-way before installation, massive ground ice could have perhaps been avoided. Only recently, however, has the equipment been developed which approaches the capabilities required. An impulse radar now appears to be a promising choice for such a survey, and it remains to be tested extensively along existing and future right-of-ways. Future right-of-way surveys deserve the most sophisticated remote sensing equipment available, and there is a need for additional development of such equipment, including computerized methods for data presentation.

The inverse problem of frost heave in fine-grained unfrozen soils is encountered when one attempts to place a chilled gas pipeline in discontinuous permafrost. Differential frost heave of the proposed chilled gas pipeline remains as the single largest unsolved technical problem at this time. Tests are in progress, but as yet no technical solution has been presented which permits burial of a chilled gas pipeline in fine-grained permafrost soils. In Appendix E, a bibliography of frost heave literature is provided so that the interested reader may explore the geotechnical problems in greater detail. A potential design alternative is to elevate the pipe above the ground, as was done in the oil pipeline case. This offers less security but greater mechanical stability. Elevation of a gas pipeline leads to the possibility of very cold temperatures during winter shutdown. Special steels with low ductile-to-brittle transition temperatures may be necessary; otherwise, greatly reduced operating pressures may be used, as is typical in the U.S.S.R.

Regardless of the type of installation, it is important to be able to identify regions of a pipeline which are beginning to develop geometrical distortions such as buckling. During the trans-Alaskan pipeline project, this was recognized and a development program was initiated for a sophisticated pipeline pig, which could be passed through the line, recording a particular pipe orientation signature, which would be compared with previous signatures. Unfortunately, the mechanical hardware aspects of that project and the statistical basis for interpretation failed to meet expectations. However, it should be possible to accomplish this objective, if careful attention is given to the appropriate instrumentation. The economic and environmental costs of failure for large pipelines, either offshore or onshore, are substantial, and the successful development of a "smart pig" could eventually save hundreds of millions of dollars.

The aurora borealis causes a time-variation in magnetic field which induces very large currents in the trans-Alaska pipeline. Wherever these currents leave the pipeline, they leave in the form of metallic ions, a corrosion current. In most cases the sacrificial zinc anodes are supplying these ions, and they will probably have to be replaced earlier than expected. However, measurements by the author have confirmed that the potential difference provided by the usual sacrificial zinc anodes in the corrosion protection system is inadequate in some locations in times of active aurora, and some corrosion at defects (holidays) in the pipe coating does occur. Laboratory experiments have also established that when steel leaves an anode due to corrosion, it forms a insoluable precipitate, an irreversable process. Thus, auroral corrosion of buried pipelines is cumulative and time-varying; Arctic pipelines should have an adaptive time-varying corrosion protection system. Development and testing of such a system remains to be accomplished. It should then be made available for the long-term protection of any land pipeline in Alaska.

The security of elevated or buried sections of pipeline against terrorists or saboteurs remains a major concern. The remoteness of Alaskan territory is generally a positive factor, but makes surveillance difficult. Instrumentation related to pipeline security deserves further attention.

DRILLING AND WELL COMPLETIONS

The presence of permafrost complicates the drilling and well completion process. Drilling fluids are usually water-based, and can contain freezing-point depressants permitting use below 0°C. However, the heat generated during drilling usually results in drilling mud temperatures above 0°C during drilling operations. The permafrost surrounding the well bore melts gradually during drilling operations, causing some limited thaw subsidence. Fast drilling rates are advantageous, and any developments leading to faster drilling rates would be worthwhile for Arctic operations. In offshore Arctic exploration drilling, during the summer, the return of the icepack represents a time constraint on drilling, testing, logging, and other operations. Rapid drilling techniques can, in ice-infested regions like the Chukchi Sea, make the difference between one and two summer seasons for an exploratory well.

The major thaw and subsidence occurs during production, for wells completed in permafrost. An excellent review of this type of Arctic problem has been given in a series of eight articles by Goodman.[77,106-112] Special cementing techniques, together with allowed strain in casing, has resulted in the successful operation of over 100 production wells through permafrost at the Prudhoe Bay field. However, in offshore production sites, clusters of well bores will penetrate relatively warm offshore permafrost, and the degree of thaw and subsidence is expected to be considerably greater, as discussed by Goodman.[77] It will undoubtedly be necessary to develop a model of thaw subsidence for clusters of offshore wells, and to attempt to devise safe and economical well completion techniques for such installations.

Another problem noted in early Arctic operations was the freezeback of permafrost around wells that had been drilled and shut in, prior to production. Casing collapse is possible in such instances, as freezeback pressures can be more than 1.6 times the overburden pressure.[106] Designs to prevent this effect are presented by Goodman,[110] and the use of sufficiently strong casing seems to have overcome this difficulty.

The presence of clathrates (solid gas hydrate crystals) in the lower layers of permafrost, and beneath the permafrost, has been noted in some Arctic drilling in Canada and Siberia.[107] Hydrate decomposition due to the heat of the drilling operation will cause the release of large volumes of gas into the mud, which is not effectively controlled by increasing mud weight.[107] A large cavity is produced, as has been determined by caliper logs.[107] Although proper temperatures and pressures prevail for gas hydrate formation, the specific local geology also helps determine whether gas escaping from deeper reservoirs accumulates in large quantities as hydrates. However, the possibility of advance detection of hydrate zones by seismic methods would enable drilling engineers to be prepared for hydrate zone penetration. Specific operational procedures should be developed to contend with the penetration of hydrate zones during drilling. The possibility of extraction of gas from hydrates, as a resource, may be of interest as well.

Logging of wells in permafrost requires special interpretation techniques. The major need for log interpretation in permafrost is to provide lithological, thermal, and mechanical properties so that appropriate casing designs can be made to accomodate thaw subsidence. Goodman[109] has described the use of gamma-ray, induction, neutron, density, crystal cable, sonic, spontaneous potential, and temperature logs in permafrost.

TECHNOLOGY FRONTIERS

The following technological frontiers can be listed as relevant to the recovery of Arctic oil and gas resources. No order of priority is implied in this list.

1. *Regional statistical distributions of extreme wind, wave, and storm tide conditions, based on hindcasting.*
2. *Design techniques to minimize ship and structure ice accretion.*
3. *Statistical predictions of pack ice edge intrusions in summer months, which would interfere with exploration drilling and emplacement of permanent production structures.*
4. *A prediction of statistical distributions of extreme ice ridge and keel sizes, degree of consolidation, and velocity, for each offshore basin. Annual and multi-year ridges must be examined and distinguished.*
5. *Development of a statistical data base for annual ice sheet thickness and movement for each basin with as high a spatial and temporal resolution as possible.*
6. *Data should be developed on sea ice mechanical properties, particularly on the compressive strength and flexural strength of warm (-2°C) annual sea ice, as a function of strain rate and orientation.*
7. *The limits of validity of Korzhavin's empirical formula should be established by a combination of theoretical analysis and large scale field tests.*
8. *A reliable contingency technique for the protection of offshore structures from ice islands should be developed.*

9. *Details of failure mechanics of an ice ridge thrusting against a sloping offshore structure boundary should be analyzed, and appropriate field tests undertaken to the extent possible.*

10. *The rate of penetration of the freezing front into artificial islands, the salinity of both the frozen and unfrozen regions, and selected geotechnical engineering properties should be monitored as a function of time.*

11. *A detailed study of beach profiles where ice rideup occurs during spring breakup would provide quantitative design rules for boundaries of artificial islands which would resist ice override and excessive pileup.*

12. *A well-instrumented structure should be built in a region exposed to multi-year ice, to provide detailed verification of design principles. Over a short time period, the design load may not be reached, but data during normal ice interaction events will assist in improving design procedures.*

13. *Representative marine geotechnical engineering data for foundation design should be collected for each Arctic offshore basin.*

14. *For Norton and Hope basins in particular, the seafloor acceleration and velocity during several significant earthquakes should be determined, to enable proper structure foundation design.*

15. *Vibration analyses of offshore structures simultaneously loaded with both ice sheet and earthquake excitation should be made.*

16. *Seafloor scouring by grounded ice features should be examined when the known grounded ice feature is present, and the relationship between scour depth and ice feature size should be established.*

17. A method for dating the age of seafloor ice scours should be developed, and a complete statistical analysis of ice scouring depths in the Chukchi and Hope basins should be completed if subsea pipelines are to be seriously considered.

18. The depth to the bonded subsea permafrost should be determined in the Chukchi and Hope basins.

19. A finite-element analusis of the thaw of subsea permafrost near a hot oil pipeline making a buried transition across the beach would be quite useful. This should include conduction, convection, and salinity gradients, and phase change at the boundary of the bonded permafrost.

20. Alternative designs for an offshore single point mooring terminal in ice-covered Arctic waters should be evaluated. Model testing of the most promising designs should be undertaken.

21. Instrumentation of existing icebreaking tankers should be executed, and data collected during routine passages. Ice morphology should also be monitored during such transits.

22. All existing data on icebreaker performance should be assembled, analyzed, and the results summarized.

23. Specific voyages of Polar-class icebreakers into difficult Arctic areas should be made with full complement of functional instrumentation, to determine operating limitations as related to oil development.

24. Methods for enhancing icebreaker effectiveness should be explored. These include lower friction, shape alteration, stress concentration at the ship/ice interface, reduction of ice milling by propellors, and other factors.

25. *A conceptual design should be made for an active satellite-borne ice surveillance system with near-real-time imagery transmission to an operating ship. If this appears feasible, a second phase could consider the inclusion of a real-time operational ice movement model into the system.*

26. *Equipment should be improved for oil spill cleanup in waters covered with moving ice.*

27. *Ice-traversing or icebreaking workboats should be designed.*

28. *Corrosion problems which may be encountered on offshore structures in the presence of ice should be examined, and corrosion protection systems developed.*

29. *Remote sensing techniques for detecting thaw-unstable permafrost should be verified.*

30. *Mechanisms for reduction of frost heave around buried, chilled gas pipelines in discontinuous permafrost should be evaluated.*

31. *A detailed design study of a sophisticated pipeline surveillance pig should be made, and the limitations of such a device clearly established. If warranted, a prototype device should be built and tested.*

32. *Corrosion of pipelines due to currents induced by the aurora borealis should be investigated, and an effective corrosion protection design should be developed for all Northern pipelines taking this into account.*

33. *Intrusion detection and other security measures for remote Northern pipelines deserve further attention.*

34. *Analysis of thaw subsidence for clusters of wellbores penetrating offshore permafrost should be made, and appropriate completion techniques developed.*

35. *The techniques for remote detection of clathrates should be examined, and drilling procedures developed to accommodate clathrate penetration without excessive gas evolution or loss of well control.*

36. *A manual for log interpretation in permafrost should be prepared, and those aspects of log interpretations which need improvement should be identified.*

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