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A REVIEW OF THE ENVIRONMENTAL CONDITIONS ON THE WEST COAST OF NEWFOUNDLAND

for

NATIONAL RESEARCH COUNCIL CANADA

File Number: RFP C57-234248

by

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October, 1997

PERD/CHC Report 20-34

CANATEC Consultants Ltd.

PERD

ABSTRACT

A study of the available environmental data for the West Coast of Newfoundland has been carried out. Data have been obtained from a variety of sources, but there are limited in-situ measurements for the area of interest. Data for the area have been used where available, otherwise, generic data from other locations have been used to fill data gaps where possible. The tables below summarize the major findings.

Climate and Oceanography

Item	Value	Units
Extreme Winds, 100 year / 20 year	42 / 37	m/s
Wind exceedence, 80% / 50% / 20% of time	5 / 8.5 / 12	m/s
Winds, predominant direction	West and Southwest	
Gust wind, maximum winter / maximum summer	48 / 20	m/s
Air temperature, mean: minimum winter / maximum. summer	-8 / +15	°C
Air temperature: minimum winter/maximum summer(in 17 years)	-40 / +20	°C
Wave height, 100 year, significant / maximum	10.6 / 19.8	m
Wave period for 100 year wave	13-14	sec
Wave height, 10 year, significant / maximum	8.5 / 16.0	m
Significant wave exceedence, 80/50/20 % of time	1 / 1.5 / 2.5	m
Predominant wave direction	To East	
Water salinity at surface, summer/winter	31 / 32	ppt
Water salinity at 50 m depth, summer/winter	32 / 32	ppt
Water temperature at surface, summer/winter	14 / -1.8	°C
Water temperature at 50 m depth, summer/winter	2 / 0	°C
Currents at surface, nearshore, average / maximum	0.05 / 0.65	m/s
Currents at surface, off shore, average / maximum	0.5 / 1	m/s
Tidal variation (large tides)	1.6 to 2.3	m
Fog, days per year (typical)	38	days
Precipitation (typical), total / rain / snow	1200 / 750 / 314	mm

Ice Parameters

Item	Values	Units
Freeze-over dates, North, earliest/mean/latest	4 Jan / 18 Jan / 3 Feb	
Freeze-over dates, Centre, earliest/mean/latest	22 Jan / 31 Jan /9 Feb	
Freeze-over dates, South, earliest/mean/latest	6 Feb / 14 Feb / 8 Mar	
Ice clearance dates, North, earliest/mean/latest	18 Mar/23 Apr/18 May	
Ice clearance dates, Centre, earliest/mean/latest	18 Mar / 15 Apr / 8 May	
Ice clearance dates, South, earliest/mean/latest	11 Mar / 8 Apr / 27 Apr	
Ice covered period, median - North/Centre/South	95 / 74 / 54	days
Open water period, median - North/Centre/South	270 / 291 / 311	days
Ice drift speed, mean / maximum	0.14 / 0.53	m/s
Ice drift direction, predominant (towards)	Northeast & Southeast	
Level ice thickness, typical annual maximum	0.8	m
Level ice thickness, estimated maximum	1.5	m
Level ice temperature, mean / minimum	-2.5 /-13.5	°C
Level ice salinity, typical	4.5 to 5.5	ppt
Level ice density, typical	0.91	$Mg\text{-}m^{-3}$
Level ice flexural strength, mean / maximum	150 / 672	kPa
Level ice horizontal compressive strength, mean / maximum	2.5 / 3.5	MPa
Ridge sail height, typical average / typical maximum	0.7 / 2.8	m
Ridge frequency, average number/km, North/Centre/South	26 / 6 / 5	/km
Ridge frequency, maximum number/km, North/Centre/South	55 / 28 / 59	/km
Consolidated layer thickness, typical annual / typical maximum	1 / 2	m
Consolidated layer ice temperature, typical	-2.5	°C
Consolidated layer salinity, typical	4.5	ppt
Consolidated layer density, typical	0.92	$Mg\text{-}m^{-3}$
Ridge keel porosity, typical (range)	28 % (10 to 40%)	
Icebergs and growlers	Few approx. every 2 years. Generally stay to north along the Quebec shore	

Soils Parameters

Item	Value
Bathymetry	The 100 m contour is close to shore at the north end of region of interest, 50 to 70 km from shore at Port au Port, and within 3 km from shore off Port aux Basques.
Soil types south region (south of Port au Port Peninsula)	Pelite, sandy pelite, typically 5 m thick but up to 20 m thick. In east end of St George's Bay sediments over 50 m thick.
Soil types central region (Port au Port to Bonne Bay)	Gravelly pelitic sand and gravelly poorly sorted sand, with sandy gravel and gravelly poorly sorted sand near shore. Sediments generally less than 20 m thick, but can reach 60 m or more in Bay of Islands.
Soil types north region (north of Bonne Bay)	Sandy gravel, with narrow strip of gravelly poorly sorted sand in water depths of less than 20 m.. North of Hawkes Bay, sandy pelite and pelitic sand predominate.
Soil shear strengths - pelites	Typically 2 to 5 kPa at surface
Ice scour	No measurements in shallow water, but it is expected that seafloor will be saturated with scours in less than 10 m water depth. Relic scours in water over 100 m.
Seismic	Low risk. See site response spectrum.

RECOMMENDATIONS

There is a lack of information on the ice conditions along the West Coast of Newfoundland; no systematic, on-ice measurements are available. The extreme waves, which will cause major loads on offshore structures, are predicted (hindcast) from wind data for the area; there are no actual wave measurements available to verify the predictions. There is no scour data for the area. Such data are essential for the design of well heads and subsea pipelines. Site specific soils data are required, however, these data can be obtained when exact production locations are known.

Specific recommendations are as follows:

1. There is a serious lack of physical and mechanical data for the ice in the area of interest, and a field program in the area should be conducted to collect the following information at various locations along the coast:

    1.1 Information is required on ice thickness. Systematic on-ice measurements should be carried out in March and April at several locations along the coast.

    1.2 The AES Ice Charts indicate the occasional presence of old ice in the area. This should be confirmed and the size and thickness of the old ice floes determined.

    1.3 There is no information on the mechanical properties of ice in the area. Measurements of temperature and salinity should be carried out as these allow determination of ice strength. Actual ice strength measurements from the area would be useful for confirmation of the calculated values.

    1.4 Ridge heights in this study are based on laser profilometer data plus empirical relationships between ice thickness and ridge height. As ridges are important in the determination of extreme loads, a field program should be conducted to measure sail heights, keel depths, consolidation, porosity, and ridge sail block sizes.

    1.5 Numbers and sizes of ridges are also required for load probability analyses. An upward looking ice keel profiler placed on the seabed would provide invaluable data on the number and size of ridge keels and ice movement throughout the winter, plus currents and wave heights. The Institute for Oceanographic Sciences in Victoria, BC, should be encouraged to conduct such measurements as they have developed the equipment.

    1.6 As first year ridges are likely to be major hazards for any offshore structure, further theoretical work is required on the determination of ice loads generated by such ridges. Measurements of ridge keel strengths should be carried out, for comparison with the theory.

    1.7 There are no actual measurements of ice drift in the area. Such measurements are needed to gain a complete picture of the frequency and magnitude of ice loading events. Satellite drift buoys (e.g., Argos buoys) placed on the ice in February would provide ice drift data with good time resolution. Also, profilers as mentioned in 1.5 above will provide ice drift data at or near the area of interest.

2. Wave heights are predicted from wind measurements; there are no actual wave measurements as far as we know. As waves can create high loads (probably comparable to

those generated by ice), the Marine Environmental Data Services (MEDS) should be encouraged to extend their summer wave measurement programs into the area. An oceanographic buoy located off Port au Port, would provide valuable data in the area of most current activity.

3. There is no data on offshore currents. MEDS should be encouraged to continue their measurements in this area.
4. Soil shear strengths are very low. When a production site has been selected based on drilling results, detailed soil testing will be required to determine the type, strength and depth of the surface sediments at the exact location. Such measurements are required prior to preliminary engineering design. No long term data collection program is needed, although samples gathered on an opportunity basis would be helpful to clarify the soil types and strengths to be expected.
5. There is no ice scour data for the area. Measurements should be made in the early summer (before the scours are eroded away), from potential production site locations to shore in locations where pipelines may be installed.
6. Due to limited resources, not all available iceberg data have been obtained from AES. These data should be obtained for a more thorough analysis of icebergs.
7. The cooling trend, which has been observed over the past few years, should be investigated and its potential effects considered. Such a trend could increase the thickness of level ice and of the consolidated layer in first ridges.

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1. INTRODUCTION

1.1 Background & Rationale

The pace of offshore activities off the West Coast of Newfoundland has increased significantly in 1996 and 1997, as indicated below.

- January, 1996, Minister of Natural Resources for Newfoundland and Labrador announces that IEXCO will acquire seismic data in the Bay of Islands/Humber Arm area.
- February, 1996, Minister announces that Talisman will drill a directional well off Cape St George.
- March 5, 1996, Minister announces a Call for Bids on four parcels off the West Coast of Newfoundland.
- May 15, 1996, Hunt and PanCanadian spud a well east of St George's Bay, using a jackup rig.
- February 1997, a port is planned for St George's Bay, to support the offshore actively in the area.
- May, 1997, a Call for Bids is made by the Canada-Newfoundland Offshore Petroleum Board for three parcels of land off the West Coast of Newfoundland.
- 1997, PanCanadian plans to drill a directional well off the West Coast Newfoundland.

BHP, Mobil, Hunt, and other major oil companies have acquired land off the West Coast of Newfoundland as indicated in the figure to the right, representing this study's area of interest.

Up to this time, the offshore wells drilled in the area have taken advantage of the open water period, typically 311 days during the summer season. Once commercially viable quantities of oil are confirmed, there will be a need to consider year-round production, and this will require operating throughout the winter, ice covered season. Although this area is considered a "temperate" ice zone, systems suitable for operating offshore year round will have to withstand harsh ice and climatic conditions.

The purpose of this PERD (Program for Energy Research and Development) funded study is to review of the environmental conditions off the West Coast of Newfoundland. This is being carried out in conjunction with a second study to evaluate structures suitable for operating seasonally or year round in the area. "Recommended" parameters are provided in this report specifically for the purpose of the review of the various structures. The parameters provided should not be used for design, as, in most cases, the data are inadequate for this purpose and no probabilistic analyses have been carried out.

1.2 Objective

The Request for Proposal put out by the National Research Council indicated that the Objectives of the project were to "….summarize the annual ice regime off the West Coast of Newfoundland, and to provide a preliminary assessment of the types of offshore structures that could be used for oil development in this region."

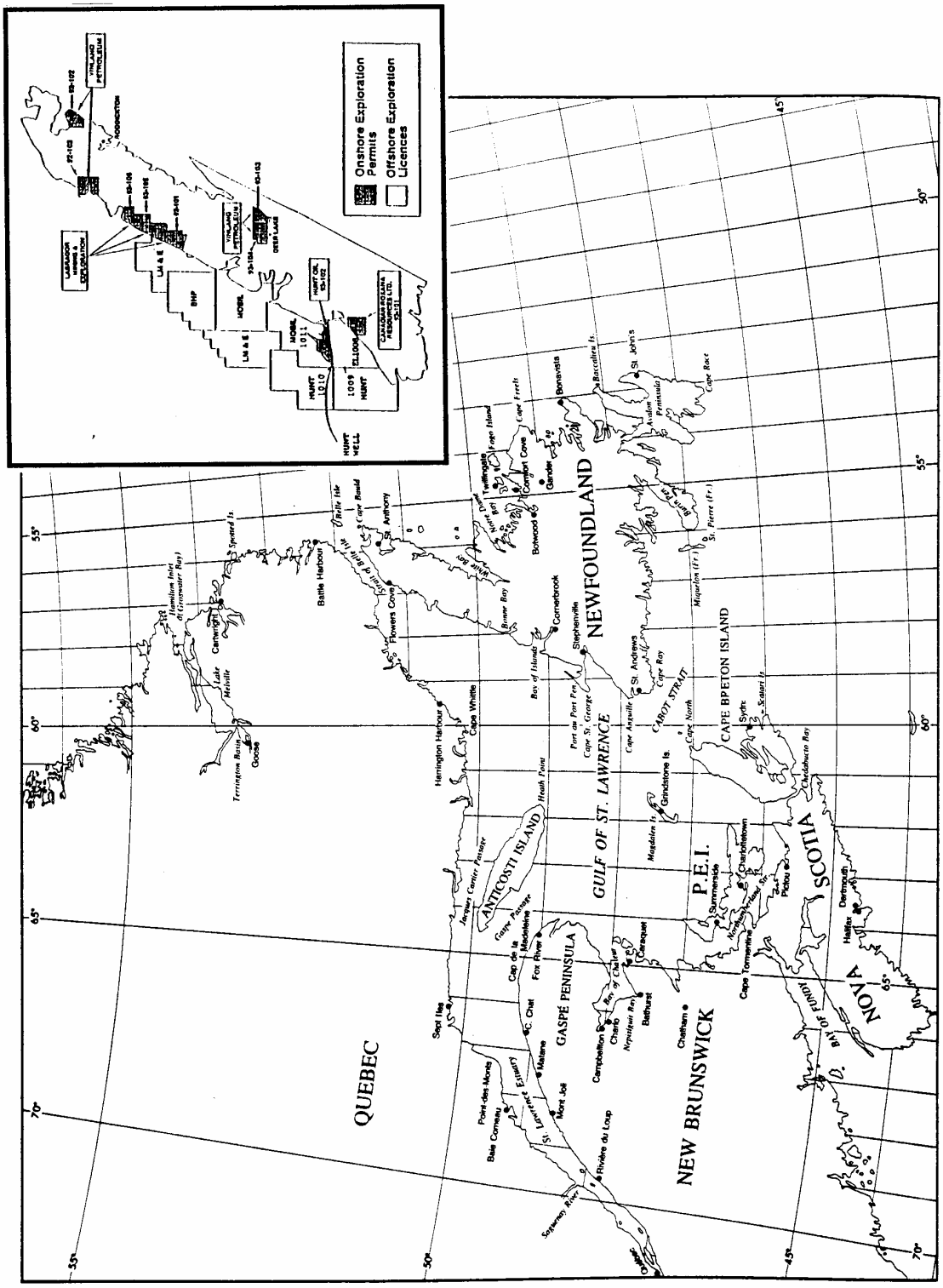

Figure 1-1: Map showing the West Coast of Newfoundland and land interests in the area

The proposal submitted by Sandwell and CANATEC indicated that to assess structures it was necessary to also define all the environmental conditions, including the summer meteorological and oceanographic conditions, in particular the winds, waves and currents, to an adequate level to ensure that any structure considered will be able to survive and operate efficiently in the local conditions.

As indicated in the proposal, the "typical" operating conditions are required when reviewing operational aspects and the extreme conditions are required when reviewing the design of a structure. Both these conditions will be considered to allow a careful assessment of the optimum structures for producing oil in this offshore region.

1.3 Approach

The requirement of the project was to collect as much information, as possible, on the West Coast of Newfoundland, and to present it in a format which would allow an assessment of structures suitable for operation in the area.

Firstly a literature search was conducted through the Arctic Institute of North America in Calgary; this provided one (1) citation.

This was followed by the collection of information from the Canadian Ice Services of the Atmospheric Environment Services and various other government agencies, Canadian Coast Guards, and institutes. This provided a large quantity of information on the weather, ice, soils, etc. One of the team members visited the Canadian Ice Services in Ottawa and reviewed their ice data. This resulted in an order being placed for ice data and aircraft radar imagery. These data were analyzed and summarized for this report.

2. ICE

2.1 General

The annual reports written by the Canadian Coast Guard (CCG) for the Gulf of St. Lawrence provide an excellent anecdotal description of the ice conditions in the area. The following treatment is based on the CCG accounts, supplemented by an examination of daily ice charts of the most recent ten year period (1987-1996).

Ice generally starts to form in the Gulf in early to mid-December, but often melts again due to mild temperatures later in the month. By year-end, any ice that has formed remains in the area for the winter. Along the West Coast of Newfoundland, ice begins to form in the north and develops toward the south by a combination of drift and new ice growth. Depending on the occurrence of offshore winds, the new ice may develop along the coast line or offshore. Whatever the mode of development, however, the ice generally closes against the West Coast in the second and third weeks of January, when the ice is reported to reach the "young" ice stage (10 to 30 cm). The first year ice thickness continues to increase, reaching the "medium" (30 to 70 cm) to "thick" (0.7 to 1.2 m) stage by mid-March.

Through February, narrow shore leads may open in response to offshore winds. The area is particularly susceptible to opening and closing of shore leads in March and April, with frequency of lead occurrence and persistence varying with the season. In some years, easterly winds can drive the ice far out into the Gulf, leaving a major shore lead for much of the winter (e.g., 1994-95). In other years, northwesterly winds can create intense pressure along the Newfoundland coast for much of the winter (e.g., 1993-94).

Ice clearance proceeds from south to north along the coast. The offshore first-year ice mass generally disperses from the central coast area in the third and fourth weeks of April. In exceptional seasons, offshore and coastal ice have persisted along the central and southern regions of the coast to mid-May. Exceptionally early offshore ice dispersal can occur in the fourth week of March.

Ice disperses from the northern coastal area and Strait of Belle Isle in May and June. Icebergs and fragments of old ice enter the area from the Labrador Sea, but these are only evident in the late winter when the local ice starts to clear. In the seasons when such incursions have been observed, most of the icebergs and old ice have tended to drift to the Quebec shore of the northeast Gulf of St. Lawrence. We have no data or observations of these features in the coastal waters along the West Coast of Newfoundland; the northward flowing current along the coast may keep away from this area. A maximum late season presence of 30% multi-year floes within thick first-year ice (greater than 1.2 m thickness) has been reported in the channel between the West Coast of Newfoundland and Quebec.

The following photographs of ice in the region of interest were kindly provided by Captain Alan Rowsell of the Canadian Coast Guard, Newfoundland Region.

Photo 1 and Photo 2 show general shots of the ice surface in March as the Abitibi Concord was being escorted into Corner Brook. The ice surface is broken up by the wind and wave action, with ice pieces of less than about 5 m across and small piles of ice in between the pieces. No large, well defined ridges can be seen. Photo 3 was taken off the stern of the MV Terry Fox as

she was towing a small vessel in close formation. The ice is very loose on this occasion, as is seen by the areas of open water between floes, and the open wake behind the tow vessel. Ice thickness is estimated to be 20 to 30 cm at the most.

Photo 4, taken on the 29 April, 1995, shows much heavier ice conditions than the other photographs. The ice on this occasion was $10/10^{th}$ concentration, heavily ridged, and probably under pressure. Ridges with sail heights estimated to be 1.5 to 2 m high are evident in front of the red hulled vessel on the left of the picture. Photo 5 shows one of the vessels moving by or ramming a large, probably grounded ridge sail. The vessel appears to have rammed into the ice, causing the flattened area on the ice pile being viewed by the seamen. This ridge sail height is estimated to be over 3 m.

The following two photographs are based on SAR data.

The Canadian Atmospheric Environment Services SAR (Synthetic Aperture Radar) aircraft, known as STAR 2 was used from 1990 to 1994 (from 1975 to 1990 a Side Looking Airborne Radar sensor was used). AES have a list of aircraft flight lines in their database and they have archived hard copy imagery obtained from the aircraft during the operation. Digital SAR data on exabyte tape can be purchased (for about $30 per tape) from AES and turned into hard copy by the user. The SAR aircraft was flown on a regular basis over the Gulf during the winter months. The image resolution used here is 25 m and the swath wide 100 km on both sides of the aircraft. These data provide information on the nature of the ice surface and the location of significant ridges and areas of ridging. Interpretation of the data is not trivial as it depends on the angle of incidence of the radar beam on the ice and the ice surface conditions (i.e., wet, dry, young, old, snow cover, etc).

Photo 6 shows the ice conditions on February 12^{th}, 1994, from Port aux Basque to the Bay of Islands, Newfoundland, with a scale of approximately 1 mm equal to 0.4 km. The fine white lines are ice pressure ridges or ice rubble piles, dark gray areas are level ice (e.g., Port au Port Bay contains smooth, level, landfast ice), and black areas are generally water (e.g., the wedge along the coast south of Port aux Basque) but can be very smooth ice in sheltered water (e.g., Humber Arm). Note that radar shadows also show as black areas. The general ice conditions offshore are believed similar to those shown in Photo 1 and Photo 2 above, small ridges or upturned ice pieces between small pieces of level ice. Heavy ridging, evident by an area of light gray texture, is present along the south shore of St George's Bay, the north shore of the Port au Port peninsula, and for about 3 to 5 km out along the coast north of Port au Port Bay. The area of rougher ice and a few distinct floes (about 1 by 4 km in size) about 65 km west of the Port au Port Peninsula, is believed to be ice which has drifted into the area from the north shore of the Gulf. Heavier ice is evident about 100 km west of Bay of Islands, near the north shore of the Gulf, and larger floes are seen in this area. There is a shear line extending north from Port aux Basque. Ice to the east of this line has moved enough to cause heavy ridging along the West Coast of Newfoundland, but is believed to be relatively stationary when this image was obtained. To the west of the shear line, the ice is moving to the south (note the area of heavier ice 65 km west of Port au Port is displaced to the south on the west side of this shear line) and exiting via the Cabot Strait. Considering that the ice cover is $10/10^{th}$ in this image, heavily deformed along the coast, there is clear evidence of southward ice drift, it is evident that the ice along the West Coast of Newfoundland was under pressure on the 12^{th} February, 1994. There are no well defined shear ridges in the area (i.e., straight ridges which shear through floes), although there are several short straight lines which may define small shear ridges in the ice north of Port au Port Bay. Note the looser ice in the Cabot Strait, where the pressure

Photo 1: Typical ice conditions on the West Coast of Newfoundland, March

Photo 2: Ice conditions on West Coast of Newfoundland, March

Photo 3: Light ice conditions on West Coast of Newfoundland, March, with boat in tow

Photo 4: Heavy ice conditions, April 29, 1995

Photo 5: Vessel ramming large ridge sail,

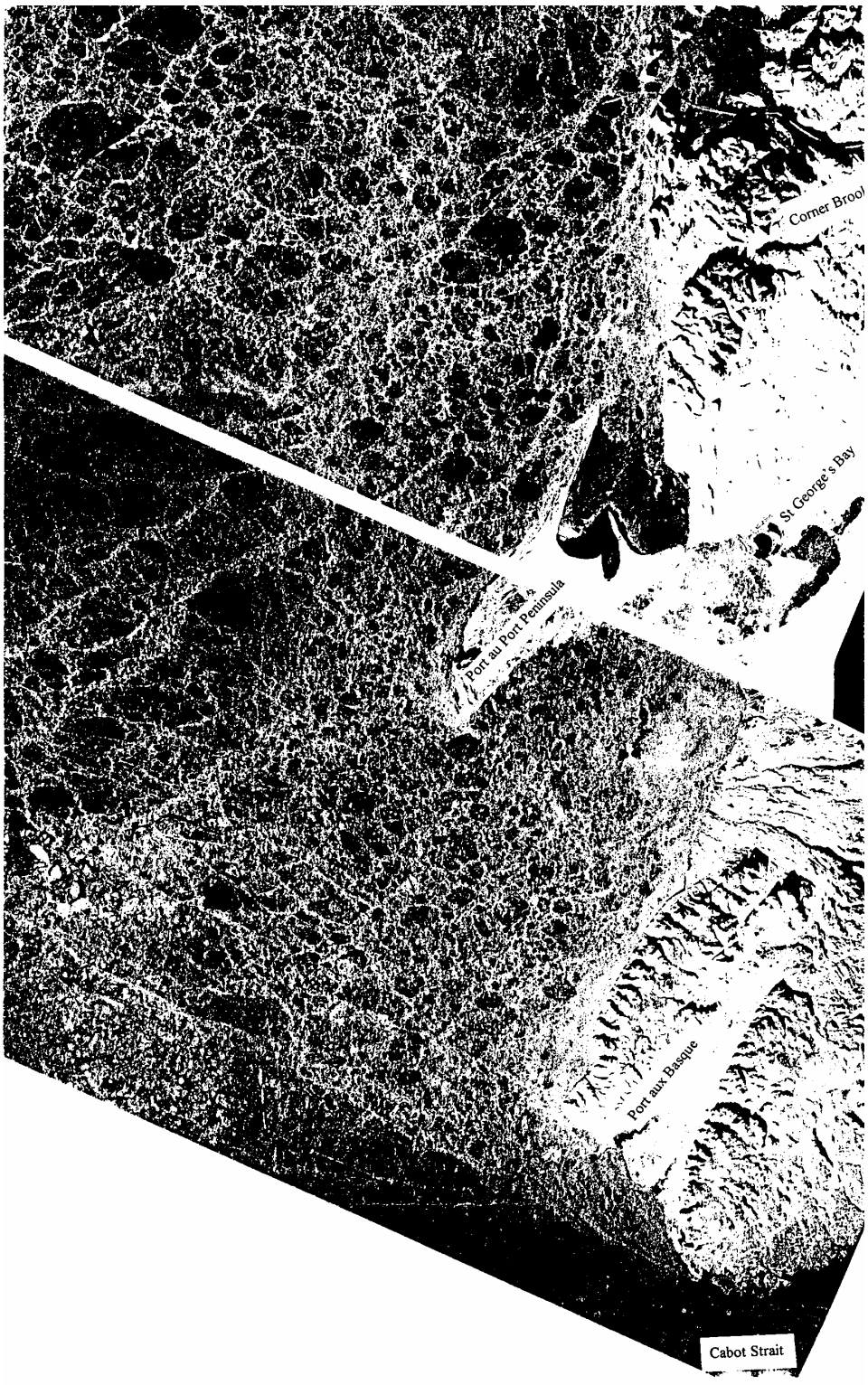

Photo 6: Synthetic Aperture Radar imagery for 12 February, 1994

Photo 7: Synthetic Aperture Radar imagery for 12 March, 1994

releases. Note also the icebreaker track going into the Bay of Islands and Corner Brook. This track can be seen, as a very fine line, extending out into the pack ice 30 km west of Cape St. George, crossing the shear line, and turning sharply south towards the Cabot Strait.

Photo 7 shows the SAR data for 12 March, 1994, again from Port aux Basque to Bay of Islands. The area to the north of Port au Port Bay is still closed in with heavy ridging along the coast; even heavier than shown in Photo 6. There is no evidence of open water or leads in this area and we believe that it is still under pressure from the effects of westerly winds or the tide. The ice in the Port au Port Bay appears much smoother, and the rubble has cleared from the northern entrance to the Bay and is pulling away from the north shore of the Peninsula. This black area in and around the Bay may be open water from ice clearing and melting in the shallow areas. The ice is seen to be moving out of St. George's Bay and exiting the area via the Cabot Strait. Open water is noted in the east end of St. George's Bay, along the south and north shores of the Bay, and in the Cabot Strait. The icebreaker track is again visible in the Humber Arm.

2.1.1 Daily Ice Conditions and Variations

Day-to-day variations in the ice conditions are presented for two years in Appendix A, based on the daily ice charts from AES. These descriptions indicate the extreme variability of the ice conditions also the West Coast of Newfoundland.

2.1.2 Ice Morphology

Variations of the average ice edge by month are shown in Figure 2-1 to Figure 2-10, reproduced from Cote (1989). This report supersedes the earlier work by Markham (1980). These figures indicate that ice forms in the northern regions of the Gulf in mid December, and slowly extends across the Gulf generally lying along the West Coast of Newfoundland by late January. Despite frequent day to day and year to year variations, the ice generally starts to recede from the coastline in the later part of March. Based on the 26 years of data reviewed by Cote, the last remnants of ice generally clear the coastal region of interest by late May-early June, but ice may still exists along the north coast of the Gulf and in the Strait of Belle Isle.

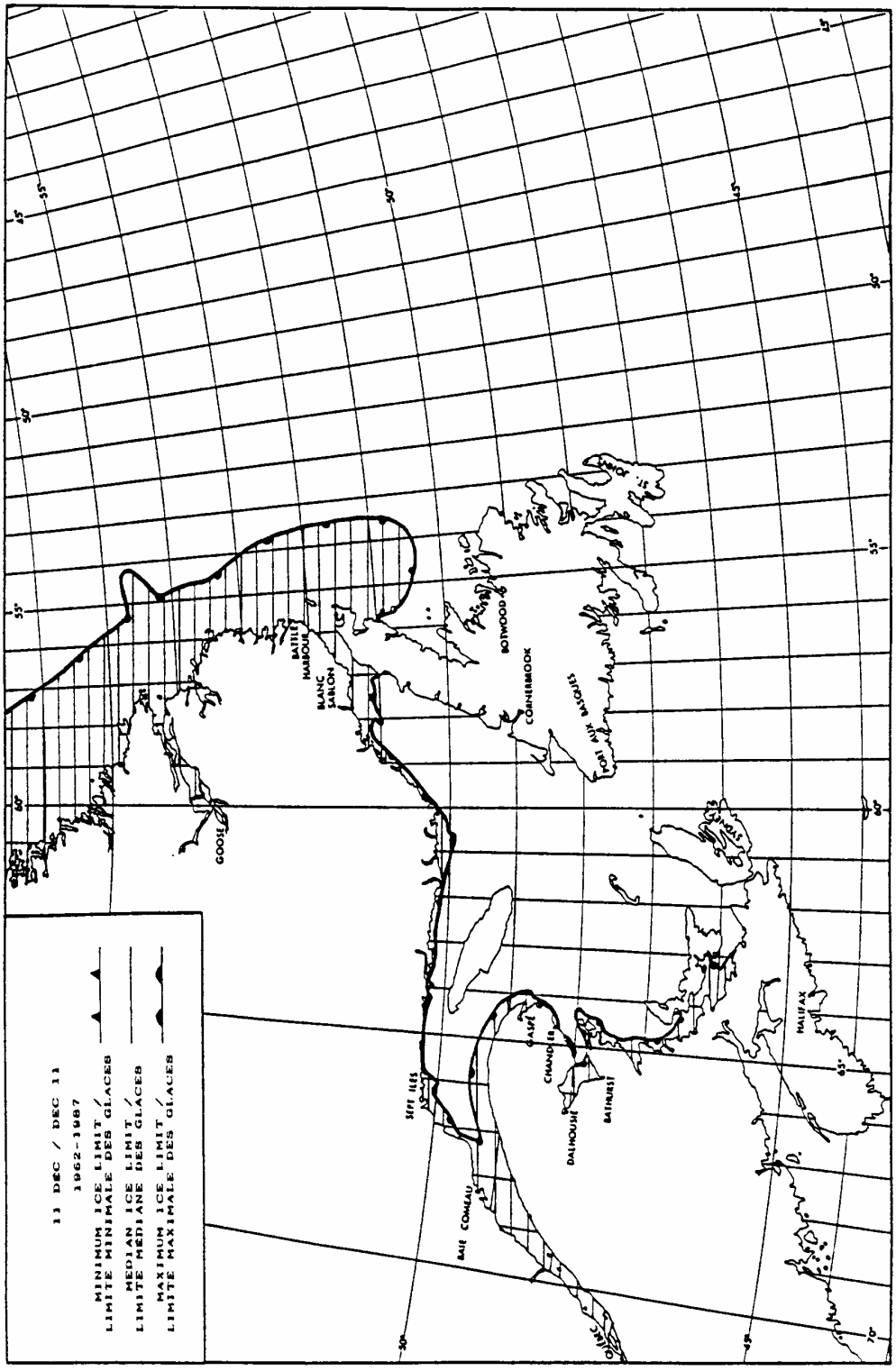

Figure 2-1: Minimum, Medium, and Maximum Ice Edges on December 11

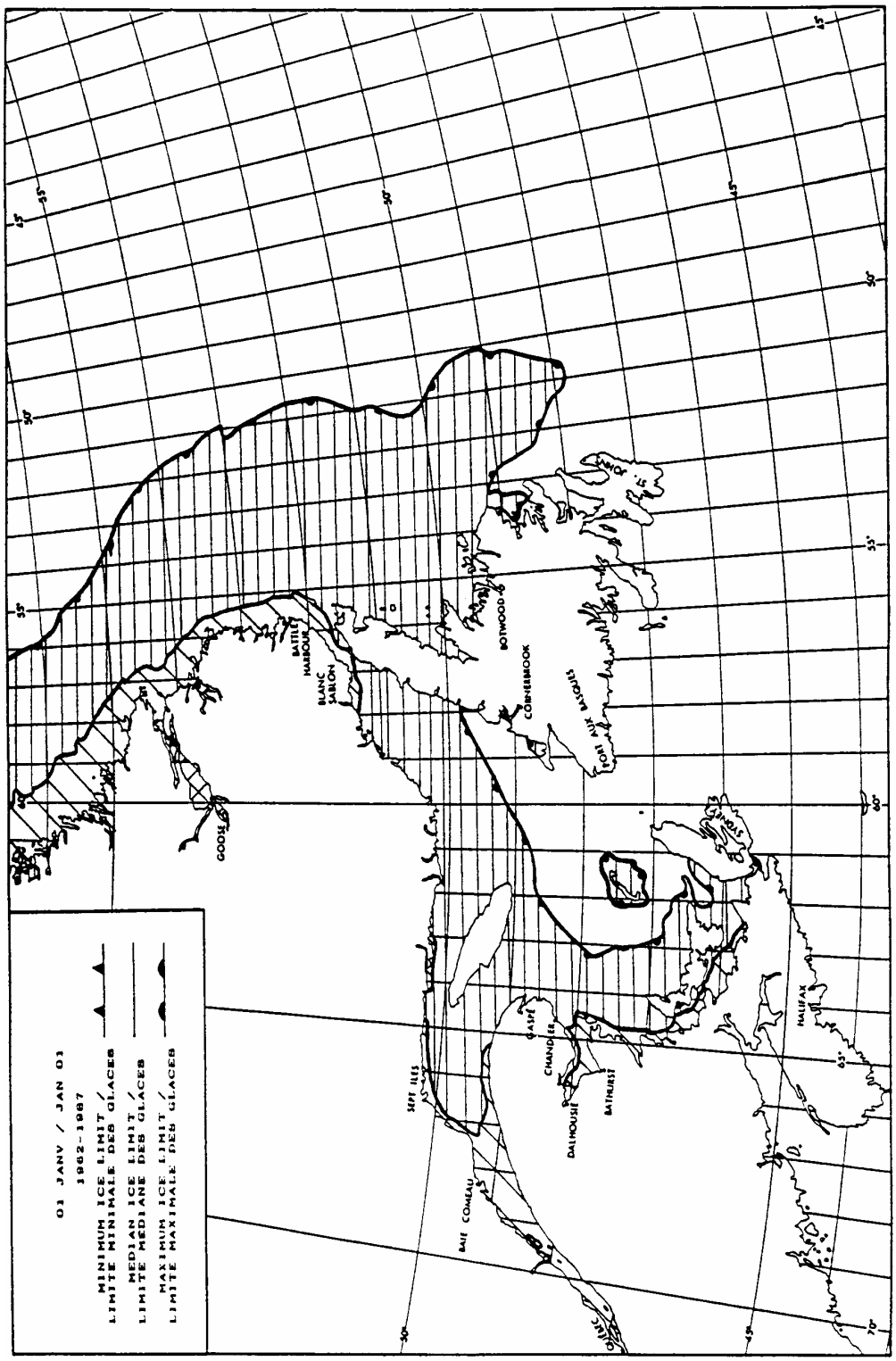

Figure 2-2: Minimum, Medium, and Maximum Ice Edges on January 1

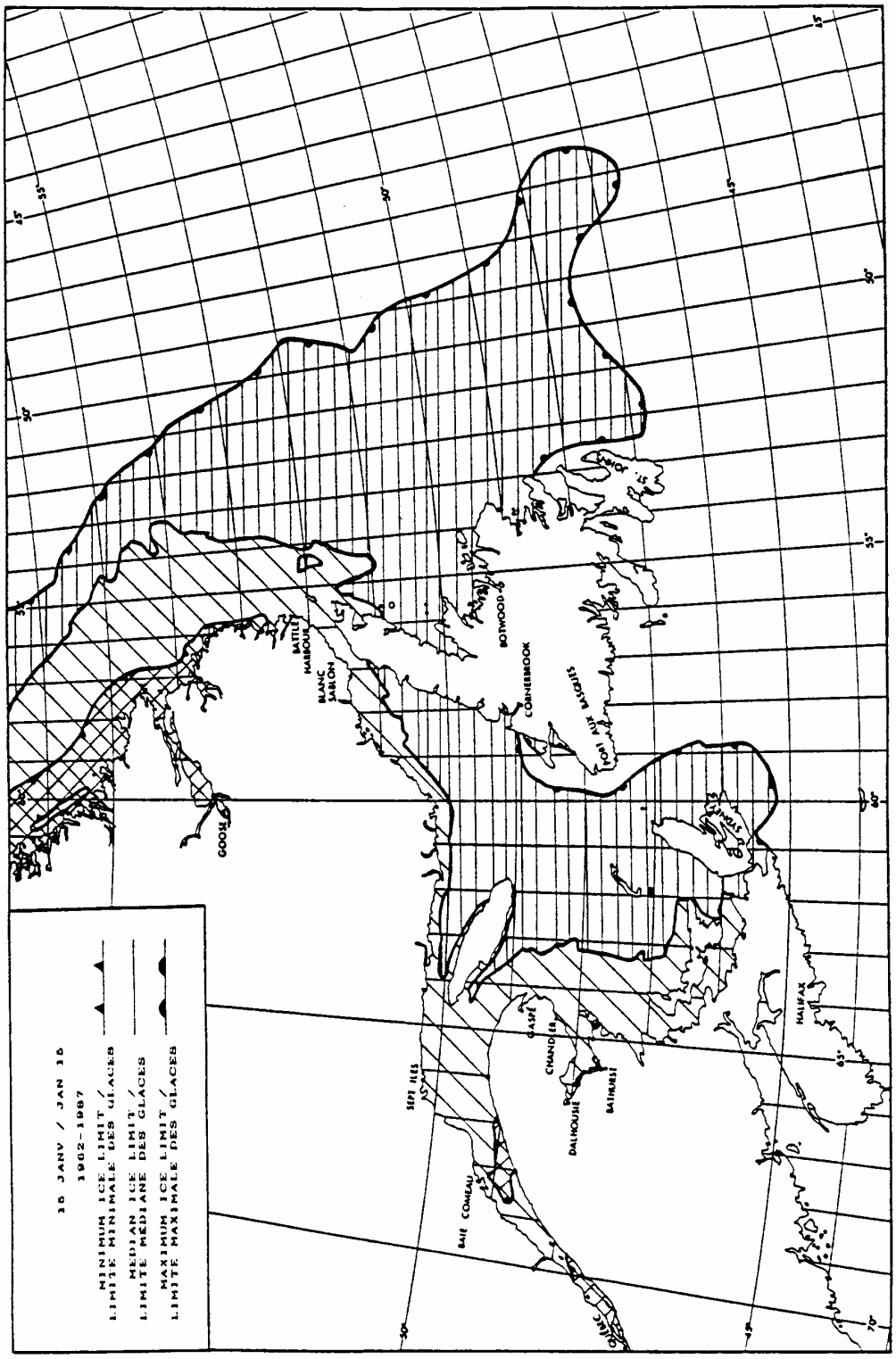

Figure 2-3: Minimum, Medium, and Maximum Ice Edges on January 15

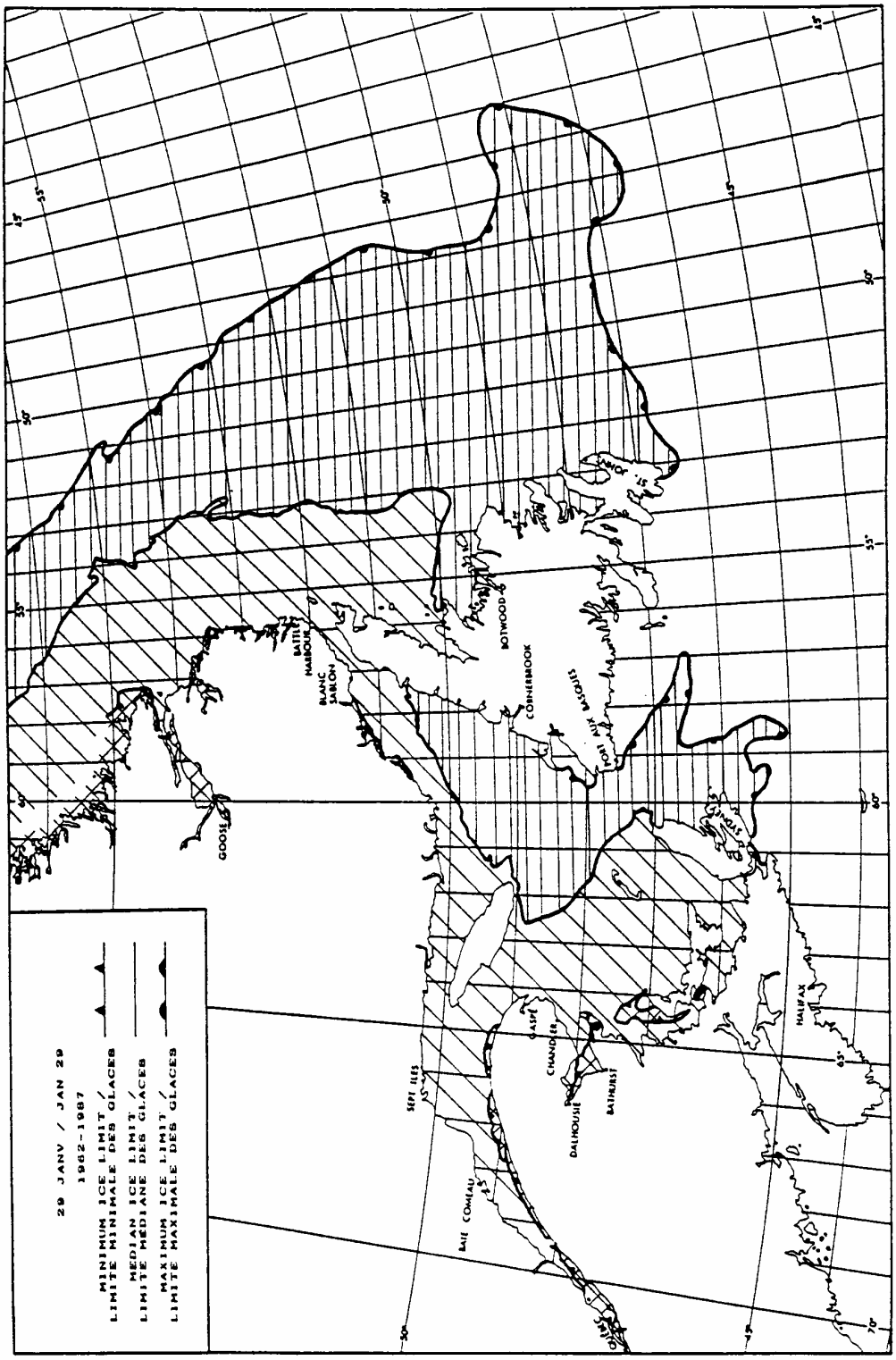

Figure 2-4: Minimum, Medium, and Maximum Ice Edges on January 29

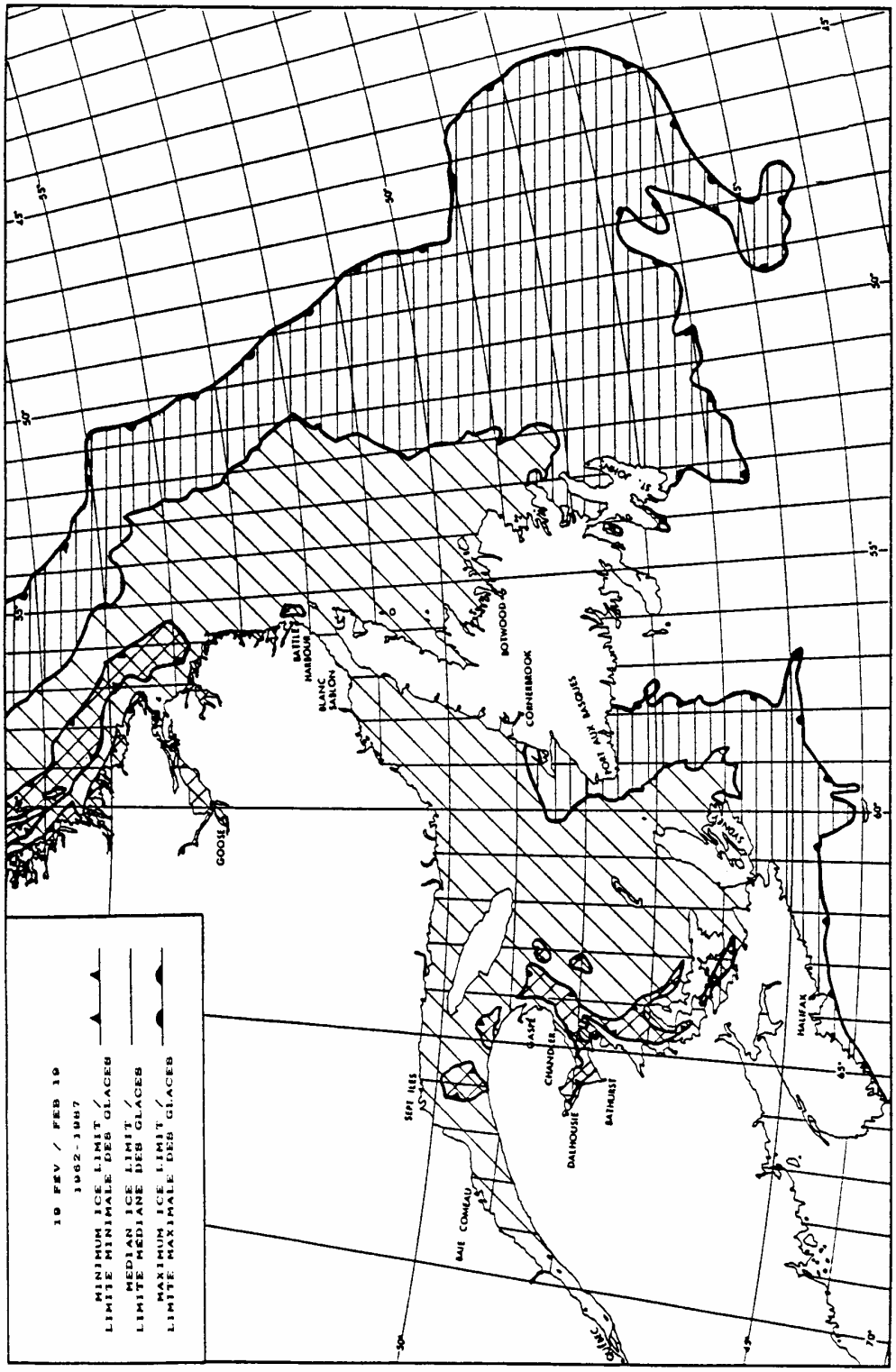

Figure 2-5: Minimum, Medium, and Maximum Ice Edges on February 19

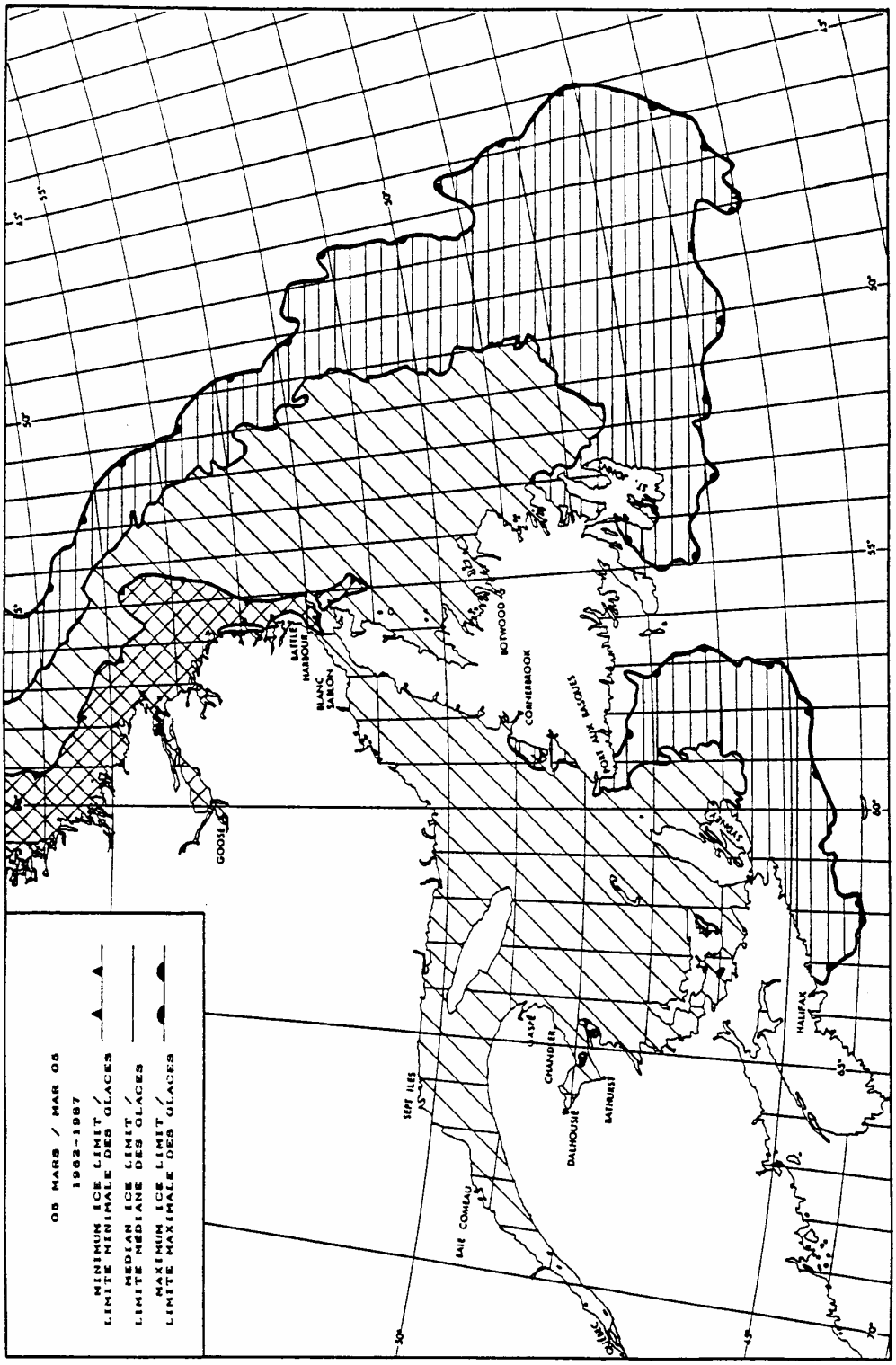

Figure 2-6: Minimum, Medium, and Maximum Ice Edges on March 5

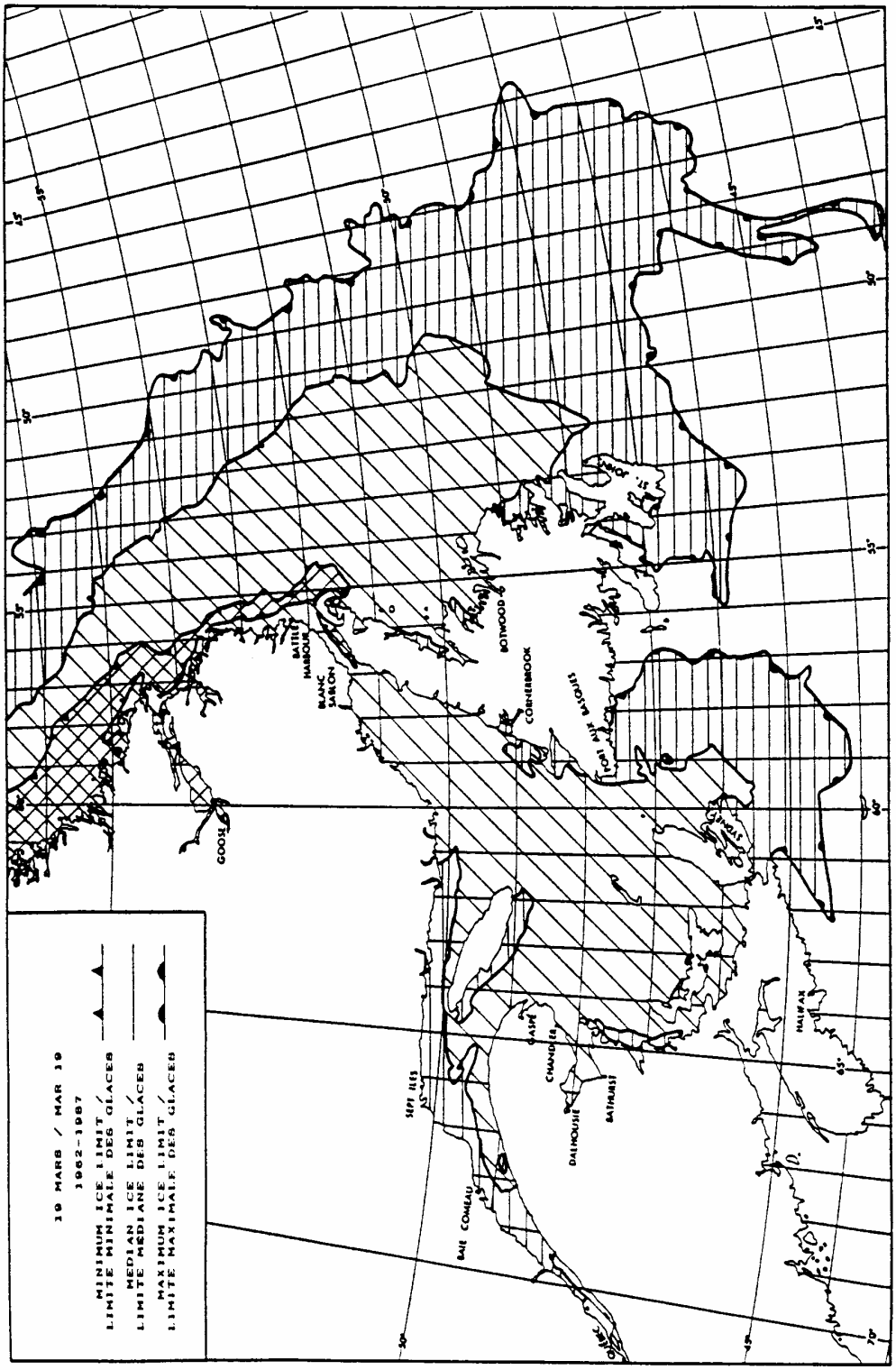

Figure 2-7: Minimum, Medium, and Maximum Ice Edges on March 19

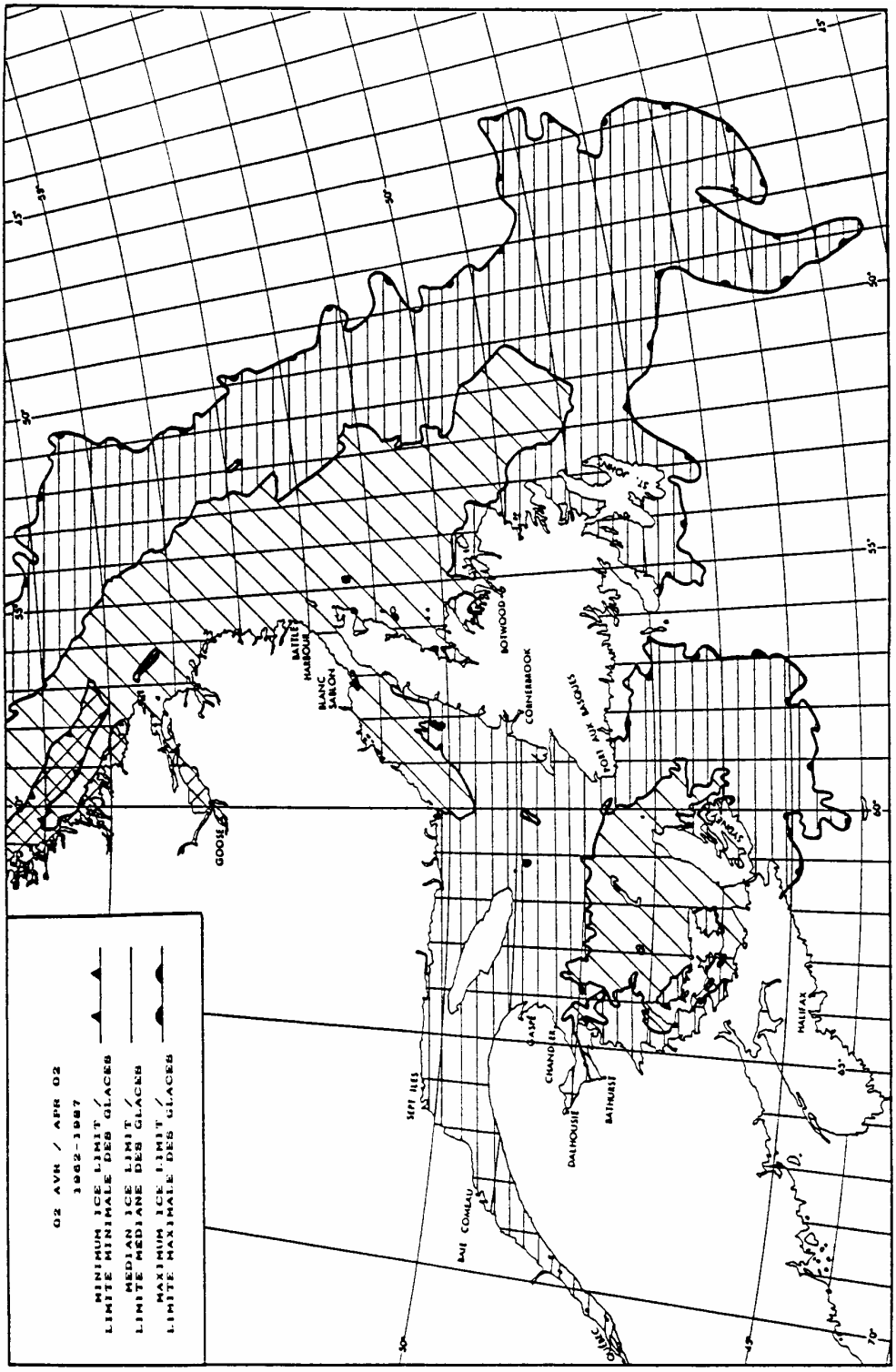

Figure 2-8: Minimum, Medium, and Maximum Ice Edges on April 2

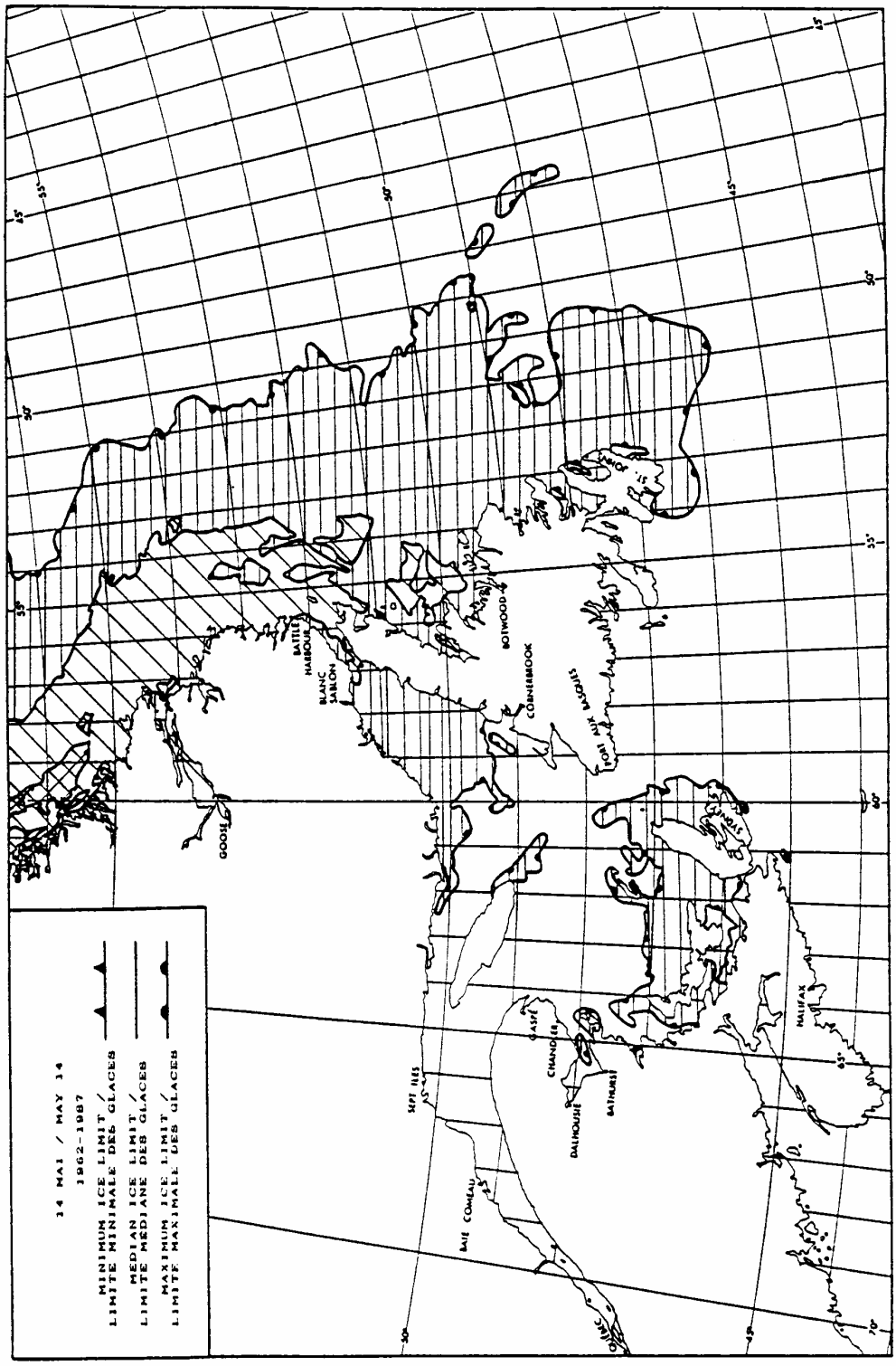

Figure 2-9: Minimum, Medium, and Maximum Ice Edges on May 14

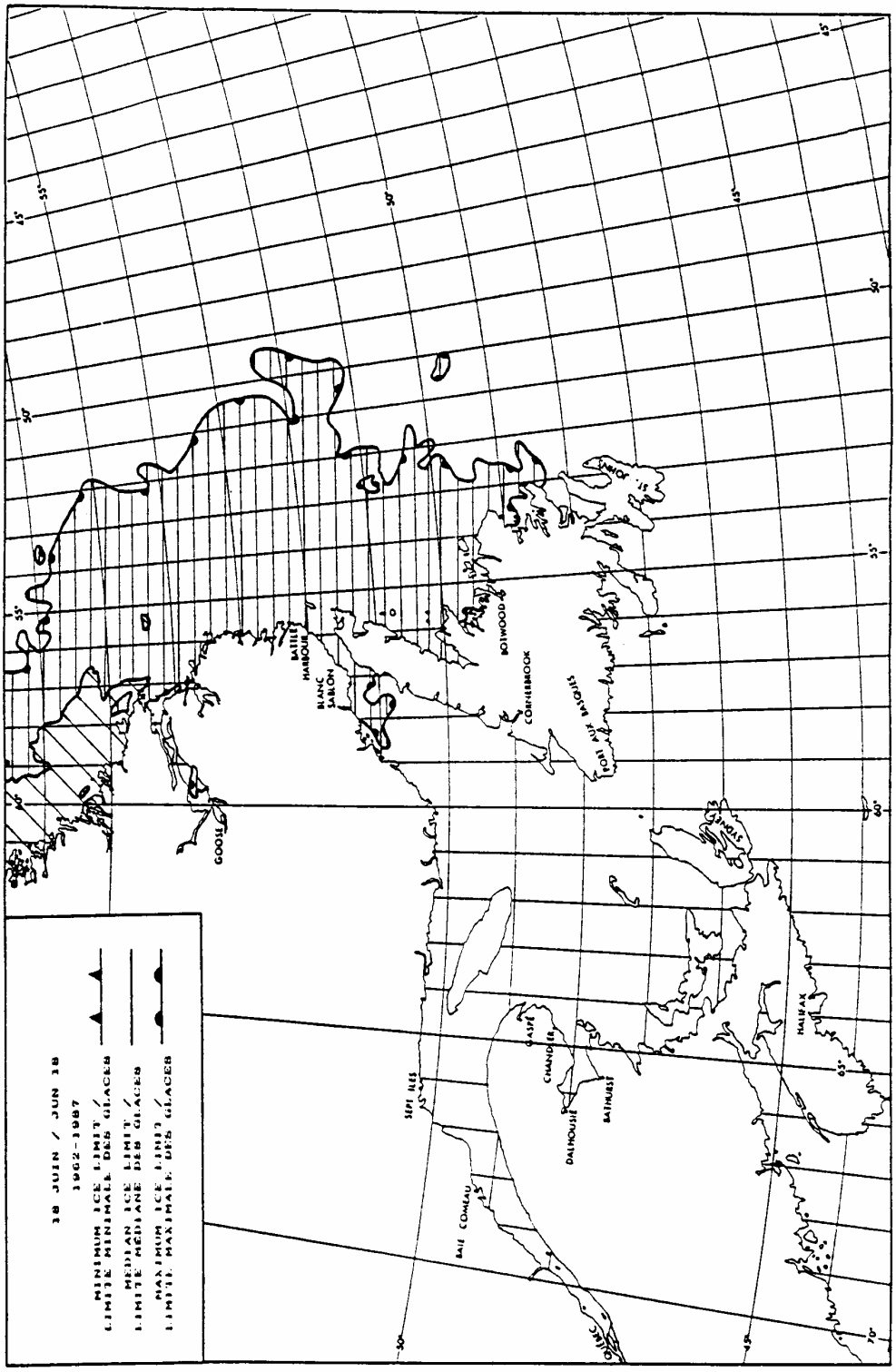

Figure 2-10: Minimum, Medium, and Maximum Ice Edges on June 18

2.2 Freeze-up and Break-up

The preceding figures indicate the development and decay of ice in the area of interest. Freeze-up and break-up dates were interpreted from eight years of daily AES ice charts (1985 - 1994 period), and the resulting summaries are presented Figure 2-11, with Corner Brook data included for comparison. The offshore conditions were noted off three fixed coastal locations adjacent to Daniel's Harbour (Northern coastal area), the Bay of Islands (Central coastal area), and St. George's Bay (Southern coastal area). The "freeze-over" date was the first chart date recording in excess of 9-tenths ice concentration against the shoreline at the three observation points. The "ice clearance" date was the chart date at which local ice concentration reduced to open water and remained so for the remainder of the season.

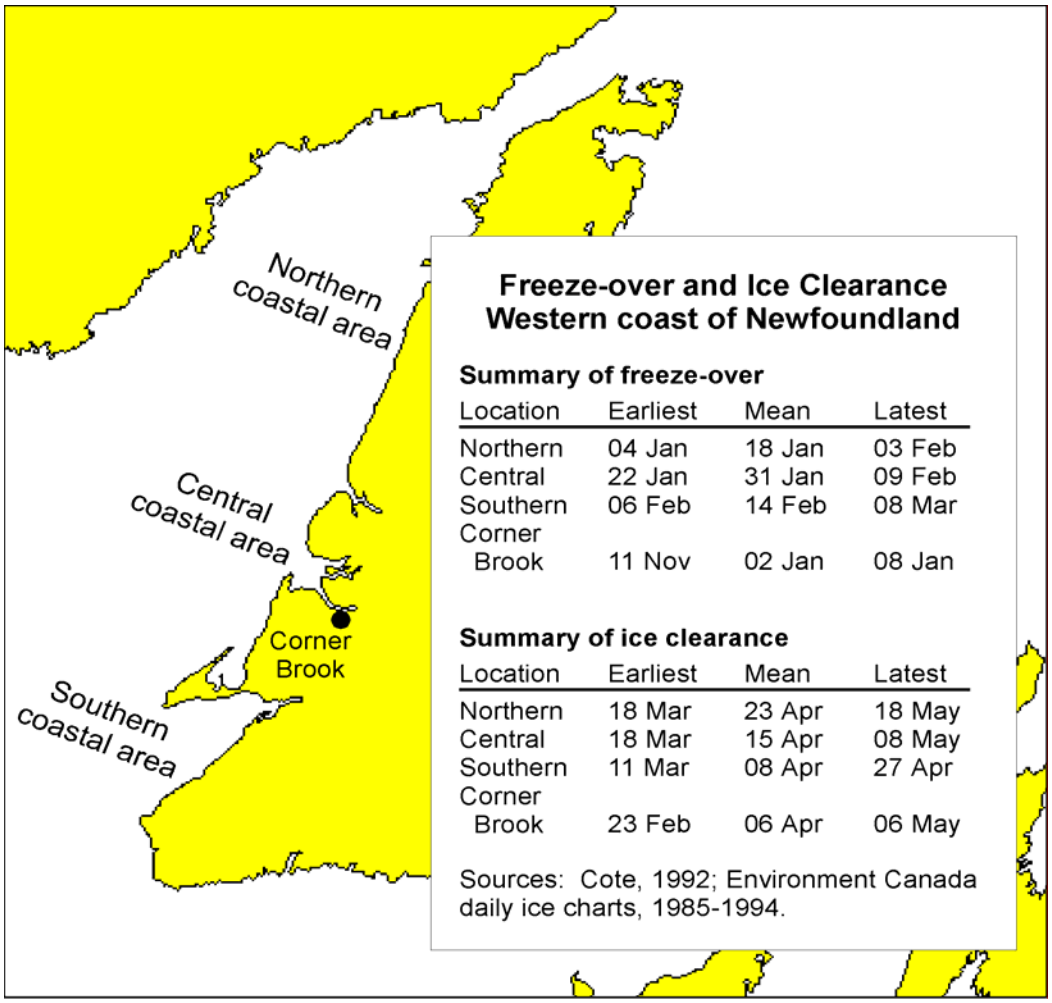

Figure 2-11: Summary of freeze-up and break-up along the outer West Coast of Newfoundland and at Corner Brook.

These dates in Figure 2-11 indicate the trend of ice development from north to south and of ice clearance from south to north. Freeze-over of the Central coastal area, in the years studied, has

always completed within a three-week window between 22 January and 9 February. Clearance shows greater variability, from 18 March to 8 May. This is attributed to onshore and southwesterly winds which, in some seasons, maintain residual concentrations of deteriorating ice floes in the area. The sheltered, brackish waters of the various inlets along the coast freeze up earlier but clear about the same time as the adjacent offshore waters. For example, in the Humber Arm, Corner Brook, freeze-up occurs between late November and early January, and break-up between mid February and mid April. Freeze-over at Corner Brook, on average, precedes freeze-over off the Bay of Islands by a month but this may approach three months in an extreme season when Humber Arm covers entirely by mid-November.

2.3 Ice Thickness

Ice thickness is extremely important in the calculation of loads on offshore structures. Of interest are both the level ice thickness and the thickest ice which may enter an area. No on-ice field program has been carried out in the area of interest as far as we are aware. Hence the different sources of information on level ice thickness will be reviewed here.

Regular Ice thickness measurements

Ice thickness for Corner Brook (1974 to 90) is indicated in Figure 2-12 from measurements taken in the Humber Arm. This station is closest to the area of interest, however, it is inshore and protected. In this area, ice starts to grow at the end of November and grows to a maximum thickness of about 40 cm at the end of March. Ice starts to melt in early April and is generally dispersed by mid-May. The Corner Brook data record of 17 years (1974 to 1990) indicates an extreme maximum ice thickness of 60 cm and an extreme minimum ice thickness of about 20 cm.

We know from section 4.2 that ice growth is quite different offshore compared to inshore, hence the ice growth data from Corner Brook can be considered only as an indication of the level ice thickness in the general area. Considering that ice starts to grow earlier inshore than offshore, the Corner Brook ice thicknesses are probably greater than those expected from ice which forms in the adjacent area offshore. However, ice moves into the area from the north shore of the Gulf, and this and the consolidation within ridge keels can be much thicker than the locally formed level ice.

AES (1991) provides the ice thickness for several stations in the Gulf of St. Lawrence and these are indicated in Table 1. Cartwright, located on the coast of Labrador, is provided as this is considered to be the maximum possible level ice thickness which would be expected in the Gulf of St. Lawrence.

Only freezing degree day values are available for several relevant stations in the Gulf of St. Lawrence (see AES 1992). The mean freezing degree day (fdd) values for Stephenville (just south of Corner Brook) of 634 suggest a mean ice thickness of 40 to 55 cm (using fdd to ice thickness conversions from Cammaert and Muggeridge, 1992). By comparison, Sept-Isle, in Quebec has a mean fdd of 1526 and a maximum of 2011. These correspond to an ice thickness of 0.8 to 1.0 m mean and 1.2 m maximum. It is doubtful that ice from Sept-Isle enters the area of interest here due to the river currents which flow to the south, however, it cannot be ruled out at present. Freezing degree day values for Harrington Harbour, Quebec, of 1269 mean and 1712 maximum correspond to ice thicknesses of 0.7 to 0.85 cm.

Location	Fresh (F), Saline (S), Brackish (B)	Mean Ice Thickness (cm)	Max Ice Thickness (cm)
Corner Brook (Nfld)	B	43.7	62
Natashquan (PQ)	F	76.2	112
Havre-Saint-Pierre (PQ)	F	67.9	91
Blanc-Sablon (PQ)	F	82.4	110
Caraquet (NB)	S	69.0	92
Summerside (PEI)	S	50.0	73
Botwood (Nfld)	F	57.9	79
Cartwright (Lab)	S	94.8	160

Table 1: Mean and maximum measured ice thicknesses in the general area of interest

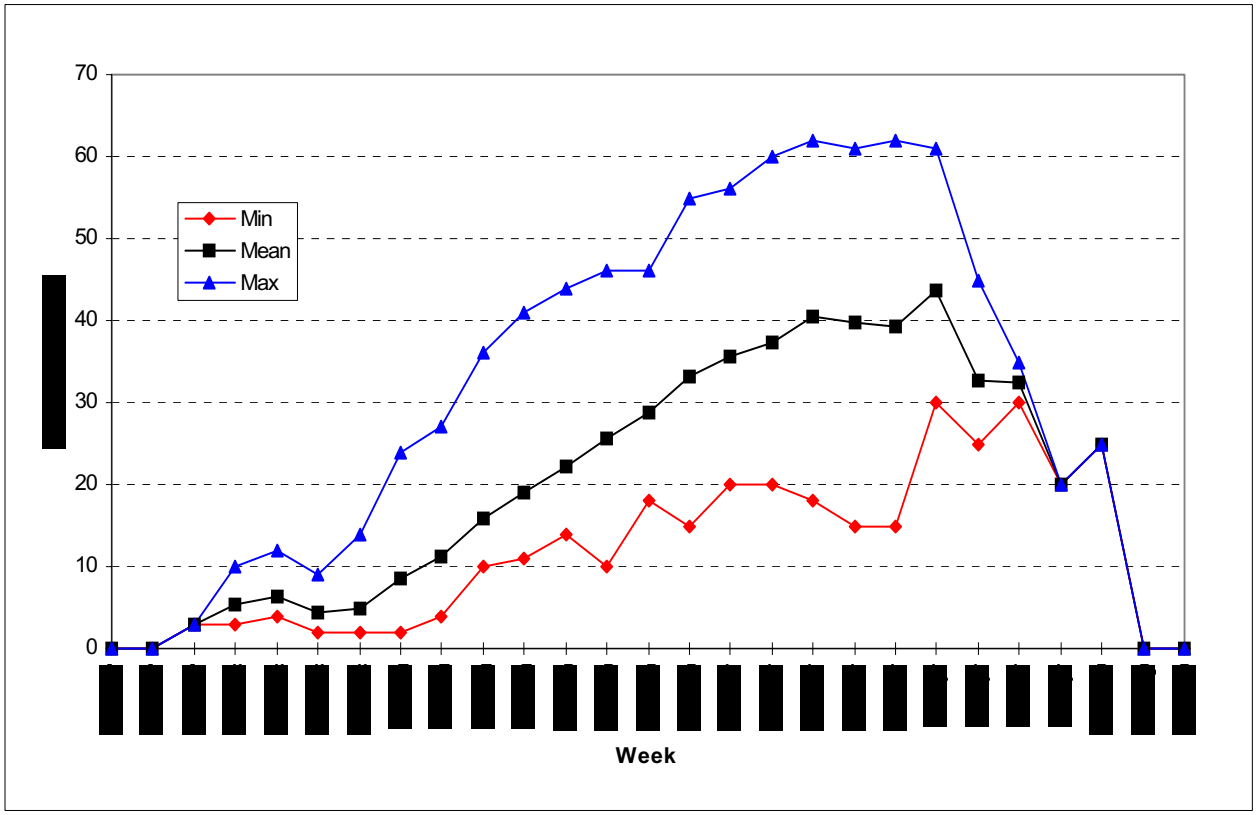

Figure 2-12: Ice Growth based on measurements made in the Humber Arm, Corner Brook.

AES Ice Charts

The AES ice charts for the Gulf of St. Lawrence indicate that the ice in the area of interest is generally in the thin first year ice class, i.e., 30 to 70 cm. However, 2 to $4/10^{th}$ concentration of ice in the 70 to 120 cm ice class, in the form of small floes, is reported in most years. Occasionally a trace (< $1/10^{th}$) to a few tenths of ice thicker than 120 cm is reported in late April in the northern regions of the area. In some years, e.g., 1991, old ice was reported in the northern regions of the area along with icebergs. These had come from the Labrador Sea down the Strait of Belle Isle.

AES Ice Thickness Measurements

Ice thickness measurements made by ice observers on board the ice breakers which operate in the area are provided as supplements to the various AES ice maps. Table 2 summarizes some of these measurements for 1990 taken as the John A. MacDonald was progressing north from Port aux Basque enroute for Corner Brook. These measurements indicate level ice thicknesses in the 30 to 80 cm range with a few measurements of very thick rough ice on 10 April, 1990.

Date	Latitude	Longitude	Ice thickness	Comments
1 April, 90	48 00 to 48 30	59 31 to 59 56	31 to 65 cm	Floes smooth. From small to vast. Trace of old rafts and/or ridges on vast floes. Wet snow. Signs of melting
2 April, 90	49 00	58 00	45 to 80 cm.	Fast ice thin to medium thickness. Bare ice in places. Ridges to 0.3 m, some puddling, ice very wet, snow slushy.
3 April, 90	48 00	59 50	39 to 54 cm	Ridges to 1.75 m. Ice very wet. All ice bare except for snow in ridge sails
10 April, 90	49 10	58 00	43 to 68 cm	Smooth fast ice. Ice 147 and 195 cm thick in area of rough old weathered rafts.
14 April, 90	49 12	58 29	38 cm and 76 cm	Big floe. Ridging to 1.5 m

Table 2: Ice thickness measurements made by ice observer on John A MacDonald

Based on the above, we recommend the following ice thicknesses for use in the review of structures suitable for the area of interest:

Situation	Ice Thickness
Annual maximum level ice thickness	80 cm
Maximum first year level ice thickness as a result of a particularly cold year (worst year in the 17 years of available data)	100 cm
Extreme first year ice thickness	1.5 m

Table 3: Recommended ice thicknesses for area of interest

2.4 Landfast Ice

As the ice in the Gulf is very mobile during the winter, often forcing into shore with the development of extensive ridging, one would expect landfast ice forming along the coastline to water depths of 5 to 10 m, about 1 to 1 ½ km from shore. AES Ice Charts indicate that landfast ice develops in some years for a few weeks in the shallow bays around Port au Port, the Bay of Islands, Daniels Harbour, the east end of St George's Bay, St John's Bay, and various other small bays. The AES SAR data indicate a narrow band of fast ice at various places along the coast between bays, to a distance of about 1 km offshore; the AES ice charts do not have adequate resolution to show this. Landfast ice is anchored by grounded ridges. The grounded ridges in this area would have to have adequate freeboard to remain grounded in the 2 m tides experienced in the area, or they would have to be formed high up the beach during a high tide. Due to the limited quantity of landfast ice, it is not considered to be the hazard that it is in other areas such as the Beaufort Sea.

2.5 Pressure Ridges

AES flew laser profilometer missions over the Gulf of St. Lawrence and Cabot Strait between 1974 to 1981. The data were provided by AES as the number of ridges in each 0.2 m sail height range per line km. For this project, we divided the data into 4 zones; a north nearshore zone from the southern end of the Strait of Belle Isle to latitude 50° 30', a central nearshore zone between latitudes 49° 30' and 50° 30', a southern nearshore zone south of 49° 30' latitude, and an offshore zone, beyond water depths of 100 m. In each zone, the number of ridges in each sail height interval were added together and the results are shown in Table 4. The Table indicates the number of km of flight line in the zones of interest, the number of ridges processed, and the average and maximum number of ridges per km. It is noted that there are 1200 km of data and 7439 ridges in the nearshore area of interest. Data were obtained in the months February to May, from 1974 to 1980, with the majority of flights being made in the months March and April.

Zone on Coast	Number of km of data	Number of Ridges	Average number of ridges/km	Maximum number ridges/km
North Nearshore	70	1812	26.3	55
Centre Nearshore	80	467	5.8	28
South Nearshore	1047	5160	4.9	59
Offshore	354	2906	8.28	40

Table 4: Ridge statistics for laser profilometer data for West Coast of Newfoundland

These data indicate that the number of ridges/km decreases from the northern zone to the southern zone. The maximum number of ridges is highest in the northern and southern zones. Figure 2-13 shows the number of ridges with height exceeding a given sail height. The figure indicates a low percentage of ridges with sail heights exceeding 2 m and a maximum ridge sail height of 2.8 m measured. This ridge would have a total thickness of 12.3 m, based on a keel to sail ratio of 4.4 (Timco and Burden, 1996). Table 5 shows ridge sail height statistics for the AES laser profilometer data. The trend lines fit the graphs shown in Figure 2-13. The equations indicate the number of ridges with sail heights exceeding x m per km.

Zone on Coast	Mean ridge sail height (m)	Trend Equation
North Nearshore	0.81	$142\ e^{-x/0.31}$
Centre Nearshore	0.66	$95\ e^{-x/0.16}$
South Nearshore	0.73	$45\ e^{-x/0.23}$
Offshore	0.69	$93\ e^{-x/0.2}$

Table 5: Ridge height statistics for AES laser profilometer data for West Coast of Newfoundland

The e-folding scale of 0.31 m for the sail height distribution corresponds to a keel of 1.37 m and less which are appreciably lower than the values of 2.16 m reported by Melling and Reidel (1996) for the Beaufort Sea. This indicates that there are relatively fewer deep keel depths in the area of interest here than in the Beaufort Sea, as one would expect.

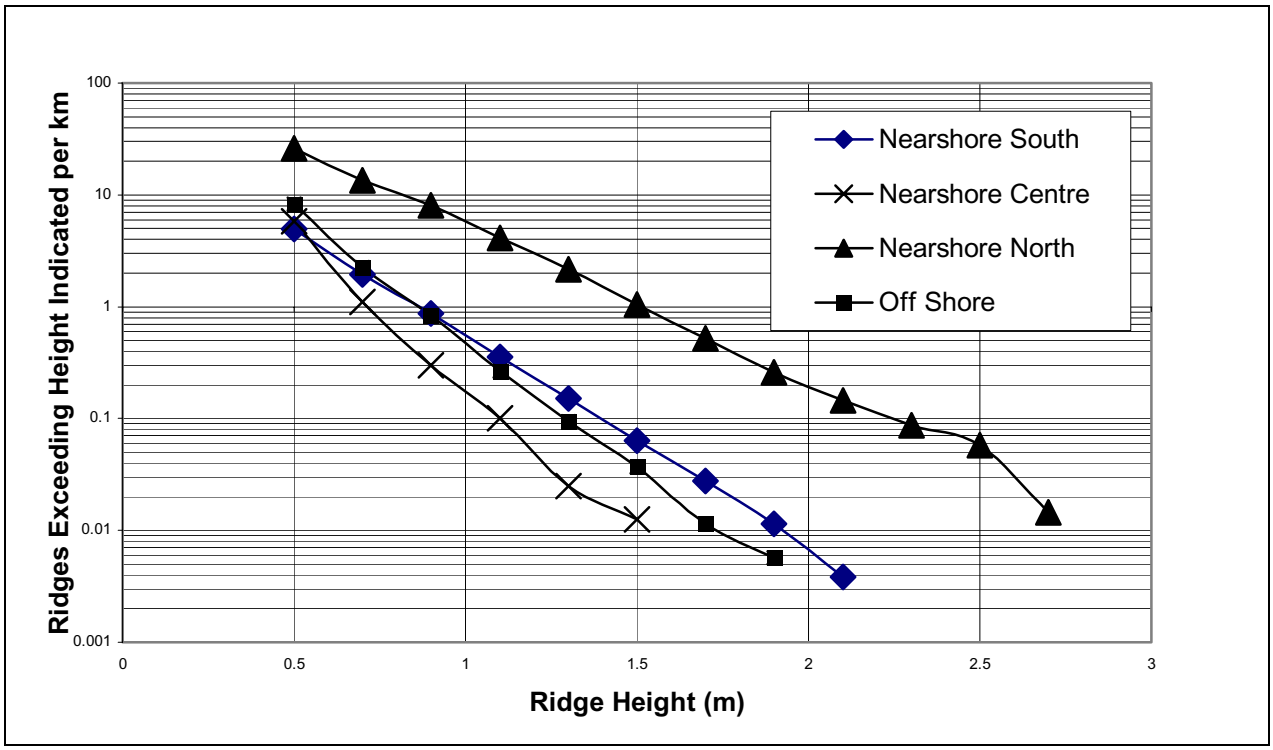

Figure 2-13: Number of ridge sail per km off the West Coast of Newfoundland (based on AES laser profilometer data, 1974-1981).

2.5.1 **Maximum Pressure Ridge Sail Heights**

Maximum pressure ridge sail heights can be estimated from the parent ice thickness. Tucker and Govoni (1981) measured 30 ridges in the Beaufort Sea and compared their height to the thickness of blocks in the ridge and found that the maximum sail height is proportional to the square root of the ice thickness within the ridge sail. Sayed and Frederking (1988) found similar results.

The mean ridge sail height is given by:

$$S = 3.71 \sqrt{t} \quad \text{m}$$

and the maximum sail height is given by:

$$S = 5.2 \sqrt{t} \quad \text{m}$$

Where t is the block ice thickness within the sail (in m)

Here we will assume that the maximum annual ridge sail height is produced by the maximum annual ice thickness of 0.8 m (see 4.3 above); this indicates the mean ridge sail height of 3.3 m and maximum of 4.65. (Note that Timco and Burden (1996) reported no correlation between level ice thickness, presumably alongside the ridge, and sail height. Melling and Riedel(1996) noted a relationship between ridge keel depth and thickness of ice to the side of the ridge. Their parameters differed from those given by Tucker et al, 1984). For the extreme ice thickness of 1 m (thickest level ice in 17 years), the average sail height is 3.7 m and maximum is 5.2 m for a floating ridge.

2.5.2 **Ridge Keel Depth**

The ridge keel depth can be obtained from the ridge sail height based on relationships derived for other ice-covered areas. Burden and Timco (1996) use the measurements of various authors and determined the ridge keel/sail ratio to be:

$$\text{Keel/Sail} = 4.4 \pm 1.8$$

for first year ridges in temperate regions.

Ridges heights and sail depths for the area of interest are indicated below.

Note that these are the thickest ridges, and ridges from zero up to these thicknesses would be expected, depending on the environmental forces and extent of ice movement.

Ridge Parameters		
	Worst Annual	Extreme (worst in 17 years)
Ice thickness	0.8 m	1.0 m
Largest ridge sail height	4.7 m	5.2 m
Ridge keel depth	21 m	23 m
Ridge keel depth plus 1 standard deviation	29 m	32 m
Porosity	0.1 to 0.3	0.1 to 0.3
Consolidated Layer thickness	1.6 m	2 m

Table 6: Ridge Parameters for the West Coast of Newfoundland

2.5.3 Ridge Porosity and Consolidation

There is no data on ridge porosity or consolidation for our area. The consolidation depends on the porosity of the ridge keel. Lepparanta and Hakala (1996) measured an average porosity of 29 %, with a lowest keel porosity of 23 % and lowest sail porosity of 9 %. Kovacs and Mellor (1974) indicate a range of porosities from 10 % to 40 % for compressive and shear ridges, with the lower porosities in shear ridges. Timco and O'Brien (1994) reviewed data on 112 first year ridges from 13 authors. Their data indicate a mean porosity of 19 % for sails and 30 % for keels. Minimum and maximum porosities of 5 % and 41 % were reported for sails, and 22 and 37 % for keels, respectively. Timco and O'Brien (1994) indicated a mean consolidation of 1.88 times level ice thickness, with a range from 0.5 to 4.

2.5.4 Ridge Keel Geometry

There is no data on ridge geometry for this area. Timco and Burden (1996) review the geometry of ridges in temperate (and Arctic) regions and found considerable variability. They develop a typical ridge geometry, as indicated in Figure 2-14.

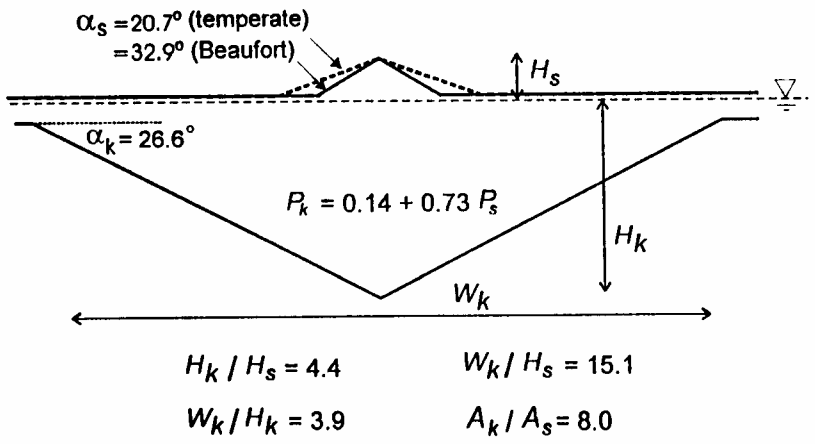

Figure 2-14: Typical first year ridge geometry (from Timco and Burden, 1996)

2.5.5 Ridge Impact Rates

Considering that pressure ridges form along the coast every year, and the ice moves around almost daily, any structure placed in the coastal regions (except possibly for some of the shallow areas) will be impacted by pressure ridges. Table 5 presents data on ridge thicknesses, which indicate that keels to 21 m are an annual occurrence and impact of such ridges with a structure should be considered an annual occurrence. Extreme ridges have keels of up to 32 m thick. The extreme ice thickness which gave this ridge (using the Tucker and Govoni theory), was the thickest ice in 17 years of data, and hence one might consider this ridge to be the 1 in 17 year extreme thickness. One would expect a 100 year extreme ridge keel of about 32 m. As ridges tend to be quite long, and one would expect several such ridges in the 100th year, it is reasonable to assume any structure would be impacted by such a ridge in the 100th year, provided the structure were in water depths exceeding 32 m.

If the ridges were compression ridges, then the consolidation within the ridge would amount to about 96 cm in the annual ridge, and 1.2 m in the 1 ridge in 17 years. However, if the ridge is a shear ridge, then the porosity will be considerably lower and consolidation of up to 1.6 to 2 m would be expected.

2.6 Rubble Fields

There is no data on rubble or rubble fields in the area of interest. The laser profilometer data indicate up to 58 ridges per km, many of these may form rubble fields.

2.7 Multi-Year Ice

The CCGS anecdotal report and AES ice charts occasionally indicate the presence of small quantities of multi-year ice on the north shore of the Gulf. This ice drifts down the Strait of Belle Isle and melts in the Gulf during the summer. A review of two decades of AES ice charts indicates that the occurrence of multiyear ice in the Gulf of St. Lawrence is rare. No multiyear ice was reported in the area from 1969 to 1978, but there were 7 occasions from 1984 to 1996 when old ice was reported during the April to June period, around the southern end of the Strait of Belle Isle. Very likely the more frequent occurrence of old ice after 1984 is a result of improved detection methods (the introduction of aircraft with radar sensors). The concentration of the old ice is generally in the trace amounts. There was one report of 2/10 old ice in the winter of 1994/95, but floe sizes were reported as "small", i.e., 20 to 100 m.

2.8 Ice Drift

The most consistent indicator of ice drift found was the forecast drift vector information noted on daily ice charts of the region. Based on area wind forecasts, presence of ice, and land configuration, the AES interpreters display a 24-hour ice drift forecast at various points on a given day's ice chart. The drift forecast indicator consists of an arrow pointing in the direction of forecast drift and a value indicating forecast nautical miles of drift over the following 24-hour period. Of 12 years of chart data examined, a total of 1361 records were extracted. Of these, 1031, or three-quarters, had associated drift vectors.

Figure 2-15 is a graphical summary of the percent frequency of drift directions at three areas along the West Coast of Newfoundland.

Although at least 50 percent of forecast ice drift is in an onshore direction (between east-northeast and southeast) not conducive to shore lead development, it should be noted that the cumulative period of regional shore lead conditions account for only three to five weeks (approximately one-fifth) of the ice season. Of note are the sub-peaks in the distribution at northeast, southeast, southwest, and north west directions. These are either parallel or perpendicular to the general trend of the coastlines of the area, suggesting that there may be a significant sea current influence on drift.

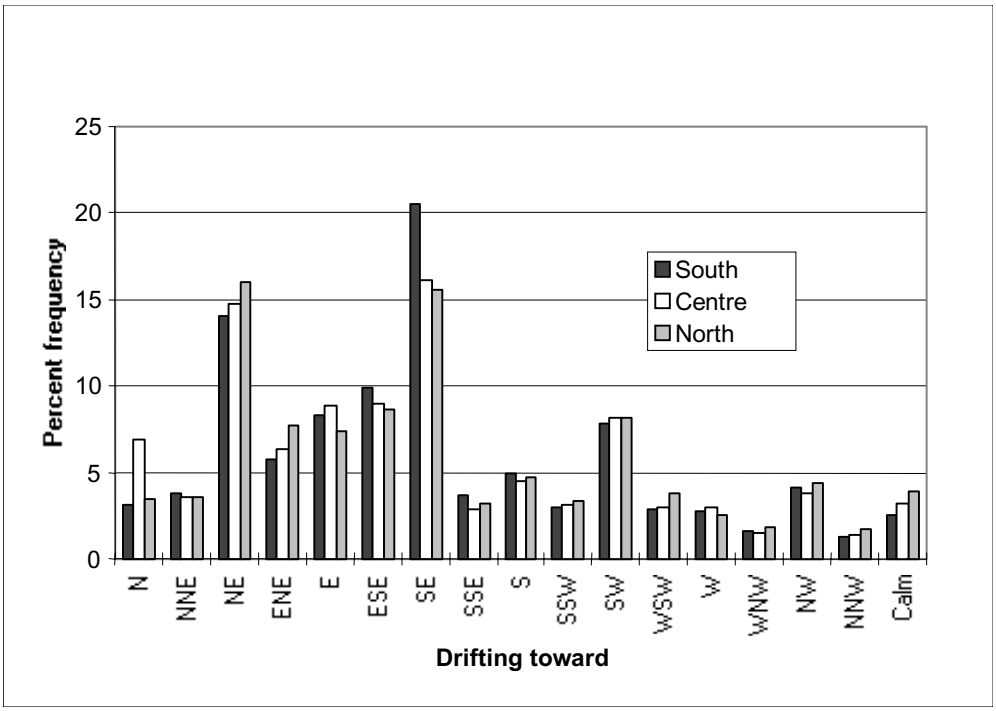

Figure 2-15: Percent frequency of ice drift direction at three areas along the West Coast of Newfoundland

The drift direction by speed statistics show no evident directional preference for the ice displacement classes. Data were reviewed for all three geographical areas of study (North, Central, and South), and all three show a similar overall division of drift magnitudes as shown for the Central region, with roughly half the observations falling in the 0.13 to 0.02 m/s range, one-quarter falling in the 0.02 to 0.1 m/s range, and one-fifth falling in the 0.23 to 0.32 m/s range. Less than five percent of drift forecasts, in any area, exceeded 0.32 m/s. The average residual drift rate was 0.14 m/s over 24 hours. No information is available on the instantaneous drift rate.

Table 8 presents a summary of offshore and onshore drift, based on the drift forecast vectors extracted from 12 years of daily ice charts. In constructing Table 8, onshore directions were assumed to be those clockwise from east-northeast (ENE) to south (S) inclusive. The offshore drift sector was taken to be directions running clockwise from west-southwest (WSW) to north (N) inclusive. The remaining directions are considered to be neither onshore nor offshore drift sectors. The recorded drift vectors for the three coastal areas repeat the pattern shown in Figure 2-15 for the region as a whole, i.e. onshore drift approximately half the time and offshore drift less than one-fifth of the time. There is a slight increase in frequency of offshore drift as one proceeds north along the coast. This is in agreement with the trend of increasing incidence of shore lead episodes to the northern end of the coast (see section 3.8, below).

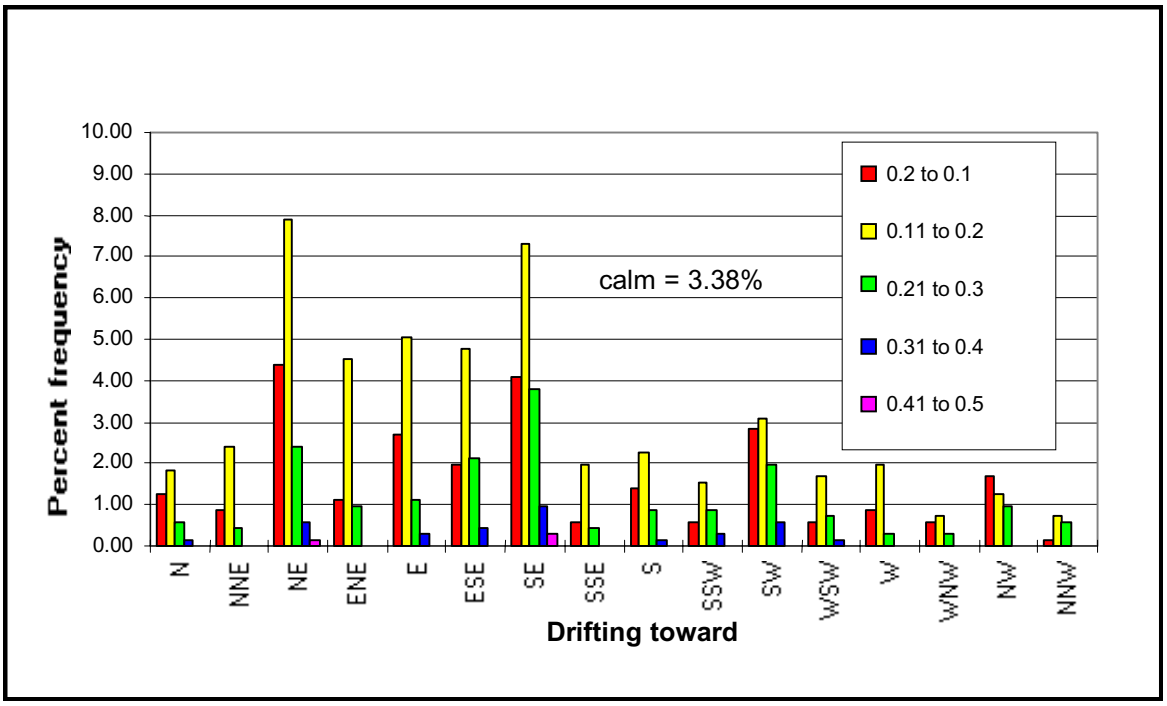

Figure 2-16: Percentage directional frequency of ice drift by displacement, in m/s, Central coastal area.

Naut mi/day:	calm	1 to 5	6 to 10	11 to 15	16 to 20	21 to 25	Totals
N		1.27	1.83	0.56	0.14	0.00	3.80
NNE		0.84	2.39	0.42	0.00	0.00	3.66
NE		4.36	7.88	2.39	0.56	0.14	15.33
ENE		1.13	4.50	0.98	0.00	0.00	6.61
E		2.67	5.06	1.13	0.28	0.00	9.14
ESE		1.97	4.78	2.11	0.42	0.00	9.28
SE		4.08	7.31	3.80	0.98	0.28	16.46
SSE		0.56	1.97	0.42	0.00	0.00	2.95
S		1.41	2.25	0.84	0.14	0.00	4.64
SSW		0.56	1.55	0.84	0.28	0.00	3.23
SW		2.81	3.09	1.97	0.56	0.00	8.44
WSW		0.56	1.69	0.70	0.14	0.00	3.09
W		0.84	1.97	0.28	0.00	0.00	3.09
WNW		0.56	0.70	0.28	0.00	0.00	1.55
NW		1.69	1.27	0.98	0.00	0.00	3.94
NNW		0.14	0.70	0.56	0.00	0.00	1.41
calm	3.38	0.00	0.00	0.00	0.00	0.00	3.38
Totals:	3.38	25.46	48.95	18.28	3.52	0.42	100.00

Table 7: Percentage directional frequency of ice drift by displacement in nautical miles/day, Central coastal area.

Coastal area	Offshore	Onshore	Parallel	No drift
South	16 %	53 %	29 %	2.5 %
Central	17 %	49 %	31 %	3.4 %
North	18 %	47 %	31 %	3.8 %

Table 8: Proportion of offshore and onshore ice drift along the West Coast of Newfoundland.

Figure 2-17 shows the percentage exceedence frequencies of the forecast ice drift rates taken from 12 years of daily ice charts. The exceedence frequency distribution is very similar for the three coastal areas, reflecting the regional nature of ice drift.

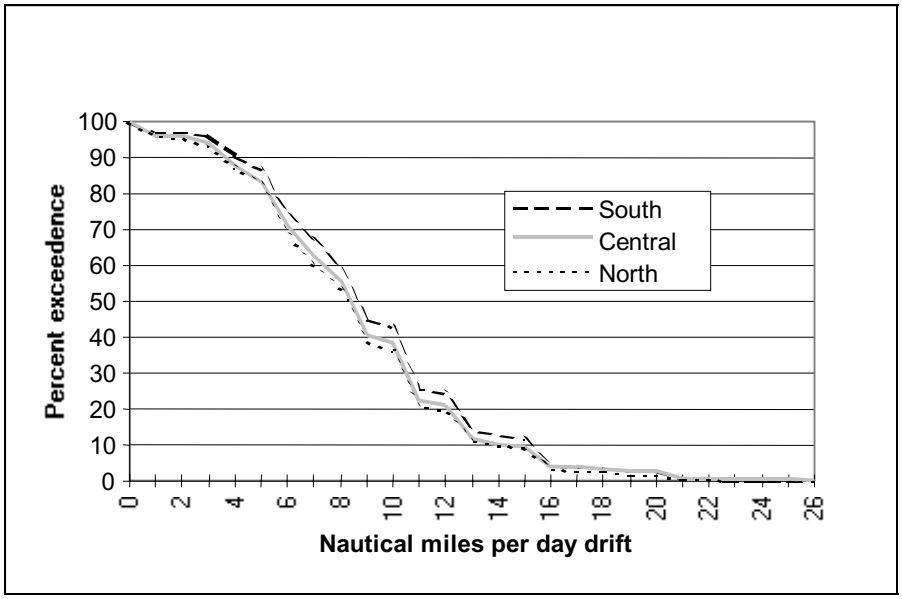

Figure 2-17: Exceedence frequency of ice drift rates at three coastal areas along the West Coast of Newfoundland.

2.9 Icebergs

2.9.1 General

Iceberg information was obtained from two sources; Coretech Inc. and AES. Table 9 lists the number of icebergs from 1960 to 1977 (from Coretech Inc.) and 1985 to 1994 (from AES) for six zones along the coast (see Figure 2-18). Coretech data came from the International Ice Patrol, who flew over the northern part of the area prior to 1977. The AES data came from the micro-film of daily ice charts. AES also have daily iceberg charts; these were not reviewed.

We assume that the mean number of icebergs in a given area is the mean of the mean number of icebergs observed per flight in that area. We assume that this is the mean number of icebergs in the area every day during the "iceberg period", typically April to June, inclusive. As noted in the Table, the majority of icebergs in the area are generally growlers. Impact probability calculations have been carried out including and excluding growlers. These calculations are probably conservative, as each flight indicates the number of icebergs seen on the particular day, and when no icebergs are reported, there were presumably no icebergs on that day or days.

Year	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Bergs(flights)
1960	13g32s0m1l(5)	2g6s(2)		1g(1)			46
1961			2m(1)			1m(1)	3
1962		1s(1)	3g(2)	1g2s1m(3)	2g (2)	1g2s1l(3)	13
1963	1g(1)						1
1965		2l(2)	10l(3)				12
1967	1g(1)	1s(1)					2
1968		2m(1)			3g1s3m1l(3)	2s8m(3)	20
1970					1g (1)		1
1972	1g(1)						1
1973					1s/1		1
1977					1g2s2m1l(3)	2g4s1m2l(4)	14
1985			1u(8)	0(8)	1s1m32u(8)	20s1m(8)	56(8)
1986					0		0
1987			1u(4)	0(4)	18u(4)	0(4)	19(4)
1988					0(1)	5u(1)	5(1)
1989					0		0
1990					0		0
1991				22u(2)	0(2)	0(4)	22(4)
1992					16u(4)	2u(4)	18(4)
1993					0(3)	0(3)	0(3)
1994					0		0
Average number of bergs in zone	0.44	0.32	0.26	0.56	0.74	0.57	Including growlers
Average number of bergs in zone	0.23	0.29	0.20	0.43	0.62	0.54	Excluding growlers
Average number of large bergs in zone	0.001	0.05	0.14	0.016	0.03	0.04	Large icebergs only
Area of Zone	3930	1960	5880	7830	4700	7830	km^2

Table 9: Listing of Iceberg sightings in the zones indicated in Figure 2-18. The symbols are explained in the text.

In above table, g = growler (< 15 m in length), s = small iceberg (15 to 60 m), m = medium iceberg (61 to 122 m), an l = large iceberg (123 to 213m), u = unknown. Number indicates the numbers in each category. Number in brackets is the number of flights. Above iceberg sizes are according to International Iceberg Patrol Classification.

We are concerned about the high numbers of icebergs in Zone 1 and 2 in the Coretech Inc. data. The daily ice charts and other information (C. Langford, private communication) indicate that the icebergs enter the area via the Strait of Belle Isle, and generally stay to the north along the coast of Quebec. The AES daily ice charts indicate decreasing numbers of icebergs as one progresses south, and none south of Bay of Islands. It is unlikely that icebergs would enter the area via the Cabot Strait, as the major current is to the south. Calculations are provided for zone 1, but the results are questionable, and more work should be done in this area, if this is considered to be a problem.

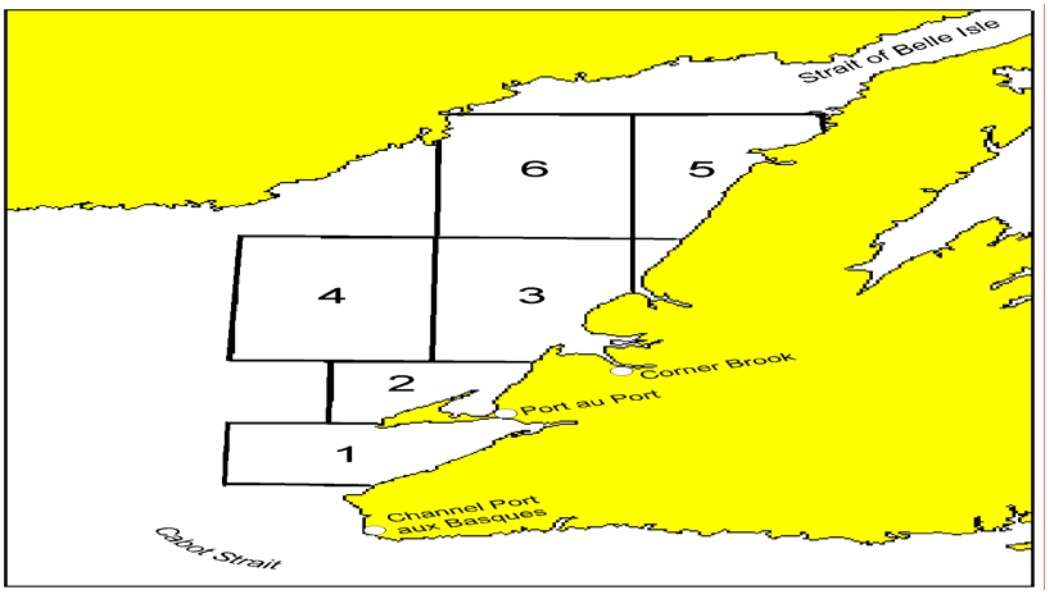

Figure 2-18: Locations of the six iceberg observation zones

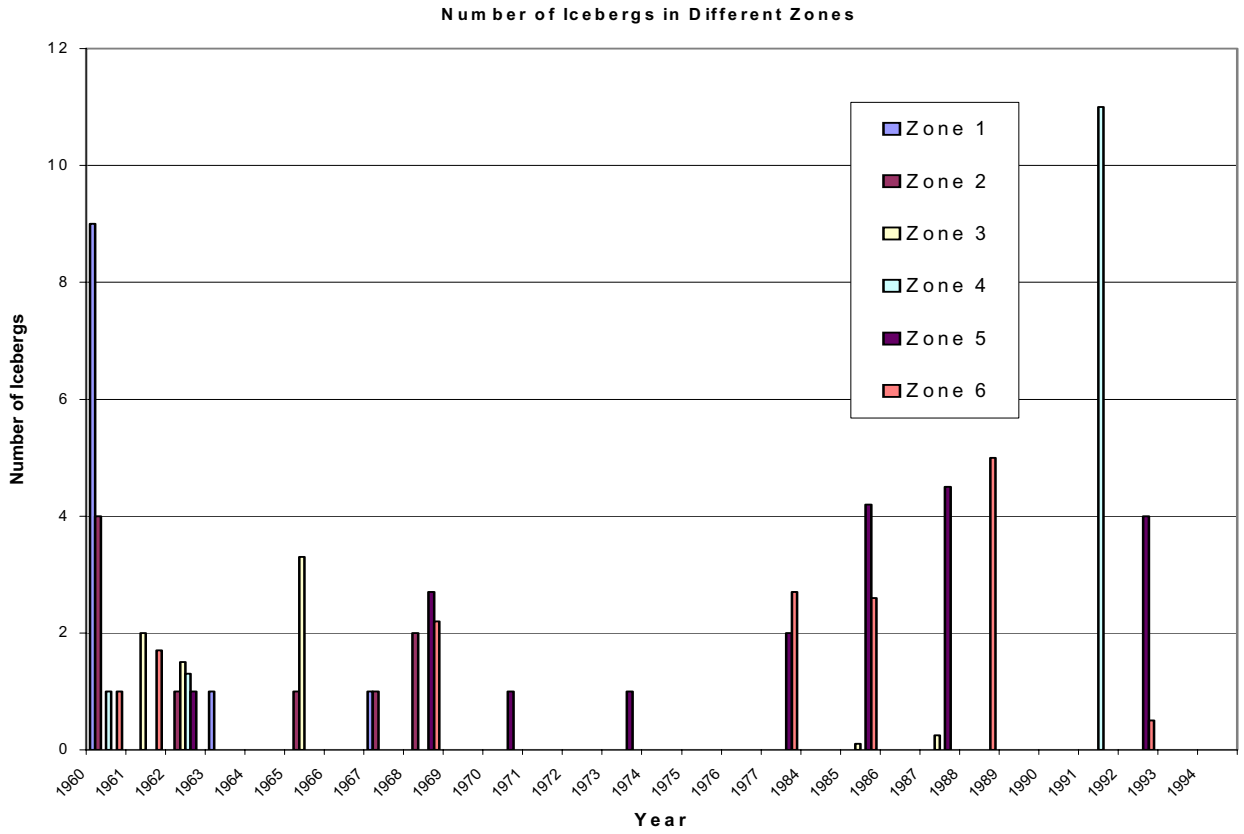

Figure 2-19: Iceberg observations off the West Coast of Newfoundland, 1960 to 1977 and 1984 to 1994, by year

2.9.2 Iceberg Impact Rate

We can use the iceberg data given in Table 9 to calculate the impact probability of icebergs with an offshore structure.

Based on Sanderson (1988, page 220) the probability of iceberg impact with a fixed structure is:

$$P = \frac{n \; v \; (d + D) \; T}{A}$$

where n is the number of icebergs in the area A
A is the area of the zone (km^2)
T is the time during which icebergs are in the area
d is the iceberg diameter (as most bergs are small, assume d = 60 m)
D is the diameter of the drilling or production structure (assume D = 100 m)
v is the average drift speed (assume v = 0.14 m/s, see section 2.5)

A review of the AES ice charts indicated icebergs reside in the north east Gulf of St. Lawrence from about ½ month (May - early June) to 5 months (May to October) with an average of 2 ½ months; hence T = 2 ½ months.

For example, for Zone 5, the number of icebergs, including growlers, is 0.74, and therefore the impact probability is:

$$P = 0.74 \frac{x\ 0.14\ (100 + 60)\ x\ (3600 \times 24 \times 30 \times 2.5)}{4700 * 10^6}$$

$$P = 0.023 \text{ per year}$$

For the four zones along the coast, the iceberg impact probabilities are:

Zone 5			
Situation	**Iceberg Density in zone**	**Annual Impact Probability**	**Impact Probability in 25 years**
With growlers	0.74	0.023	44 %
Without growlers	0.62	0.02	38 %
Large icebergs	0.03	0.002	4 %
Zone 3			
With growlers	0.26	0.006	15 %
Without growlers	0.2	0.005	11 %
Large icebergs	0.14	0.006	15 %
Zone 2			
With growlers	0.32	0.024	45 %
Without growlers	0.29	0.021	42 %
Large icebergs	0.05	0.007	16 %
Zone 1			
With growlers	0.44	0.016	34 %
Without growlers	0.23	0.008	19 %
Large icebergs	0.001	0.00007	0.2 %

Table 10: Iceberg impact Probabilities for 4 zones along the West Coast of Newfoundland over the 25 year life of a structure.

2.10 Leads and Polynya

An annual recurring feature in the ice cover off the West Coast of Newfoundland is a shore lead, which may appear at any time throughout the winter. Eight complete years of daily ice charts were examined in compiling the summary data in Table 11. In analyzing the ice charts, a lead was defined as a reduction of local ice concentration to 3-tenths or less following the date of local freeze-over (see 4.2, above). The early season pattern of ice formation seaward from the Quebec shore results in an open water condition along the Newfoundland coast prior to freeze-over of that region. These early season lead-like conditions were not counted in compiling shore lead statistics. When leads were present, widths were measured along three fixed lines extending west-northwesterly from three point along the Newfoundland coast. These three points were Daniel's Harbour (representing the northern coastal area), Guernsey Island at the mouth of the Bay of Islands (representing the central coastal area), and the intersection of west longitude 59° with the shore of St. George's Bay (representing the southern coastal area) - see map in back pocket of report.

	Southern section	**Central section**	**Northern section**
Days of lead, total	175	218	269
Mean days of lead per season	22	27	34
Maximum duration of lead	13 days	56 days*	36 days*
Minimum duration of lead	1 day	1 day	1 day
Mean lead episodes per season	7	6	7.5

* Occurred in final lead episode of season.

Table 11: General statistics on shore lead occurrence and duration at three locations along the West Coast of Newfoundland.

The number of days in a season in which a lead occurs increases from south to north along the coast. This is consistent with the overall ice regime (see 4.1), and is a result of the more northerly regions experiencing ice cover for a longer period, and hence there is a longer period during which a lead can form. Extremely long periods of uninterrupted shore lead conditions are noted in the maximum duration values for the central and northern coast areas. In both cases, a lead formed in higher concentration ice and ultimately closed back in on the coast again or otherwise experienced compression sufficient to increase ice concentration beyond 3-tenths. In both cases, this period of lead closing was of brief duration just prior to final ice clearance at the end of the season.

Figure 2-20 shows the percentage exceedence of duration of lead occurrence at three areas along the coast. This shows the number of consecutive days during which lead conditions (3-tenths of ice concentration or less) prevail.

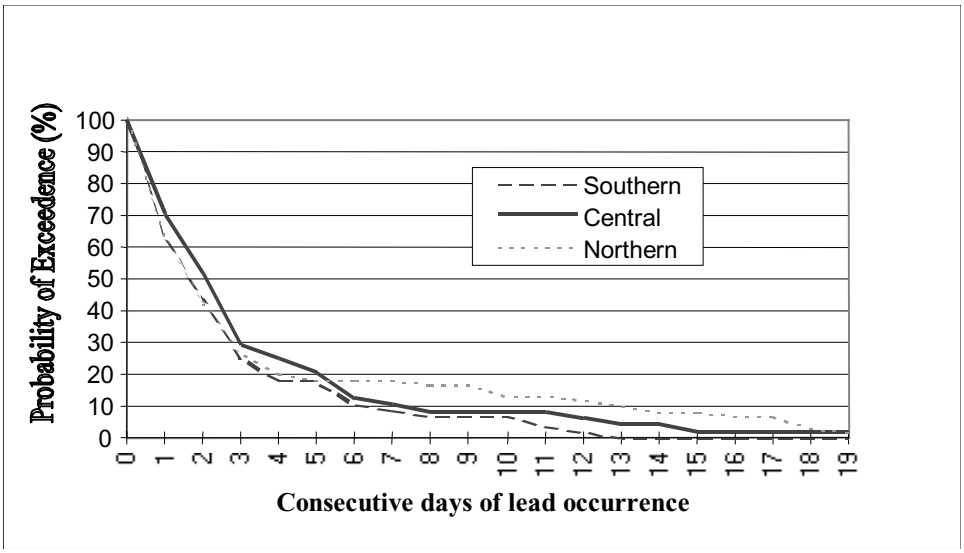

Figure 2-20: Percentage exceedence frequency of duration of shore lead conditions, for ice on West Coast of Newfoundland.

2.11 Ice Properties

The physical and mechanical properties of the ice cover are important, since they influence the ice forces that are experienced by fixed offshore structures and vessels. Design ice loads for terminal structures depend on the thickness and geometry of the ice features that may be encountered, and also on the mechanical and physical properties of the ice. Similarly, the performance of tankers and ice management vessels that operate at each terminal location will be affected by the range of ice conditions encountered, including ice properties such as flexural strengths, ice densities, and ice/hull friction coefficients. The normal and extreme loads that tanker mooring systems experience during oil loading operations will also depend on some of these ice properties.

2.11.1 Ice Temperature

No actual ice temperature measurements are available for the area of interest, as far as we know. Ice temperatures can be calculated from the ambient air temperature for different ice and snow thicknesses, assuming thermal equilibrium though the ice, which is a reasonable assumption (Cammaert and Muggeridge, 1988). If we take the Corner Brook air temperatures and snow and ice thicknesses, we get the following:

Month	Ice thick-ness (cm)	Snow thickness (cm)	Mean Air Temp (°C)	Mean Ice Core Temp (°C)	Minimum Air temp (°C)	Minimum Ice Surface Temp (no snow) (°C)	Minimum Ice Core Temp (°C)
Feb	22.3	13.4	-8	-2.2	-35	-25	-13.5
March	35.6	13.5	-5	-2.0	-30	-22	-12
April	39.3	13.5	0	-1.5	-18	-15	-8.5

Table 12: Sea ice temperatures for ice at about 48° north latitude, on the West Coast of Newfoundland.

The Mean Core Ice Temperatures given above indicate the temperatures in the centre of the ice for the Mean Air Temperatures corresponding to offshore locations in the vicinity of Corner Brook, with a snow cover similar to that at Corner Brook. The Minimum Core Ice Temperatures are the temperatures in the centre of the ice for the minimum air temperatures, without snow. The temperature profile through the ice is assumed to be linear, varying from a minimum temperature at the snow surface similar to the persistent air temperatures (using relationship given in Timco and Frederking, 1989) to a maximum temperature of -1.8°C at the bottom of the solid ice (i.e. the freezing point of sea water).

It is recommended that the minimum core ice temperature values given in Table 12 should be used for any analyses.

The above Table provides best estimates of level ice temperatures based on available inshore data. If more accurate offshore ice temperatures are required and temperatures within ridge consolidation layers, then direct on-ice measurements should be carried out.

2.11.2 Salinity

Again, no actual measurements are available on the ice salinity. Cammaert and Muggeridge (1988) indicate that the ice salinity is proportional to the parent water salinity and to the rate of ice formation. As the water salinity in the area is 30 to 33 ppt, about 10 % less than the typical value of 34.5 ppt in other areas, and the rate of freezing is lower than in the Arctic, then the resulting ice salinity is expected to be lower than the Arctic by about 10%. The ice salinity varies with depth, being higher at the surface where the freezing rate is highest. Figure 2-21 shows the bulk salinity of first year sea ice from Kovacs, (1996).

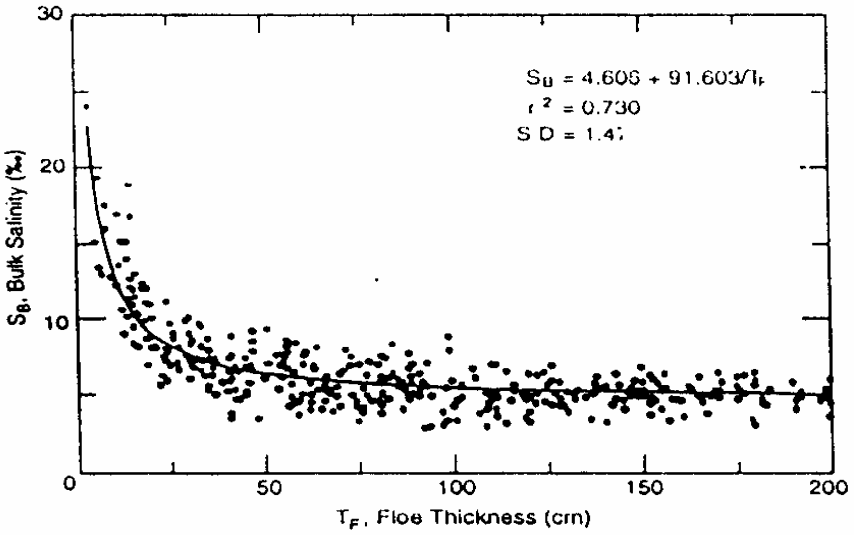

Figure 2-21: Bulk Salinity versus ice thickness in first year ice

The bulk ice salinity ranges shown in Figure 2-21 have been combined with the ice thickness data given in section 4.3, to estimate salinity values for the area of interest.

Langleben (1959; reported in Timco, 1994) made density and salinity measurements at Shippegan, New Brunswick, which is in the Gulf of St. Lawrence but closer to the river estuary. At this location the salinity decreases to 28 ppt (min 24 ppt) in the summer, but just prior to freeze-up in January and February, the water salinity near Shippegan rises to 31 ppt, which is similar to that in the area of interest. Hence Langleben's ice salinity and density measurements (Figure 2-22) can be used here as no other direct measurements are available, see Table 13.

Ice Thickness (cm)	Bulk Salinity (ppt)
50	5.5 ± 2
100	4.5 ± 2

Table 13: Bulk salinities for two different ice thicknesses for ice on the West Coast of Newfoundland.

Lower salinities may occur due to rain and brine drainage during warm periods.

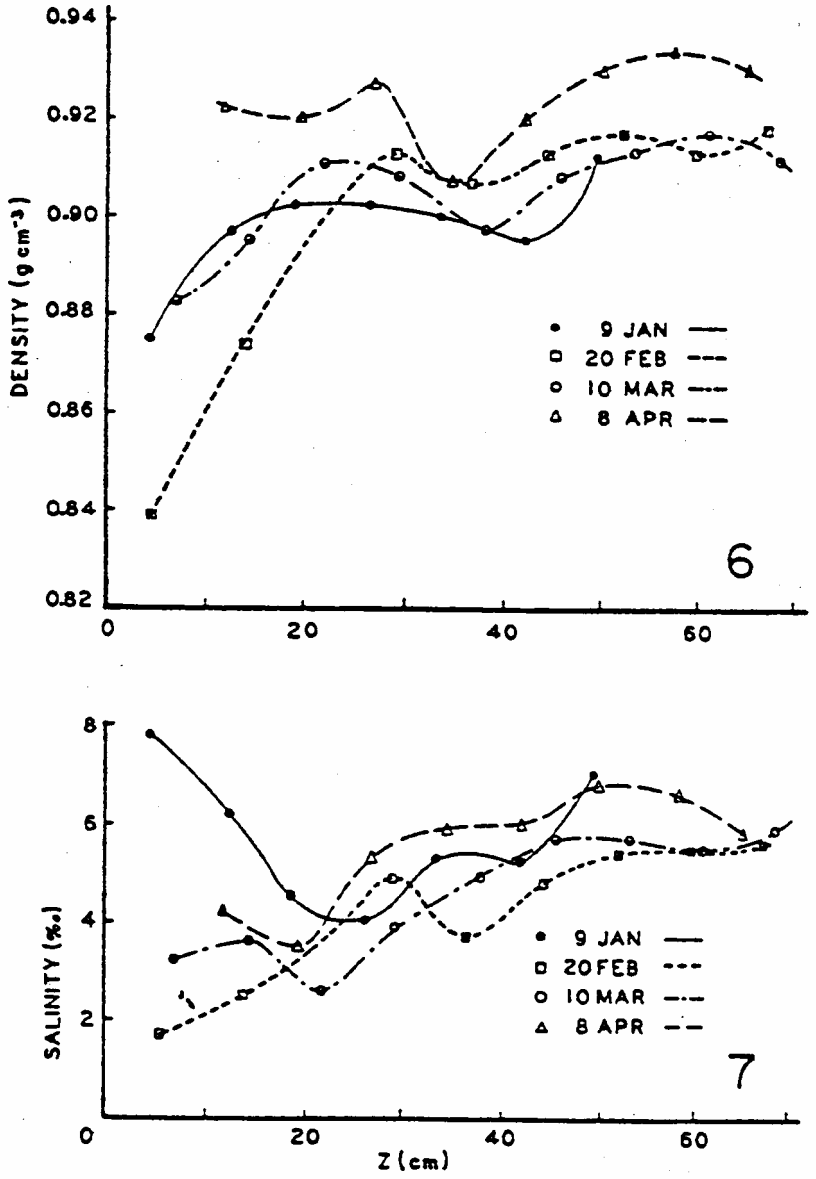

Figure 2-22: Salinity and density measurements from Langleben (1959) for Shippegan, N.B.

2.11.3 Density

No actual measurements of ice density are available for the area of interest. The density of level ice and of the consolidated layer in ridges varies depending upon the presence of snow ice, the amount of entrapped air, the ice temperature, salinity, crystallography and the method of measurement. Timco (1994) discusses all these factors and reported that a mean density of 0.91 Mg-m^{-3}, with a range from 0.78 to 0.94 Mg-m^{-3} covered the values measured by a number of authors. Langleben's measurements shown in Figure 2-22, which were in-situ and hence with minimal brine drainage, indicated densities of 0.84 to 0.92 at the ice surface, and 0.90 to 0.92 below 20 cm, for measurements made between early January and early April. It is important to recognize that for engineering applications, the in-situ ice density is the value of most importance. Due to brine drainage, many of the reported ice density field measurements underestimate the correct in-situ ice density value. Table 14 summarizes the recommended ice density values to employ.

Level Ice	
Month	**Density (Mg-g^{-3})**
All months	0.84 to 0.94
Consolidated Layer	
All months	0.84 to 0.94

Table 14: Recommended ice density values for ice on the West Coast of Newfoundland.

2.11.4 Ice Flexural Strength

There is no field data for the flexural strength of ice in the area of interest here. Flexural strength values can be estimated from Timco and O'Brien (1994).

Brine volume can be obtained from

$$\nu_b = S\,(49.185/\,|T|\, +\, 0.532)$$

where S is salinity in ppt (parts per thousand)
T is the ice temperature (°C)
ν_b is the brine volume in ppt

The flexural strength is then given by (Timco and O'Brien, 1994)

$$\sigma_f = 1.76 \exp(-5.88 \sqrt{\nu_b}/1000) \quad \text{MPa}$$

Month	Snow Thickness (cm)	Ice Thickness (cm)	Average Flexural Strength (kPa)	Maximum Flexural Strength (kPa)
Feb	13	22	134	310
Mar	13	36	164	416
Apr	13	39	77	419
Feb	0	100	388	672
Feb	0	120	225	

Table 15: Calculated flexural strength values for ice on the West Coast of Newfoundland.

The average flexural strengths are based on average air temperatures and the maximum flexural strengths are based on extreme low air temperatures with and without a snow layer.

2.11.5 Ice Compressive Strength

There is no field data for the compressive strength of sea ice in the area of interest. Compressive strength values have been estimated from Timco and Frederking (1994), and are provided in Table 16. These values are based on small scale tests, but the above authors indicate that there is good agreement with large scale tests if the small scale values are averaged over the thickness of the ice sheet, taking into account the salinity and temperature at the different depths in the ice. The mean values are based on the mean monthly air temperatures; the range being the situations with and without snow on the ice surface. The maximum values are based on the minimum air temperatures quoted in Table 12, and again the range is with and without snow. The mean temperatures in April (and March for vertical loading) are too high to obtain reasonable strength values based on the equations used.

Timco and Frederking (1994) provide three equations to calculate the compressive strengths of ice depending on the loading direction and ice crystal structure, viz.:

Horizontally loaded columnar ice $\sigma_{ch} = 37 (\dot{\varepsilon})^{0.22} [1 - (\nu_T /270)^{0.5}]$

Vertically loaded columnar ice $\sigma_{cv} = 160 (\dot{\varepsilon})^{0.22} [1 - (\nu_T /200)^{0.5}]$

Granular Ice $\sigma_{cg} = 49 (\dot{\varepsilon})^{0.22} [1 - (\nu_T /280)^{0.5}]$

where

$\dot{\varepsilon}$ = strain rate (from 10^{-7} to 10^{-4})
ν_T = total porosity = $\nu_b + \nu_{gas}$
ν_b = $S (49.185/|T| + 0.532)$
ν_{gas} = gas volume, typically 5‰, (Sanderson, 1988)
S = ice salinity (‰)
T = ice temperature (°C)

Horizontally-Loaded Columnar Ice (MPa)		
Month	**Mean**	**Maximum**
Jan	1 - 2.6	3.2
Feb	1 - 2.7	3.2
March	1 - 2.5	3.1
April	* -1.6	2.8
Vertically Loaded Columnar Ice (MPa)		
Jan	6 - 11	12
Feb	6 - 11	12
March	* - 9	12
April	* - 4	11
Granular Ice (MPa)		
Jan	2.5 - 3.5	4.3
Feb	2.5 - 3.7	4.2
March	0.9 - 3.3	4.1
April	* - 2.2	3.8

Table 16: Uniaxial compressive ice strength values based on analysis of small scale tests

Compressive strengths values were calculated for fixed levels through the ice and averaged for the entire ice thickness. The ranges given are based on the air temperature range; the Mean being based on the annual mean maximum and minimum temperatures, and the Maximum being based on the extreme minimum temperature measured, indicated in Table 12.

2.12 Other Ice Data Not Used in this Study

For the benefit of the reader who wishes to carry out further analyses of the ice condition off the West Coast of Newfoundland, this section summarizes the other available ice data, which were not used in the current project.

1. **NOAA and other satellite data**. These data have a resolution of 1 to 4 km, hence they show little detail of the ice surface, only ice edges and larger floes (no ridges or surface features). These data are available from 1975 to the present and usable images are available on consecutive days in several periods. Cloud cover does however limit the number of usable images to less than half the total number available.

These data are stored in boxes by month and year, at AES offices in Ottawa, but are not sorted by area, hence one has to sort through a large number of images to find the ones which might be of interest. Image quality is good in most cases. No NOAA or satellite data were obtained for this project, due to the availability of the daily ice charts and SAR data, which provide more detailed information.

2. **St George's Bay Ice Grid Point Data.** This data set, available from AES, contains the ice concentration in a grid within St George's Bay. The data set is obtained from the AES composite ice charts and covers the period from 1982 to the present.

3. **Bedford Institute of Oceanography Ice Database.** These are digitised data from the AES weekly composite Ice charts (see 2 above) for a grid of ½° Latitude and 1° Longitude in the area of interest. The data cover the period from 1986 to 1995, and are available free of charge from BIO.

4. **AES Grided Ice Data.** These data are again based on the AES weekly composite ice charts from 1962 to 1984. Data were digitised on a ¼° latitude by 1° longitude grid, and are available for 10¢ a point. These data were not purchased for this study in light of the other sources of data available from AES.

5. **Soft Copy Ice Maps**: Many of the ice maps are available on floppy disk in GIF format, via the AES CIDAS. The reader is referred to the AES document CIDAS HOLDINGS, which is available from AES Client Services in Ottawa.

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3. CLIMATE

3.1 General

The following descriptions for climatic conditions for the area of interest are based on climate statistics contained in the Environment Canada publication "Canadian Climate Normals 1961-90 for the Atlantic Provinces".

3.2 Temperature

Temperature plots for Daily Maximum, Minimum, Mean and Extreme Minimum are presented in Figure 3-1 and Figure 3-2 for Daniel's Harbour and Stephenville. These two sites were chosen as representing the north and south boundary conditions for the area of interest. Maximum temperatures for both sites occurs in July and are 20.0 °C for Stephenville and 17.6 °C for Daniel's Harbour, minimum temperatures are -11.3 °C and -12.9 °C respectively in February. Extreme minima are -29.5 °C in February for Stephenville and -39.4 °C for Daniel's Harbour in January.

Offshore air temperatures may be moderated by up to 4 degrees during the winter in calm conditions, due to the presence of open water between the ice.

3.3 Winds

Wind statistics extracted from the Transport Canada Wind and Wave Climate Atlas, Vol. II, for the Gulf of St. Lawrence are shown in Figure 3-3 to Figure 3-5. AES (1993) indicates that the most predominant winds at Daniel's Harbour are from the southwest with an average speed of 24 km/hr and maximum hourly speeds up to 132 km/h from the southwest. At Stephenville the average winds are 18 km/hr from the west with maximum hourly speeds up to 93 km/h from the southeast. Gusts are up to 140 to 150 km/hr from the south and southwest.

The percentage exceedence winds are indicated in Figure 3-3 and summarized in Table 17.

Percentage Exceedence (%)	Wind Speed m/s
80	5.1 (10 kt)
50	8.7 (17 kt)
20	12.7 (25 kt)

Table 17: Percentage exceedence winds for the West Coast of Newfoundland

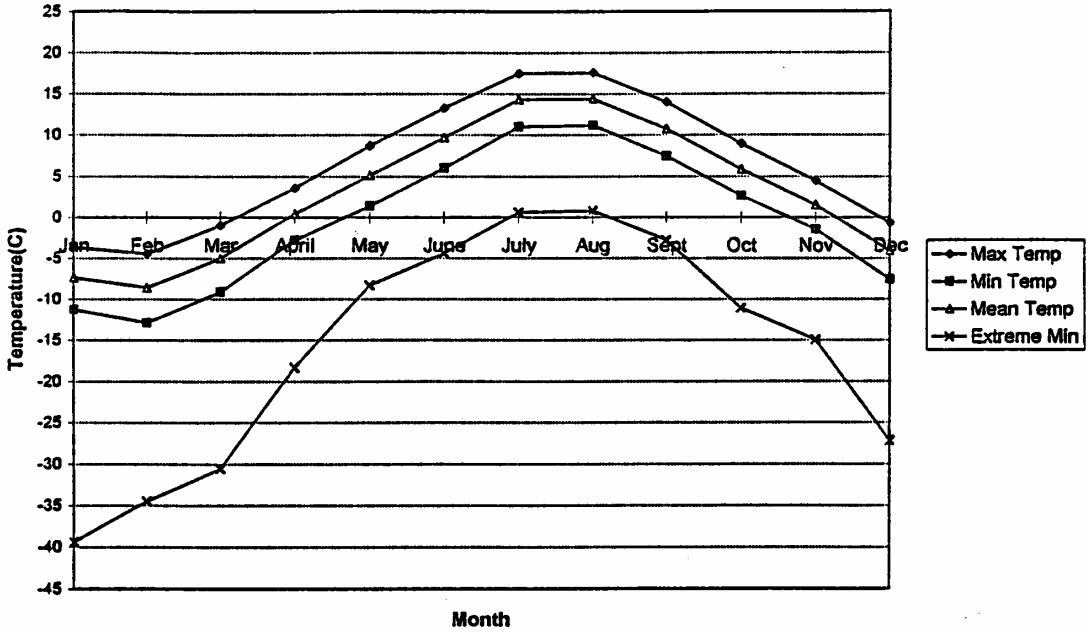


Figure 3-1: Daily Temperature Statistics for Daniel's Harbour

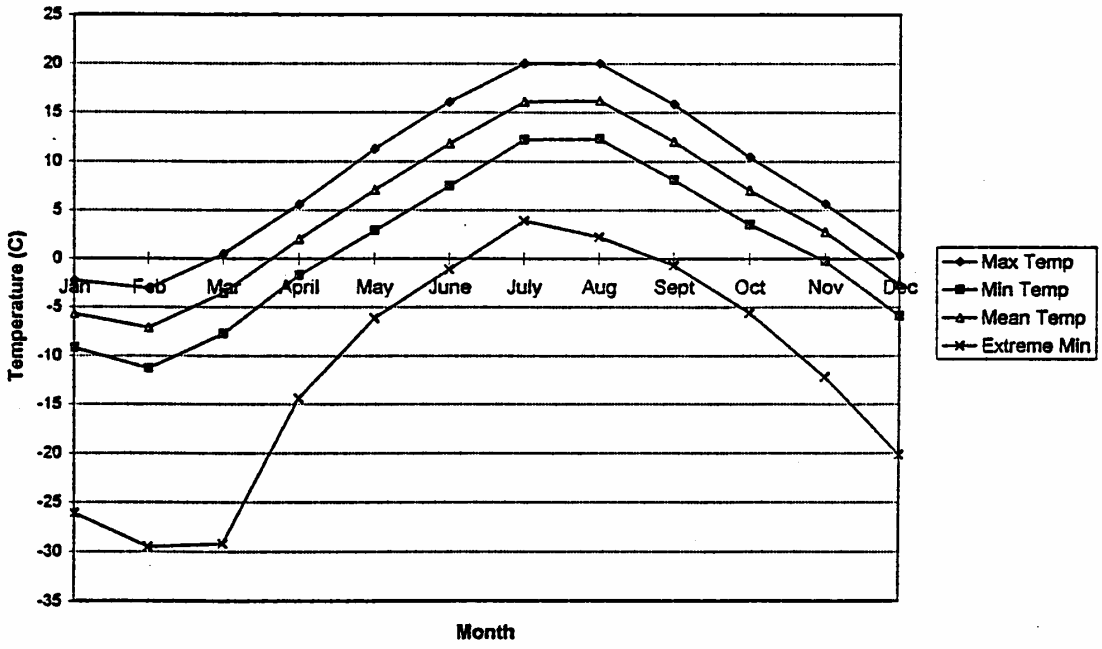


Figure 3-2: Daily Temperature Statistics for Stephenville

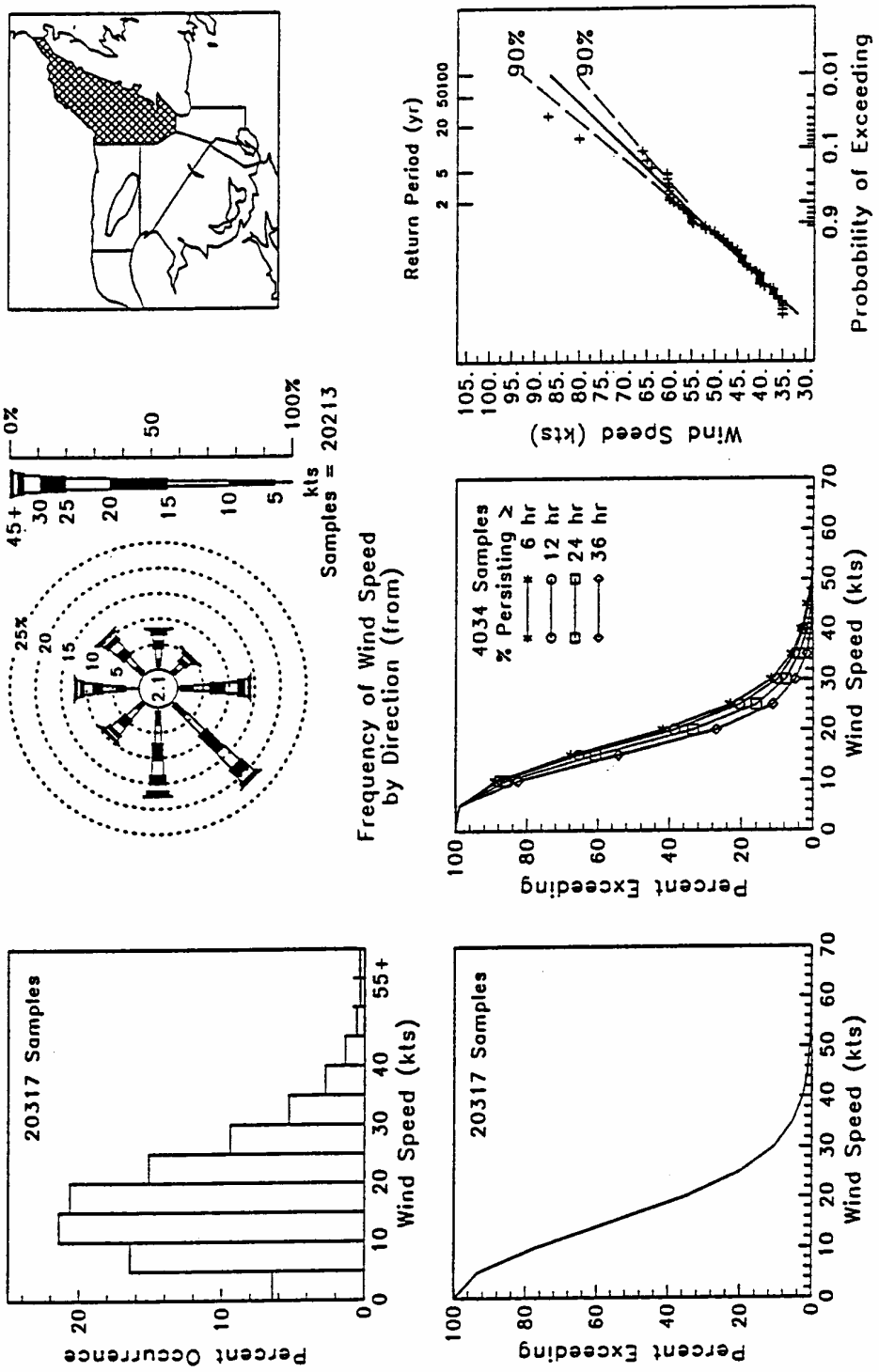


Figure 3-3: Annual Wind Statistics for NE Gulf of St. Lawrence

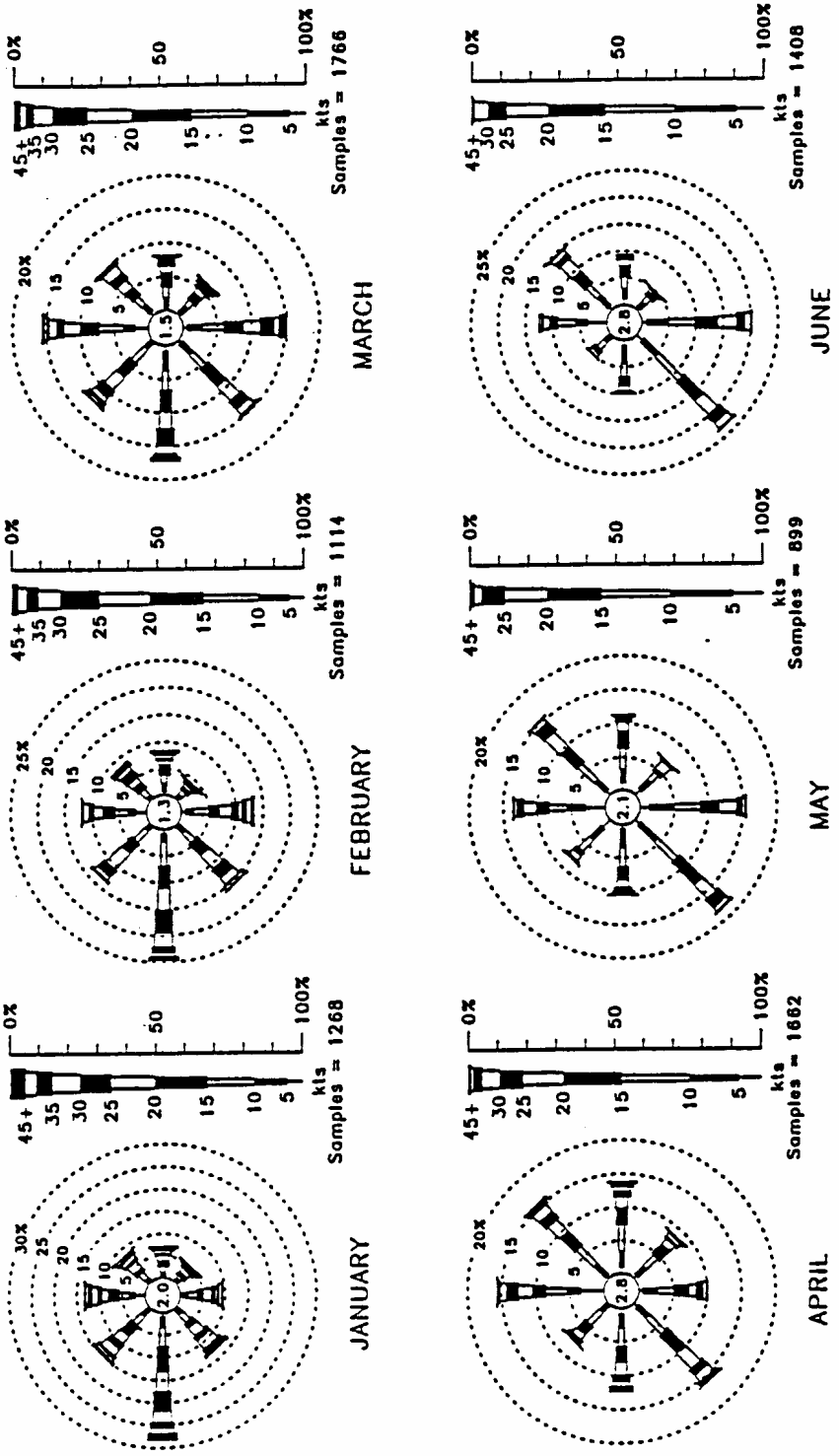


Figure 3-4: Monthly Wind Direction Statistics

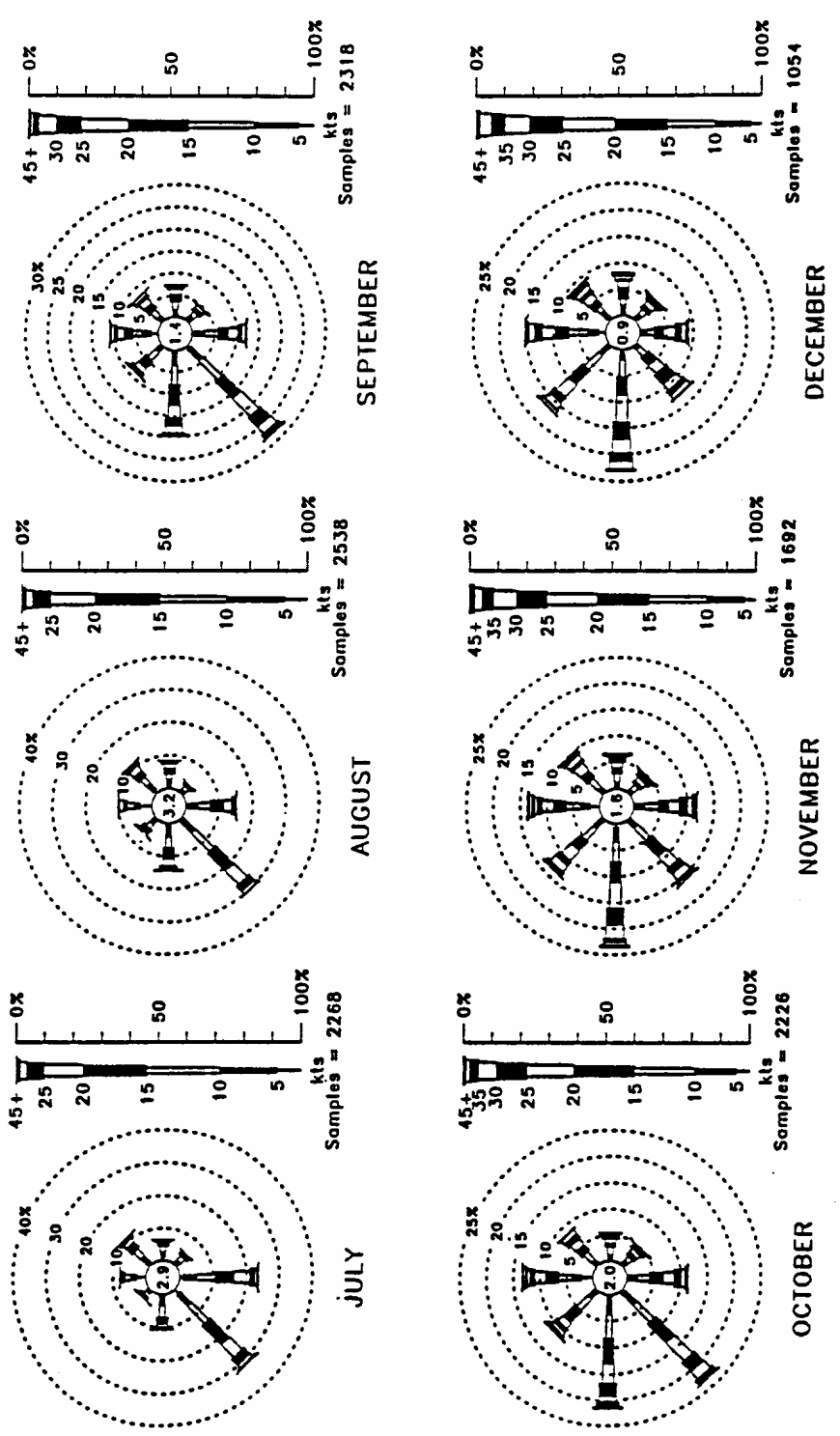


Figure 3-5: Monthly Wind Direction Statistics

Figure 3-3 also shows the percentage winds exceeding 6 to 36 hours.

The extreme winds are indicated in Table 18 below.

Return Period (years)	Wind Speed (m/s)
2	29 (57 kt)
20	38 (75 kt)
100	43 (85 kt)

Table 18: Extreme winds on West Coast of Newfoundland

Figure 3-3 to Figure 3-5 indicate the monthly wind direction statistics. They indicate that the winds come from all directions but with a slight preference to the south west.

3.4 Precipitation

Stephenville experiences a monthly maximum of 26 days of measurable precipitation (rain or snow) in January and a monthly minimum of 14 such days in May and June. There is a total of 217 days of precipitation during the year. There is a total of 1272 mm of precipitation, of which 940 mm is in the form of rain and 411 in the form of snow.

At Daniel's Harbour, the maximum number of days of measurable precipitation, 24 days/month, occurs in January and the minimum of 13 days per month in May. The spring and fall are the worst seasons for measurable precipitation of both varieties. A total of 1137 mm of precipitation falls in Daniel's Harbour throughout the year, of which 757 mm is in the form of rain and 426 mm is in the form of snow.

3.5 Visibility

Stephenville experiences, typically, a maximum of 1 day of fog in December, 6 days of fog in both June and July, and a total of 39 days of fog per year. Daniels Harbour experiences, typically, a maximum of 1 day of fog in both December and March, 8 days in both June and July, and a total of 38 days of fog annually.

4. OCEANOGRAPHY

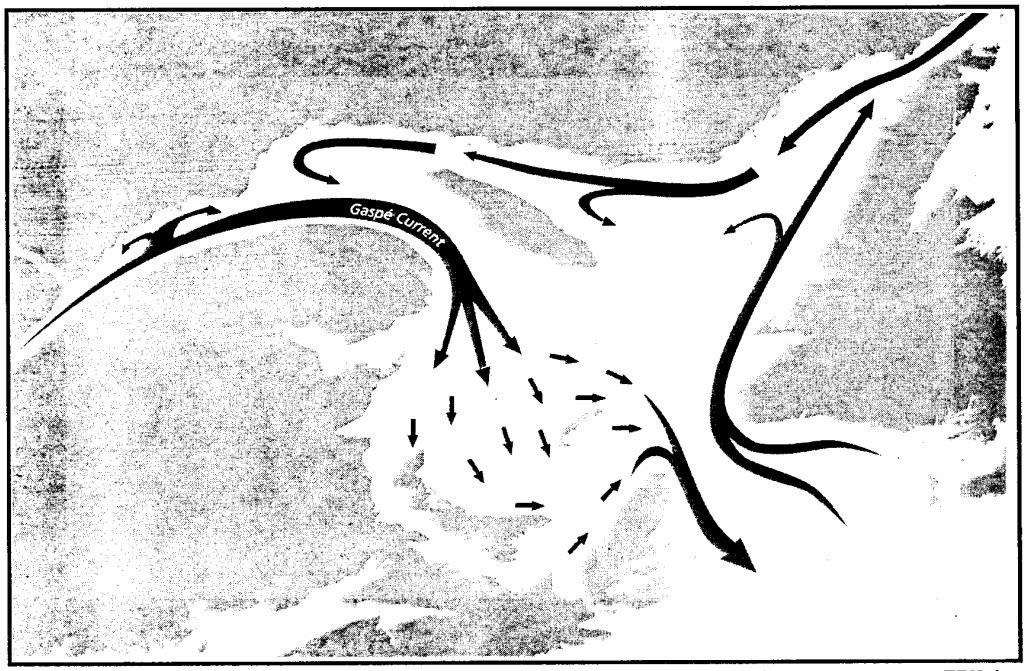
4.1 General

This chapter summarizes the oceanographic data available for the area of interest. The Gulf of St. Lawrence in some ways acts like a large estuary which has some characteristics which are more typical of an enclosed sea. The forces that act on the marine waters of the Gulf are the inflow of fresh water, exchanges of heat between the atmosphere and the surface waters, winds and tides. These forces undergo daily, seasonal and annual fluctuations, and they determine the vertical and horizontal characteristics of the waters, the occurrence of sea ice and prevailing water currents.

4.2 Water Exchange

The St. Lawrence estuary is a complex system receiving large inflows of both fresh water and sea water. The fresh water originates from an extensive drainage basin which is about nine times the area of the Gulf itself. Sea water flows into the Gulf from the Atlantic ocean through the Cabot Strait and to a lesser extent, the Strait of Belle Isle.

Figure 4-1 shows the dominant horizontal surface circulation in the Gulf. The St. Lawrence river forms the Gaspe Current which flows along the Laurentian Channel into the Atlantic Ocean, on the west side of the Cabot Strait. A salt water current flows northward through the east side of the Cabot Strait along the West Coast of Newfoundland. The coastal regions of



Newfoundland are exposed to this Atlantic current, rather than water from the St. Lawrence river.

Figure 4-1: Dominant horizontal surface circulation in the Gulf and Estuary (White and Johns, 1997)

The total fresh water flow into the Gulf is 19,000 m3/second, of which the St. Lawrence contributes about 84 %. The net inflow through the Strait of Belle Isle is 1.3×10^5 m^3/s in summer and 3×10^5 m^3/s in winter. An estimated 4 to 6×10^5 m^3/s flows out through the Cabot Strait, 20 to 30 times the fresh water flow into the Gulf.

4.3 Water Temperature and Salinity

Figure 4-2 and Figure 4-3 show the water salinity and temperatures for regions 2 and 3, respectively, along the West Coast of Newfoundland (Figure 4-4) from Petrie et al. (1996). The water salinities of 29 to 31 ppt noted in the area of interest in the summer months are slightly lower than the salinity of 34.5 ppt typical found in sea water due to the influence of the St. Lawrence river.

4.4 Waves

Wave statistics, from Eid et al. (1991), are provided in Figure 4-5 to Figure 4-9. The figures show the basic wave statistics, percentage exceedence, extreme waves and wave directions, and the data are summarized in the two tables below.

Probability of Exceeding (%)	Significant Wave Height (m)	Wave Period (sec)
20	2.5	8
50	1.5	6
80	1	4

Table 19: Percentage Exceedence Wave Heights and Periods

Return Period (years)	Significant Wave Height (m)	Maximum Wave Height (m)*
2	6.6	12.3
10	8.5	15.9
100	10.6	19.8

Table 20: Extreme Wave Heights:

* based on $H_{max} = 1.87\ H_s$ (U.S. Army, 1966)

Wave directional information is shown in Figure 4-5 to Figure 4-8. These figures indicate that during the worst months, October to January plus April, waves come from the west and north-west, and in the calmer months, June to August, from the South-East. During the winter months, February and March, waves are inhibited by ice cover.

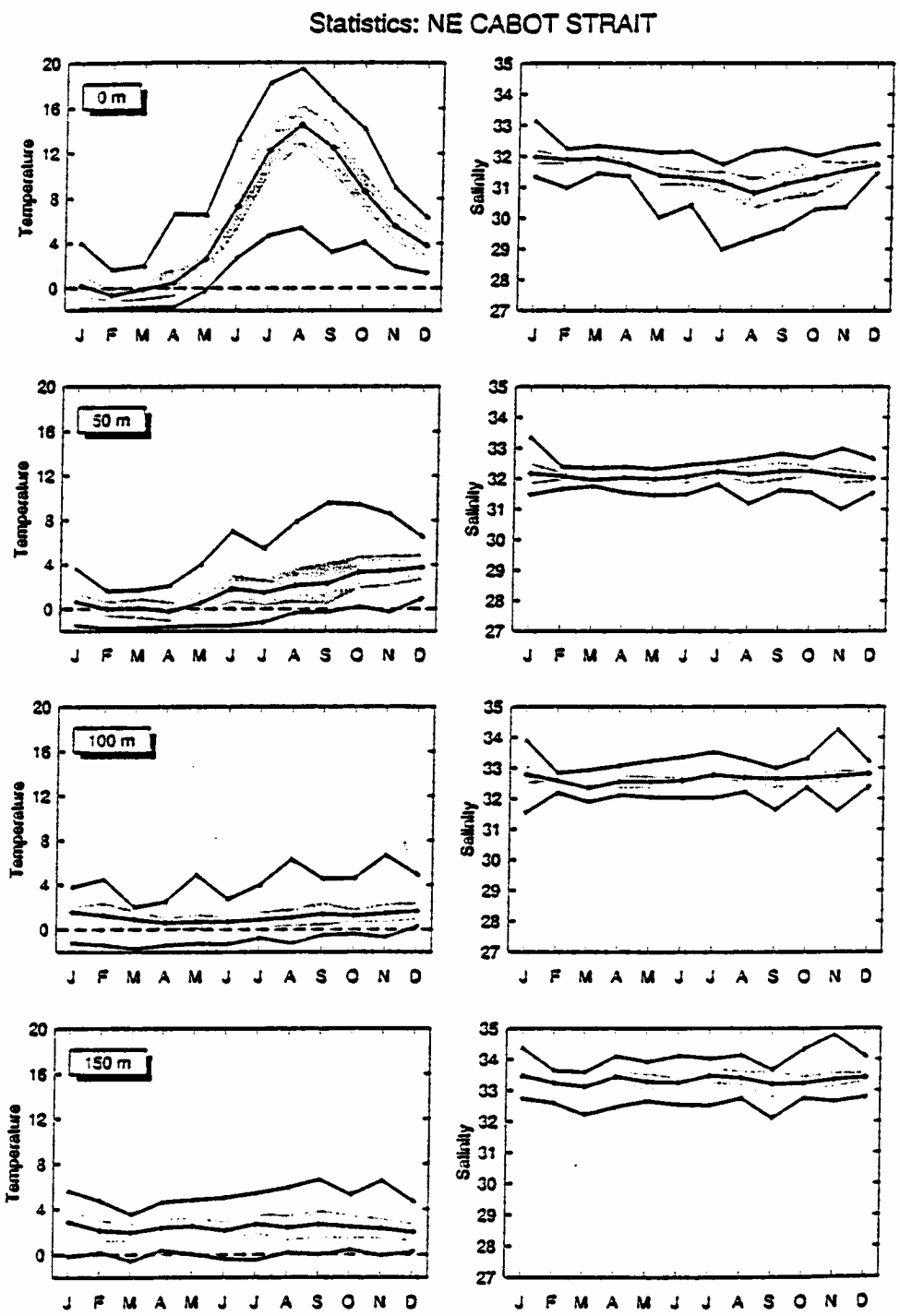


Figure 4-2: Temperature and Salinity for Subarea 2

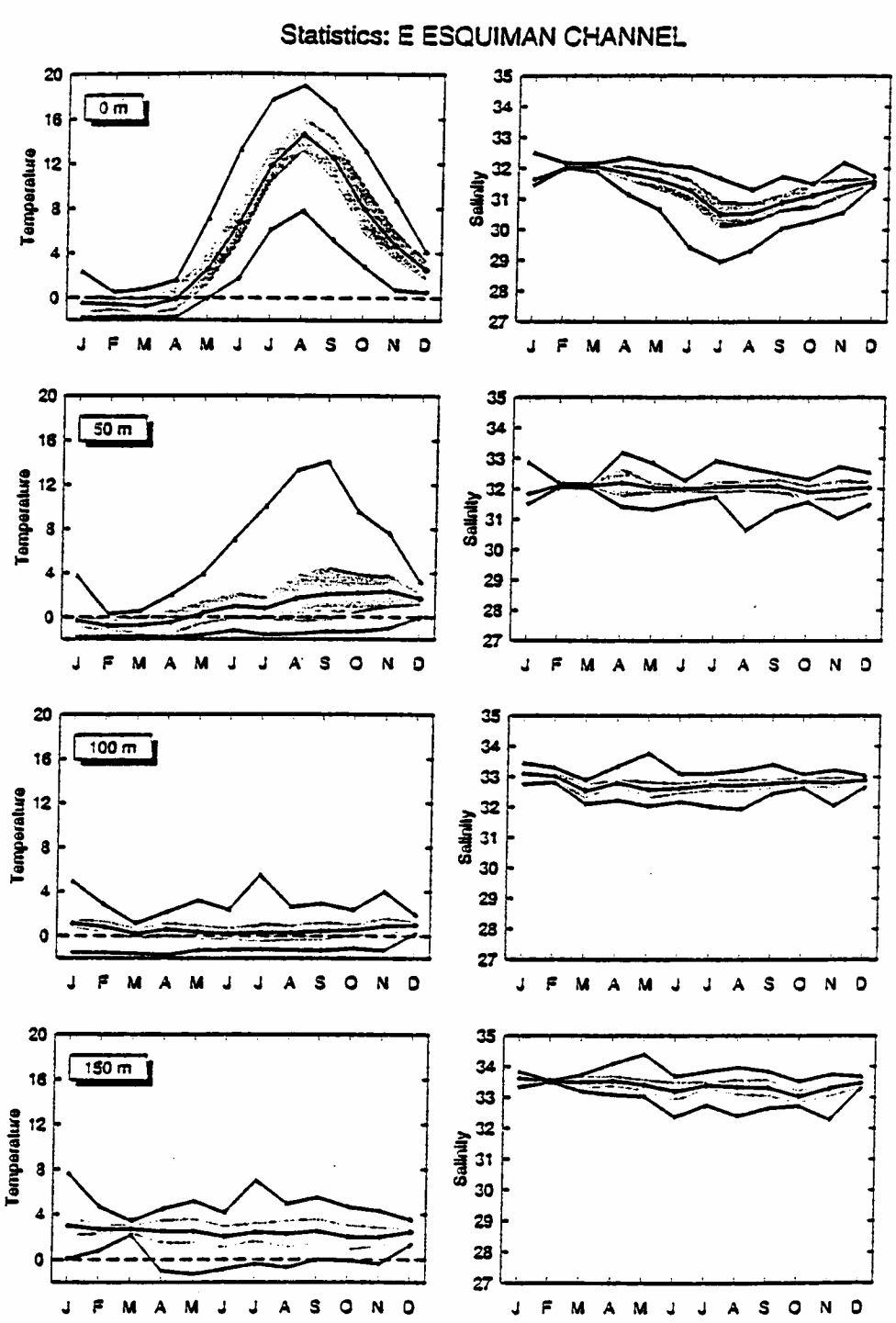


Figure 4-3: Temperature and Salinity for Subarea 3

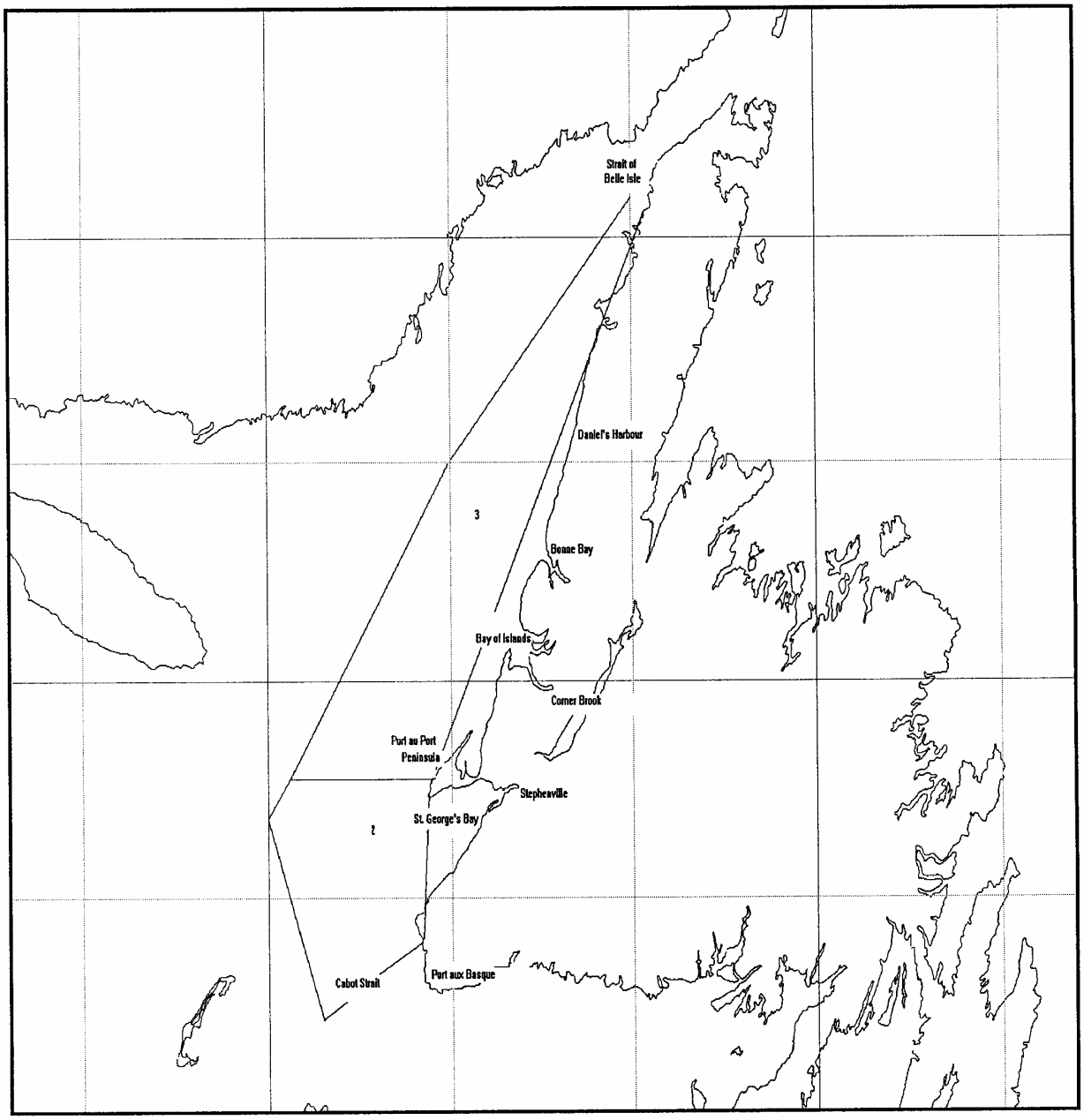


Figure 4-4: Gulf of St. Lawrence Oceanographic Subareas

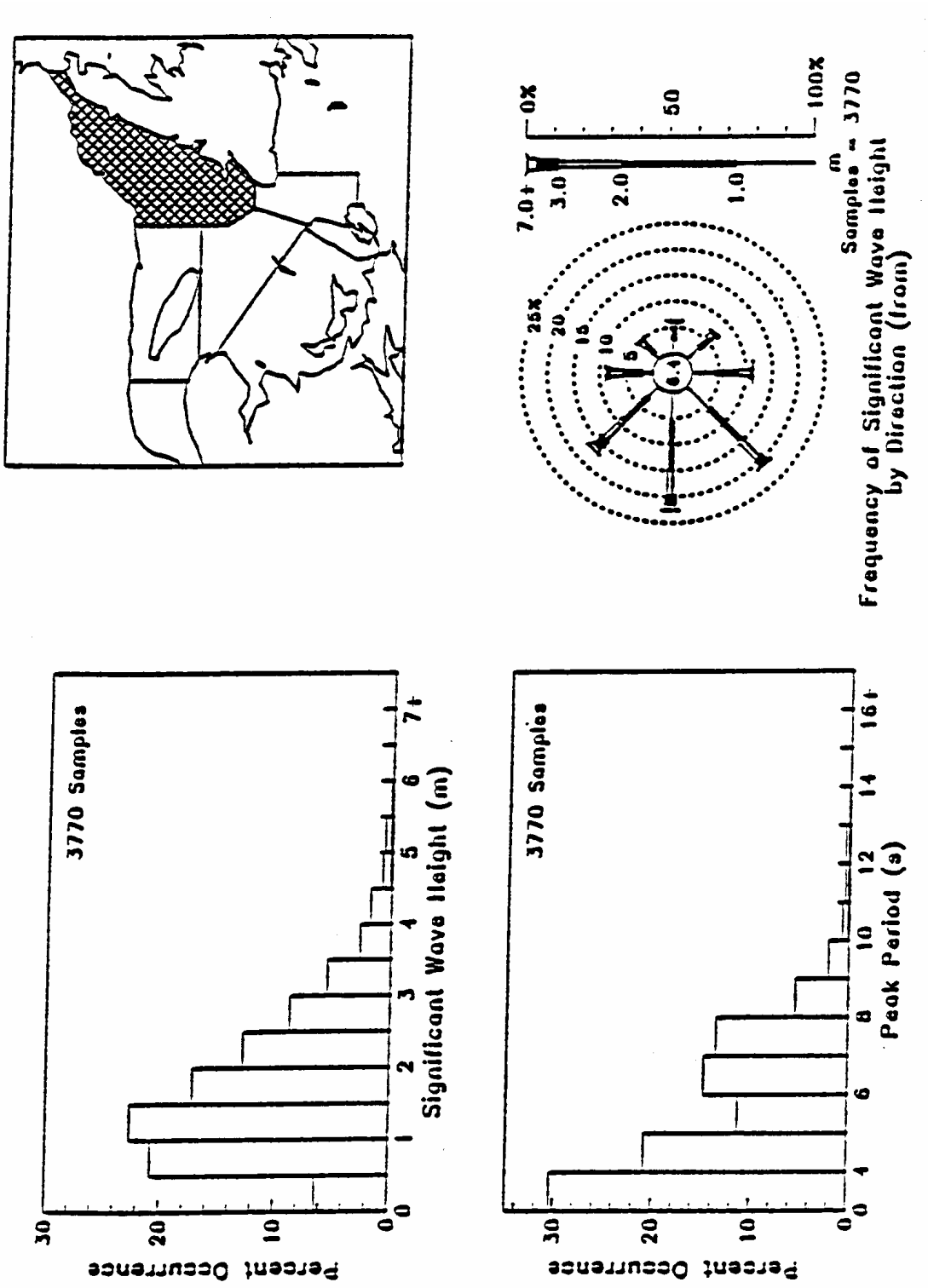


Figure 4-5: Annual Wave Statistics for North-East Gulf of St. Lawrence

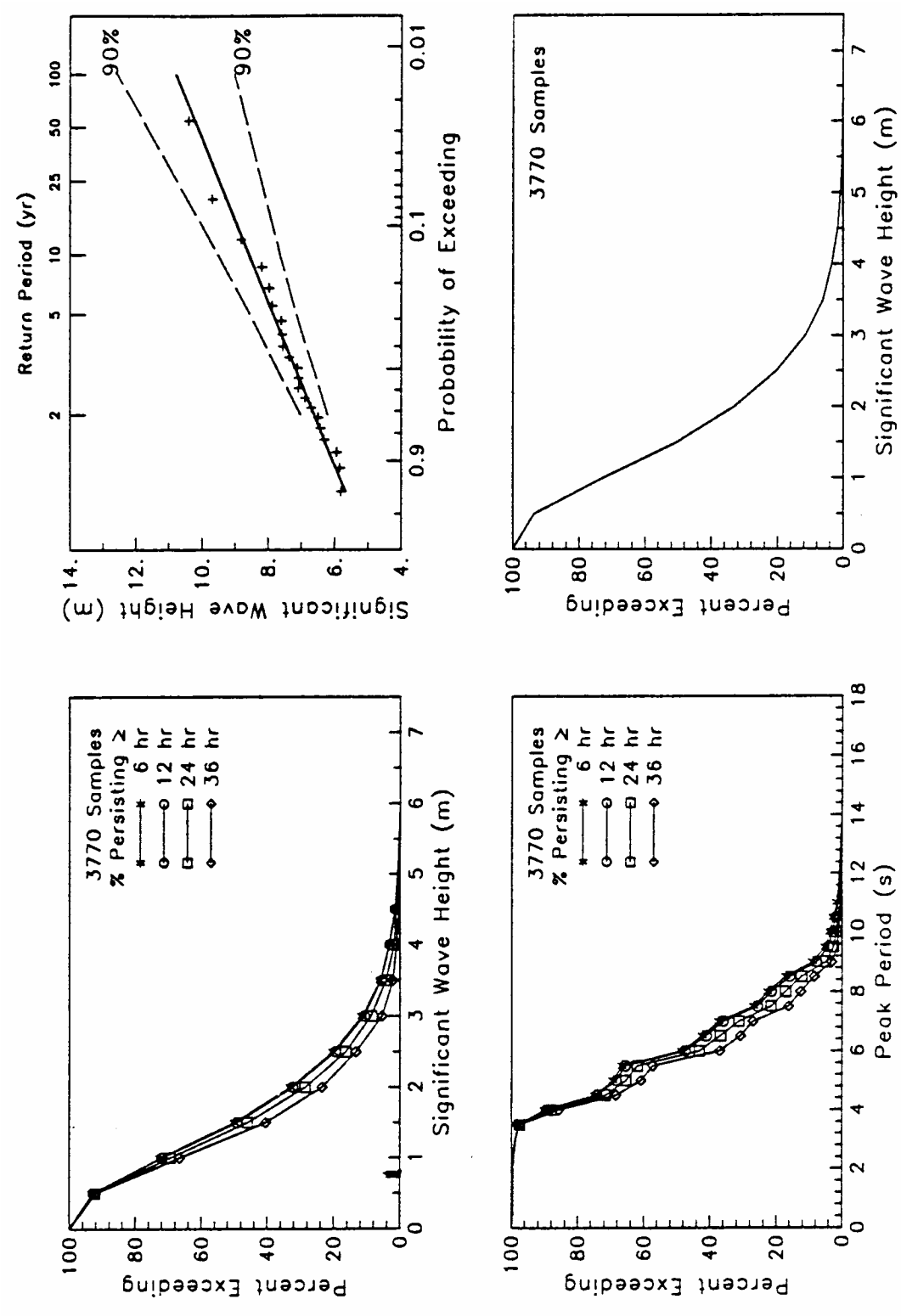


Figure 4-6: Annual Wave Statistics for the North-East Gulf of St. Lawrence

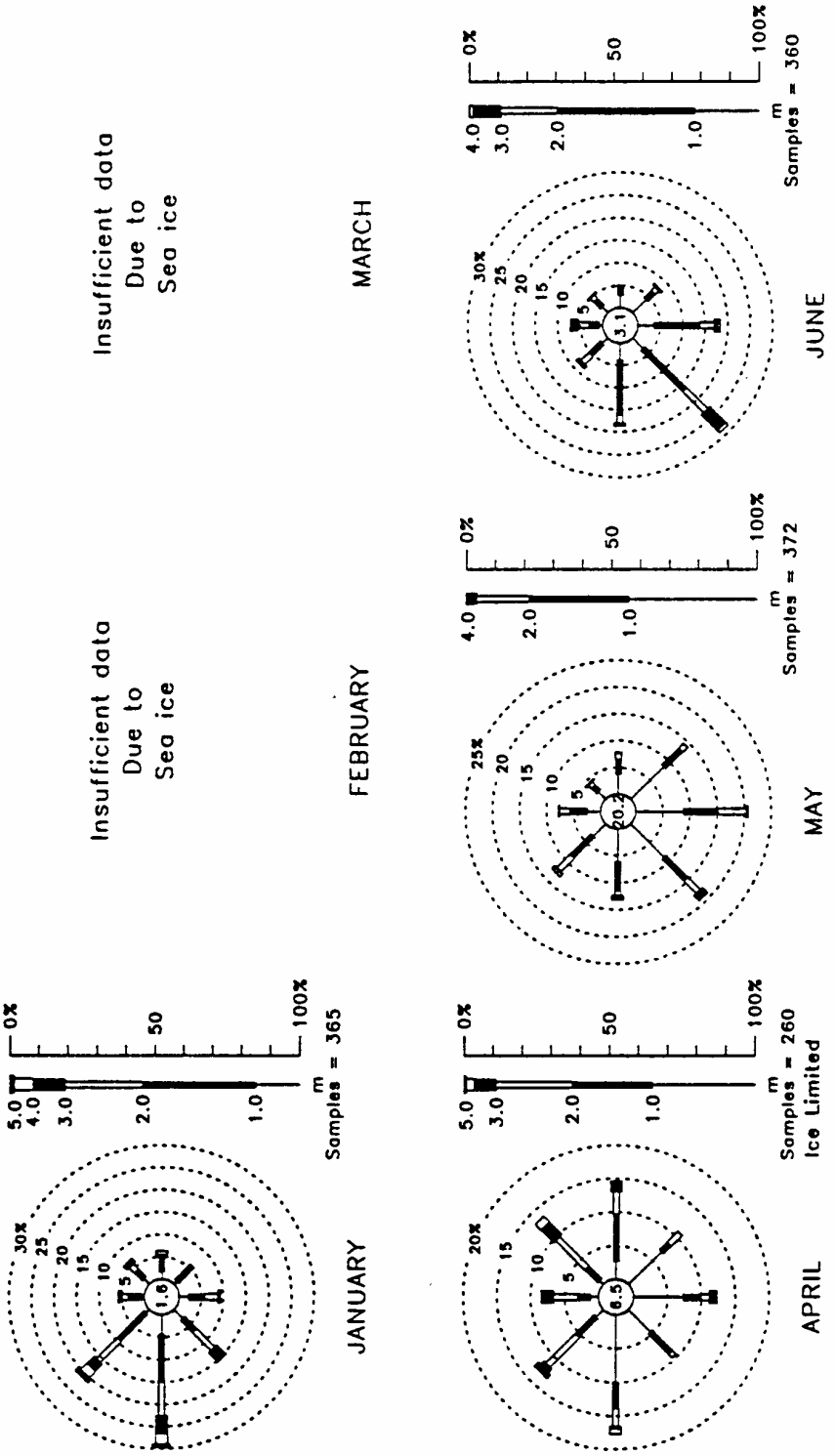


Figure 4-7: Monthly Wave Direction Statistics for the North-East Gulf of St. Lawrence

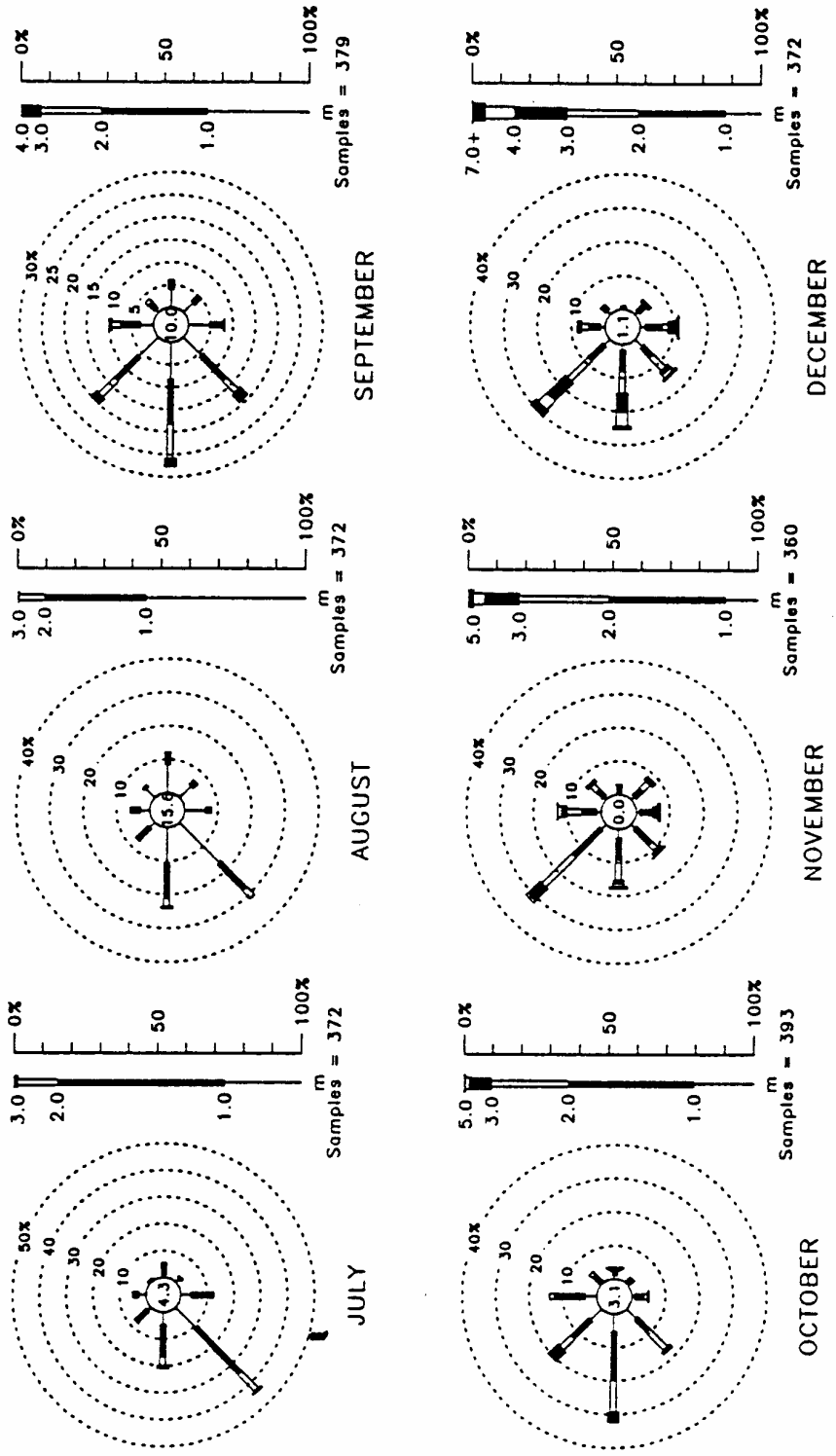


Figure 4-8: Monthly Wave Direction Statistics for the North-East Gulf of St. Lawrence

ANNUAL OCCURRENCE OF SIGNIFICANT WAVE HEIGHT and WIND SPEED

ODGP

Sig. Wave Height	Wind Speed (knots) 0- <5	5- <10	10- <15	15- <20	20- <25	25- <30	30- <35	35- <40	40- <45	45- <50	50- <55	>55	Total	%Occur
0.0 - < 0.5 m	232	8	—	—	—	—	—	—	—	—	—	—	240	6.4
0.5 - < 1.0 m	309	430	35	9	—	—	—	—	—	—	—	—	783	20.8
1.0 - < 1.5 m	126	594	84	36	10	1	1	—	—	—	—	—	852	22.6
1.5 - < 2.0 m	26	385	187	52	15	3	—	—	—	—	—	—	648	17.2
2.0 - < 2.5 m	13	128	252	50	30	7	3	2	—	—	—	—	483	12.8
2.5 - < 3.0 m	1	40	203	36	23	19	4	1	2	—	—	—	329	8.7
3.0 - < 3.5 m	—	7	102	54	11	22	3	7	—	—	—	—	206	5.5
3.5 - < 4.0 m	—	1	32	36	8	9	5	7	1	—	—	—	99	2.6
4.0 - < 4.5 m	—	—	7	31	11	5	7	2	2	—	—	2	87	1.8
4.5 - < 5.0 m	—	—	—	9	6	4	5	2	3	—	—	—	29	0.8
5.0 - < 5.5 m	—	—	—	4	9	3	1	1	5	—	—	—	23	0.6
5.5 - < 6.0 m	—	—	—	1	2	2	—	—	1	1	1	—	8	0.2
6.0 - < 6.5 m	—	—	—	—	1	—	—	—	—	—	—	—	1	0.0
6.5 - < 7.0 m	—	—	—	—	—	—	—	1	—	—	—	—	1	0.0
7.0 - < 7.5 m	—	—	—	—	1	—	—	—	—	—	—	—	1	0.0
7.5 - < 8.0 m	—	—	—	—	—	—	—	—	—	—	—	—	0	0.0
8.0 - + m	—	—	—	—	—	—	—	—	—	—	—	—	0	0.0
Total	707	1571	902	318	127	75	29	23	14	1	1	2	3770	
%Occur	18.8	41.7	23.9	8.4	3.4	2.0	0.8	0.6	0.4	0.0	0.0	0.1		100.0

ANNUAL OCCURRENCE OF SIGNIFICANT WAVE HEIGHT and PEAK PERIOD

' ODGP'

Sig. Wave Height	Peak Period (seconds) < 4	4- >5	5- >6	6- >7	7- >8	8- >9	9- >10	10- >11	11- >12	12- >13	13- >14	14- >15	15- >16	16- >17	17- >18	18- >19	19- >20	>20	Total	%Occur
0.0 - < 0.5 m	69	103	17	8	7	21	12	—	—	1	2	—	—	—	—	—	—	—	240	6.4
0.5 - < 1.0 m	283	322	89	14	26	31	14	7	1	3	10	3	—	—	—	—	—	—	783	20.8
1.0 - < 1.5 m	1	361	370	38	20	19	18	11	8	4	1	1	—	—	—	—	—	—	852	22.6
1.5 - < 2.0 m	—	8	313	254	42	7	12	8	1	3	—	—	—	—	—	—	—	—	648	17.2
2.0 - < 2.5 m	—	—	15	110	317	25	6	5	4	1	—	—	—	—	—	—	—	—	483	12.8
2.5 - < 3.0 m	—	—	—	2	134	174	10	1	6	2	—	—	—	—	—	—	—	—	329	8.7
3.0 - < 3.5 m	—	—	—	—	11	174	18	5	—	—	—	—	—	—	—	—	—	—	206	5.5
3.5 - < 4.0 m	—	—	—	—	—	52	45	1	—	1	—	—	—	—	—	—	—	—	99	2.6
4.0 - < 4.5 m	—	—	—	—	—	7	54	5	1	—	—	—	—	—	—	—	—	—	87	1.8
4.5 - < 5.0 m	—	—	—	—	—	1	16	10	1	—	1	—	—	—	—	—	—	—	29	0.8
5.0 - < 5.5 m	—	—	—	—	—	—	3	18	—	—	1	1	—	—	—	—	—	—	23	0.6
5.5 - < 6.0 m	—	—	—	—	—	—	—	5	3	—	—	—	—	—	—	—	—	—	8	0.2
6.0 - < 6.5 m	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—	1	0.0
6.5 - < 7.0 m	—	—	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	1	0.0
7.0 - < 7.5 m	—	—	—	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—	1	0.0
7.5 - < 8.0 m	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	0.0
8.0 - + m	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	0.0
Total	353	794	784	426	557	511	206	77	25	16	16	5	0	0	0	0	0	0	3770	
%Occur	9.4	21.1	20.8	11.3	14.8	13.6	5.5	2.0	0.7	0.4	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0		100.0

Figure 4-9: Significant Wave Height Statistics

4.5 Tides and Tidal Currents

The following description is based on extracts from Sailing Directions (1983) and the Current and Tide Tables for the Gulf of St. Lawrence (Tide Tables, 1997).

The tidal range along the coast from south to north (St George's Bay to Flowers Cove), is 1 to 1.5 m for neap tides and 1.6 to 2.3 m for large tides. The tidal wave itself progresses northward up the coast with an approximate 20 minute time lag between the occurrence of high and low water at the two sites. Coastal currents within 16 km of the coast associated with the tidal regime vary in maximum strength between 0.5 to 1 m/s, with the northward flowing current (flood tide) being the stronger and more likely to attain a velocity of about 1 m/s, particularly in the approaches to the Strait of Belle Isle.

In St George's Bay at the southern end of the coast, currents are somewhat less severe with flood tide velocities of 0.5 m/s only being experienced with the help of a southeasterly wind.

4.6 Local Currents

Only limited current data could be found for the area of interest. Detailed studies have been made of the currents in the Strait of Belle Isle, Cartier Passage (north of Anticosti Island), Gaspe Current and Cabot Strait. These data could possibly be used with mathematical modeling - which is beyond the scope of this study - to generate some idea of water circulation and velocities.

The following description is based on Sailing Directions for the Sailing Directions (1983), Tide Tables (1997), and personal experience of one team member (Colin Langford).

Offshore (distances beyond 32 km) current velocities will be considerably reduced, except for occasions when wind and tidal currents coincide in direction to produce strong surface currents probably in the order of 0.5 to 1 m/s. Otherwise maximums of 0.3 to 0.5 m/s are expected at the surface, diminishing rapidly with depth. At water depths of less than 100 m, bottom currents are expected to be in the 0.15 to 0.25 m/s range.

Two sets of current measurements are available for this area on Bedford Institute's Web page. One set was taken in St George's Bay (48° 29.3'N and 58° 35.9'W) in the summer of 1971 and covers the depth range of 3 to 47 m. The other set was obtained in the mouth of Bonne Bay (49° 37.3'N and 58° 00.3'W) in the summer of 1991, and covers the depth range of 15 to 100 m. The data are summarized below in Table 21. These currents were taken in bays and are of little use for offshore development.

St George's Bay (May and June, 1971)				
Location	Depth (m)	Mean (m/sec)	Max (m/sec)	Direction (° True)
Surface	< 10 m	0.049	0.4	340
Mid depth	10 to 30 m	0.034	0.3	350
deep	>40 m	0.029	0.2	289
Bonne Bay (May to September, 1991)				
Surface	15 m	0.07	0.65	027
Mid-Depth	30 m	0.05	0.56	028
Deep	62 and 70 m	0.04	0.55	012
Very Deep	100 m	0.045	0.48	014

Table 21: Summary of current meter readings for two sites on West Coast of Newfoundland

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5. GEOTECHNICAL

5.1 Bathymetry

The bathymetry of the area is indicated in a hydrographic map in the rear pocket of this report. The water depth drops to 50 m within 5 km of the shoreline in George's Bay and within 10 km of the shoreline along the shoreline north of the Hudson River. Water depths range from 100 to 300 m in the Esquiman Channel which runs northeast-southwest 50 to100 km offshore. Just north of Port au Port peninsula, there is a wide shelf less than 50 m deep for about 40 km. The 100 and 200 m isobaths run approximately parallel to the shore about 30 and 50 km from the shore, respectively.

5.2 Seabed Sediments

This review is extracted from the report by Zevenhuizen and King (1992), which is based predominantly on data collected by Memorial University, the Atlantic Geoscience Centre cruises from 1987 to 1990, and data collected as early as 1961 by the Woods Hole RV Vema. The Zevenhuizen and King report is based primarily on a regional grid of high resolution seismic reflection data, complemented by piston cores and bottom samples. Seismic sources included a 655 cubic centimeter sleeve gun and airgun for bedrock assessment. Seafloor morphology and sediment distribution were determined using data collected with 50, 70, and 100 kHz sidescan sonar systems. All seismic reflection data have been systematically interpreted and four seismo-stratigraphic units have been determined to represent the surficial sediments. These units have tentatively been interpreted as bedrock, till/ice contact deposits, glacio-marine sediments and post-glacial muds, and reworked sands and gravels. In the original report, the data are presented with 12 interpreted cross-sections, 18 figures and 36 maps.

Maps in Zevenhuizen and King (1992) describing the shallow bedrock and surficial sediments have been consolidated and compressed into Figure 5-1 to Figure 5-3.

The unconsolidated sediments overlying the bedrock are generally very thin. Gas venting and possibly recent faulting were observed. Ice scouring observed in the deeper portions of the study area appear to be relict.

The seabed soils in the area are gravels, sands, and Pelite. Pelite constitutes a major portion of the sediments in the area. Pelite is a term used instead of mud (see Loring and Nota, 1973 for full description of Pelite), and is composed of particles between 0.05 and 0.002 mm and clay particles less than 0.002 mm in diameter. The coarse-grained material (2 to 0.05 mm) in the pelite is composed of feldspar, quartz, accessory heavy minerals, and rock fragments. In the calcipelites, which occupy the deep central parts of the Laurentian Trough south and east of Anticosti island as well as the Anticosti and Esquiman troughs, the coarse material is mainly composed of gravel and sand-size limestone particles. The granulometrical composition of the pelites indicates that the pelite-size material has been deposited recently from suspension and that the coarse material is mainly derived from the adjacent shorelines by ice rafting.

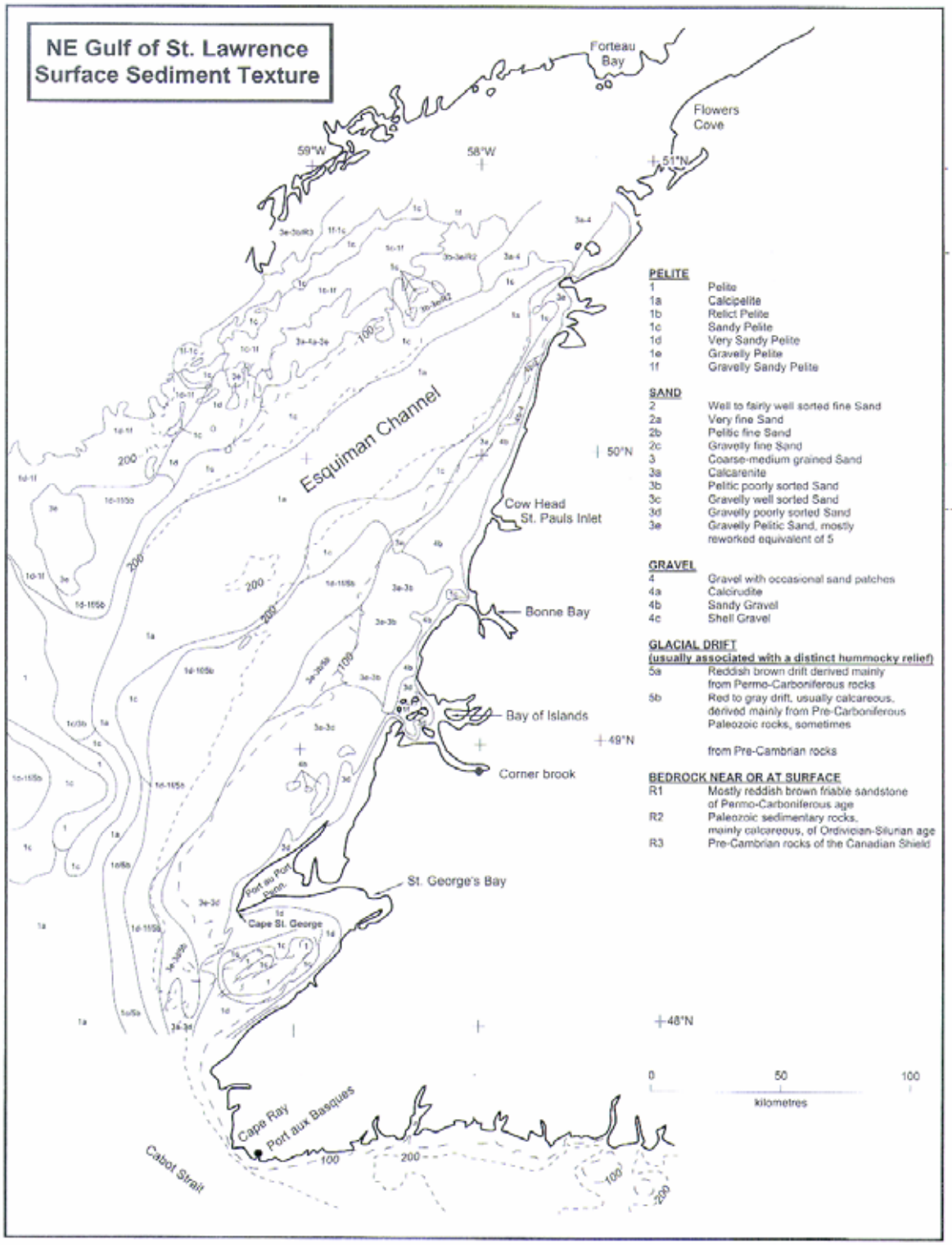

Figure 5-1: Surface Sediment Texture.

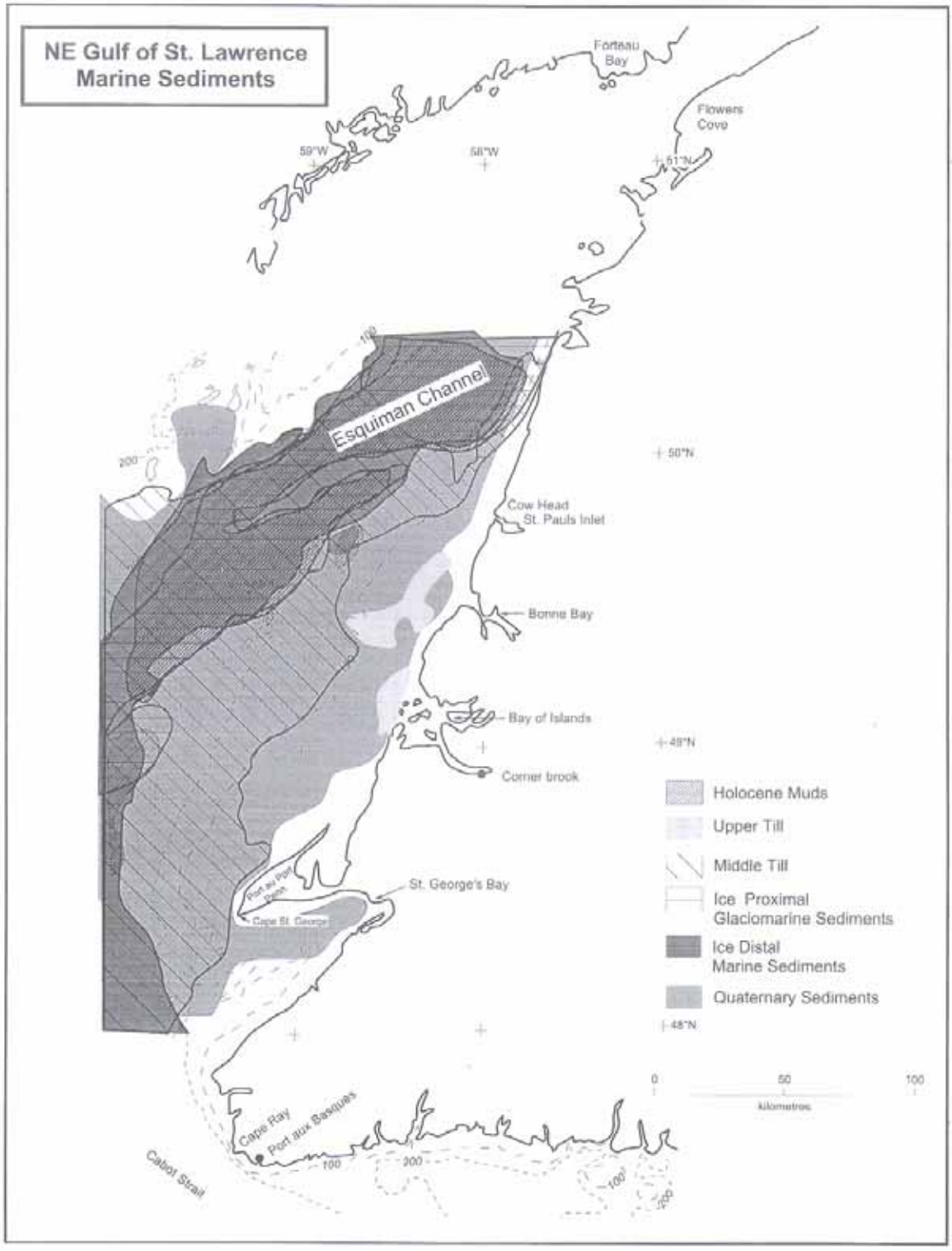

Figure 5-2: Seabed Sediments

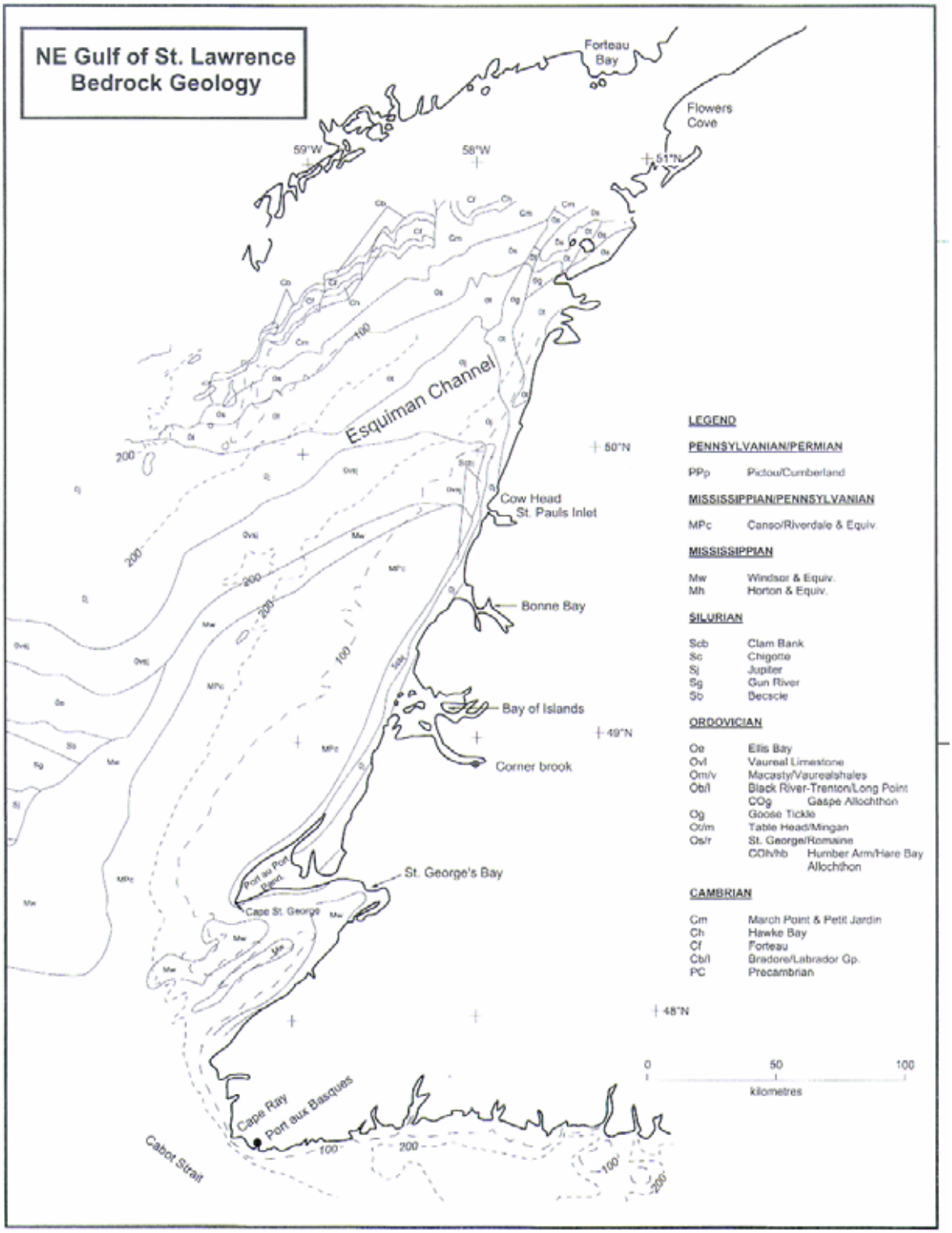

Figure 5-3: Bedrock Geology

Deposition of very silty pelites and calcipelites in the shelf valleys and in depressions surrounding the trough has also formed protected basin deposits, i.e., in St George's Bay, Newfoundland. The main features of these sediments are their high silt content (45-60%) and lower clay content (<50%). The high silt content of these sediments is believed to result from the presence of bottom currents which are of sufficient strength to prevent the accumulation of clay-sized particles as the dominant constituent.

Figure 5-1 indicates that the surficial sediments along the West Coast of Newfoundland out to 100 m are as follows:

i) St George's Bay seabed consists of pelite in various forms. These sediments are up to 20 m thick in places, but generally less than 5 m thick.

ii) North of Port au Port Peninsular to Bay of Islands, the seabed consists of gravelly pelitic sand and gravelly poorly sorted sand, with a very narrow region of gravelly poorly sorted sand in water depths of less than about 20 m along the shoreline.

iii) Between Bay of Islands and Bonne Bay the seabed is composed of gravelly pelite sand and pelitic poorly sorted sand, with a very narrow region of sandy gravel and gravelly poorly sorted sand in water depths of less than about 20 m along the shoreline.

iv) From Bonne Bay to Hawkes Bay, the seabed is composed of sandy gravel, with a narrow region of gravelly poorly sorted sand in water depths of less than about 20 m along the shoreline.

v) North of Hawkes Bay, the sandy pelite and pelitic sand predominate.

5.3 Soil Strengths

Soils strengths are given in Josenhans and Zevenhuisen (1992). Soil strengths are given in Table 22; core sample locations are indicated in Figure 5-4. No measurements were made in the area of interest here, however, several cores were obtained in the general vicinity which pertain to soils which are found in the study area. Undrained shear strength was measured on all cores at 10 cm intervals with an AGC motorized miniature vane device. A 1.27 cm^2 vane was used at a rotation rate of 50° per minute. Residual strength was measured by continuation of the test post-peak. Shear vane measurements were initially made in the centre of the working half of the core. The shear vane was offset from centre and the measurements were made on the archive half of the core.

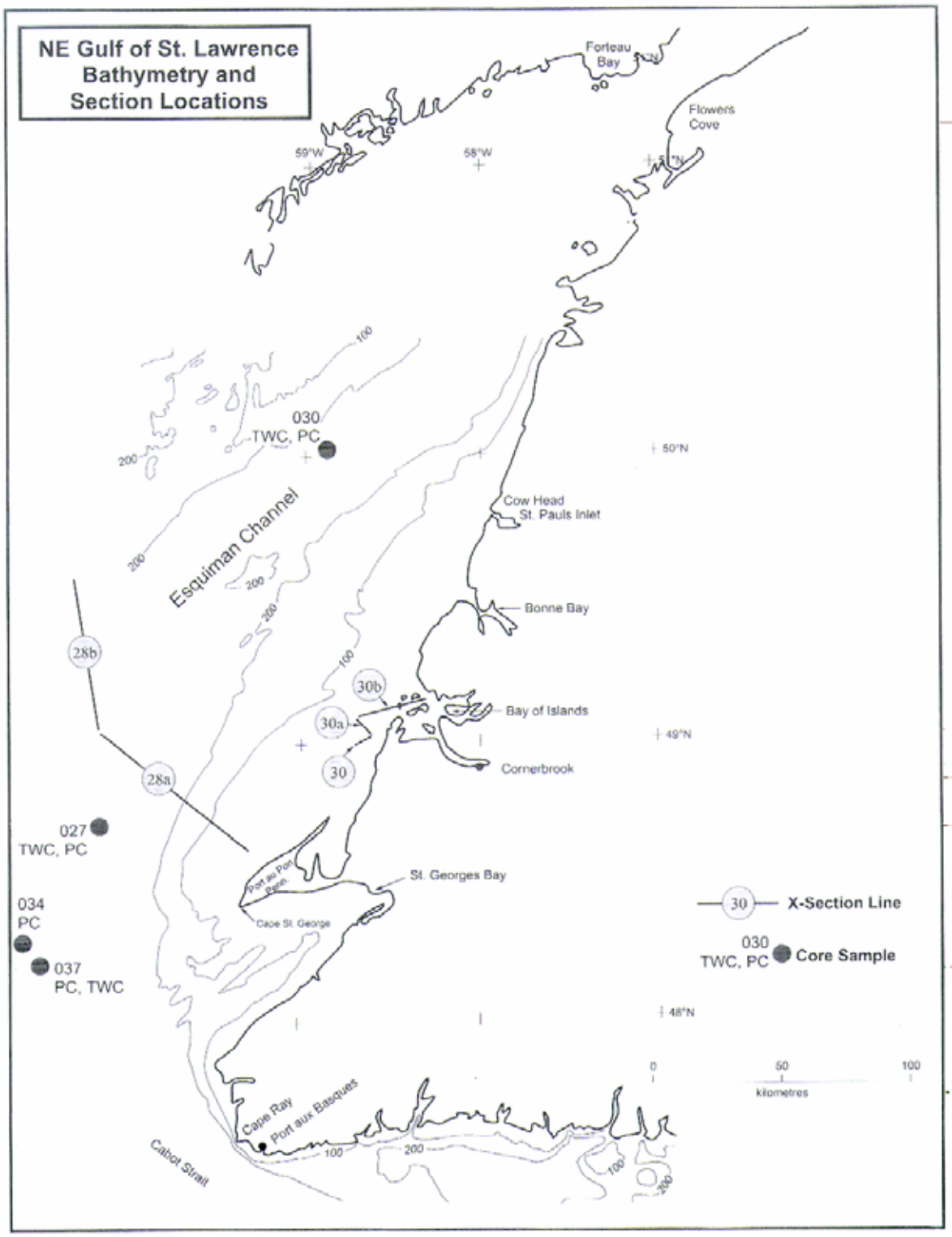

Figure 5-4: Core Sample and Section Locations

Core Sample Number	Location	Water Depth (m)	Soil Description	Surficial Soil Classification as used in Fig 7-1	Residual Shear Strength (kPa)	Peak Shear Strength (kPa)
027-PC (PC = Piston Core)	Port au Port Peninsula	331	Surface: silty mud, moderately calcareous, to sandy silt with pebbles. At 450 cm, massive sandy silt diamicton, becoming stiff and dry.	1c (Sandy pelite)	2 ½ ± 2 kPa increasing at 400 cm to 13 kPa at 470 cm. Core depth 471 cm.	5 ± 2 kPa increasing at 400 cm to 28 kPa at 470 cm.
030-TWC (TWC= Trigger Weight Core)	Esquiman Channel	294	Massive, moderately calcareous silty clay. Sand layer at 125 cm.	1a (Calcipelite)	2 ± 1 kPa. Core depth 153 cm	3.5 ± 1 kPa to 153 cm
034-PC	Laurentian Channel	438	Surface: Brown silty clay, slightly calcareous. Pebble line at 220 cm, with clayey silt, bedded with sand layer and pebbles below.	1a	2 ½ ± 2 kPa. Core depth 265 cm	3 kPa at surface increasing to 7 at 200 cm.
037-L-PC	Laurentian Channel	439	Massive, silty mud and clay in top m. Clay and silt to 500 cm. Then change to massive stiff, highly calcareous silty clay and some sand.	1a	5 kPa increasing to 30 at 600 cm. Core depth 648 cm.	10 kPa increasing to 65 kPa at 600 cm.

Table 22: Example of soil strengths for pelite in the general area of interest.

5.4 Sediment Thickness

The Holocene mud is less then 5 m thick throughout the coastal region from about 30 m out to 100 m water depth. In St George's Bay, Holocene muds reach up to 20 m thick in isolated places but are generally 5 m thick or less.

The total quaternary sediments (composed mainly of till) are generally less than 20 m thick but do vary up to 40 m thick in isolated shallow water areas along the coast. There are regions of quaternary sediments over 60 m thick in the Bay of Islands and a small area where the sediment is over 100 m thick in an isolated spot at the northern entrance to the Bay. In the eastern end of St George's Bay, the sediments are over 50 m thick, but are generally 0 to 10 m in most parts of this Bay.

5.5 Ice Scour

Very little data exist on scouring and no specific scour programs have been conducted in the area of interest, as far as we are aware. BIO(1995) indicates extensive iceberg scouring in water depths greater than 110 m down the Strait of Belle Isle and in the centre of the Esquiman Channel, which are referred to as relic. Considering the rough ice which occurs off the West Coast of Newfoundland, we would expect scouring in the shallow waters off the coast. Section 2.3 indicates that the thickest annual ridges are expected to be about 23 m, and we would expect the majority of ridge keels to be less than 14 m, considering the average annual ice thickness. Hence we would not expect minimal ice scouring in water depths greater than about 23 m with the majority of scouring in water depths less than 14 m. As the 20 m contour lies about 1.6 km from shore, one would have to conduct a survey very close to shore. Also, scours in the soft silty sediments (pelite) would tend to be eroded by the wave and current action and scour surveys would have to be done in the early summer.

5.6 Seismic Activity

Seismic risk for the Eastern Canadian Offshore Regions is discussed in Atkinson et al (1987). The work was undertaken to assist in the development of new Canadian standards for the design, construction, and installation of fixed offshore production structures in Canadian waters. The maps provided are part of the CSA Standard S471 which deals with general requirements, design criteria and loads.

The report provides zoning maps of seismic ground motion parameters that can be used for the preliminary design of offshore structures. Preliminary design would indicate whether seismic hazards are of sufficient severity to warrant more detailed site specific investigations.

Earthquakes may cause damage to a structure in a number of ways. The most fundamental of these is that the shaking of the ground on which the structure is founded may induce damaging dynamic loads within the structure, which could lead to the collapse of the structure.

Damage may result from differential ground displacements, if the structure is located directly on an active surface fault. This situation may arise in parts of Western North America, but in Eastern North America surface faults are rare to non-existent and so this mechanism can be generally discounted.

Finally, damage may be caused indirectly by earthquake effects such as liquefaction or seismic slope instability. Under this scenario, the earthquake shaking causes the loss of strength of the soil supporting the structure or triggers large scale slumping up-slope of the structure. This could be a problem in the area of interest here due to the silty soils and the seabed slope.

The Atkinson et al report deals with ground shaking and liquefaction hazards. The Report provides maps of the area from which parameters can be extracted to develop response spectrum, which can be used to determine the motions of a structure and the liquefaction risk in the soils.. These response spectra indicate the pseudo-response velocity (PSRV), for a damping of 5% of the critical damping, over the natural frequency range 0.2 to 10 Hz. The values correspond to the mean value of the random (or average) horizontal component. A damping of 5% is most commonly assumed to apply to offshore structures and the frequency range covers the natural frequency of most offshore structures, although the spectra can be extended to slightly higher or lower frequencies.

Liquefaction depends on the amplitude and duration of ground shaking, as well as the resistance of the soil. Studies have shown that a grounds resistance to liquefaction can be defined in terms of the standard penetration resistance. The Report indicates how strong a soil has to be to resist liquefaction in terms of cone penetration tests.

Probabilities are expressed as 10^{-2} and 10^{-4} per year, the accepted risks for minor and major damage, the latter involving possible loss of life.

Figure 5-5 shows the Response Spectrum for the area of interest. The spectrum is calculated for bedrock for a damping factor of 5%. The soil values are bedrock values multiplied by 2 at frequencies of 2 Hz and below, and are relevant to a site located on soil over 10 m thick. For this response spectrum, the soil strength required to prevent liquefaction corresponds to a corrected penetration resistance of 5 and 25 blows/ft for the probabilities of 10^{-2} and 10^{-4} per year, respectively.

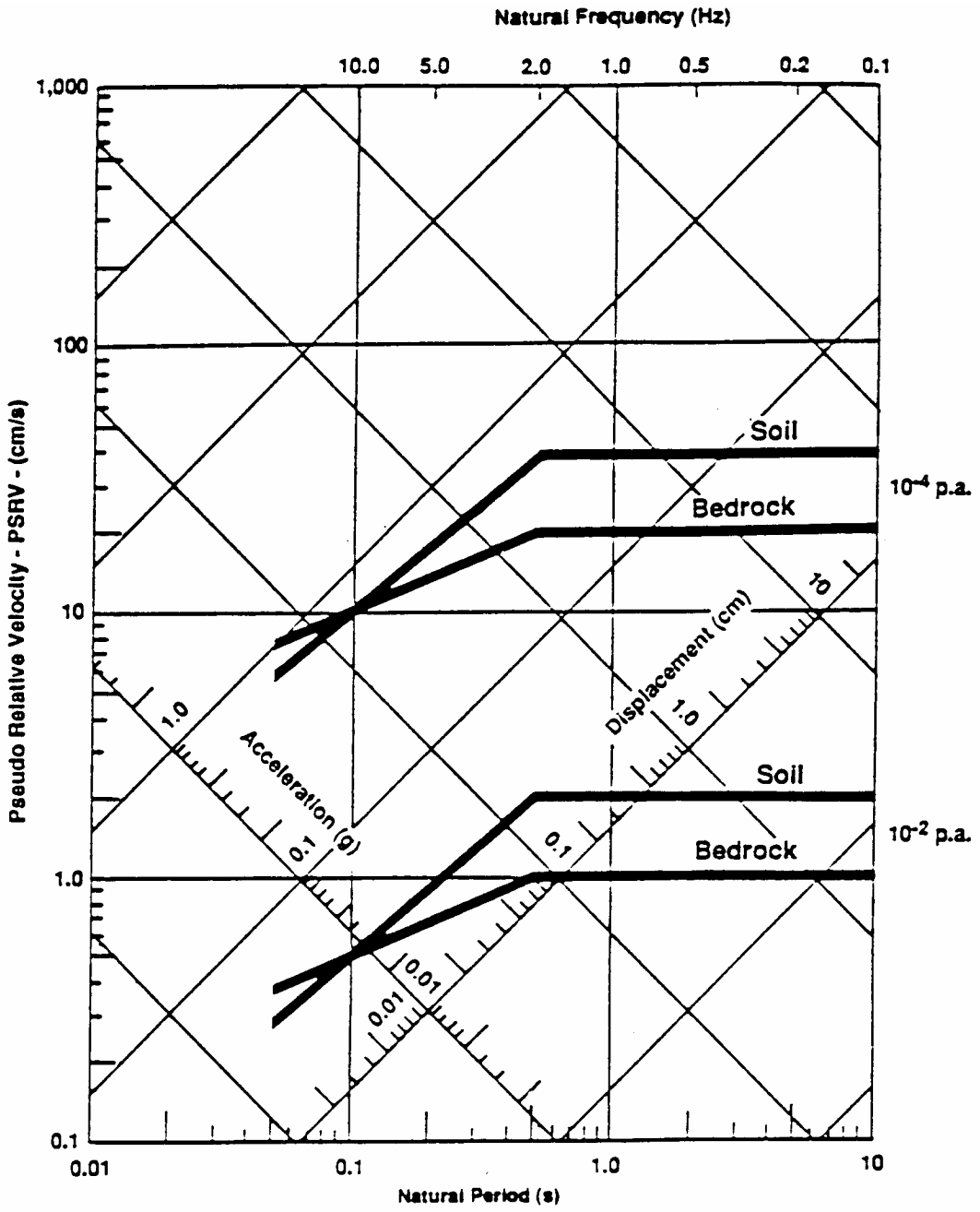

Figure 5-5: Response Spectrum for the West Coast of Newfoundland (from Atkinson et al, 1987)

6. CONCLUSION

6.1 General

This report covers a description of the environmental conditions along the West Coast of Newfoundland. A considerable amount of information has been obtained for the area from the Canadian Atmospheric Environment Service (AES), Bedford Institute of Oceanography, the Canadian Coast Guard, and the Transport Development Centre of Transport Canada. However, there is still a lack of in-situ marine environment measurements in a number of fundamental areas as indicated in the recommendations.

The data presented here is intended as a guide to industry or government agencies planning development in the area. It should not be used for the design of specific structures. At the design stage for a specific structure, much more information is required and actual field measurements should be carried out.

Although a harsh climate exists in the area, the conditions are not as severe as in other locations where structures have already been installed and used. The open water conditions in summer are relatively benign compared to Hibernia and the North Sea, and the ice covered conditions in winter are relatively benign compared to the Beaufort Sea. Conditions on the West Coast of Newfoundland are similar to the Northumberland Strait, where the Causeway to Prince Edward Island was recently completed.

The two principle concerns are ice and waves. Ice growth in the area is typical of a temperate zone, with level ice growth to about 50 cm (range 20 to 80 cm) in April. However, considerably colder temperatures occur on the north shore of the Gulf, and these colder conditions cause considerably thicker ice which drifts into the area of interest. Extreme loads on offshore structures will be caused by ridges, and possibly icebergs and remnants of old ice which enter the area from the Labrador Sea via the Strait of Belle Isle. No design loads have been provided here as considerably more environmental data are required to determine the "extreme ice feature" and information is required on the actual form of the structure. Ice free conditions usually prevail by late April in the south and last for about 311 days, and by mid May in the north and last for about 274 days. These provide an appreciably longer open water construction season than is available in the Arctic.

The 100 year significant wave is calculated (hindcast) to be about 10.6 m, with a corresponding maximum wave of 19.8 m. The median wave height is 1.5 m. These are typical of the Beaufort Sea, where fetches are also limited. These waves are considerably smaller than experienced off the East Coast of Newfoundland, where extreme waves are up to three times higher.

Fog, a limiting factor for air and marine transportation, occurs about 38 days per year on the West Coast of Newfoundland. By comparison, this is appreciably less than the 121 days per year of fog experienced in St John's on the East Coast of Newfoundland. Precipitation of 1200 mm per year is slightly less than that experienced in St John's.

Seabed sediments in the area are extremely weak, similar to the soft sediments found in the Beaufort Delta. These sediments will most likely have to be removed for any gravity structure. However, the sediments are typically less than 5 m thick along the shore, except in the bays. There is no data on ice scour in water depths less than about 100 m, but scours in water depths

over 100 m appear to be relic, and possibly from the pre-glacial period when water levels were lower. A detailed scour survey in the shallow waters is required, for the design of well head protection systems and subsea pipelines.

In conclusion, from an environmental point of view, we see no major obstacles to year round development in the area, although the cooling trend observed over the past few years (see section 6.2 below) should be investigated and, if necessary, taken into consideration in any design.

6.2 Climate Trends

White and Johns (1997) summarize some aspects of the climate, ice, and water trends over the past few years. They point out that most of Atlantic Canada has experienced a lowering of temperatures since the 1980's, and this has also been true for the Gulf of St. Lawrence. The winter of 1992-93 was one of the worst on record and the summers of 1991 to '93 were colder than the long term average. The summer of 1993 was also very wet, with 50 % more precipitation than the average for the period 1951-1980. Winter air temperatures for all 6 years from 1988 to 1994 were below the 1961-1990 normals.

For the winter of 1991-92, the ice edge extent exceeded the median and, in April, approached the maximum. The winter ice duration also exceeded the mean for most of the Gulf. The extremely cold winter of 1992-93 resulted in extensive ice formation in the area close to the maximum extent ever recorded for sea ice, and the ice lasted longer than normal. Although above normal air temperatures in the first half of January, 1993, resulted in little ice forming, this was followed by a cold Arctic air mass which resulted in a rapid spread of ice in the second half of the month. By February, the Gulf was ice covered, and remained so for the month of March. New records were set for late dispersal of ice on the Magdalen Shallows.

As regards the water temperature, 1994 was the ninth consecutive year that the cold intermediate layer in the Laurentian Channel showed mid-summer temperatures nearly 1°C below the 1948-1985 average and the Strait of Belle Isle was 2.2°C colder than average. Deeper waters (100-200 m) were colder than average throughout the Gulf except for the Cabot Strait.

Considering the above, climate trends should be investigated and any aspects which might worsen the design criteria be taken into account.

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A. DESCRIPTION OF ICE CONDITIONS FOR TWO YEARS

Following is a description of the sea-ice conditions along the West Coast of Newfoundland for two years, based on information from daily AES ice charts. Two types of ice charts are available.

1. **Daily Analysis Ice Charts:** The daily analysis ice charts provide the ice conditions as described by expert ice observers based on information obtained from visual (aircraft) observations from early 1960 to 1975, the AES SLAR aircraft from 1975 to 1990, the SAR (STAR2) aircraft from 1990 to 1994, RADARSAT (since 1995), vessels in the area, and other satellites. The maps show the total ice concentration plus the concentrations of the three thickest ice types, and the nature of the ice, i.e., floe sizes, if the ice is in patches and strips, etc. Several charts have been copied and included in this Appendix, along with a description of the ice conditions. These data are available from AES for $50 per year on micro-film, or for $5 per sheet in hard copy format. About 20 ice charts are required per winter to define the ice conditions, although about 100 ice charts per winter are typically available. The ice charts are available from 1962 to the present, however, with the improvements which resulted with the introduction of the SLAR and SAR data, only the most recent 10 years of data are utilised here.
2. **Weekly Composite Ice Charts**: These are similar to the daily charts except that they are published once a week or sometimes twice a week, depending on the conditions. Data sources are the same as above. The daily charts are generally more useful than the weekly, as they show the day-by-day variations of the ice in an area. Cost of the weekly charts is $5 per chart or $50 per year on micro-film.

A.1 Ice Season of 1994-1995

Until early February, the northeast Gulf of St. Lawrence, off the West Coast of Newfoundland, lay in a wedge of open water with its apex at Daniel's Harbour (chart of 15 January). Over the ensuing season, an irregular ice pattern developed in which the Newfoundland coast was adjacent to open water, the Quebec coast was adjacent to a band of new ice and thicker ice types occurred in mid-channel.

Gray ice predominated in the ice-covered areas to mid-January. Equal proportions of gray and gray-white ice were present by the end of January (chart of 1st February), with a gray/gray-white/thin first-year mix occurring to the north, off Daniel's Harbour and St. John Bay. Thin first-year and gray-white ice predominated by mid-February, when the continuous coastal open water area closed up, except in St. George's Bay at the southern end of the coast (chart of 15 February). By the beginning of March, thin first-year ice was the predominant type. At this time, too, a narrow lead parallel to shore developed between the Bay of Islands and St. John Bay. Open water conditions persisted along the coast of St. George's Bay (chart of 1st March).

A second coastal lead episode occurred in mid-March between Port au Port Peninsula and the Strait of Belle Isle (chart of 16 March). The final week of March saw a general reduction in ice concentrations and the formation of a broad, open water area off the West Coast (chart of 27 March). Sea-ice continued to disperse from this time onward, leaving the northeast Gulf open as far as the Strait of Belle Isle at an exceptionally early date, making .

Through April, icebergs from the Labrador Sea drifted into the west coast area through the open Strait of Belle Isle, reaching the latitude of Bonne Bay by mid-month (chart of 15 April). The maximum area of bergy water coverage, from Port au Port to Anticosti Island, was mapped in late May (chart of 26 May). This represented the maximum penetration of icebergs over the 12 years of ice chart records studied.

Table A-1 below shows the ice codes used in the maps that follow in this chapter. The coding is presented here for easier readability. The method used to display the ice codes is known as the "egg" code and is indicated by a number of ovals on the ice map, which indicate the ice for a given region. The number on the top line in the code, C, is the total ice concentration in tenths of aerial coverage. The numbers in the second row (C_a, C_b, C_c) indicate the concentrations (in tenths) of the three most dominant ice types. The ice thicknesses (S_a, S_b, S_c) are indicated in the third row and the ice forms (F_a, F_b, F_c) in the fourth row. Numbers outside of the egg indicate the types of ice in trace (<1/10th) amounts. Details of ice thickness and ice form codes are indicated in Table A-1. Note that the thickness codes for first year ice over 120 cm and old ice are followed by a ".". As an example, code G in Figure A-1 indicates that in the area to which G pertains, the total ice concentration is 6/10th, there are two ice types; 4/10th of ice thickness 10-15 cm ice in the form of "Big" floes, and 2/10 of 0-10 cm thick ice of "Undetermined" type.

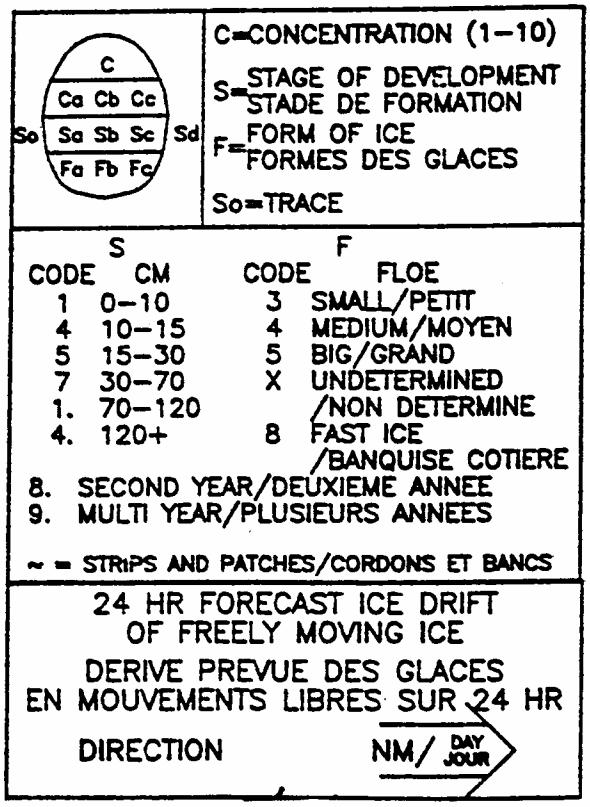

Table A-1: Ice codes used in the AES Ice Charts that follow

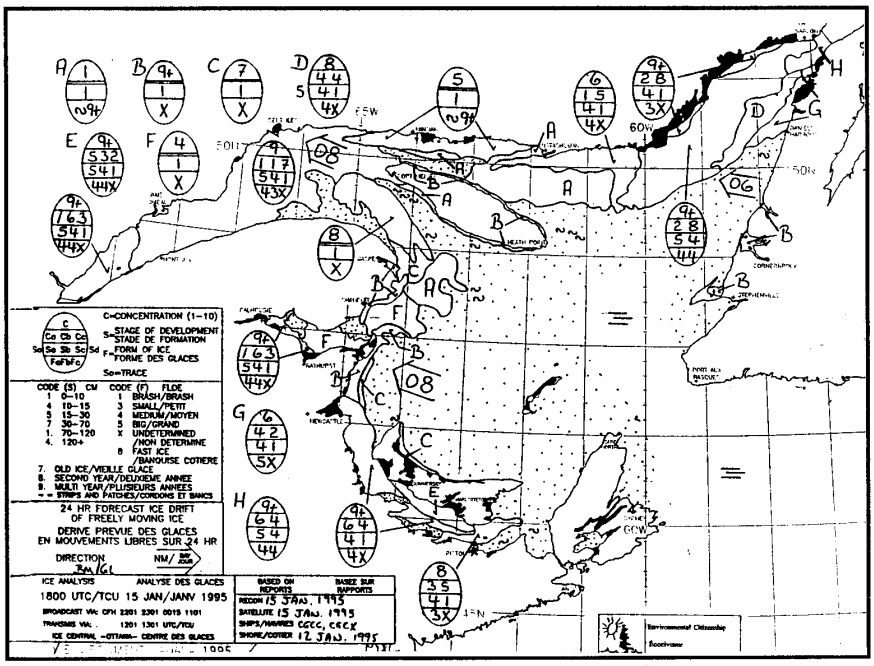

Figure A-1: Ice chart of 15th January 1995, showing wedge of open water along Newfoundland coast.

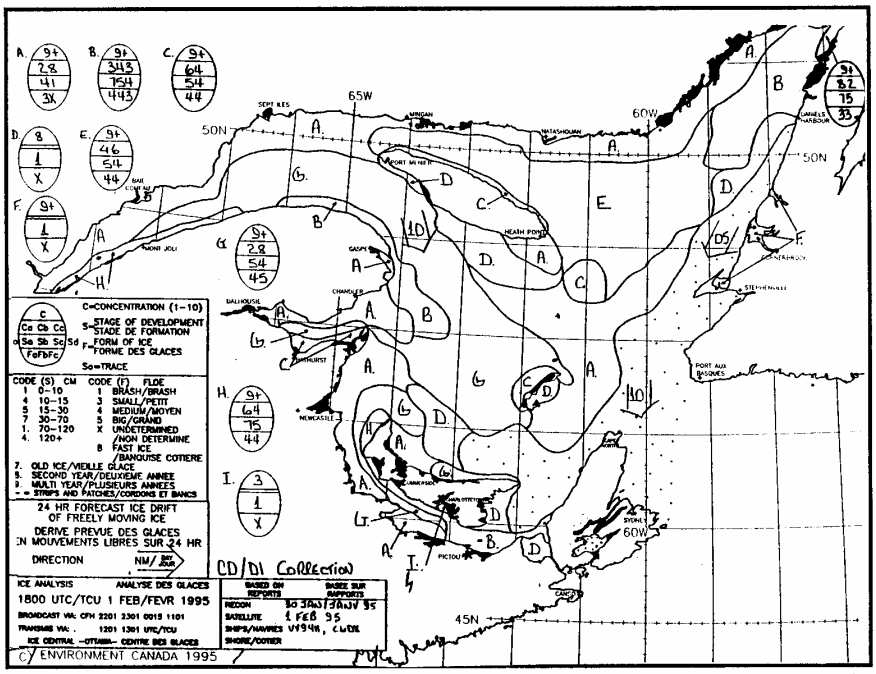

Figure A-2: Ice chart of 1st February 1995, showing ice development and restriction of open water along the Newfoundland coast.

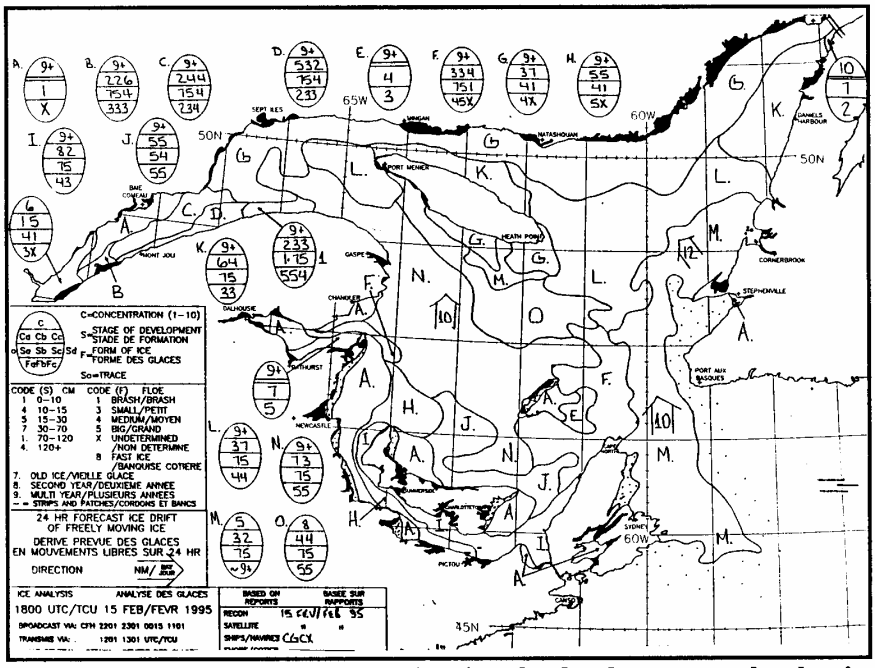

Figure A-3: Ice chart of 13th February 1995, showing the development and reduction of open water along Newfoundland coast.

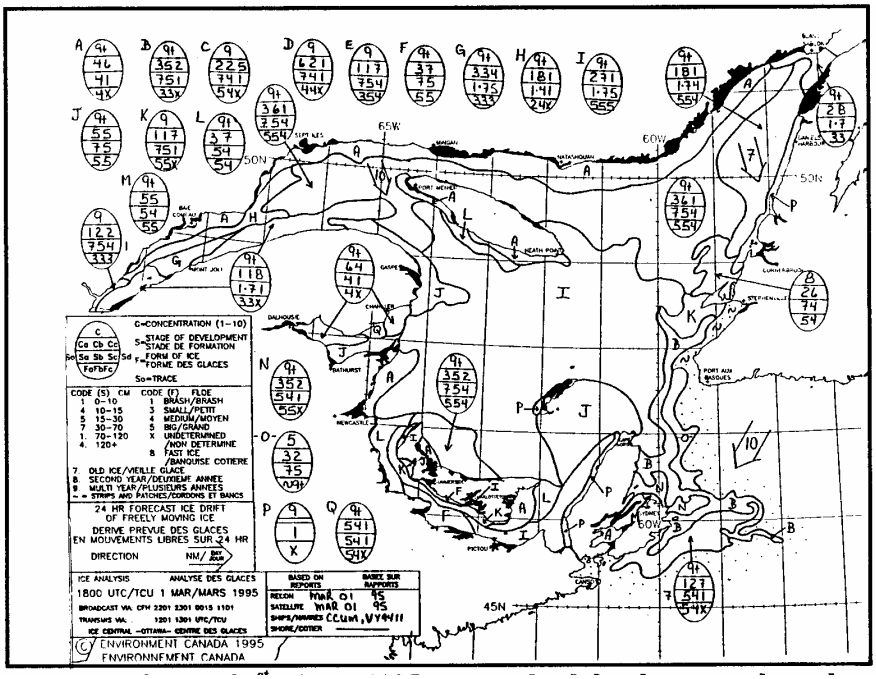

Figure A-4: Ice chart of 1st March 1995, narrow lead development along the Newfoundland coast.

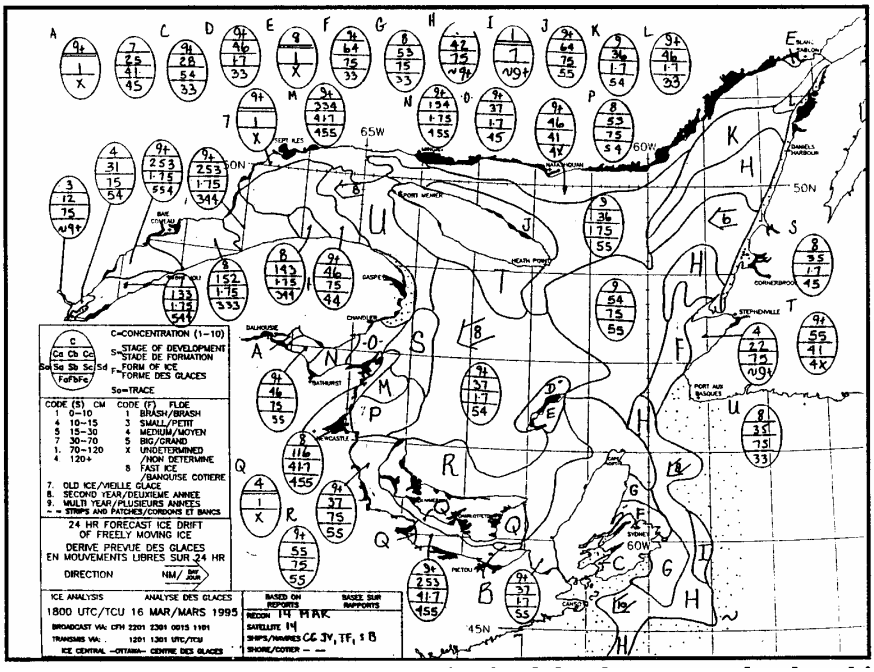

Figure A-5: Ice chart of 16th March 1995, showing lead development and reduced ice concentration along the West Newfoundland coast.

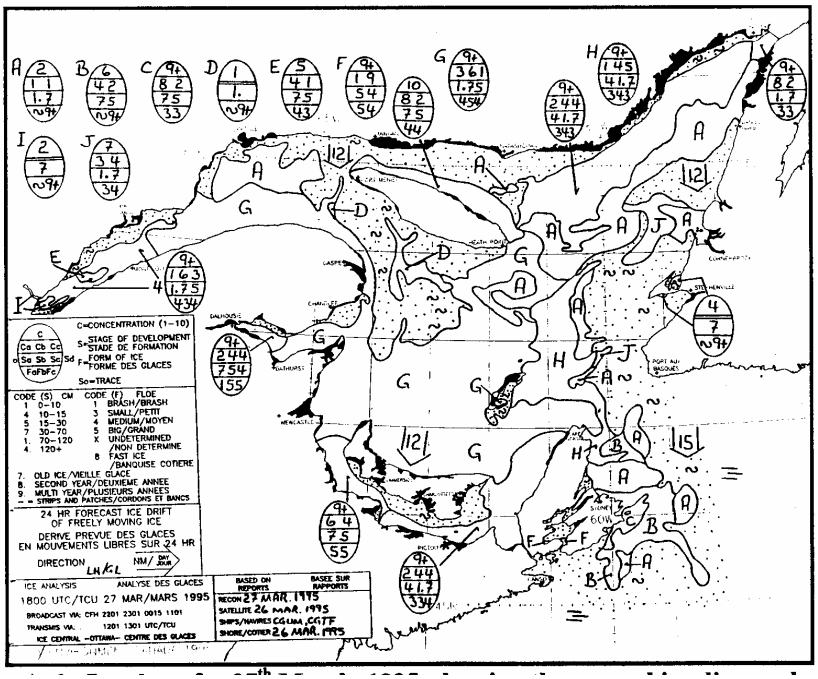

Figure A-6: Ice chart of 27th March 1995, showing the general ice dispersal.

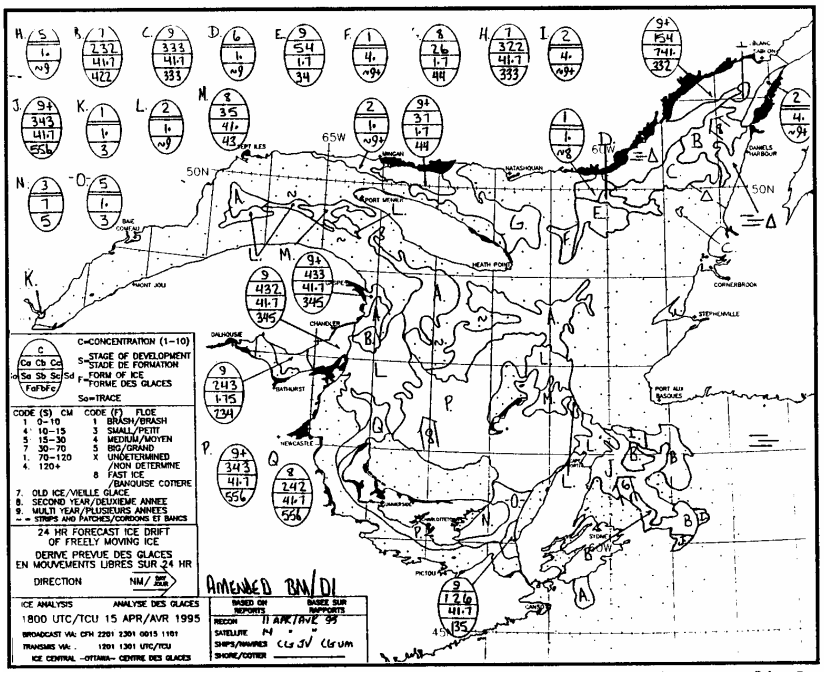

Figure A-7: Ice chart of 15th April 1995, showing ice clearance and evidence of iceberg incursion via Strait of Belle Isle.

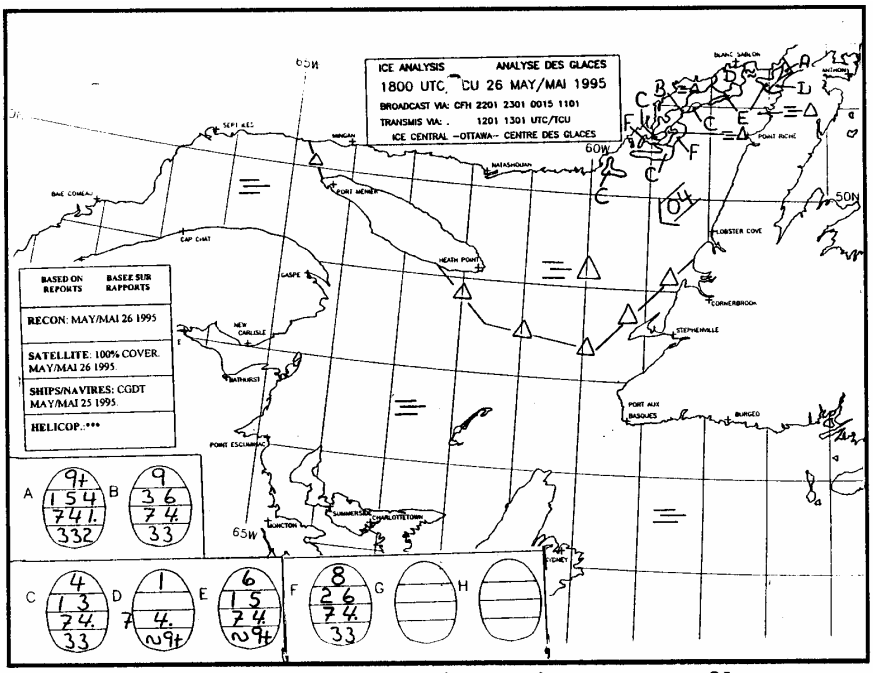

Figure A-8: Ice chart of 26th May 1995, showing maximum extent of bergy water.

A.2 Ice Season of 1995-1996

As in other years, ice in the area first formed at the end of December along the Quebec shore. A wedge of open water persisted off the West Coast of Newfoundland (chart of 1st February) until the first week of February when coastal areas north of Port au Port froze over or were invaded by offshore gray and gray-white ice (chart of 6 February). Off Daniel's Harbour, 2-tenths of the observed ice concentration was thin first-year. The thickest ice occurred in mid-channel, with new ice observed along the Quebec shore.

At mid-February, a discontinuous wedge of open water formed offshore, interrupted by gray ice concentrations off the Bay of Islands (chart of 15 February). At the end of February, a very broad area of open water and very open pack concentrations (3-tenths and less) developed along the West Coast (chart of 28 February). Concentrations of gray, gray-white, and thin first-year ice increased within a week, leaving a narrow lead of 2-tenths concentration along the central and northern coastal sectors and open water in St. George's Bay (chart of 7 March).

At mid-March, an open water lead formed on the Quebec shore while most of the Newfoundland coast faced a full cover of gray-white and thin first-year ice (chart of 15 March). On 22 March, a coastal lead had formed along the full length of the Newfoundland West Coast while mid-channel concentration had decreased to 8-tenths of gray-white and thin first-year ice. Ice continued to disintegrate and disperse thereafter, with a wide open water area present by 1st April. The first evidence of iceberg incursion via the Strait of Belle Isle was on 15 April when bergy water was interpreted off St. John Bay in the north of the coastal area.

The extensive mid-season clearance and lack of medium first-year ice thickness development marked 1995-1996 as an exceptionally mild ice year.

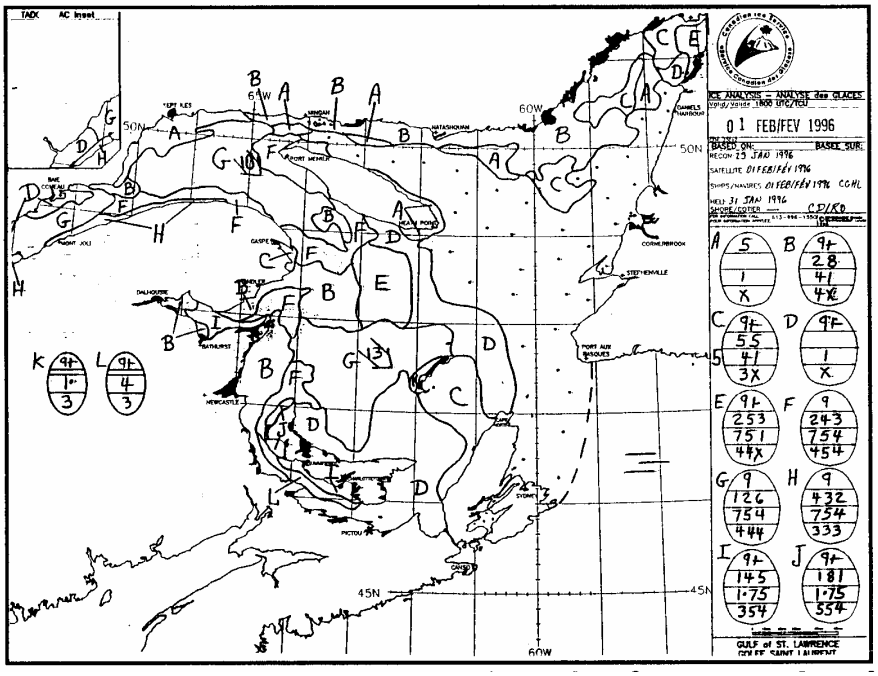

Figure A-9: Ice chart of 1st February 1996, showing wedge of open water along the Newfoundland coast.

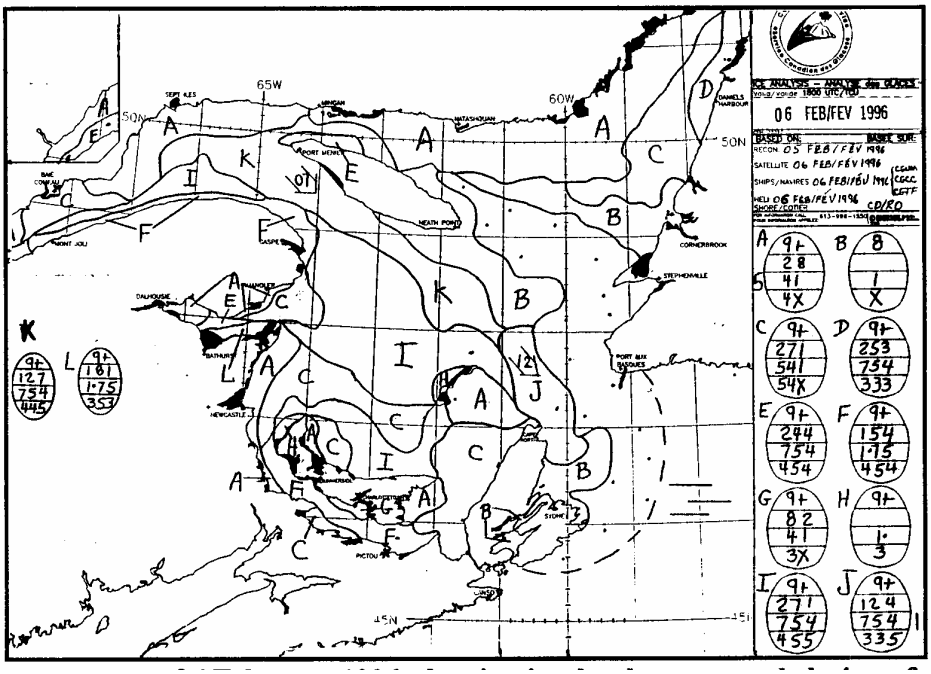

Figure A-10: Ice chart of 6th February 1996, showing ice development and closing of open water along the Newfoundland coast.

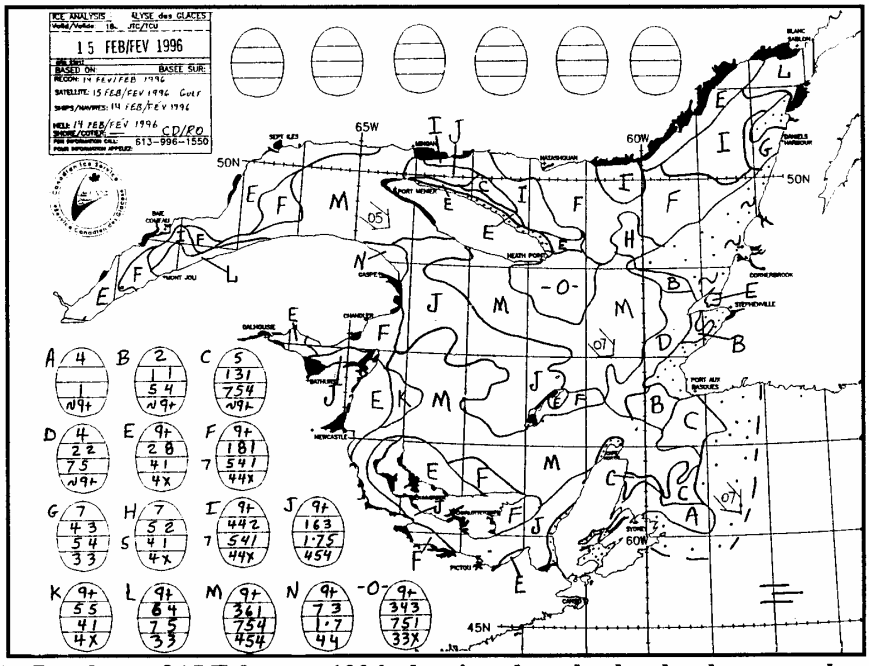

Figure A-11: Ice chart of 15th February 1996, showing shore lead redevelopment along the Newfoundland coast.

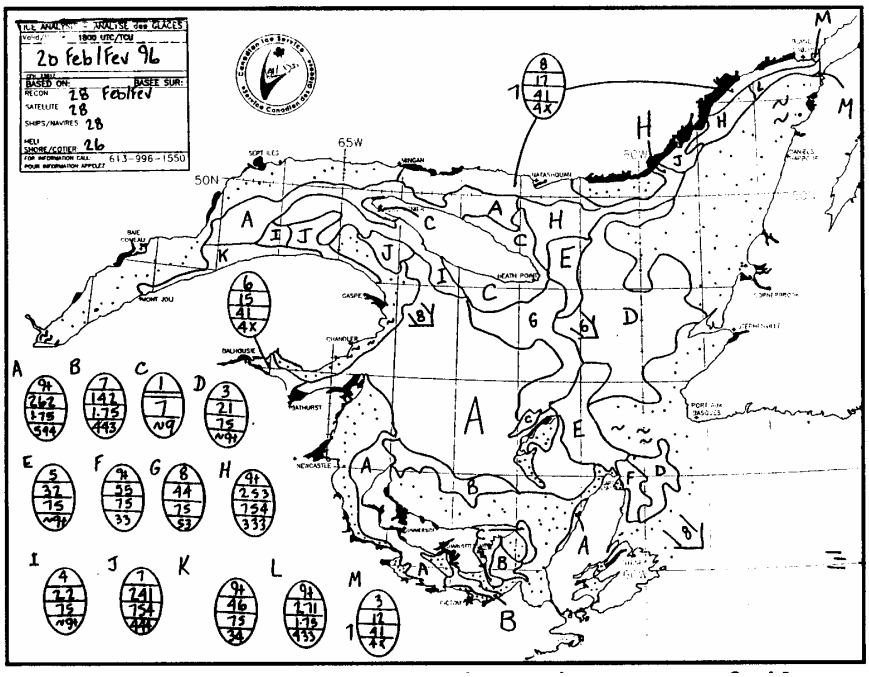

Figure A-12: Ice chart of 28th February 1996, showing maximum extent of mid-season ice clearance.

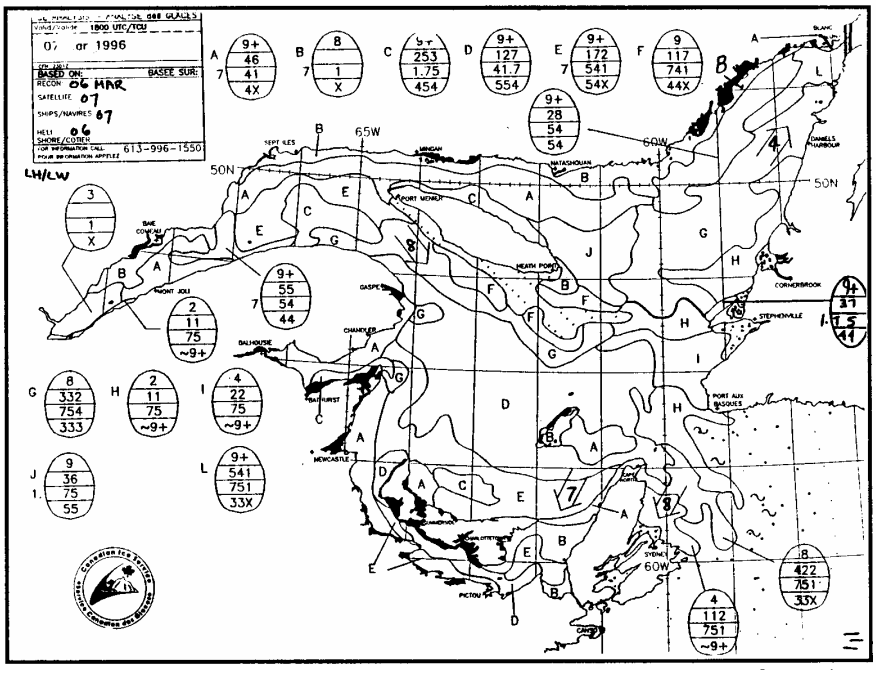

Figure A-13: Ice chart of 7th March 1996, showing ice cover redevelopment following open water episode.

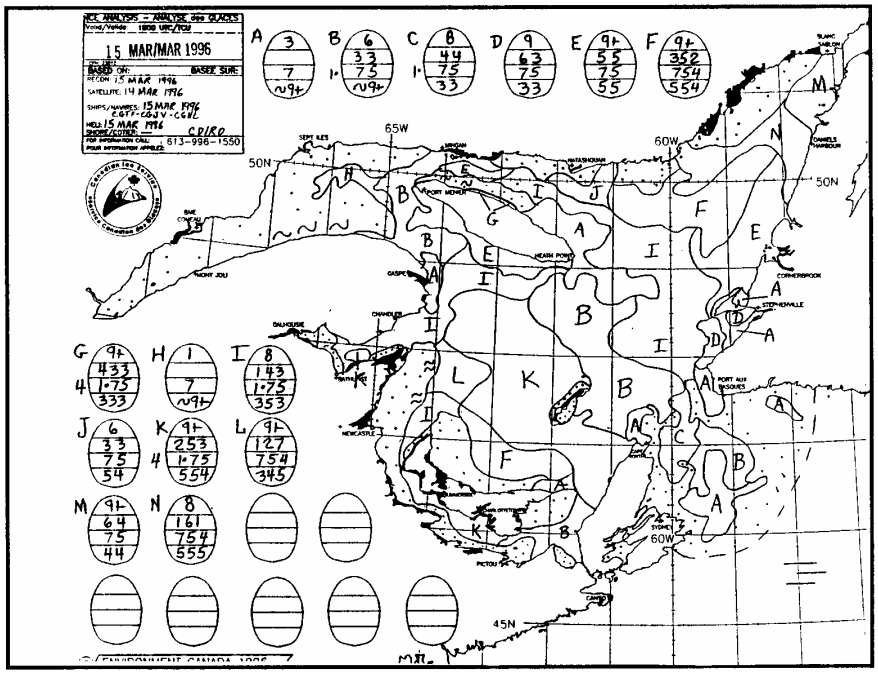

Figure A-14: Ice chart of 15th March 1996, showing late season ice development and lead on Quebec shore.

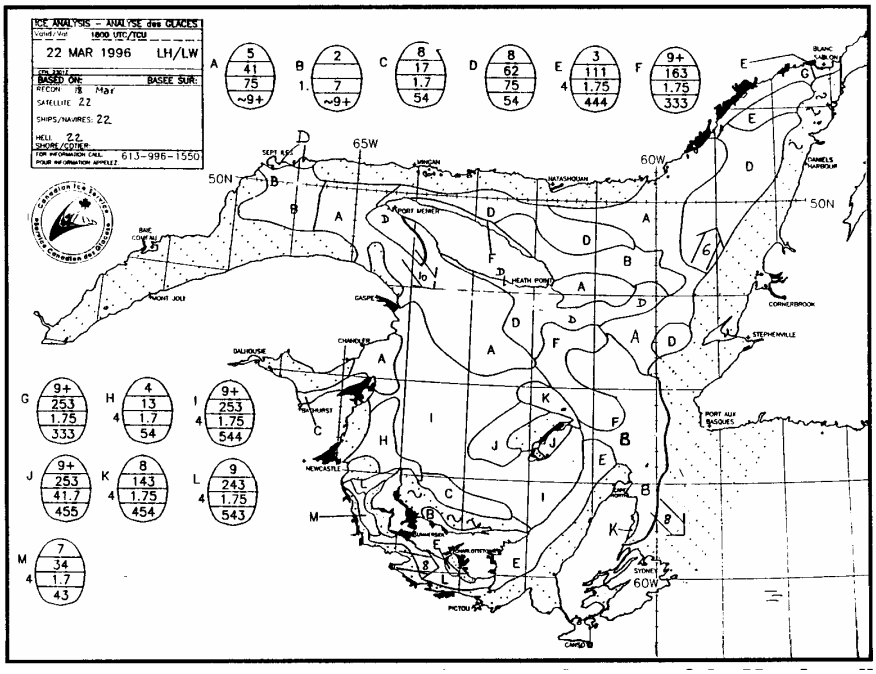

Figure A-15: Ice chart of 22nd March 1996, showing redevelopment of the Newfoundland coast shore lead.

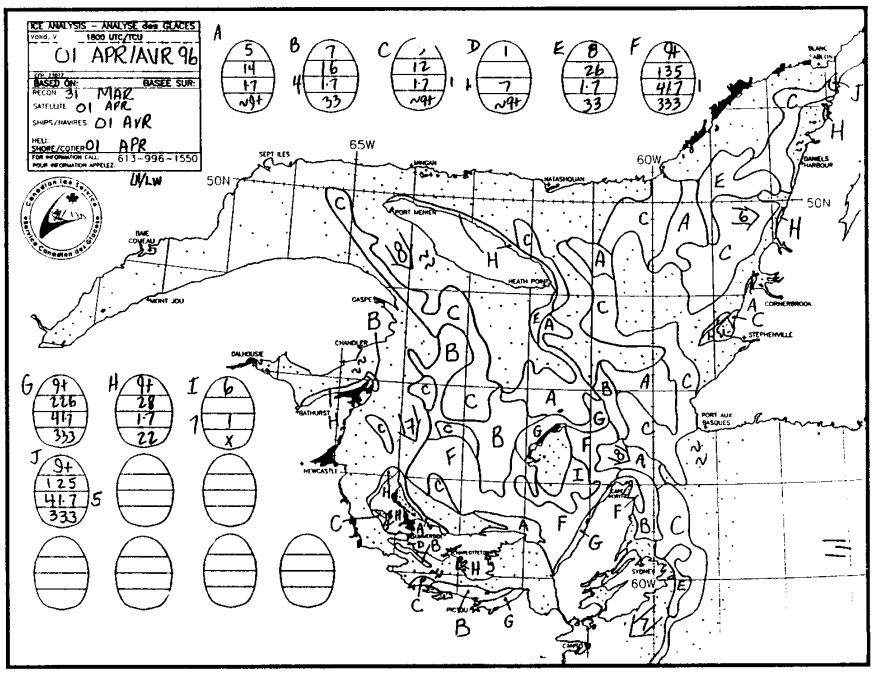

Figure A-16: Ice chart of 1st April 1996, showing pattern of final ice dispersal.

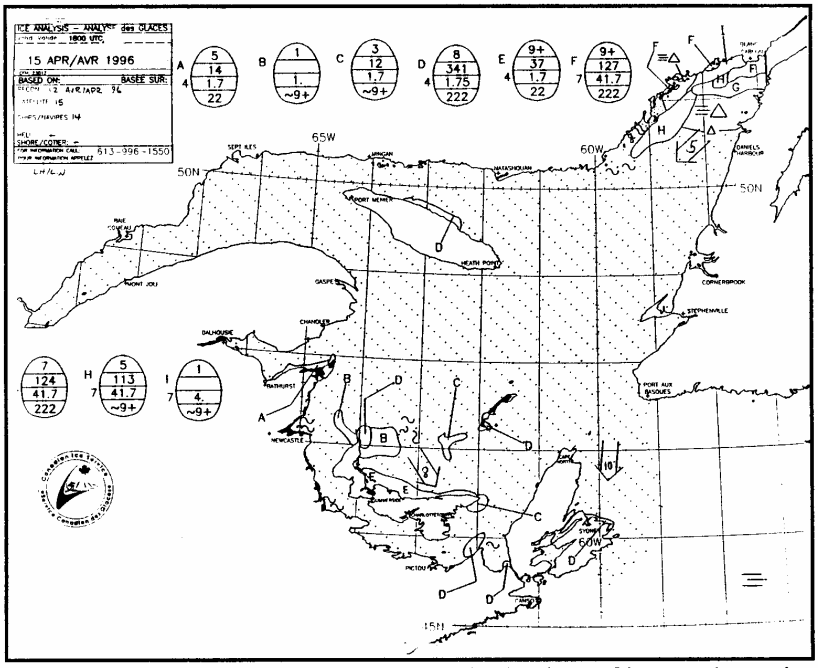

Figure A-17: Ice chart of 15th April 1996, showing first indication of iceberg incursion from Strait of Belle Isle.

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Abstract

A study of the available environmental data for the West Coast of Newfoundland has been carried out. Data have been obtained from a variety of sources, but there are limited in-situ measurements for the area of interest. Data for the area have been used where available, otherwise, generic data from other locations have been used to fill data gaps where possible. Tables summarize the major findings.

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