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ICE-SCOUR TRACKS ON THE BEAUFORT SEA
CONTINENTAL SHELF

- their form and an interpretation of the
processes creating them

by

Roland Vincent Wahlgren

A thesis submitted to the Faculty of
Graduate Studies in partial fulfillment
of the requirements for the degree of
Master of Arts

Department of Geography

Carleton University

Ottawa, Canada

1979

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The undersigned recommend to the Faculty of
Graduate Studies acceptance of the thesis

"ICE-SCOUR TRACKS ON THE BEAUFORT SEA
CONTINENTAL SHELF: THEIR FORM AND AN
INTERPRETATION OF THE PROCESSES CREATING
THEM"

submitted by Roland Vincent Wahlgren, B.A.

in partial fulfilment of the degree of Masters
of Arts.

J. Kenneth Torrance
.....
Supervisor of Graduate Studies,
Geography Department

Daniel B. Knight
.....
Chairman, Geography Department

Carleton University

January 29, 1979

ABSTRACT

Quantitative geomorphological analyses are made of ice-scour tracks created by drift ice scraping the seabed of the southeastern Beaufort Sea. The data consists of measurements from echograms and sonograph mosaics. Methods are developed for making the measurements. A classification scheme for ice-scour track planimetric form is developed. The results of the analyses include: grounding ice having less than 45 m draft usually does not dig further into the sediment as the ice keel proceeds upslope; keels approaching normal to the slope leave shorter tracks than keels which travel along the slope; ice floe interaction processes can explain the various planimetric forms of tracks; deep ice keel drafts and tracks are fairly rare events; and excess pore water pressure beneath a moving, grounded ice keel evidently can support negative buoyancy of the keel. The ice-scouring process is analysed using an energy flow model which is adaptable to computer simulation.

PREFACE

Ice-scour tracks on the seabed have become the object of increased attention over the past few years. This is because they provide unique evidence of ice keels having struck the seabed. Organizations involved in offshore hydrocarbon exploration, development, and production have a need to understand the magnitude of this hazard.

On a personal level, I first became aware of the existence of ice-scour tracks in 1974 offshore of the north coast of Somerset Island, N.W.T. while working as a student field assistant for the Geological Survey of Canada. It was not until September 1975, however, that an opportunity arose to help out with seabed surveys in the Beaufort Sea on board the M.V. Theta. This experience led to working several months in Ottawa for Dr. C.F.M. Lewis, helping to prepare analyses of ice-scour track data for the Beaufort Sea Project. Interest then developed in doing more detailed analyses for a Master's thesis project.

I would like to say, "Thank you!", to several people. The data analysed herein would not exist were it not for the efforts of the officers and crew of the M.V. Pandora II in 1974, the

M.V. Theta in 1975, and the C.C.G.S. Nahidik in 1978. Dr. C.F.M. Lewis greatly facilitated the completion of this project in numerous ways. I am extremely grateful for his interest in the project and the stimulating discussions we have had. My thesis supervisor, Professor J.P. Johnson, has been equally supportive of the work and has patiently critically read the chapter drafts and offered many helpful suggestions. S.M. Blasco of the Geological Survey of Canada explained to me various aspects of underwater acoustics and how to collect sonographs and echograms from a survey ship during the course of seabed surveys in 1977 and 1978 on board the C.C.G.S. Nahidik. He also took time out from his busy schedule to critically read Appendix A. D. Monahan of the Canadian Hydrographic Service, Ottawa, gave me helpful advice regarding the construction of the bathymetric overlays for the sonograph mosaics. J.M. Shearer, who collected the 1974 data used in this project, was always helpful and provided several stimulating discussions. Professor J.K. Torrance critically read a draft of part of the thesis and contributed several useful suggestions. Professor A.P.S. Selvadurai discussed with me soil mechanics as it pertains to ice-scour tracks. A. Pendlington, of the Geography Department staff, did a fine job of photographing record sections for inclusion as figures in this thesis. The typing was done expertly by D. Buie. A special thanks goes to the Arctic Petroleum Operators' Association for allowing me to reproduce the sonograph

mosaics and portions of the original records (permission via
J. Hnatiuk, 26 June 1978, Calgary).

Notwithstanding the excellent help given by all of the
above, I remain responsible for those shortcomings that exist
in this report.

Finally, but certainly not least, the moral support given
me by my parents and brother is most appreciated!

Ottawa, Canada

8 January 1979

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CHAPTER 1

INTRODUCTION

1.1 Ice-scour tracks

Ice-scour tracks in sea floor sediments are known to be fairly common on certain areas of the continental shelves of the northern hemisphere. The features may range in scale from minor furrows (volume less than one cubic metre) caused by grounding of small ice floes in the nearshore zone to major features caused by sea ice pressure ridge keels and icebergs contacting the sea floor and displacing hundreds or thousands of cubic metres of unconsolidated sediment. The best impression of their form and distribution comes from side-scan sonar imagery (figure 1.1). In several instances this data has been supplemented by echo-sounding records (figure 1.2) and diving observations (figure 1.3).

1.2 Scope of Study

This thesis will examine ice-scour tracks occurring below sea level on the Beaufort Sea continental shelf (see map, figure 1.4). These features provide the best available evidence of the forces involved when ice hits the sea floor. From characteristics of the tracks the ice impact hazard for sea

la.

2

0 1 km

Figure 1.1 Side-scan sonar records, obtained in 1974 by the Geological Survey of Canada, using an EG&G Mark 1B system, were assembled in a mosaic to form this planimetric image of the seabed in water depths of 35 to 42 m on the eastern slope of the Mackenzie Canyon (shallower water towards the east of the image). Numerous ice-scour tracks are visible on the mosaic. The tracks crossing the ship's survey line between 'X' and 'Y' are shown in cross-profile in figure 1.2 and are identified by letter labels. The narrow, light grey strips are regions of no side-scan signal return beneath the path of the side-scan sonar towfish. North is to the right of the image. Only a portion of the complete 'East Mackenzie' mosaic is shown in this figure.

An appreciation of the dimensions of the ice-scour tracks in this area of the Beaufort Sea can be obtained by noting that many of the features shown in this figure are 10 to 30 metres wide and about 0.5 to 1 m deep. An observer standing in the middle of a typical track would have a similar impression of dimension to that which would be experienced by a person standing in a two or four lane highway which is sunken 'knee-high' to 'waist-high' below the surrounding terrain.

1c.

Figure 1.2 The 30 kHz Krupp Atlas-Deso 10 echo-sounder record shown above corresponds to the seabed profile between the points 'X' and 'Y' that are indicated on figure 1.1. The tracks can be correlated between the two types of record as indicated by the labels 'A' to 'L'. Note the relatively deep sub-bottom penetration that was obtained into the soft muds that prevail in this region. Vertical exaggeration is 36 times the horizontal scale.

Figure 1.3 SCUBA diver's view of an ice mass that has ploughed into unconsolidated sediments in Byam Martin Channel. Water depth is 15 m. The embankment is about 80 cm high. (Photo GSC 202842-Q by P. McLaren, Geological Survey of Canada; courtesy of P. McLaren).

Figure 1.4 Bathymetry of the continental shelf of the Canadian Beaufort Sea (from C.H.S. Beaufort Sea Plotting Base). The three Geological Survey of Canada side-scan sonar mosaic areas are labelled: (1) 'East Mackenzie', (2) 'Pullen I.', (3) 'Elf'.

floor installations can be quantified. Depth, width, and length measurements of ice-scour tracks can be used to estimate volumes of sediment disturbed while an ice keel is excavating the seabed. In turn, the energy required to move the ice keel can be estimated, thereby relating the hazard to certain combinations of wind direction, ice conditions, and ocean currents.

1.3 Relevance of study to the offshore petroleum exploration industry in the Beaufort Sea

Offshore drilling in the Beaufort Sea during the summer of 1977 gave encouraging shows of oil and natural gas according to an article in Oilweek (October 10, 1977, p. 8). The article also stated that there exist two transportation alternatives for the natural gas; undersea pipelines or tankers carrying liquified natural gas.

If a pipeline is used to transport oil or gas from offshore fields to the coast, an analysis of the economics of pipeline construction will have to include, for example, a consideration of the following factors:

- (1) the minimum safe depth of burial of wellheads into the seabed (refer to figure 1.5).
- (2) the minimum safe depth of burial of a pipeline into the seabed.
- (3) safest route for the pipeline; taking into consideration bathymetric features offering protection from ice keels.

Drillship system showing method of protection against bottom scouring by ice.

Figure 1.5 Drawing of a buried wellhead system (from Ross, Logan, Rowland, and Milne, 1977, figure 2).

(4) the predicted ice keel impact rate per unit length of a pipeline running across the continental shelf in order to determine the spacing of cutoff valves in the pipeline.

In order to provide safe design criteria, the processes responsible for formation of tracks in the seabed by ice keels must be understood as fully as possible.

1.4 Relevance of study to other fields of research

Reworking of the Beaufort Sea shelf sediments by grounding ice keels has important consequences for various studies of the seabed.

Biological studies, for example, must take into account the fact that those portions of the Beaufort Sea continental shelf that are being affected by ice keels ploughing into the sediments will have their productivity and benthos distribution altered. Box cores taken on the Alaskan shelf (Barnes and Reimnitz, 1974) showed little evidence of bioturbation if the cores were from zones where ice-scour tracks were common. Fauna and evidence of bioturbation were found, however, in cores taken from zones on the shelf where ice-scour tracks were not as prevalent. Another study on the Alaskan shelf between Prudhoe Bay and Barter Island concluded that the "Evidence shows that ice gouging seriously disrupts the shelf environment and probably increases the variability of the in-faunal communities" (Carey, Ruff, Castillo and Dickinson, 1974, p. 678).

Sedimentological studies of the seabed must take the ice-scouring process into account. If the stratigraphy of mud layers is disturbed then radiocarbon dates from shells found in a disturbed layer cannot be relied upon when estimating sedimentation rates.

Geomorphological features observed in other areas such as dry glacial lake beds and uplifted marine nearshore areas may be explainable in terms of ice-scouring of sediments. For example, a review of the literature shows that many authors have attributed contorted strata in unconsolidated sediments to the action of grounding ice (e.g., Geikie, 1874; Salisbury and Atwood, 1897; Kindle, 1917; and Brenner, 1939). The origin of many involutions or contorted strata remains a subject for debate (Washburn, 1973, p. 147-149). Those features that can, however, be linked to ice-scouring of lake-beds or seabeds could give a better understanding of the paleo-environment (e.g., currents and winds) at the time of scouring. Such information on the environment could help clarify the origin of other geomorphological features in the vicinity of the 'fossil' ice-scour tracks.

A further value of a study of ice-scour tracks is that it can aid in reconstructing events during the Pleistocene deglaciation such as rise of sea level and extent of shorelines (cf. King, 1976).

1.5 Character of this study

The present study of ice-scour tracks is believed to be unique because it is based on the interpretation of side-scan sonar mosaics covering a substantial portion of ice-scoured seabed. The mosaic areas are shown on figure 1.4. Only the 'East MacKenzie' and 'Pullen Island' areas are discussed in this report because only for these two areas were the mosaics of relatively high quality. In addition; the original records were readily available. Previous studies have made use of side-scan sonar records in their original form which contain unavoidable planimetric distortions. The total length of most tracks could not be determined from these records because of the limited amount of seabed image recorded on either side of a ship's survey line.

The side-scan sonar mosaics are comparable to air photo mosaics. Some 'ground truth' is available, in the form of other researcher's scuba diving observations and core samples, which give confidence that the features being studied were indeed caused by ice ploughing into the seabed. This is important because there exist seabed features which superficially resemble ice-scour tracks but which are formed by current action (cf., Belderson et al., 1972 and Hollister et al., 1974). Other remote sensing methods such as echo-sounding aid in interpreting the side-scan sonar mosaics.

The mosaic interpretation along with reference to echo-

sounding records obtained simultaneously with the side-scan records offers information on the morphology of the ice-scour tracks. The next step after the interpretation is to form hypotheses about processes that could have caused these forms to occur. The method of multiple working hypotheses is used (Chamberlin, 1890). Several hypotheses have already been proposed in the literature and each of them can be placed in a systems analysis framework whereupon it can be determined if real data input produces realistic output. If a realistic output is not achieved, there is probably a fault in the hypothesis being examined. Ultimately, a single, best hypothesis incorporating both new and existing results with the results of this analysis of the Beaufort Sea side-scan sonar mosaics can be presented. A major goal is to understand the energy transfer process from the sea surface to the seabed during the ice-scouring process.

CHAPTER 2

HISTORICAL PERSPECTIVE

2.1 General statement

Before discussing the writer's investigations of ice-scour tracks on the Beaufort Sea continental shelf, the development of knowledge of the effects of floating ice on seabeds and lakebeds will be reviewed chronologically along with an outline of events leading to recognition of the need to have this information. This review is intended to be similar to an annotated bibliography in order that an easily accessible source of historical information on the topic of ice-scour tracks be available to the interested reader.

In the mid-nineteenth century, geologists were abandoning the diluvial hypothesis (Charlesworth, 1957, p. 618) and modern geological concepts were beginning to be introduced. Before 1970, the relatively sparse literature shows varying degrees of understanding of the origin of features that now readily can be attributed to the action of floating ice on subaqueous sediments.

The literature dealing with ice-scour tracks increased rapidly starting in 1970. This can be attributed to three

related events. In 1968, the vast amount of petroleum available from Alaska's North Slope was finally determined (Pimlott, Brown and Sam; 1976, p. 9). This made it necessary to face the problem of transportation of the petroleum to market. One solution envisaged was the use of supertankers as exemplified by the experimental voyage of the oil tanker, Manhattan, in 1969. During the voyage, the lack of bathymetric information in the Beaufort Sea caused concern when abrupt shoaling along the ship's route was encountered (Shearer, McNab, Pelletier and Smith, 1971, p. 816). In 1970, therefore, the Canadian Hydrographic Service began a comprehensive bathymetric survey program in the Beaufort Sea. Concurrently, the Canadian Department of Energy, Mines and Resources began a study of the marine sediments in the Beaufort Sea (Shearer et al., 1971). This latter study was the first to use side-scan sonar equipment in the Beaufort Sea.¹ The sonographs showed clearly that the microrelief that had been noted on earlier echograms was due to long curvilinear furrows on the sea floor (Pelletier and Shearer, 1972). Within the next five years, side-scan sonar surveys in various places in the Northern Hemisphere were showing that both relict and recent ice-scour tracks are not an uncommon geomorphic feature on continental shelves. The three-dimensional view afforded by side-scan sonar imagery made quantitative studies possible. Therefore most post-1970 papers on the subject are in marked contrast to the earlier papers.

¹ Side-scan sonar was first used by geologists in the late 1950's, according to Belderson et al., 1972, p. 2.

2.2 Extent of knowledge prior to observation of Beaufort Sea features by side-scan sonar in 1970

The earliest realization that floating ice impinging on subaqueous sediments is a significant geomorphological process was probably an outgrowth of the widespread acceptance, prior to the 1850's, of the concept of a universal flood (the biblical Deluge) having caused the till deposits in Europe. By the early nineteenth century, this concept had developed to include drifting icebergs dropping their sediment load as the agency responsible for the occurrence of till or 'drift' (Flint, 1971, Ch. 2). From this scenario of icebergs drifting on a worldwide ocean it was not an unlikely step for early geologists to speculate that grounding icebergs must modify the sea floor morphology.

Charles Lyell, who favoured the Drift Theory wrote:

Large islands and bergs of floating ice came from the north, which, as they grounded on the coast and on shoals, pushed along all loose materials of sand and pebbles, broke off all angular and projecting points of rock, and when fragments of hard stone were frozen into their lower surfaces, scooped out grooves in the subjacent solid strata (Lyell, 1845, v. 2, p. 83).

The reader should note that when Lyell was speaking of modification to solid rock he was attempting to use the Drift Theory to explain the occurrence of striae and grooves (which he observed just south of Lake Ontario) which modern geologists attribute to the action of a continental glacier. His explanation is, however, still valid insofar as unconsolidated

submarine and lacustrine sediments are concerned.

Lyell also made note of features on mudbanks in Nova Scotia in what is perhaps the earliest published reference to tracks observed to have been scoured into unconsolidated sediments by sea ice. He wrote:

Dr. Harding informed me that the surface of mudbanks along the estuaries near Wolfville, are often furrowed with long, straight, and parallel ruts, as if large waggons had passed over them. These conform in their general direction to the shore, and are produced by the projecting edges of irregular masses of packed ice, borne along by the tidal current (Lyell, 1845, v. 2, p. 147).

Flint (1971, p. 12) pointed out that the iceberg concept (Drift Theory), "... was promoted by an interest in polar exploration then rapidly expanding." The following quotation from Dr. Elisha Kane of the United States Grinnell Expedition to the Arctic whose narrative was published in 1857 shows an understanding of the geomorphological importance of floating ice:

The berg is beyond all doubt a most important agent in modifying the soundings upon the coast. The grounded bergs off Disco are known to leave troughs, plowed by their projecting tongues, as they float and ground with the rise and fall of the tides. Where the bottom is of mud and till, as is the case on the west coast generally, this action must be very marked ... (from Dana, 1857, p. 242, reviewing Dr. Kane's writings).

In his 1874 edition of The Great Ice Age and its Relation to the Antiquity of Man, the Scottish geologist James

Geikie (an advocate of the Glacial Theory) described vividly the effects of grounding icebergs (p. 72-73). Of even greater interest is his discussion of contorted beds of sediment observed near Edinburgh, Scotland some 10 m above sea level (elevation from Geikie p. 260-261). Geikie's figure 45, p. 267 is reproduced here as figure 2.1. Geikie stated that the contorted beds (approx. 1 m thick) are the result of grounding, "... coast ice and perhaps icebergs ..." (p. 266). He claimed that the irregular nature of the contortions argued against their being the result of landbased glacier ice (p. 266-267). It will be seen that references to contorted sediment layers occur fairly often in the literature. Often, grounding ice was invoked as the cause.

During the 1889 Western Arctic Cruise of the U.S.S. Thetis, a hydrographic survey was made of an area near Point Barrow, Alaska. This survey:

... demonstrated that the contour of the bottom is constantly changed by the ploughing and planing done by the heavy ice grounded and driven up by the pressure of the mighty ice-pack, under the influence of northerly winds and gales (Stockton, 1890, p. 182).

Salisbury and Atwood (1897) discussed their discovery of a relatively narrow (30 cm) band of contorted sand, silt, and clay strata between series of horizontal strata in the bed of an ancient glacial lake in Wisconsin. They said that:

The grounding of an iceberg on the surface before the overlying layers were deposited, or the action of lake ice may have been

Fig. 45.—Contorted beds: clay *c*, and sand *s*; Portobello. [Depth of cutting, 6 ft., J. Croll.]

Figure 2.1 Sketch of uplifted (approx. 10 m above sea level) contorted beds of sediments found near Edinburgh, Scotland. Structure was attributed to the effect of ice-scouring (from Geike, J., 1874, figure 45, p. 267).

responsible for the singular phenomenon
(Salisbury and Atwood, 1897, p. 143).

The narrowness of the band may cast doubt on their interpretation but nevertheless Salisbury and Atwood did show an awareness of the geomorphic effects of grounding ice.

Also in 1897, R.S. Tarr published a paper on sea ice as a geological agent in Greenland and Canadian Arctic waters (Tarr, 1897). He mentions bottom scouring by both sea ice (p. 223) and glacier ice (p. 226-227).

A rare example of a feature in metamorphic rock that may be due to ice-scouring in the Carboniferous or Permian period was provided by Lahee (1914). He described a contorted band of laminations in a slate series at Boston Harbor, Massachusetts and Lahee made the point that the contortions in the consolidated sediments were similar to contorted strata observed in a previously submerged sand deposit of Pleistocene age at Auburndale, Massachusetts. A better understanding of the effects of grounding ice on subaqueous sediments is clearly needed in order to prove or disprove Lahee's hypothesis and other such speculations regarding the origin of contorted sediment layers that appear frequently in the chronology.

A 1917 paper by E.M. Kindle contained reference to contorted sand beds (3 to 4 m thick) which he observed on the shore of Lake Erie near Port Rowan, Ontario. The disturbed beds were overlain by horizontal and cross-bedded sands. Kindle

conjectured that floe-ice and icebergs must have been present when the beds were deposited. He concluded that ice action is the reason for the appearance of the sand beds (Kindle, 1917, p. 334). It should be noted that Kindle was probably familiar with James Geikie's book although Kindle did not give it as a reference in making his conclusion.

In 1924, E.M. Kindle published a useful review of observations and work done to that date on floating ice as a geological agent in the Canadian Arctic. He discussed the formation of pressure ridges and also quoted (from Scoresby) an estimate of the force available in a large ice field as being 10^{10} tons (Kindle, 1924, p. 264). This is perhaps the earliest such quantitative estimate. He also claimed that the erosion accomplished by sea ice is, "... comparable with that of [land-based] glaciers" (p. 264).

Another relatively early consideration of iceberg scouring of the seabed is found in an article by Brenner (1939) in which he offered this process as an hypothesis for the origin of 30 to 40 cm thick contorted clay layers at two locations in eastern Finland. In his hypothesis, Brenner invoked a sea level 100 m higher than at present. He considered a typical iceberg, reaching 18 m above the waterline and having a draft of 100 m, as being responsible for the disturbance of the clay layers.

In 1951, L. Horberg presented a detailed discussion of the possible origins of "intersecting minor ridges" occurring in the glacial Lake Agassiz Basin in North Dakota. Most of the features Horberg described are now quite readily seen to be the products of grounding lake ice (Clayton, Laird, Klassen, and Kupsch, 1965) but unfortunately Horberg did not accept this possibility (Horberg, 1951, p. 15). Even the involutions (visible in cross-sections of the features) he described are very similar to the contorted sediment layers observed by earlier workers who hypothesized that grounding ice had caused involutions to occur.

A 1952 article criticizing Horberg's conclusions (Nikiforoff, 1952) also did not consider the possibility that the Lake Agassiz features are the remnants of ice-scour tracks. Nikiforoff's article serves as a reminder of how elusive the search can be for the correct geomorphological process to explain a feature. It is remarkable, however, that both Horberg and Nikiforoff did not seem to be aware of Salisbury and Atwood's article or Kindle's (1917) article on contorted sediment layers.

At this stage in the chronology, the increasing availability of echo-sounding records begins to influence the development of knowledge with regard to the processes creating ice-scour tracks.

Perhaps the earliest readily accessible discussion of microrelief on the Beaufort Sea floor is that by Carsola (1954). It is pointed out by Kovacs (1972, p. 101), however, that echograms were obtained from the Chukchi Sea as early as 1947, by the U.S.S. Nereus.

Carsola was concerned mainly with the microrelief that he observed in water depths of 60 to 400 m. He considered five hypotheses regarding their origin. These were:

1. Glacial deposition: moraines et cetera
2. Grounding of sea ice and icebergs
3. Sea ice melt deposits
4. Surface permafrost features
5. Mass movement (Carsola, 1954, p. 1596).

In his discussion of the second hypothesis, Carsola invoked lower sealevels during the Pleistocene and the presence of icebergs in the area in an attempt to explain the microrelief (p. 1597). He did not completely accept this explanation, however, because he felt that sedimentation and erosion could have removed traces of the impact of grounding ice (p. 1597).

For microrelief in shallower water (i.e., less than 40 m deep), however, Carsola appeared quite prepared to accept grounding ice as the cause (p. 1597).

Microrelief noted on echograms taken in water depths up to 50 m near Barrow, Alaska was described by Rex (1955).

He was probably the first to notice that the degree of development of microrelief in various water depths could be correlated with the distribution of pressure ridges in the sea ice cover.

Rex did consider other possible origins of the microrelief but came to the conclusion that "Pack ice grounding could cause the development of microrelief in a way that explains all the observed features" (p. 184). He noted that microrelief only extends out to the 30 m depth in his study area. This he attributed to the possibility that 30 m may be the greatest depth to which a pressure ridge keel can extend. Rex also made the point that ice disturbance of the sea bed is biologically significant (Rex, 1955, p. 185). The present writer is of the opinion that Rex' paper can be considered the first 'modern' attempt at explaining the process of sea floor disturbance by sea ice.

Ice-scoured sediments are also a phenomenon associated with fresh water bodies. Present-day and 'fossil' ice-scour tracks in Great Slave Lake and its surroundings were described by Weber (1958). Interestingly, his list of references did not include any of the work cited above. Weber hypothesized that the tracks were created by ice floes driven by the prevailing wind during spring breakup.

A 1965 paper by Clayton et al. (op. cit.) credited Weber with having made them realize that many of the Lake Agassiz features were likely to be the result of wind-driven lake ice

scouring the glacial lake floor. They did not, however, use ice-sediment interaction to explain the origin of the involutions described by Horberg (1951). Their origin seems to be an unresolved problem even now.

In 1967, Zenkovich's 1962 text on processes of coastal development was translated from the Russian. He dealt briefly with ice-scouring of the nearshore zone, writing as follows:

If ice covers an entire sea, or if a large gulf is frozen over, continuous wind action may lead to hummocking and great pressure of the ice on the shore. When this happens, compact masses of ice of great thickness in shallow water rest on the bottom and furrow it, or pile up detritus in front of them and move it shorewards (Zenkovich, 1967, p. 170).

Zenkovich noted that other investigators in the U.S.S.R. have reported modification of bottom relief by ice in the Laptev Sea, the northwestern Black Sea and in the northern Caspian Sea. Of the latter area, described by Koshechkin in 1958 he wrote:

In spring a profusion of trenches several kilometres long in the shallows of the northern Caspian is visible from the air. These forms have been produced in the silty and sandy bottom by large icefloes ... (Zenkovich, 1967, p. 172).

An interesting paper on tidal flat erosion by ice during spring break-up in the Middle St. Lawrence Estuary was published in 1969 by Dionne. The ice-scour tracks he described and presented photographs of (taken at low tide) are

remarkably similar in form to those later seen in the Beaufort Sea using side-scan sonar. The tidal flat ice-scour tracks are, however, at least an order of magnitude smaller in width than the tracks in the Beaufort Sea. Depths and lengths, however, do not appear to be very different from those of many tracks observed in the Beaufort Sea.

In his paper, Dionne claimed that erosion and transportation of tidal flat sediments by ice floes is a significant process involving "Millions of tons of sediments ..." annually (Dionne, 1969, p. 1179).

2.3 Recent research on ice-scour tracks

2.3.1 Canadian Beaufort Sea

The intensive survey of the Beaufort Sea in 1970 led to the first publication of a side-scan sonar record showing ice-scour tracks in the Beaufort Sea along with pingo-like features (Shearer, McNab, Pelletier, and Smith, 1971).

Pelletier and Shearer (1972) obtained a large amount of data from surveys in 1970 and 1971. The deepest ice-scour track that they observed had a relief of 10 m (p. 252). Tracks were often tens of metres wide and as long as 8 km (p. 252). In water depths less than 50 m the linear density of the features was observed to be 15 to 20 per kilometre. Further offshore, the density decreased considerably and beyond 75 m water depth no ice-scour tracks were seen on the records (p. 252).

The orientation of the tracks was also analysed. The dominant directions appeared to correspond to the westerly and north-westerly winds prevailing in wintertime. Pelletier and Shearer also discussed sea level changes influencing the areal distribution of ice-scour tracks, frequency of ice impact on the sea floor, and the ages of tracks. Estimates of sedimentation rates were utilized in discussing the ages of the tracks.

Further surveys were carried out in the Canadian Beaufort Sea in 1972 and 1974. Shearer and Blasco (1975) reported on their 1974 seabed surveys which utilized side-scan sonar, high frequency echo-sounding and shallow seismic reflection techniques. Their observations led them to speculate that solitary grounding ice floes are not responsible for the ice-scour tracks on the seabed. They suggested, rather, that ice-scour tracks are created by ice keels frozen into the polar pack and reasoned that such a process would account for the existence of multiple ice-scour tracks. These researchers also found that deeper basins on the continental shelf, which were often protected by shallow sills, were not as subject to being scoured by ice as were the surrounding areas. Regional variability in the morphology of ice-scour tracks observed in profile on echograms was also noted. Finally, valuable information on the interpretation of ice-scour tracks as seen on echograms and sonographs was provided by several record excerpts illustrated and described in the article.

A review of research by the petroleum exploration industry (Arctic Petroleum Operators' Association) and by the government in the Canadian Beaufort Sea was presented at the ninth annual Offshore Technology Conference (Houston, Texas) by Hnatiuk and Brown (1977). They gave the results of analyses of ice-scour track depths, widths, azimuths, and linear density (number of tracks per unit length of ship's survey line) and briefly interpreted these.

One of the most important reports of recent research on ice-scour tracks (Lewis, 1977b) presented new methods for estimating the seabed ice impact hazard. A method for prediction of extreme penetration depths into the seabed by ice keels was developed. This was done using extreme value statistics to analyze a large number of recorded ice-scour depths. Estimates were then made of the probability of ice striking seabed engineering structures placed at various depths below the sea bed. Lewis also discussed results of repetitive sea-floor mapping at a site in 15 to 20 m water depth north of Pullen Island (refer to Figure 1.4). The period of time required for ice keels to completely rework the seabed sediments in this area could range from 50 to 500 years according to Lewis. This is still the only such estimate available to designers of offshore structures in the southeastern Beaufort Sea. When Lewis plotted his extreme scour depth data versus water depth, a definite peak at the 47 m water depth became apparent. He pointed out that this agreed with submarine

observations of the depth of pressured ice keels and the maximum depth of keels predicted from considerations of ice mechanics. A method for determining the frequency of occurrence of ice impacts on the seabed was also presented. This method was based upon estimates of the sedimentation rate in various parts of the Beaufort Sea. An ice impact budget was described, namely:

$$\text{number of new impacts} = \left(\begin{array}{c} \text{number of tracks} \\ \text{infilled by} \\ \text{sedimentation} \end{array} \right) + \left(\begin{array}{c} \text{no. of new impacts} \\ \text{superimposed on} \\ \text{existing tracks} \end{array} \right)$$

2.3.2 Alaskan Beaufort Sea

American investigations of ice-scour tracks in the Alaskan Beaufort Sea have been carried out mainly in response to the increased petroleum exploration activity in the region. It should be noted that the environment in which ice-scour tracks occur is not identical in the Alaskan and Canadian Beaufort Seas, particularly with regard to sediment type and sea ice cover.

Studies were initiated during 1970 by the United States Geological Survey in the Prudhoe Bay area (Reimnitz et al., 1972). Diving observations were made around grounded ice masses and in areas where microrelief had been indicated on echo-sounding records. A radiograph of a core taken in ice-disrupted sediment (Reimnitz et al., 1972, p. 332) showed horizontal laminations overlain by disturbed strata similar to those described by J. Geikie (1874), Salisbury and Atwood

(1897), Lahee (1914), Kindle (1917), and Brenner (1939).

Kovacs' (1972) review article addressed primarily to the petroleum industry emphasized that the effects of grounding ice on the seabed have been known since at least the 1880's. His article provides a good overview of the Beaufort Sea environment and possible explanations for the formation of ice-scour tracks.

In 1974, the Arctic Institute of North America held a symposium on research conducted on the coast and shelf of the Beaufort Sea. Three of the papers presented at the symposium dealt in considerable detail with the problem of pressured sea ice and ice islands striking the seabed.

Kovacs and Mellor (1974) examined the Beaufort Sea environment, discussed characteristics of the pressure ridge keels which would be expected to scour the seabed, and presented a mathematical model for the formation of ice-scour tracks by sea ice.

The other two articles, by Reimnitz and Barnes (1974) and Barnes and Reimnitz (1974) dealt with sea ice as a geological agent in the Alaskan Beaufort Sea. They were both extremely wide ranging articles, containing numerous hypotheses regarding the formation of ice-scour tracks. Interpretations were based mainly on side-scan sonar surveys, diving observations, bottom photography, coring operations, and high

resolution seismic reflection data. The diving observations described by Reimnitz and Barnes are particularly valuable as the 'ground truth' for the remote sensing methods that are usually more convenient to use in the study of ice-scour tracks. These researchers "... actually observed one gouge being produced and saw other fresh gouges leading to grounded ice" (p. 322).

Repetitive mapping of a portion of seabed in order to determine rates of addition of ice-scour tracks has been carried out by the U.S.G.S. north of the Colville River delta (just west of Prudhoe Bay). Data from water depths of 6 to 14 m indicated that in the two year period from 1973 to 1975, at least, the first 20 cm of bottom sediments was being scoured at a rate such that in 50 years all of the seabed sediments in the area would have been reworked (Reimnitz, Barnes, Toimil, and Melchior, 1977).

The relationships between seabed microrelief on the Alaskan Beaufort Sea continental shelf and sea ice zonation were discussed by Reimnitz, Toimil, and Barnes (1977). They considered the existence of four distinct ice zones. These were: (1) bottom-fast ice; (2) floating fast ice; (3) a grounded pressure ridge zone; and (4) the seasonal pack ice. They concluded that it is in the grounded pressure ridge zone that, "Much of the available marine energy is expended on the seafloor..." (p. 41). Furthermore, this energy expenditure,

"... is manifested in the high ice gouge density, deep ice gouges, and intensely disrupted internal sedimentary structures..." (p. 41).

2.2.3 Studies elsewhere in the Northern Hemisphere

Side-scan sonar and echo-sounding surveys in Western Lake Superior have shown that ice-scour tracks are present on the lake floor particularly in water depths from 54 to 165 m (Berkson and Clay, 1973). These tracks were regarded by these authors as being relict features, formed by icebergs calved from a lobe of the continental glacier.

In Lake Erie, present-day scouring of the lakebed by pressured ice keels is known to occur in water depths down to 20 m (S.M. Blasco, Geol. Surv. Can., pers. comm., 1978).

Diving observations and side-scan sonar surveys have shown that the nearshore zone along the east coast of Melville Island is affected by ice-scouring into the bottom sediments (McLaren, 1975; Taylor, 1976). The ice-scour tracks observed were up to 60 m long, 12 m wide and 2 m deep (Taylor, 1976, p. 56). Ice-scour tracks have also been noted along the southern shore of Barrow Strait in water depths down to 45 m (Taylor and Lewis, 1975, p. 506). Studies in Lancaster Sound off the south coast of Devon Island have revealed the presence of ice-scour tracks in water depths exceeding 150 m (Lewis et al., 1977, p. 499). The possibility exists that these

tracks were caused recently by icebergs.

The iceberg-scour tracks observed on the floor of the Labrador Sea have been discussed by Harris (1974), Harris and Jollymore (1974) and van der Linden et al. (1976). The paper by Harris and Jollymore is particularly valuable in that the authors set up a strict quantitative procedure for analysing orientation, width, and depth of the tracks.

Researchers at The Memorial University of Newfoundland have been conducting studies on iceberg-sediment interaction using laboratory models in order to develop a mathematical model for the ice-scouring process (Chari and Allen, 1972, 1973, 1974a, 1974b, and Chari 1975, 1977). The applicability of this model to the Beaufort Sea depends upon whether or not similar processes create sea ice-scour tracks and iceberg-scour tracks.

Ice-scour tracks in the northeastern Atlantic, west of the United Kingdom, were described by Belderson, Kenyon, and Wilson (1973). Side-scan sonar records showed tracks in water depths between 140 and 500 m. These the authors attributed to current-driven icebergs, associated with the last continental glaciation, ploughing into the continental shelf sediments.

Belderson and Wilson (1973) discussed their discovery of iceberg-scour tracks in water depths of 160 - 320 m in the

Norwegian Trough along the southern coast of Norway. These tracks were regarded by the authors as being relict. Many of the features were being buried by sediments according to interpretation of the side-scan records by Belderson and Wilson.

The effects of iceberg-scouring of the seabed in the fiords of Spitsbergen were summarized by Moign (1976, p. 56). Diving observations in water depths of 10 to 20 m revealed that ice keels had penetrated about 2 m into unconsolidated sediments. The tracks were 2 to 5 m wide and from 10 to 20 m long (Moign, 1976, p. 57). The rather short length of the tracks may be related to the relatively small size of the Spitsbergen icebergs. Typical maximum berg dimensions are 40 m long, 20 m wide and 10 m in height above the waterline (Moign, 1976, p. 52).

Ice-scour tracks and contorted sediment layers found on tidal flats of the German coast of the North Sea were described briefly by Reineck (1976). This article is significant because it showed that certain types of contorted sediment layers can result from the vertical pressure of a grounded ice mass.

Although Belderson, Kenyon, and Wilson (op. cit.) briefly discussed the implications of a study of iceberg-scour tracks for the interpretation of Glacial and post-Glacial events, King (1976) attempted a more quantitative analysis for similar features. He was using side-scan sonar information on the

characteristics of relict iceberg-scour tracks in the Laurentian Channel (in the eastern Gulf of St. Lawrence) and on the western Grand Banks. Partly by using information on the shallowest depth of occurrence of the tracks, King was able to evaluate the reliability of previously published sea level curves for his study area (King, 1976, p. 1089). This facilitated further interpretations of the region's glacial history.

Diving observations of ice-scour tracks east of Melville Island were made by McLaren (1977). These led him to propose a standard terminology for the seabed features caused by grounding ice. This is the terminology that was adopted by C.F.M. Lewis (1977a, b) with only some minor modifications such as hyphenating the words 'ice' and 'scour'. The present writer has also adopted this terminology along with Lewis' modifications. McLaren made diving observations in three different seabed environments (cobble bottom, shallow sandy bottom, sand-silt-clay bottom) located along the eastern coast of Melville Island and the western coast of Byam Martin Island. Stationary grounded ice masses and associated ice-scour tracks were observed thereby providing additional 'ground truth' for the origin of the tracks. On the basis of his having observed ice-scour craters at the end of ice-scour tracks, McLaren (p. 176) suggested that, "... small mobile ice blocks are capable of scouring the bottom significantly." This is contrary to the conclusion reached by Shearer and Blasco (op. cit.). McLaren also pointed out that the mathematical

models of Kovacs and Mellor (op. cit.) and Chari and Allen (op. cit.) are not realistic in that they assume that all the driving forces acting on an ice mass cease when grounding commences. Furthermore, McLaren claimed that the equations used to describe the ice-sediment interaction are only applicable to a stationary mass of ice resting on sediment rather than a moving ice mass ploughing into sediments. McLaren believed that the driving forces act during the scouring process and that the length of the ice-scour track is not related to dissipation of energy but depends on the ice keel strength and bathymetry of the region in which grounding occurs. He speculated that as soon as an ice mass begins to ground the pore water pressure in the surrounding sediment increases thereby decreasing the strength of the sediment and the coefficient of friction. Furthermore, McLaren thought that the fact that an ice-scour crater is usually deeper than the bottom of the track leading to it possibly could be explained by 'uplifting' or support of the ice mass as a result of the increase in pore water pressure during the scouring process (McLaren, 1977, p. 176). When the ice mass stops moving it would settle into the sediment because time becomes available for the expulsion of interstitial water and for consolidation of the sediment.

Reference to charts of Arctic Ocean bathymetry shows that the continental shelf north of the U.S.S.R. is several times wider than the shelves elsewhere in the world. This should vastly increase the chances of formation of ice-scour

tracks on the continental shelves of the Chukchi, East Siberian, Laptev, Kara, and Barents Seas. Features similar to those on the Beaufort Sea continental shelf must undoubtedly occur (cf. Zenkovich, op. cit., p. 170). Mackay (1972) pointed out that echograms from the Laptev-East Siberian Seas published in Kluiev (1965) resemble echograms of ice-scour tracks in the Beaufort Sea. Kluiev, however, considered the microrelief he observed to be thermokarst features. Using the scale given for figure 5 (p. 867) in the Soviet article, the largest ice-scour track in that excerpt of record was found to extend 4 m below the undisturbed sea floor and its apparent² width was 60 m. Several other ice-scour tracks extend about 2 m into the seafloor and have apparent widths of 30 to 40 m. These dimensions are fairly typical of the tracks observed on the Beaufort Sea shelf.

The general lack of attention in the Soviet literature given to ice-scour tracks suggests that Arctic offshore petroleum exploration and hence detailed examination of bottom morphology is not a priority for the U.S.S.R. at this time. In a recent issue of the Oil and Gas Journal, Auldrige (1977, p. 72) stated that the "... Soviet Union is not confronted by a severe near-term shortage of hydrocarbons, let alone an energy crisis." An article by Meyerhoff (1977) in the same issue made the point that many onshore oil and gas

² 'apparent width' because it is not known at which angle the ship's track crossed the furrow.

basins in the U.S.S.R. remain to be developed. Meyeroff did discuss Arctic offshore prospects, however. He stated that in the Barents Sea (and the other Seas north of the Siberian coast) offshore prospects for oil and gas are good but, "... the icepack and lack of offshore technology have prevented the Soviets from exploiting the offshore except for a single well drilled on Kolguyev Island" (Meyerhoff, 1977, p. 78). It appears therefore, that in the future, North American expertise in quantifying ice impact hazards for petroleum exploration and production in ice-infested waters may be in demand by the U.S.S.R.

2.4 Summary

Lest the reader think that this literature review has been particularly extensive it must be pointed out that the publications cited have dealt only with the end product (the ice-scour tracks) of a complex natural process. There is another important body of literature dealing exclusively with floating ice and its response to wind and current stress. Pertinent examples of that literature will be referred to later in this thesis.

Ice-scour tracks appear to be unique geomorphic features that are widely distributed in the northern hemisphere (see figure 2.2 and Table 2.I). Individual tracks cover a wide range of spatial scales depending upon the magnitude of the processes creating them. It was found that features with

Figure 2.2 Map of Northern Hemisphere showing locations of ice-scour features cited in literature review. Symbols indicate recent ice-scour tracks (∇), relict ice-scour tracks ($\blacktriangledown$), and features that may be the result of disturbance of sediments by grounding ice (e.g., contorted clays) ($\bullet$). Please refer also to Table 2.1.

Table 2.I Locations of observed recent ice-scouring of seabed (▽), relict ice-scour tracks (▼), features that may be result of ice disturbance of sediments (e.g., contorted clays) (●).

Map reference (figure 2.2)	Location	Remarks	Reference (in order of appear- ance in text, chapter 2)
▽ 1	Wolfville, Nova Scotia	Ice-scour tracks created by ice floes on mudflats	Lyell (1845, v.2, p. 147)
▽ 2.	Disko, Greenland	grounded icebergs	Kane, in Dana (1857, p. 242)
● 3	Edinburgh, Scotland	1 m thick con- torted unconsol- idated strata 10 m a.s.l., iceberg caused (?)	Geikie, J. (1874, p. 267)
▽ 4	Point Barrow, Alaska	sea ice modif- ication of seabed	Stockton (1890, p. 182)
● 5	Baraboo, Wisconsin	30 cm band of contorted unconsolidated strata in glacial lake bed	Salisbury and Atwood (1897, p. 143)
● 6	Boston Harbour, Mass. Auburndale, Mass.	contorted band in Carboniferous or Permian slate contorted strata in Pleistocene sand deposit	Lahee (1914)
● 7	Port Rowan, Ontario	3 to 4 m thick contorted sand beds on shore of Lake Erie	Kindle (1917)

Table 2.I (cont'd)

Map reference (figure 2.2)	Location	Remarks	Reference (in order of appear- ance in text, chapter 2)
● 8	Eastern Finland	40 cm thick con- torted clay layers	Brenner (1939)
● 9 ▼	Glacial Lake Agassiz	'fossil' ice-scour tracks and assoc- iated (?) contorted unconsolidated strata	Horberg (1951)
▽10	Beaufort Sea		Carsola (1954)
▽11	offshore of Barrow, Alaska		Rex (1955)
▽12 ▼	Great Slave Lake	'fossil' and present day tracks caused by wind driven lake ice	Weber (1958)
▼13	Glacial Lake Agassiz		Clayton, Laird, Klassen, and Kupsch (1965)
▽14	Laptev Sea	modification of bottom relief by ice has been noted	Zenkovich (1967)
▽15	NW Black Sea		
▽16	N. Caspian Sea		
▽17	St. Lawrence Estuary	ice floes scour tidal flat during ebb tide	Dionne (1969)
▽18 ▼	Canadian Beaufort Sea	recent and relict tracks caused by pressured sea ice and ice islands	Pelletier and Shearer (1972) Shearer and Blasco (1975) Hnatiuk and Brown (1977) Lewis (1977 b)

Table 2.I. (cont'd)

Map reference (figure 2.2)	Location	Remarks	Reference (in order of appear- ance in text, chapter 2)
▽19 ▼	Alaskan Beaufort Sea (Barter Island) (Prudhoe Bay) Alaskan Beaufort Sea	recent and relict tracks caused by pressured sea ice and ice islands	Reimnitz et al. (1972, p. 324) Reimnitz et al. (1972, 1977) Kovacs and Mellor (1974) Reimnitz and Barnes (1974) Reimnitz, Toimil, and Barnes (1977)
▼ 20	W. Lake Superior	'fossil' ice-scour tracks	Berkson and Clay (1973)
▽21	Lake Erie	ice-scouring by wind driven ice	S.M. Blasco, G.S.C. (pers. comm., 1978)
▽22	E. coast Melville I.	recent tracks	McLaren (1975, 1977) Taylor (1976)
▽23	S. shore Barrow Strait	recent tracks	Taylor and Lewis (1975, p. 506)
▽24	Lancaster Sound	present day (?) iceberg scour tracks	Lewis et al. (1977, p. 499)
▽25 ▼	Labrador Sea	iceberg scour tracks both recent and relict	Harris (1974), Harris and Jollymore (1974), van der Linden et al. (1976), Charl- and Allen (1972, 1973, 1974 a, 1974 b), Charl (1975, 1977)

Table 2.I (concluded)

Map reference (figure 2.2)	Location	Remarks	References (in order of appear- ance in text, chapter 2)
▼26	NE Atlantic	relict iceberg scour tracks	Belderson, Kenyon, and Wilson (1973)
▼27	Norwegian Trough	relict iceberg scour tracks	Belderson and Wilson (1973)
▽28	Spitsbergen	recent iceberg scour tracks	Moign (1976)
▽29 ●	North Sea, Germany	ice-scour tracks and contorted sediment layers on tidal flats	Reineck (1976)
▼30	Gulf of St. Lawrence and W. Grand Banks	relict iceberg scour tracks	King (1976)
▽31	Laptev-East Siberian Seas	ice-scour tracks (?)	Kluiev (1965)

a

similar morphology can be caused by the largest icebergs that strike the seabed as well as by small ice floes grounding on tidal flats. Knowledge to date suggests that similar physical processes operate at all scales. Therefore a study of Beaufort Sea ice-scour tracks must draw on all the available literature, not just that concerned with pressured sea-ice, for example.

The ice-scour tracks provide a good example of a geomorphic feature that was for a long time only of academic interest but which suddenly has become of 'commercial' importance. Now the Arctic offshore petroleum exploration industry and the governments responsible for Arctic continental shelf areas are urgently demanding detailed, quantitative information regarding the ice impact hazard associated with the origin of the tracks.

Interestingly, the growing practical value of the study of ice-scour tracks is stimulating progress in the academic study of the features (e.g. Pleistocene chronology).

The level of detail of the studies cited was noted to be quite dependent on the technology (echo-sounding, side-scan sonar, SCUBA diving, seismic reflection, etc.) that was available to the researcher.

Finally, it is noteworthy that during the development of knowledge regarding ice-scour tracks it took a relatively long time for the connection to be made between the same type of

features when they were found in different environments
(e.g. Great Slave Lake and Glacial Lake Agassiz).

CHAPTER 3

GOALS, DATA SOURCES, AND METHODOLOGY

3.1 Goals

This chapter is designed to set the present study in perspective in relation to the work which was reviewed in the preceding chapter.

One of the goals of this study is to develop methods for the quantitative analysis of ice-scour tracks on the seabed that are observed by means of side-scan sonar and high frequency echo-sounding techniques. Previous studies have usually presented results derived from analyses of survey lines across the seabed. In contrast, the results of this study are based upon analyses of an area of seabed. The extensive use of side-scan sonar mosaics and accompanying echo-sounding information in quantitative investigations of seabed geomorphology (in particular, for studying smaller scale relief features) is uncommon at this time. It is hoped that the work reported here will lead to a greater awareness of the potential and also of the limitations inherent in studies utilizing a combination echogram/sonograph data base.

The other goals in this investigation involved the practical application of the analysis methods to the following interdependent problems:

- (1) determining the relative importance of winds, ocean currents, tidal currents, and ice pressure in driving the ice masses which eventually scrape along the seabed.
- (2) determining ice-scour depth and ice keel depth frequency distributions from information obtained on an areal, rather than on a linear basis. The depth information obtained from echograms in this study has each value associated with an individual ice impact event identifiable from a sonograph. The data should, therefore, be more reliable than that derived solely from echogram measurements, wherein 'false tracks' may inadvertently be included in the set of measurements (see figure 3.1 and its accompanying explanation).
- (3) determining the relative importance of large scale bathymetric features in 'steering' ice pressure ridge keels that are making contact with the seabed.
- (4) accounting for the various planimetric forms of ice-scour tracks.
- (5) investigating the influence of ice zonation upon the degree of seabed disturbance by ice keels in an area.
- (6) developing a model of the processes involved in the formation of ice-scour tracks based on the results of (1) to (5).

Unfortunately, all of these goals could not be realized as fully as had been desired. A major problem was the variable quality of the sonographs and echograms that were available for this study. Enough success was realized in the work,

Figure 3.1 This is an idealized representation of an echogram trace across an ice-scoured seabed. Feature 'E' is likely to be an actual track, as evidenced by the relatively flat, undisturbed seabed to either side of its lateral embankments. If each track has two lateral embankments associated with it, the deduction can be made that features 'A' and 'C' are also real tracks. If no key feature such as 'E' were present in this series, however, an analyst could believe, wrongly, that features 'B' and 'D' (which are simply gaps between two independent lateral embankments, that is, 'B' and 'D' are false tracks) were caused by ice ploughing into the seabed.

however, to warrant bringing the techniques, methods, and preliminary results to the attention of interested researchers.

3.2 Data sources

3.2.1 Echograms and sonographs from 1974 survey

The echograms and sonographs which form most of the raw data base for this report were collected in late August and early September of 1974 by Geological Survey of Canada scientists working on board the vessel, M.V. Pandora II. The echosounder used was a Krupp Atlas-Deso 10 operated mainly at 30 kHz (beam angle between half-power points: 20° longitudinal; 30° transverse). An EG&G Mark 1B side-scan sonar system (105 kHz, 1.2° horizontal beam angle between half-power points) produced the sonographs. Adverse ice conditions, equipment problems, problems with the Decca Lambda positioning system (usual accuracy ± 30 m), and retention of varying degrees of side-scan sonar slant range distortions in the final mosaic assemblies all contributed to degrading the ultimate quality of the 'East Mackenzie' and 'Pullen Island' side-scan sonar mosaic assemblies (figure 3.2 a,b and figure 3.3 a,b; in front pocket. See also location map, figure 1.4), from which much of the information on ice-scour track morphology is derived.¹ The presence of ice floes in the mosaic areas made it impossible always to

¹ The side-scan sonar mosaics were assembled using a process of anamorphic photography by BEICIP (Bureau d'Etudes Industrielles et de Cooperation de l'Institut Français de Pétrole) working under contract to the joint industry-government Beaufort Sea Project. The mosaics are reproduced here with the permission of the Geological Survey of Canada and the Arctic Petroleum Operators' Association.

run perfectly overlapping, parallel lines within the areas. Equipment malfunctions (mainly the echo-sounder) caused much valuable bathymetry data to be lost. Discrepancies in navigational fixes caused by the malfunctioning positioning system led to difficulties in assembling the side-scan sonar mosaics, thereby introducing distortions and mismatches between lines. Nevertheless, it must be said that the 1974 Beaufort Sea survey yielded the best available set of raw data when compared with the 1971, 1972, 1975, and 1977 surveys. Criticism of the quality of the 1974 data only arises because the analysis methods presented in this paper depend on near perfect mosaic construction and the availability of extensive bathymetric information to make use of the methods practical. A portion of the 1974 data was indeed amenable to detailed quantitative investigation, leading this writer to believe that future seabed surveys, using improved and reliable equipment and positioning systems, can be of the necessary quality.

For the investigation at hand, however, the variable quality of the 1974 data meant that the same amount of information could not be obtained from all of the surveyed areas. This in turn limited the types of analyses that could be done and influences the degree of confidence one can have in the generality of the results.

3.2.2 Echograms and sonographs from 1978 survey

During early September 1978, Geological Survey of Canada scientists working on board the C.C.G.S. Nahidik successfully resurveyed a 3 km by 12 km portion of the 'Pullen Island' seabed mosaic area using a Klein model 531 side-scan sonar system (100 kHz), Raytheon RTT-1000 echo-sounding system (200 kHz and 7kHz), and a Kelvin Hughes MS 45 echo-sounder (45 kHz). Shoran positioning (± 30 m) was used for navigation. At the time of writing, arrangements were yet to be made for construction of a side-scan sonar mosaic so no use could be made of this particular data in this report. But, reference is made later in this chapter and also in chapter four to two 200 kHz/7 kHz echo-sounding lines that were run in the northern part of the 'East Mackenzie' mosaic area in water depths of 40 to 46 m. The lines are referred to as '78A' and '78B' and their approximate positions, inferred mainly from bathymetric information, are plotted on figure 3.4. These lines were obtained under adverse conditions of 10 to 15 knot easterly winds and a rough sea but are valuable in that they confirm the existence of rather well developed stratigraphy in the surficial seabed sediments of part of the 'East Mackenzie' area.

Positions along line '78A' were located using satellite navigation and a deduced reckoning course maintained at 180° . The wind caused a strong set to westward which made it difficult to correlate this line precisely with the 1974 data.

The second 1978 line in this area (78B) was run using Shoran positioning. By comparing the water depths traversed along this line with the 1:20 000 scale bathymetric chart (figure 3.4) it became apparent that the 1974 UTM grid is incorrectly positioned on the 'East Mackenzie' mosaic. It is shifted about 600 m eastward of its correct position. Nevertheless, in this report it is more convenient to continue to use the 1974 grid to describe the location of features because it is inscribed directly on the copies of the mosaic that were available for use in this work.

3.2.3 Published information

The Beaufort Sea Project report series, published by the Department of Fisheries and Environment, Canada, contains much of the latest information available on winds, currents, storm surges, sea ice zonation, and seabed sediment properties. Regional bathymetric information was obtained from charts based on the Natural Resource Series (1973), prepared by the Canadian Hydrographic Service, Department of Fisheries and Environment. A large portion of the published data which concerns the physical environment of the Beaufort Sea is summarized or referred to in chapter four of this thesis.

3.3 Methodology

3.3.1 Bathymetric chart assembly

A task of fundamental importance in this study was to

construct bathymetric charts on plastic film to overlay the 1:10 000 and 1:20 000 scale seabed mosaics. The availability of processed bathymetric information in direct conjunction with the pattern of ice-scour tracks on the seabed provides a method for inferring the direction of ice movement during scouring events (hypothesized to be upslope in nearly all cases) and obtaining a better understanding of the relationship between gross seabed morphology and the microrelief created by ice impacts. The echo-sounding records, obtained simultaneously with the side-scan sonar records that make up the mosaics, were used to compile the charts. The charts show water depth contours for a seabed undisturbed by ice impacts. It was possible to produce a complete bathymetric overlay for the 'East Mackenzie' mosaic area (figure 3.4, whiteprint in back pocket). For the 'Pullen Island' mosaic area, however, only part of the area is covered by a bathymetric overlay (figure 3.5, whiteprint in back pocket) because a considerable amount of bathymetric information was lost as a result of echo-sounder malfunctions.

The method of constructing bathymetric charts used here is unique in that the mosaic itself served as a horizontal control for the location of the depth data points which were used to draw the depth contours. In particular, the hazard of unknowingly having a series of depth points on a survey line offset from their true positions ('slipping' of the survey line) due to navigational positioning errors should have been largely

eliminated. A seabed having distinctive linear features, such as is the case in much of the southern Beaufort Sea, is particularly useful in aligning the survey lines visually to eliminate gross errors in line positioning. Since the alignment of individual ice-scour tracks seems to be fairly good on the two mosaics presented here, the 'spot depths' plotted on the bathymetric overlays are believed to be in their correct relative positions. Ultimately, however, a good mosaic suitable for detailed quantitative analysis depends upon precise and accurate navigational information so that is the reason why only gross errors would have been uncovered in this manner.

A complete summary of the bathymetric charting procedure is provided in Appendix B of this thesis.

3.3.2 Measurements from ice-scour tracks

Several types of measurements can be made on the ice-scour tracks that are visible on the sonograph mosaics and on the echograms. At this time, the reader may wish to refer to Appendix A to become aware of the factors lying behind the resolution capability of the sonographs and echograms. It is shown that tracks less than 3 or 4 m in width will not show up at all on either the echograms or sonographs. At the scale of the mosaics (1:10 000; 1:20 000) experience shows that tracks less than 5 m in width will usually not be visible. It is not practical to make measurements on the narrower tracks directly from the original sonographs with their inherent

distortions. Therefore, the methods described here, based on the use of 1:10 000 and 1:20 000 scale seabed mosaics, may lead to an underestimation of the ice impact hazard.

To facilitate identification of the tracks, a plastic overlay was placed on a certain area (e.g. 15 km²) of the mosaic plus its bathymetric overlay. All the tracks in a study area were outlined in ink. If it is agreed that the planimetric width of an ice-scour track is the shortest distance between the ridge lines of the parallel lateral embankments, the characteristics of the side-scan sonar method of remote sensing can be used to advantage. Referring to figure 3.6, it is seen that in the case of an embankment there is a strong signal return from the slope facing the towfish. The strong signal return is represented on the record as a dark tone. The acoustic shadow of the embankment shows up as a lighter toned or even as a white area on the record. The line along which the reflection and shadow zones meet is taken to represent the ridge line of the embankment. An identification number was printed beside each outlined track. If doubt existed as to the location of the origin or the endpoint of a track, a question mark was shown on the overlay. The major reasons for doubt were:

- (1) no record available;
- (2) record quality poor
 - often, beyond mid-slant range on the sonographs, many features appear to end at similar distances from the long axis of the towfish. This indicates a severe loss of resolution beyond this range (see figure 3.7a for an illustration of this effect);

Figure 3.6 Tracing ice-scour tracks on a side-scan sonar mosaic. The planimetric width, w , of an ice-scour track is the shortest distance between ridge lines of the lateral embankments.

(3) overlap by another track.

Those tracks beginning within the confines of a chosen sample area but extending beyond it were also measured and labelled with an identification number. Multiple ice-scour tracks (two or more parallel tracks believed to have been caused by several keels connected to the same ice mass) were given only one identification number. The overlay that was produced for the 15 km² study area designated as 'East Mackenzie (North)' is shown as figure C.2 in Appendix C of this report. Figure C.1 provides a general guide to tracing overlay locations in the 'East Mackenzie' area.

To improve the accuracy of the tracing overlay, it was necessary to refer to the original sonographs. The mosaics suffer significant loss of detail in comparison to the records from which they were constructed (compare, for example, the photographs of the original sonograph and corresponding section of mosaic in figures 3.7a and 3.7c and figures 3.8a and 3.8c). Some features on the mosaics that superficially resemble ice-scour tracks are the result of folds in the recorder paper or blemishes apparently introduced during the anamorphic photography of the records (see, for example, figure 3.8c).

Those measurements considered important for achieving the goals as well as being practical to collect are discussed in the following sections (a) to (k). The actual measurement values for 103 ice-scour tracks in the 'East Mackenzie' mosaic

42a.

Figure 3.7 a

Figure 3.7 (a) This is an example of a sonograph from the southern part of the 'East Mackenzie' mosaic area which has many closely spaced ice-scour tracks on the seabed. Note that the port and starboard channels were accidentally reversed because of an incorrect cable connection to the towfish. This resulted in a mirror image of the seabed being recorded. The distinctive dark trace on the upper channel (starboard) is a reflection from a floating ice mass. The similar, but weaker, image on the lower half of the record is the result of 'crosstalk' between channels during reception of the relatively strong echoes from the ice mass. A severe loss of resolution beyond mid-slant range is noticeable on both channels. The reader should compare this original record to the photographically rectified image appearing on the record excerpt shown in figure 3.7 (c). Notice particularly the loss of detail between the mosaic and the original sonograph. Also compare 3.7 (a) to the corresponding echogram in 3.7 (b). The fix marks for the two types of record are not at the same geographical location because the side-scan towfish was towed some distance astern of the echosounder transducer which was mounted on the ship.

12c.

-20 m

fixmarks
l = 2345 l = 2346

2245

vertical mag. 44x

0.4 m

-40 m

-50 m

0.15

29 m

-60 m

Figure 3.7 b

Figure 3.7 (b) This is an example of a 30 kHz echogram from a relatively highly dissected seabed in the southern 'East Mackenzie' mosaic area. It corresponds to the seabed profile along the centreline of the sonograph shown in figure 3.7 (a). Although some of the major depressions on the echogram can be correlated with tracks appearing on the sonograph, this becomes rather difficult and unreliable for the smaller tracks. Water depth may be read directly from this echogram because the transducer draft was compensated for at the time of recording.

Figure 3.7 (c) The enclosed area on the 1:20 000 scale sonograph mosaic shown above with the bathymetric overlay is a photographically rectified image of the original sonograph shown in figure 3.7 (a). The planimetric distortions in the sonograph, caused by unequal lateral and transverse scales, have been removed by a photographic process as has the 'mirror image' effect discussed for figure 3.7 (a). It is apparent that some detail is lost from the mosaic image, making it essential to refer to the original sonograph when tracing outlines of the ice-scour tracks. Note also that the image of the ice that appears on the original sonograph remains in the mosaic. References to field note books and to remarks written directly on the records are necessary to explain such features.

Figure 3 8'a

Figure 3.8 (a) Sonograph showing a portion of seabed in the 'East Mackenzie (North)' mosaic study area. Here the tracks are spaced far enough apart that reliable correlations can be made with the accompanying echogram (see figure 3.8 (b)). The loss of resolution beyond mid-slant range on this record is not as severe as that in figure 3.7 (a). Had the resolution been poorer it is conceivable that track 'EMN 34' would have appeared as two separate tracks because the link (arrow) would not have been visible. This particular sonograph was obtained early in the 1974 survey before the towfish cable connections were accidentally reversed so it shows the port and starboard channel records in their correct positions.

42h.

Figure 3.8 b

Figure 3.8 (b) This 30 kHz echogram corresponds to the section of seabed shown in sonograph figure 3.8 (a). The ice-scour tracks are identified on the records. The reflecting surface at 'A' (seabed surface) is the result of a large acoustic impedance contrast at the seawater-sediment interface. The sub-bottom reflectors at 'B', 'C', and 'D' are the results of contrasts in acoustic impedance between sediment layers. Acoustic impedance is the product of the seismic velocity and density of a material (McQuillan and Ardus, 1977, pp. 52-54). The sub-bottom reflectors may be interpreted as being indicative of changes in the lithology of the surficial sediments (cf., McQuillan and Ardus, 1977, pp. 78-80). Although a type of multiple acoustic reflection known as a 'ghost multiple' could also cause features such as 'B' and 'C' to appear on an echogram, consideration of this possibility has been eliminated by the results of the two sub-bottom profiling lines run in the 'East Mackenzie' area in 1978. Line 78A, in particular, shows similar stratigraphy to that shown here. A portion of line 78A is illustrated in figure 4.12. If the stratigraphy was merely an acoustic artifact, the use of a different transducer set-up on a different ship should have changed the character of the reflections entirely. Since this did not happen it is presumed that the reflectors are real.

Figure 3.8 (c) The enclosed area on this section of the 1:20 000 scale 'East Mackenzie (North)' mosaic study area (with bathymetric overlay) corresponds to the original sonograph shown in figure 3.8 (a). Some degradation of resolution is apparent in comparison to the sonograph. Note that the feature labelled 'A' is not an ice-scour track and does not even appear on the original sonograph. The tracing overlay for this area is shown in figure C.2, Appendix C.

area are tabulated in Appendix C.

(a) classification of ice-scour tracks

To facilitate collection of information from the mosaics, a simple classification system was devised (see Table 5.I, chapter 5). The classification considers the type of track created by an ice keel scouring into seabed sediments, the planimetric form of the track, and modifications to the planimetric form. Chapter five of this paper describes the classification system and suggests that it can be regarded as a genetic classification system (see figure 5.8).

(b) length of ice-scour tracks

The total lengths of tracks were measured on the mosaics with a ruler graduated in millimetres. Tracks that were strongly arcuate or sinuous had their lengths measured by 'walking' along their track with a pair of dividers set at a suitable length increment. Uncertainty in the length measurements is taken to be ± 100 m primarily because of the loss of resolution beyond mid-slant range that affects many of the sonographs. Length measurements are inherently imprecise because during the ice impact process, the initial contact of the ice keel with the seabed may only cause a minor modification of the seabed surface which may not be detectable on the sonographs. Reference was made to the original sonographs when establishing the total length. If the locations of either or both of the origin and endpoints could not be determined,

the length was recorded as 'zero' to indicate a missing value.

The length measurements used in the net rise analysis (see section (h)) were more precise (± 20 m; one division on mm scale) because they were made between ship's survey lines. The uncertainty is greater than for the width measurements, however, because of the curvature displayed by many tracks.

(c) planimetric width of ice-scour tracks

The average planimetric widths of tracks were measured on the mosaics using a millimetre scale. No missing values occur for this measurement. The uncertainty in width values is ± 10 m for the 1:20 000 scale mosaic. This uncertainty reflects the limit of resolution on a millimetre scale (± 0.5 mm = ± 10 m at the 1:20 000 scale).² Width measurements on the 1:10,000 scale mosaic have an uncertainty of ± 5 m associated with each value (i.e., ± 0.5 mm = ± 5 m). Figures 3.6 and 3.9 illustrate the definition of track width used in this study. This width measurement method is unique to this report and differs slightly from the width measurement conventions used by other researchers. The reasons for adopting this definition were given in section 3.3.2. For multiple ice-scour tracks, the planimetric width value that is recorded represents the average distance between the ridge lines of the outermost lateral embankments.

² Width values were, however, estimated to the nearest 5 m if planimetric width was less than 20 m. Values of width with '5' in the units column could also occur if the width varied significantly. For example, a track about 20 m wide at one end and 30 m wide at the other would be said to have an average width of 25 m.

Figure 3.9 Idealized cross-section of an ice-scour track showing the definitions for planimetric width (w) measurements made from sonograph mosaics and ice-scour depth (d) measurements made from echograms.

(d) mean depth of ice-scour tracks

If ice-scour tracks were crossed by the ship's survey line, their depths could usually be obtained from the corresponding echogram if the tracks were not too closely spaced in the area (as in figure 3.8a to c, for example). If the seabed was highly dissected by ice impacts (as in figure 3.7 a to c) it was usually impossible to make reliable correlations between the tracks appearing on the sonographs and echograms unless a track was unusually deep or wide. The depth value that was recorded was the average depth of the ice-scour bottom below the undisturbed seabed as depicted in figure 3.9. In the case of multiple ice-scour tracks, the average depth of the deepest track was recorded. If an ice-scour track was clearly only the surface expression of a partially buried track, as is the case for track 'EMN 38' shown in figure 3.8b, then the average depth of the ice-scour bottom below the buried undisturbed seabed (surface 'B') was measured. No measurements on deeply buried tracks such as in surface 'C' (figure 3.8b) were made because of the absence of expression of the features at the present seabed surface 'A'. The uncertainty associated with each depth measurement depended upon the vertical scale of the echogram. Usually the uncertainty was ± 0.2 m (half of the smallest scale division on the echogram, see figures 3.7b and 3.8b). In the northern part of the 'East Mackenzie' area, an unknown degree of underestimation of ice-scour depths may have occurred for tracks less than 15 m wide because of the

Figure 3.10

An example of the measurement of ice-scour track azimuth on a side-scan sonar mosaic. The direction from which the ice keel came is inferred from bathymetric information. It is assumed that scouring into sediments normally occurs as an ice keel moves upslope.

beam angle characteristics of the 30 kHz transducer (refer also to section A.4.3 and figures A.4 and A.5 in Appendix A). Missing values for ice-scour depth were recorded as 'zero'.

(e) azimuth of ice-scour tracks

The azimuth of an ice-scour is defined to be the direction from which an ice keel came (to conform with the convention of naming winds according to the direction from which they blow). Azimuth was measured on a mosaic using a protractor having the $0^{\circ} - 180^{\circ}$ diameter oriented along a north-south UTM grid line.³ A decision was made as to the likely direction of ice movement (upslope in nearly all cases) before recording the measurement to the nearest whole degree with an uncertainty of $\pm 1^{\circ}$ associated with each value. For arcuate and sinuous tracks the net azimuth for a line between the visible origin and endpoint was recorded. These origins and endpoints may not have been the true locations, but rather than accept missing values for azimuth measurements, it is believed that this method yields azimuth values that will approximate the direction from which ice movement occurred. If the track showed evidence of an abrupt change in direction of ice movement, the azimuth of the longest limb was recorded. Figure 3.10 illustrates the method of measuring azimuth.

(f) angle of approach of ice to a slope

The angle of approach was also measured on the mosaic

³In the 'East Mackenzie' area, grid north is $02^{\circ}08'$ west of true north and in the 'Pullen Island' area, grid north is $00^{\circ}36'$ east of true north.

Figure 3.11 Illustration of the measurement of the approach angle (θ_{app}) of an ice keel to a slope.

2

plus its bathymetric overlay. The use of this variable in the analyses that follow presumes that the seabed gradient is constant. Data was not collected from regions where the seabed gradient changed significantly such as the ridge and trough system in the southeastern corner of the 'East Mackenzie' area (figure 3.4). The angle was measured to the nearest whole degree with a protractor. Uncertainty in this measurement is taken to be $\pm 1^\circ$. Arcuate and sinuous tracks, and tracks with abrupt changes in direction were handled in the same manner as described for azimuth measurement in order to avoid missing values. Once again, scouring of ice into sediment is presumed to have occurred when the ice keel was moving upslope. Figure 3.11 depicts the approach angle measurement method.

(g) water depth at origin and terminus of ice impact on the seabed

The water depths at the inferred origin and terminus of an ice-scour track could be determined by reference to the bathymetric overlay. Interpolations between the depth contours using ten-point dividers could be made with an uncertainty of ± 0.1 m when the contour interval was 1 m. As before, upslope ice movement was assumed. Missing values were recorded as 'zero'.

(h) net rise

The vertical distance that the bottom of an ice keel was raised or lowered as it traversed a seabed slope could be

$$\text{rise} = \text{W.D.}_A - \text{W.D.}_B$$

$$\begin{aligned} \text{net rise} &= \text{W.D.}_A + d_A - (\text{W.D.}_B + d_B) \\ &= (\text{W.D.}_A - \text{W.D.}_B) + (d_A - d_B) \\ &= (\text{W.D.}_A - \text{W.D.}_B) - (d_B - d_A) \end{aligned}$$

$$\text{net rise} = \Delta \text{W.D.} - \Delta d$$

Figure 3.12

Definition sketch for 'net rise' variable.

W.D. denotes water depth and d denotes ice-scour depth.

Figure 3.13

This illustration shows two single, arcuate ice-scour tracks. The direction of ice keel movement is presumed to be upslope in both cases. Arcuate track 'A' is turning to the right of the direction of ice movement while track 'B' is turning to the left. Furthermore, it can be postulated that the turning to the right of track 'A' is consistent with the angle of approach of the ice keel to the slope. In contrast, the turning to the left of track 'B' can be regarded as being inconsistent with the ice keel's angle of approach to the slope. Hence, for arcuate tracks, data can be collected on direction of turning (left, right) and on consistency of the turning with the angle of approach to a slope (consistent: yes, no).

determined for those ice-scour tracks that were crossed by at least two ship's survey lines. This variable is defined in figure 3.12 and is referred to as 'net rise'. It is given by the expression:

$$\text{net rise} = \Delta W.D. - \Delta d \quad (\text{eqn. 3.1})$$

where $\Delta W.D.$ is the difference in water depth (measured to level of 'undisturbed' seabed) between the locations of two cross-sections on an ice-scour track.

Δd is the difference in ice-scour depth at the two locations on the track. The downslope ice-scour depth value is subtracted from the upslope ice-scour depth value.

(i) direction of curvature of arcuate tracks

As part of the investigation of ice keel movement across the seabed, a study was made of the direction of curvature of twenty-four arcuate tracks that occur in the "East Mackenzie" mosaic area. The type of information collected is illustrated in figure 3.13.

(j) sediment infilling ratio

The sediment infilling ratio is a variable applicable to those ice-scour tracks that are covered by a blanket of sediment (e.g. track 'EMN 38' in figure 3.8b) and for which some surface expression still remains. The ratio is given by:

$$\text{infilling ratio} = b/a \quad (\text{eqn. 3.2})$$

where a is the thickness of the sediment blanket which overlies the buried ice-scoured seabed.

b is the total thickness of sediment overlying the original ice-scour bottom.

Ice-scour track EMN 2 (cross-section A-A')
 at UTM coordinates 409 150; 7 710 460 as
 it appears on Krupp AD 10 echogram.

Figure 3.14

Evidence from echograms suggests that some ice-scour tracks are preferentially infilled with sediment (with respect to the surrounding seabed). The sediment infilling ratio is given by b/a , where 'b' is the total thickness of the sediment lying above the original ice-scour bottom and 'a' is the thickness of sediment above the buried seabed surface into which scouring occurred.

A typical infilled ice-scour track is diagrammed in figure 3.14.

(k) effect of sedimentation on validity of measurements
discussed in (a) to (i)

For those ice-scour tracks covered with a 2 m thick sediment blanket, as shown in figure 3.8b, the classification scheme will usually be valid except in cases where a broad, flat-bottomed character (see Table 5.1) is a direct result of sediment infilling the track. The length measurements may be in error if part of a track has infilled to the degree that no surface expression is visible on the sonographs. In most cases, planimetric width measurements will be similar to those of the unburied track. As noted in part (d) of this section, ice-scour depth measurements have to be made on the sub-bottom reflector (original surface) rather than on the present surface expression of the track. Azimuth, angle of approach, and direction of curvature information is not influenced by the fact that infilling of the ice-scour tracks has occurred. Water depths at the origin and terminus of an ice-scour track must be measured to the buried surface rather than to the present seabed (this assumes that negligible sea-level change has occurred since the now buried tracks were formed).

3.3.3 Outline of data interpretation procedures

The measurements for variables discussed in (a) to (g) of the last section were recorded on computer coding forms. The data was then key-punched so that frequency distributions of the variables could be computed and so that further statistical procedures such as finding correlations between the variables could be carried out relatively quickly. Some data, such as that described in 3.3.2 (h) to (j) were not handled by computer because of the relatively small data sets. Depending on the results of the descriptive statistical analyses, further analysis methods could be developed. Chapter six contains the results of the statistical analyses and their interpretation.

(a) 'East Mackenzie (North)' mosaic area

Analysis of all ice-scour tracks in a contiguous area could only be done for the 'East Mackenzie (North)' area (15 km^2) lying on the eastern slope of the Mackenzie (submarine) Canyon in water depths of 40 to 50 m (refer to the ice-scour track tracing, figure C.2, Appendix C). This area is, unfortunately, not necessarily representative of other regions of the continental shelf that are affected by ice impacts. The approximately 2 m thick sediment blanket which covers an older ice-scoured seabed surface is a unique feature of parts of this area that lie in water depths of more than 42 m. Nevertheless, features such as the relatively steep slope (approximate gradient 1/400) in the area proved

advantageous in that the direction of ice keel movement could be inferred with some certainty. This area was also amenable to analysis in that ice-scour tracks are not spaced too closely. Therefore, unambiguous correlations of individual tracks appearing on the sonographs and echograms could be made (refer to figures 3.8a and b). The raw data was of good quality for the 15 km^2 area and the mosaic was well assembled with relatively few mismatches between adjacent sonographs. The basic measurements (3.3.2 (a) to (g)) obtained from ice-scour tracks in this area are tabulated in Table C.I, and are referred to as data set 'A'.

(b) problems in analysis of the central and southern portions of the 'East Mackenzie' area

The remainder of the 'East Mackenzie' mosaic area was partially analysed. The major problem with doing an analysis as detailed as that for the 15 km^2 northern portion was that there is very little undisturbed seabed in the central and southern portions of the mosaic area (see figures 3.7a to c). Primarily because of the fact that the side-scan sonar tow-fish and the ship's echo-sounder transducer were not located at the same point along the ship's survey line, the ice-scour track profiles on the echogram could not be reliably correlated with the tracks on the sonographs. Therefore ice-scour depth measurements could not be obtained. There was also enough loss of detail between the mosaic and the original sonographs so that outlining the tracks on the mosaic overlay

became difficult and time consuming. An unusual problem associated with most of the sonographs from the 1974 survey is that they were output from the recorder with the port and starboard channel images reversed, thereby giving a mirror image of the seabed (figure 3.7a). To view the seabed features in their natural relationship, the sonographs had to be placed face down on a light table and be 'viewed from behind'. Needless to say, much detail is lost to the observer even from original records by this procedure, unless the analyst opts to refer primarily to the mirror image and mentally juggles the features to fit the corresponding mosaic image (when the mosaic was assembled photographically the mirror image effect was removed). Several hours were spent trying to trace ice-scour tracks in this manner but the results were determined to be unreliable so the attempt was abandoned. A rather expensive solution, not available to this writer, would have been to photographically copy the mirror image sonographs onto transparent plastic film. The problems mentioned earlier in this paragraph would have remained, however.

(c) coping with problems

In order to obtain some measurements at least, it was decided to limit the amount of choice for ice-scour tracks on which measurements were to be made. The selection criterion used was that tracks had to cross at least two

ship's survey lines (or cross the same line twice), so that at least two ice-scour depth measurements could be made. The information that was obtained provided data set 'B' (basic measurements) and data set 'C' which is useful in a study of changes in ice-scour depth along the ice-scour tracks and in studying 'net use' of an ice keel up a slope. Information on thirty 'long' ice-scour tracks was collected. The track tracings and measurements are given in Appendix C. The analysis results are discussed in chapter six.

As another method of increasing the scope of the analyses possible from the available data, information was gathered on all ice-scour depths and corresponding water depths along two north-south oriented echogram/sonograph lines (from 1974) in the 'East Mackenzie' area. One line (UTM coordinates⁴ 410 820;7 694 560 to 410 860;7 706 420) covered water depths of 32 m to 42 m. The other line (UTM coordinates⁴ 409 240;7 703 340 to 408 920;7 718 480) covered water depths from 43 m to 50 m. This data (Tables C.VIII (a) and (b) in Appendix C) enabled the correlation of ice-scour depth with water depth and development of an ice keel draft distribution.

(d) 'Pullen Island' mosaic area

It would have been very useful to do a detailed analysis of ice-scour tracks in the 'Pullen Island' area. This area

⁴ UTM coordinates as shown on the 1974 mosaic assembly.

lies in shallower water (12 to 15 m deep) than the 'East Mackenzie' area and may lie in a different average wind and ice regime than the latter area. Unfortunately, a detailed study could not be carried out. The seabed is virtually 'saturated' with tracks of ice impacts. Meaningful sonograph to echogram correlations for individual tracks were impossible to make. Furthermore, upon close examination, numerous minor mismatches (tens of metres, actual scale) exist in the mosaic. These mismatches are probably the result of the positioning problems discussed earlier. Finally, all of the original sonographs from this area suffer from the 'mirror-image' problem and many gaps (some extending several kilometres) occur in the echogram record. This mismatching problem makes length measurements very time-consuming and unreliable. This fact, added to the lack of ice-scour depth information for a large proportion of the tracks made it seem fruitless to carry on with an extensive quantitative analysis of the 'Pullen Island' area. Even a selective study such as one of depth changes along tracks proved to be impossible.

For the purposes of this paper then, the importance of the 'Pullen Island' mosaic lies in the following:

- (1) this is the only area where repetitive side-scan sonar surveys have been successful and for which it is known for certain that new ice-scour tracks have been added to the seabed in the past few years (Lewis, 1977b).

- (2) there are two prominent submarine mounds within the borders of the bathymetric overlay chart which can be correlated with regions of low observed ice-scour track spatial density on both the sonographs and echograms. This is discussed in chapter four.
- (3) good examples of the various planimetric forms of ice-scour tracks are found in this area. Some selected examples are illustrated in chapter five.
- (4) some individual cases of ice impacts with the seabed in this area are examined in detail in chapter six.

3.3.4 Hardware model for interaction of floating ice masses

In an effort to understand better the influence that interactions between floating ice masses might have on the planimetric form of ice-scour tracks, a simple physical model was employed. About thirty large hexagonal machine nuts (2 cm diameter, 1 cm thick) were distributed randomly on a 21 by 28 cm sheet of paper laid horizontally. Two of the hex nuts were equipped with drafting pen nibs mounted through the holes so that they could leave a record of their movement across the sheet of paper. A steady force was applied to the hex nuts in the form of a wooden ruler (turned on edge) pushed by hand across the sheet of paper. As the hex nuts became subject to the steady force they jostled each other about while they were moving forward. A slowly applied force gave the most interesting results. The recorded tracks associated with four trials of this experiment are included as figures C.4a to C.4d in Appendix C. The implications of the results obtained from the model are discussed in chapter six.

3.4 Recommendations

The mosaic analysis methods discussed here were successful when applied to the 'East Mackenzie (North)' mosaic area. The results of various statistical analyses are discussed in chapter six. Because no rigorous comparisons between different areas on the Beaufort Sea continental shelf can be made, however, only tentative conclusions can be drawn from these results.

For future studies, the following conditions need to be met during collection of the data base:

- (1) a reliable electronic or acoustic (installed on sea-bed) positioning system for the ship should be available so that assembly of the sonograph mosaic can be done with a minimum of mismatching and distortion problems.
- (2) the high frequency echo-sounder and side-scan sonar transducers that are used should be mounted along the same vertical axis so that correlations of individual features between fix marks, from one record type to the other, become reliable. In order to obtain bathymetric information, an extra transducer aimed towards the ocean surface would have to be installed on the towed body.
- (3) there should be equal resolution capability across the slant range of the sonographs. This condition is being met by recent equipment. Since sound refraction effects caused by thermoclines limits side-scan range, the towfish should be towed below the thermocline.
- (4) the electronic and mechanical equipment that is used for the survey must be reliable. It is realized that this is a difficult goal to achieve under field conditions despite the best intentions of all concerned. When studying linear geomorphological features which may be several kilometres long, however, continuity of the records is essential for meaningful results.
- (5) favourable weather and ice conditions should prevail in the study area.

The final assembly of the mosaic should attempt to minimize mismatches between segments of long ice-scour tracks crossing several survey lines. Preferably, the mosaic scale should not be smaller than 1:10 000. Implementation of the latter suggestion may help solve the problem of having poorer resolution on the mosaic than on the original sonographs. This would also help to avoid the relatively large uncertainties in width measurements. Before constructing the mosaic, it would be preferable to remove the distortion caused by the fact that slant range distances to objects were recorded on the sonographs. That is, all planimetric distortions should be removed from the mosaics.

The actual outlining of the ice-scour tracks on a mosaic, in ink, should preferably be checked in detail by another person to ensure that all the tracks that can be resolved are accounted for.

CHAPTER 4
PHYSICAL ENVIRONMENT OF THE 'EAST MACKENZIE' AND
'PULLEN ISLAND' SIDE-SCAN SONAR MOSAIC AREAS

4.1 Introduction

Data for winds, currents, and sea ice motion and distribution in the Beaufort Sea are still scanty and often suffer from having been collected over a restricted time span (i.e., often less than five years or only during certain seasons - usually summer). The Beaufort Sea Project report series provides the best up to date summary of environmental conditions in the study area and these publications were referred to extensively during the compilation of this section.

In a consideration of the processes causing ice-scour tracks on the seabed, it is helpful to have an overall perspective of the processes. One suggestion for a process-response model of the atmosphere, ocean, sea ice, and seabed relationships in the Beaufort Sea environment is presented in figure 4.1. It is seen that the atmospheric pressure field over the Western Arctic is ultimately responsible for several characteristics of the continental shelf environment. The sections that follow discuss those characteristics that are

Note 1. Relatively short term changes in pressure field may occur at any time of the year.

(R.V. Wahlgren, 1979)

Figure 4.1 Process - response model for the Beaufort Sea environment.

relevant to this study of ice-scour tracks in the 'East Mackenzie' and 'Pullen Island' mosaic areas.

4.2 Regional and local bathymetry

4.2.1 'East Mackenzie' mosaic area

The bathymetry of the region surrounding the 'East Mackenzie' mosaic is depicted in figure 4.2. Perhaps the most striking feature in the area is the submarine canyon known as the Mackenzie Canyon. Shearer (1971, 1972a) offered the explanation that the canyon was scoured out of a pre-existing river valley by a northward flowing ice-tongue associated with the Wisconsin glaciation. As the sea level rose in post-glacial time, the glacially modified valley was successively infilled by glacial outwash and then silts and clays from the Mackenzie River. The sediments settled preferentially on the eastern side of the canyon. The actual 1974 mosaic area (8 km x 32 km, or 256 km²) lies on the eastern slope, towards the head of the canyon. The average gradient in the mosaic area is about 1/500 or 0.2%. The continental shelf edge (200 m contour) lies from 50 to 85 km to the north of the northern edge of the mosaic area.

Local bathymetry within the mosaic area is illustrated at the 1:20 000 scale in figure 3.4 (whiteprint, back pocket). This shows a fairly regular slope facing to the northwest and west-northwest which has an average gradient of 1/400 to 1/500.

Figure 4.2 Regional bathymetry (in metres) for the 'East Mackenzie' side-scan sonar mosaic area. From Canadian Hydrographic Service Beaufort Sea Plotting Base (Lambert Conformal Conic Projection, Standard Parallels 68° 40' and 71° 20', Scale 1: 1 000 000).

In the southeastern corner of the mosaic area, there is a ridge and trough system with relief of about 5 m and a west facing slope having a gradient of 1.5%.

4.2.2 'Pullen Island' mosaic area

Figure 4.3 shows the regional bathymetry associated with the 'Pullen Island' mosaic area (14 km x 9 km, or 126 km²). About half of this area has local bathymetric information available in the form of the 1:10 000 scale mosaic overlay (figure 3.5, whiteprint in back pocket). Water depths in the area range from just over 10 m to 20 m. Within a radius of 25 km of the centre of the mosaic, the continental shelf bathymetry is very gentle, having an average gradient of only 1/1600 or 0.06%. To the northeast of the study area is an embayment which may be a drowned river valley (Lewis, 1977a). The 200 m depth contour lies about 90 to 95 km to the north of the 'Pullen Island' mosaic area.

The 1:10 000 scale bathymetric overlay chart shows a very regular bottom slope facing the north-northwest in the western half of the overlay region. To the east, however, the submarine topography is more irregular, featuring a subdued swale (maximum relief 0.5 m) about 4 km long and two mounds (diameter about 1 km) with relief of 1 m to 3 m.

Figure 4.3 Regional bathymetry (in metres) for the 'Pullen Island' and 'Elf' side-scan sonar mosaic areas. The 'Elf' area is not discussed in detail in this report but is shown for completeness only. From Canadian Hydrographic Service Beaufort Sea Plotting Base (Lambert Conformal Conic Projection, Standard Parallels $68^{\circ} 40'$ and $71^{\circ} 20'$, Scale 1: 1 000 000).

4.3 Driving forces for ice movement

4.3.1 Winds

The magnitude of the shearing stress due to wind blowing across an ice surface is given by the expression:

$$\tau = \rho u^2(z) C_D(z) \quad (\text{eqn. 4.1})$$

where τ is shearing stress,

ρ is air density,

z is height above the ice surface. It is conventionally set at 2 m or 10 m,

$u(z)$ is windspeed measured at z ,

$C_D(z)$ is the surface drag coefficient at height z
(after McIntosh and Thom, 1972, p. 171).

The wind force on an object (such as an ice pressure ridge) that presents a substantial cross-sectional area to the wind is given by the form drag equation:

$$F = \frac{1}{2} C_f \rho u^2 A_{xs} \quad (\text{eqn. 4.2})$$

where F is the drag force,

C_f is the form drag coefficient,

ρ is the air density,

u is wind speed,

A_{xs} is the cross-sectional area facing the wind
(after Monteith, 1973, p. 81-82).

The equations show that the wind stress is proportional to the square of the windspeed. A doubling of the windspeed results in a fourfold increase in the stress exerted on the ice. The formation of ice pressure ridges can be associated

with storm winds (see, for example, Weeks et al., 1971, p. 162). Grounding of two multi-year pressure ridge fragments 35 km northwest of Prudhoe Bay was attributed to storm winds (Kovacs and Gow, 1976). Emphasis is therefore placed on examining data on strong winds over the Beaufort Sea although this does not mean that more moderate winds can be ignored. Wind information for the Canadian Beaufort Sea was summarized by Berry et al. (1975). These researchers used two arbitrary definitions of strong winds although the reason for this was not explained. Their two definitions are also used here.

The directional frequency distribution for winds with speeds exceeding 14 m/sec or 28 knots is shown in figure 4.4. Clearly, most of these winds blow from the northwest. When studying the ice-scour tracks in the mosaic areas, a correlation between the track azimuths and the directional frequency distribution of strong winds can be sought.

The influence of the normal shift in the atmospheric pressure field from summer to winter in the Beaufort Sea area is illustrated by the directional frequency distributions of 'strong' winds (this time defined as having speeds greater than 8 ms^{-1} or 17 knots) shown in figures 4.5a, b, and c. During the summer open water season, strong winds are usually easterlies. In the fall the directional frequency distribution shifts as strong westerly winds become more common. The new winter ice cover will usually be affected by the westerly wind regime.

Figure 4.4 Directional frequency of strong winds (speed exceeding 14 m/sec or 28 knots) over the Beaufort Sea. Plotted from information in Table 3, p. 1.8, of Berry et al., 1975.

Figure 4.5 Percentage directional frequency of strong winds (greater than or equal to 8 m/sec or 17 knots) over the Beaufort Sea for July, August, and September. Plotted from information on pages III.6 to III.8 of Berry et al. (1975).

Burns (1973) stated that the largest monthly extreme wind speeds occur during winter 'along the coast and that destructive storms in the region usually occur in the fall.

The tables in Berry et al. (1975) show that the directional frequency distribution for all wind speeds is similar to that for 'strong' winds. Therefore, rose diagrams for 'all wind speeds' are not illustrated here even though some ice motion may be a result of more moderate winds.

Berry et al. pointed out that their analysis for the wind frequency distributions was based on observations taken over a period of 10 to 15 years at coastal stations and ship's observations. It included no data from the northwestern Beaufort Sea. With this in mind, their analyses will be tentatively taken to be valid for both mosaic areas.

A summary of surface wind data for Shingle Point, due south of the 'East Mackenzie' mosaic area (see figure 1.4), was given by Wilson (1974). This information indicates that for windspeeds between 7 m/sec and 13 m/sec the most frequent directions are south-southwest, west-northwest, and east-southeast (listed in order of importance). For all windspeeds, on an annual basis, west-northwest winds are most frequent (40 per cent of time), followed by south-southwest (25 per cent), east-southeast (21 per cent), and north-northeast (11 per cent). This is important local information which does not show on the generalized frequency distributions in figures 4.4 and 4.5 (a) to (c).

4.3.2 Currents

Ice motion may also be caused by water currents. It is generally accepted, for example, that icebergs with their deep drafts are driven primarily by currents (Murray, 1969; Russell, Riggs, and Robe, 1977). The deepest draft pressure ridge keel that has ever been recorded on a submarine traverse was found to extend 47 m below sea level (Lyon, quoted in Kovacs; Weeks, Ackley, and Hibler, 1973). It is presumed that the motions of deep draft pressure ridge keels are influenced to some degree by the various currents encountered throughout the water column as is the case with icebergs. In a discussion of previous studies of iceberg motion, Russell et al. (p. 785) pointed out that the motion of deep draft bergs was attributable mainly to deep currents whereas the motion of smaller bergs was more a result of wind-induced surface currents. The direct influence of wind on iceberg motion was significant only for strong winds of long duration.

This discussion of currents in the Beaufort Sea will summarize information (with particular reference to the mosaic areas) that is known about tidal, surface, and bottom currents.

(a) tidal currents

Tidal streams have low speeds (0.02 to 0.03 m/sec) and are in general much less significant than ocean currents in the area (Herlinveaux and de Lange Boom, 1975; Huggett et al., 1975). The mainly semi-diurnal tides have a range of only 0.3 to 0.5 m (Huggett et al., 1975).

(b) surface currents

Surface currents in the Beaufort Sea have been analysed by MacNeill and Garrett (1975). Their report is based on observations of the drifts of drogues and ice floes during July to September (the open water season) of 1974 and 1975. These researchers concluded that the surface currents are wind driven and that northwesterly and easterly winds play a dominant role in establishing the average current field. Figures 4.6(a) and 4.6(b) show MacNeill and Garrett's interpretation of the current fields during northwesterly and easterly winds respectively. This writer has added the locations of the 'East Mackenzie' and 'Pullen Island' survey areas to the figures.

With regard to the 'Pullen Island' area it is found that northwesterly winds will generally cause surface currents to flow towards the east and hence parallel to the bathymetric contours. The Ekman spiral effect exists in the wind driven surface layer of ocean, meaning that, in the case of northwesterly winds, the deeper currents will have an increasingly southerly component with increasing depth (although the speed of the currents would decrease with depth). The implication for an ice mass having a draft similar to the water depth in this area (10 to 15 m) would be that an ice keel would move upslope across the seabed thereby increasing the chance of scouring taking place. When easterly winds prevail, the surface current across the Pullen area will flow westwards according to figure 4.6(b). This is parallel to the bathymetric contours.

In this case, however, the turning to the right of the deeper currents would most likely cause an ice keel to move in a more downslope direction across the seabed thereby reducing the risk of contact between the ice and the seabed.

For the 'East Mackenzie' mosaic area, reference to the figures 4.6(a) and (b) shows that the surface current during a northwesterly wind is crossing the eastern wall of the Mackenzie Canyon almost directly upslope. Given the standard deviation ($\pm 17^\circ$) of surface currents caused by northwesterly winds (MacNeill and Garrett, 1975, p. 16) and the Ekman spiral effect, it is clear that ice impacts with the seabed are probable in this area during a northwesterly wind. During easterly winds, however, the risk of scouring is probably low because of the 'downslope' drift of the surface water and any ice mass contained within it.

MacNeill and Garrett found that in any one locality the surface current directions showed relatively little deviation from the mean in the case of northwest winds. The standard deviation, as quoted above, is $\pm 17^\circ$. For easterly winds, more variability in local surface current direction occurs. Over large regions it was found difficult to correlate the surface current field with the wind field in terms of both speed and direction. This was explained by MacNeill and Garrett (1975, p. 16-17) as being the result of perturbations by random processes only slightly smaller in scale than the wind field. These processes were thought by them to be related

to the internal density distribution of the Beaufort Sea water resulting from the Mackenzie River outflow and the bathymetric configuration of the continental shelf.

MacNeill and Garrett (1975), Herlinveaux and de Lange Boom (1975), and Marko (1975) mentioned another important characteristic of the Beaufort Sea environment. That is the existence of zones of divergence and convergence of surface currents. It is possible that the long term ice impact hazard is lower for a seabed lying consistently within a divergence zone. This hypothesis could be tested by identifying the zones on satellite imagery showing sediment plumes or ice floes. In zones of low concentrations of suspended sediment or ice floes side-scan sonar surveys could be done to see if the spatial density of ice-scour tracks is significantly lower than in a convergence zone. Of course, other variables that may influence the distribution of ice-scour tracks (e.g., bathymetry, sediment properties) must be similar in the two test areas. The use of satellite imagery in such a study would mean that only a short term record of divergence and convergence zones would be considered. Seabed areas containing few ice-scour tracks might, however, be explained in this way if no other factors are obvious.

The Beaufort Sea Gyre, a major anticyclonic (clockwise) surface current in the Beaufort Sea is not of direct importance to this study because it usually does not extend south of the edge of the continental shelf (Herlinveaux and de Lange Boom,

1975, p. 76).

(c) bottom currents

Bottom currents in the Beaufort Sea are a function of the following factors, most of which are interdependent: wind stress, barometric pressure gradient, tidal forces, Mackenzie River discharge, bottom topography, ice cover, and momentum possessed prior to entering the region (Huggett et al., 1975, p. 10).

Summertime observations by Huggett et al. (1975) indicate that at the edge of the continental shelf, bottom currents are generally flowing towards the northeast. The same investigators found that ice cover was not usually a major influence on the bottom currents at the shelf edge. They pointed out, however, that at stations closer inshore the absence of ice cover led to direction and velocity changes in the bottom current. These changes were thought to be a result of wind stress. At a current meter station in about 30 m of water just northward of the 'Pullen Island' survey area there was good correlation between wind and the bottom current directions. The maximum velocity recorded at this particular station was 0.24 m/sec with a heading of 110° clockwise from true north (related to a westerly or northwesterly wind). A similar maximum speed (0.23 m/sec, heading 143° true) was recorded by a current meter moored in the vicinity of the 'East Mackenzie' mosaic area (Huggett et al., 1975, p. 27, Table 1).

4.3.3 Storm surges

Information regarding storm surges in the Beaufort Sea was found in Henry (1975). Strong onshore (northwesterly) winds in the Beaufort Sea region can cause rises in sea level of more than 2 m along the coast. The amplitude of a surge usually decreases with increasing distance from the coast. Surges are generally most destructive when there is no ice cover present. From the point of view of the present study, however, it is of interest that winter surges can occur. Although ice cover inhibits the development of surges, such an event can occur if there is the possibility for slight movement of the ice (e.g., in closing leads) and amplitudes of about 1 m have been observed. Winter surge amplitudes tend to be similar between coastal and offshore sites. R.F. Henry, when analysing a surge event of 5 to 7 January 1974, found that although wind-speed remained high until 7 January, the peak water level occurred on 6 January. It was hypothesized by Henry that the period from 5 to 6 January represented the amount of time taken to close the leads in the ice cover. During the time when the leads were open, the wind stress could be transferred to the water. Once the ice cover had consolidated, no further transfer of energy from atmosphere to ocean could take place.

This writer wishes to add to this hypothesis the possibility that ice pressure ridge and keel systems were formed as the leads closed. Perhaps some ice impacts on the seabed occur during winter surges. Since Henry (p. 35) stated that winter surges are "... rare or at least unusual", this hypothesized

association of ice-scouring events with winter surges has implications for a determination of the ice impact hazard on the seabed. The more common summertime and autumn surges should be of importance to the formation of ice-scour tracks on the seabed if ice islands or pressure ridge fragments having deep keels are driven towards shore (Reimnitz and Barnes, 1974). On the other hand, McLaren (1977) pointed out that storm surges could be used to explain the absence of ice-scour tracks around some grounded ice masses that have been investigated.

4.4 Floating ice

The presence of floating ice in the Beaufort Sea is an outstanding characteristic of the physical environment which must be considered in any study of coastal or submarine geomorphology in the region. In the following sub-sections, a general description of ice conditions in the Beaufort Sea will precede a discussion of those conditions that pertain specifically to the 'East Mackenzie' and 'Pullen Island' mosaic areas.

The open water season in most of the Beaufort Sea lasts only for about two to three months and may be shortened considerably by storm caused invasions of polar pack ice which is a permanent feature of the Arctic Ocean.

In the Beaufort Sea, the floating ice may have two distinct origins. It may be glacier ice or it may be frozen

sea water (sea ice). Floating glacier ice can itself be derived from either of two sources; namely ice shelves or glaciers. Icebergs, which are derived from glaciers, are now extremely rare in the Beaufort Sea since no tidewater glaciers exist in locations where currents could carry icebergs into the Beaufort Sea. In early post-Wisconsin times, however, they may have been more common. On the other hand, ice islands, derived from Ellesmere Island ice shelves, occur frequently in the Beaufort Sea.

4.4.1 Ice islands

A summary of ice island observations in the Beaufort Sea was provided by Kovacs and Mellor (1974). The ice islands entering the Beaufort Sea usually originate from the 35 to 60 m thick floating ice shelves which exist along the northwestern coast of Ellesmere Island. Since floating ice has approximately nine tenths of its mass submerged, a rough calculation shows that a 60 m thick ice island would have a freeboard of about 6 m and would draw about 54 m of water. By the time ocean current transported fragments of the ice shelves reach the Beaufort Sea, the ice islands are usually 30 to 100 m in diameter although diameters of 3 km have been observed. Kovacs and Mellor stated that ice island thicknesses usually range from 12 to 30 m although the Pilot of Arctic Canada (C.H.S., 1970) gave a draft range of 30 to 50 m for ice islands in general. Ice islands are conspicuous features within the ice

cover, being rather flat, tabular masses with an upper surface significantly higher than the surrounding sea ice surface (see, for example, the photographs presented by Kovacs and Mellor, 1974, p. 140-143). Several hundred ice islands, including some grounded ones, have been observed during ice reconnaissance flights during the last decade. Kovacs and Mellor also stated that sightings of ice islands were often made by Arctic explorers within the last two centuries. It is generally believed that production of ice islands is not constant but that periodic breakouts occur.

Ice island bottoms may be fairly flat in the case of small fragments as evidenced by wide, flat, 0.3 m deep depressions in the seabed caused by grounding fragments near Barter Island, Alaska (Kovacs, 1972). Reimnitz and Barnes (1974, p. 315) presented a sonograph of a "... broad, flat gouge ..." which they presumed had been caused by an ice island fragment. Large ice islands, however, are not flat-bottomed according to studies cited by Kovacs regarding ice island T-3 and therefore their tracks on the seabed should exhibit some relief.

4.4.2 Sea ice

(a) sea ice zonation

The winter sea ice cover in the Beaufort Sea is generally considered to consist of three distinct zones which are approximately correlated with water depth over the continental shelf

Figure 4.7 Ice zones in the Beaufort Sea. The average limits for the zones are based on C.H.S. (1970). The variable zone limits in Mackenzie Bay are from Marko (1975). The mosaic areas are labelled: (1) 'East Mackenzie', (2) 'Pullen Island', (3) 'Elf'.

mosaic areas

(see figure 4.7). The three zones will be referred to as the fast ice zone, transition zone, and gyral pack ice zone.

(i) fast ice zone

The fast ice zone (W.M.O. nomenclature) usually extends from the shoreline seaward to the 20 or 30 m depth contour (C.H.S., 1970; Wadhams, 1975; Marko, 1975). Variability in the width of the zone arises from varying meteorological and ice conditions at the time of initial formation of the fast ice. The relatively immobile fast ice usually exists from late October or early November to July, although it can remain intact longer if the summer pack ice is blown close inshore or if a large number of multi-year floes were incorporated into the zone at the time of formation of the fast ice (Marko, 1975).

The time of formation of the fast ice is determined by at least three interrelated events: namely, decreased solar radiation input, a seasonal shift in the atmospheric pressure field, and the seasonal decrease in the Mackenzie River discharge. In late October or early November, freezing of seawater is facilitated by the prevailing sub-zero (Celsius) temperature (C.H.S., 1968, p. 3). The prevailing winds tend to blow onshore in the winter months and the decreased Mackenzie River discharge possibly (Marko, 1975, p. 125) allows the surface currents to shift from the observed northeastward flow which prevails in summertime to the observed southwestward flow which prevails in winter.

The character of the fast ice for a particular winter depends mainly upon the frequency and severity of early winter storms. Rough seas at freezeup time will result in the newly formed first year ice having a relatively rough surface (Kovacs and Mellor, 1974). Furthermore, strong onshore winds often result in relatively thick (greater than 2 m) multiyear ice being incorporated into the fast ice zone. Satellite microwave images as interpreted by Ramseier et al. (1975) suggest that the proportion of multiyear ice in the fast ice zone usually exceeds fifty per cent. In November and December the first year fast ice steadily increases in thickness (Markham, 1975). As brine drainage occurs over time, the salinity of the newly formed ice gradually decreases thereby causing its strength to increase (Kovacs and Mellor, 1974).

Storm winds may drive the pack ice into the fast ice zone while the ice in the latter zone is still relatively weak and thin (0.5 to 0.8 m thick in October/November; Cooper, 1974) and pressure ridges will be formed. These ridges will tend to favour inshore ice growth because wave amplitudes will be damped in the lee of the ridges. The depths to which the keels of these ridges extend is believed to be partially dependent upon the thickness of the ice from which the jumbled ice blocks in the ridge are derived (Markham, 1975). The fast ice zone can be visualized as expanding seawards in a series of steps mainly by pack ice floes being frozen to the existing fast ice boundary until finally in February or March

a large number of the pressure ridge keels (formed mainly out of the first year ice that is bonding the pack ice floes together) have begun grounding in water depths of 20 to 30 m. The maximum depth of grounding is largely responsible for the location of the seaward limit of fast ice (Markham, 1975). The Pilot of Arctic Canada (C.H.S., 1970) stated that the thickness of first year ice at the end of the winter season is likely to be 1.2 m to 1.5 m. This ice thickness seems, therefore, to be correlated with a grounded keel draft of 20 m at which depth the fast ice edge usually stabilizes in spring. Deviations from the 20 m limit are possible. Stringer (1974), for example, mentioned that a "... large seaward bulge of shorefast ice" occurred in Harrison Bay, Alaska where ice had grounded in 27 m of water. Cooper (1974) pointed out that east of the Mackenzie Delta, fast ice can extend beyond the 20 m limit but that usually the extension will later break off at this limit.

In the case of the fast ice in Mackenzie Bay, the above generalizations must be qualified. Cooper (1974) stated that the fast ice in Mackenzie Bay should be considered as "quasi" fast ice. In Mackenzie Bay, for example, open water can exist right up to the shoreline in the area west of Shingle Point (see figure 4.7) even in mid-winter although this certainly does not happen every year (see for example, the satellite images in Marko, 1975). Cooper pointed out that the stability

of the fast ice zone is likely to be linked to the water depths in a region. The relatively deep water of Mackenzie Bay makes for an unstable fast ice cover.

An important characteristic of the entire Canadian Beaufort Sea fast ice zone that is unlike the Alaskan situation is that there is usually no continuous grounded pressure ridge or shear ridge zone at the seaward edge of the fast ice in the southeastern Beaufort Sea. Cooper (1974) hypothesized that the fast ice is anchored, but only by relatively isolated grounded pressure ridges. A 1971 survey by Cooper found only one possibly grounded feature in a 50 km by 50 km area north of Kugmallit Bay.

The freedom of movement of discrete ice masses in the fast ice zone is greatest in early winter before the first year ice has thickened and strengthened and before the pack ice floes have become welded together by first year ice (Kovacs and Mellor, 1974). These authors also stated that winter storms are most intense early in the season and tend to become less intense just at the time that stronger winds are required to cause any significant ridging in the stronger ice. These conclusions are supported by an analysis of the spatial distribution of pressure ridges. This analysis by Hibler, Mock and Tucker (1974) used laser profiles taken across the ice in the Arctic Basin. It was found that in 1970-72, the maximum change in 'ridging intensity' (a parameter involving the mean number of ridges per unit length and mean ridge height) occurred

Figure 5.1 Single, straight ice-scour track with pronounced crater on east end. From 13.5 to 14 m water depth in 'Pullen Island' survey area, 1974. Scale 1: 10 000. Classification code for outlined track is S st d (see Table 5.1).

on 10 April 1973, a satellite image shows the fast ice boundary lead to be about 25 km wide (Marko, 1975, figure 3).

The pack ice in the transition zone is mainly first year ice which can be up to 2 m thick. According to the Pilot of Arctic Canada, (C.H.S., 1970, p. 158), the floe concentration usually exceeds seven eighths and the floes exhibit "intermittent restricted motion". Ice floe velocities in this zone can exceed 15 km per day but when lead refreezing occurs the ice drift speeds can drop to less than 4 km per day (Marko, 1975). Occasionally, as Marko pointed out, significant motion can cease altogether when the pack ice temporarily becomes attached to the fast ice. In general, ice motion is a function of the following variables: wind, currents, internal ice stress, Coriolis effect, and pressure gradients (Herlinveaux and de Lange Boom, 1975, p. 12). There is a seasonal shift in the motion of ice in this zone probably corresponding to changes in the flow of the Beaufort Sea Gyre current as it responds to seasonal changes in the atmospheric pressure field. In winter the ice drifts southwestward while in summer the mean ice motion is to the northeast (Marko, 1975). Generally, drift speeds are two per cent of the wind speed and are directed about 30° to the right of the wind due to the Coriolis effect at these latitudes (Herlinveaux and de Lange Boom, 1975, p. 11). These writers stated that for particularly low ice concentrations the ice drift speed can exceed the two percent value and for high ice concentrations the ice drift speed may fall below two

percent of the windspeed. High ice concentrations are likely to cause considerable variability in the direction of ice movements (Markham, 1975, Table 1B, p. 25).

(iii) gyral pack ice zone

The gyral pack ice zone (nomenclature from Marko, 1975) lies seaward of the edge of the continental shelf and the recurring lead at the 500 m depth contour which approximates the seaward limit of the transition zone. The ice in the gyral pack ice zone consists mainly of multiyear floes 3 to 4 m thick which are in continuous motion (C.H.S., 1970, p. 158). Refreezing of leads and polynyas can, however, result in the presence of significant quantities of first year ice in the zone (cf., Wadhams, 1975, p. 24 and 28). The Pilot of Arctic Canada (C.H.S., 1970) stated that the ice and surface water drift in the gyral zone is related to the overall atmospheric pressure field that exists over the Arctic Basin. Marko (1975) observed that the pack ice motion was "rigid". That is, within the pack, relative displacements between floes were usually much less than the displacement of the floes relative to the seabed. This fact implies that "... collective effects and internal ice forces" are of major importance in the dynamics of the gyral pack ice (Marko, 1975, p. 122).

During periods of strong onshore winds the gyral pack ice can move inshore. Cooper (1975, p. 2), for example, mentioned that sometimes "... large amounts of old polar ice occur

southeast of Herschel Island". Such events are of great interest for this study of ice-scour tracks because it is in the gyral pack ice or polar pack that some of the deepest ice keels have been encountered on submarine traverses. For example, Lyon, (1961, p. 663; 1967, p. 708) stated that submarine cruising depth "... is set sufficiently deep to clear all pressure ridges easily, or the very rare ice island, draft perhaps 160 feet [49 m] ." Furthermore, observations of pressure ridge heights in the Beaufort Sea by Wadhams (1975) have indicated that the region west of Banks Island may be an important source of high ridges (and therefore it is presumed, deep keels). Wadhams also found that this area had moderate ridge frequency (linear density along a traverse) and a large mean height for ridges. Pressuring of the ice in a large refrozen polynya could be responsible for the heavy ridging that is sometimes observed in the gyral pack ice (Wadhams, 1975).

(b) sea ice ridges

By linking together some of the points covered in the preceding sections (a-ii) and (a-iii), it seems reasonable to presume that deep draft sea ice ridges can be transported into the shallower waters to the southwest of the main source area. Ridges formed in the gyral pack ice zone west of Banks Island in early winter, for example, could drift southwestward with the prevailing winter currents and eventually work their way landward through the transition zone. By a combination of

circumstances, the ridge may eventually ground close to the fast ice boundary within a few months of formation of the ridge in the gyral pack ice zone. Therefore it becomes important to consider the formation and evolution of sea ice ridges in some detail. There are two types of sea ice ridges that may occur: shear ridges and pressure ridges.

Shear ridges are formed when adjacent ice floes move parallel to each other (Parmerter and Coon, 1972). The ridges have a "... highly pulverized granular sea ice structure ..." with a porosity as low as 10% (Kovacs and Mellor, 1974).

Pressure ridges are formed when compression, rather than shear, is the major process during deformation of ice floes. This type of ridge forms when adjacent floes move toward each other (Parmerter and Coon, 1972). Pressure ridges are composed of a loose agglomeration of large ice blocks and consequently may have a porosity as high as 40% at the time of formation (Kovacs and Mellor, 1974). According to Kovacs et al., (1973), the best bonding between ice blocks should occur if the ice is very cold at the time of ridge formation. They point out, however, that most of the first year ridges that have been investigated had "poorly bonded" ice blocks.

As is usual with natural processes, there occurs a complete gradation of ridge type between these two classifications. The actual ridge morphology and porosity depends upon the relative proportions of the shear and compressive forces that were acting

on the ice at the time of formation of the ridge (Kovacs and Mellor, 1974, p. 135). The term 'pressure ridge' is rather loosely used in the literature to refer to any type of sea ice ridge no matter what the details of its origin are. This may be because pressure ridges are more common than shear ridges. This writer is, however, not aware of any detailed classification of ridge types comparing average dimensions or frequency of occurrence in space and time. Since deeper keels and hence widespread ice-scouring of sediments are more likely to be associated with high porosity ridges (i.e., pressure ridges) the term 'pressure ridge' is favoured in this report.

Extreme events are always of interest when considering any type of hazard. The largest free floating pressure ridge that has yet been observed (Kovacs et al., 1973; Kovacs and Mellor, 1974) had a ridge peak that reached 12.8 m above sea level. This pressure ridge was composed of first year ice and was situated where two large floes met. The uppermost block of ice was 2.2 m thick, 3 m wide, and 7 m long. This ridge was situated near 75°N, 148°W which is within the permanent polar pack (gyral pack ice zone).

A computer model study by Parmeter and Coon (1972) showed that there is a limiting height for ridges (and, it is inferred, a limiting depth for keels). Once the limiting height and depth was reached a growing ridge would only increase in width. This limiting height was defined as the "... height

that brings the bending stresses in the sheet to the fracture level" (Parmerter and Coon, 1972, p. 6573). In other words, the strength of the ice sheet that surrounds a pressure ridge will affect the ridge size. Parmerter and Coon's figure 12 shows that the limiting height of ridge sails and keels tends to increase when the ice sheet is thicker. These authors also pointed out that high ridge porosities (i.e., looser packing of ice blocks) allows for the formation of higher ridges. In terms of the keel draft, the low overall buoyancy of a high porosity ridge is important because the keel can then extend farther below sea level.

The heat sink capacity of the ice blocks that have been incorporated into a ridge is usually large because they have been exposed previously to air temperatures much lower than the freezing point of the sea water in which they became submerged (Kovacs and Mellor, 1974). Freezing of the interstitial water therefore occurs. According to A. Gill (pers. comm. to Kovacs et al., 1973, p. 23), two melt seasons are usually needed for complete consolidation of a pressure ridge. Upon freezing of the water in the voids between the ice blocks, the displacement of water by the ice mass is increased and the buoyancy of the ridge will be enhanced causing the original keel draft to decrease. Usually, however, ablation of a keel and sail will occur and the effect of decreased mass of the pressure ridge may be primarily responsible for any decrease in

keel draft. In fact, Diachok (1976) claimed that a "majority" of ice keels are "... flattened at the bottom due to ablation ...". This statement also has implications for ice-scour track morphology in that relatively wide, smooth tracks in seabed sediments would commonly be expected to be created when mature pressure ridges become grounded. Wadhams (1977) illustrated several relatively wide, rounded keel profiles observed by submarine which serve to support Diachok's statement.

The morphology of a first year pressure ridge keel as observed by divers was described by McLaren (1974). The ridge that he studied was located near the North Pole. The ridge height was 4 m while the keel was 19 m deep (sail height to keel depth ratio 1:4.8). The keel consisted of "... large platelets of ice (20-30 m square) similar in thickness to the new ice in the lead [0.3 to 0.4 m] as well as more massive blocks ...". McLaren described the arrangement of ice blocks and platelets as being random. The water in the voids between the ice blocks had not frozen (the observations were made in late April, 1974) and the blocks had a "jagged" appearance. Finally, it was noted that the ice pack moved the keel about 3 km in 72 hours.

First year ridges have been observed to have sail height to keel depth ratios ranging from 1:3 to 1:9 with the average ratio being about 1:4.5 (Kovacs and Mellor, 1974). This empirical ratio is of importance because it is simpler to measure ridge heights than keel depths.

Multiyear ridges are fairly common in the Beaufort Sea. They consist of solid ice and have smoothed relief (Kovacs and Mellor, 1974). The sail height to keel depth ratio of this type of ridge has been found to be fairly constant at 1:3 (Kovacs and Mellor, 1974) and the multiyear ice mass is thought to be in isostatic equilibrium (Kovacs et al., 1973).

Multiple keel ice pressure ridges do occur as is shown by the existence of multiple ice-scour tracks (figure 5.6). The preceding paragraphs are also presumed to apply to this type of ridge.

4.4.3 Relationship of mosaic areas to ice distribution

Markham's (1975) study of ice climatology in the Beaufort Sea included a discussion of median ice conditions.

In the 'East Mackenzie' area, the median clearing date, after which ice concentration is less than two-tenths, is July 2. There is no great variability from north to south although just offshore of the Mackenzie Delta open water usually occurs by June 18. This area can be covered at various times by ice from all three major ice zones probably as a result of the relatively deep water in this area being so close to the coast.

The 'Pullen Island' area usually lies within the fast ice zone although at times it may lie within the transition zone. The median clearing date is July 16 which is a bit later

than in the 'East Mackenzie' mosaic area.

In both areas freezeup usually occurs by the second week of October.

4.5 Seabed sediments

4.5.1 Characteristics and properties

Pelletier (1975) provided a comprehensive description and analysis of the surface texture and mineralogy of surficial sediments in the southern Beaufort Sea. Table 4.I is a summary of sediment attributes that pertains to the three existing A.P.O.A. - Geological Survey of Canada side-scan sonar mosaic areas. The summary of attributes was compiled mainly from the maps presented in Pelletier's Beaufort Sea Project report. All of these attributes can conceivably have some influence on the dimensions of ice-scour tracks. A detailed understanding of the influence of these variables does not, however, exist at this time.

The first few metres of seabed sediments appear to have poorly developed structure. On radiographs of cores taken in 1975 by the Geological Survey (C.F.M. Lewis, pers. comm.) only weak laminations can be seen in most cores. In fact, many of the core sediments have a massive appearance. Sometimes the laminations are steeply inclined, suggesting disturbance of the mud layer. Sandy inclusions within the silt and clay layer are also fairly frequent, again suggesting disruption of the seabed surficial sediments by ice.

Table 4.1 Summary of sediment attributes for the three Geological Survey of Canada side-scan sonar mosaic areas. Information is from maps presented in Pelletier (1975) unless otherwise noted. The 'Elf' area is included for completeness only and is not otherwise discussed in this report.

<u>Sediment Attribute</u> (from surface sampling)	<u>Mosaic area</u>		
	<u>'East Mackenzie'</u>	<u>'Pullen Island'</u>	<u>'Elf'</u>
gravel concentration	less than 1%	less than 1%	less than 1%
sand concentration	less than 1%	1 - 10% 10 - 20% (extreme E)	1-10%
silt concentration	20-40% (S part, 40-60%)	20-40% (S edge, 40-60%)	20-40%
clay concentration	60-80% (S quarter, 40-60%)	W half, 60-80% E half, 40-60%	60-80%
illite concentration	50-60%	50-60%	NE corner 50-60% 40-50%
chlorite concentration	10-30%	20-25%	10-15%
kaolinite concentration	20-30% (N edge, 30-40%)	20-30%	20-30%
montmorillonite conc'n.	0-5%	0-5% (N edge, 5-10%)	10-15%
CaCO ₃ (wt. per cent)	3-4%	3-4% (N edge, 2-3%)	2-3%
organic carbon (wt. %)	1.6-1.8%	1.4-1.6%	1.4-1.6%
$\bar{I}_\phi$ diameters	greater than 8, clay	greater than 8, clay; E edge 4-8, silt	greater than 8, clay
phi modes	greater than 8, clay	greater than 8, clay	greater than 8, clay
sorting (std. dev.) ϕ values	good (S third, fair)	fair	fair (poor at W edge)
sorting (rel. entropy) Hr %	low, less than 50%	high, 50-70%	high, 50-70% (W edge, low, less than 50%)

.../ cont'd.

Table 4.1 (continued)

<u>Sediment Attribute</u> (from surface sampling)	<u>Mosaic area</u>		
	<u>'East Mackenzie'</u>	<u>'Pullen Island'</u>	<u>'Elf'</u>
skewness (positive - erosion, negative - deposition; see p. 11 Pelletier, 1975)	positive	positive	positive
silt/clay ratio	0.25-0.75	0.50-0.75	0.25-0.50
hydrodynamic environment	very low energy	very low energy	very low energy
sediment transport	from S to N, area lies within Mack. R. sediment plume	from S to N, only SW part of area lies in sed. plume	from W to E ? outside of sed. plume by 35 km
mud thickness (from echograms, Shearer, 1972)	exceeds 20 m	3-10 m	less than 3 m
sedimentation rate (inferred from mud thickness and sea level history), Lewis (1977 b)	exceeds 0.5 mm/yr	avg. 0.5 mm/yr	avg. 0.5 mm/yr
shear strength (in situ) (Lewis, 1977a)

4.5.2 Mud thickness over pre-Holocene sediments

Because much of the Beaufort Sea continental shelf was exposed during the Wisconsin glaciation, it has been suggested (e.g., Shearer, 1971; Pelletier, 1975) that fluvial and beach sands are of widespread occurrence on the continental shelf. As marine transgression took place, finer materials ('mud') were deposited on top of the 'basal sand'. The mud thickness in an area of seabed is of importance to the study of ice-scour tracks because the shear strength of the basal sand is likely to be considerably greater than that of the overlying mud. This has implications for the expected dimensions of a track in that the resistance met by an ice keel scouring into the seabed would be relatively high for those keels penetrating into the seabed by more than the mud thickness. Also, since sandy sediments are cohesionless, the areas of seabed that have a thin mud cover may not preserve the form of ice-scour tracks very well. In such an area, ice-scour tracks are likely to be removed preferentially by the action of bottom currents and biological organisms and might not provide reliable estimations of the ice impact hazard.

In the 'East Mackenzie' mosaic area, mud thickness exceeds 20 m (Shearer, 1972b). This is twice as much as the ice-scour depth of the deepest observed ice-scour track in the Beaufort Sea (Lewis, 1977b).

For the 'Pullen Island' area, however, it becomes important to consider mud thickness. Unpublished data from Geological Survey of Canada oceanographic coring operations in 1975 indicates that near the centre of the 'Pullen Island' area, the basal sand lies 1.6 m below the seabed surface (C.F.M. Lewis, pers. comm.). The 1975 core data indicates that in the northwestern part of the area mud thickness exceeds 1 m. In the southern and eastern portions, however, the mud layer thins considerably. In fact, the cores taken about six kilometres to the east of the 'Pullen Island' area hit sand and gravel only 0.1 and 0.2 m below the seabed surface.

The origin of the two mounds in the eastern 'Pullen Island' area is unclear. Figure 4.8 is an echogram taken across the summit of the most northerly one (see also bathymetric map in back pocket, figure 3.5). They may be incipient pingos or remnants of eroded pingos. Pingos are known to be fairly common on the Beaufort Sea continental shelf (Shearer et al., 1971). A seismic reflection survey across the features and core collection at the sites would be useful in explaining the origin of the mounds. In any case, their association with a hard sandy bottom (indicated by the thin trace; Raytheon Company, no date) has important consequences for the determination of ice impact hazard in that ice impacts may be frequent but the sandy bottom does not preserve a good record of the passage of grounding ice keels. To either side of the mounds, ice-scour tracks are well preserved as shown in figure 4.9

88a.

Figure 4.2

Excerpt from 30 kHz echo-sounding record obtained while crossing the northernmost mound shown on the 'Pullen Island' mosaic area bathymetry chart (figure 3.5). Note the thin trace of the seabed reflector. This is presumably the result of the bottom sediment containing a high proportion of sand.

88b.

574

-0

transmitted
pulse

-10

m

seated
echo
pulse

-20

-30

1
0

1
500 m

Figure 4.9 Excerpt from 30 kHz echo-sounding record obtained about 1.5 km eastward of the echogram portion shown in figure 4.8. Note that pulses returning from the seabed are relatively long, indicating a softer seabed. That is, the mud layer overlying the basal sand must be thicker. The thicker mud blanket allows the form of the ice-scour track to be preserved much better than in the cohesionless sandy material at the summit of the mound shown in figure 4.8.

which is from an area about 1.5 km eastward of the seabed profile in figure 4.8.

In summary, mud thickness generally decreases from west to east between 138° and 134° longitude although local variability is evident as shown on J. Shearer's (1972b) mud thickness map. This trend is primarily a consequence of the sediment input from the Mackenzie River's channels which enter Mackenzie Bay. The sediments are then transported mainly eastward (see for example, figure 31 in Pelletier, 1975).

4.6 Sea level changes, climatic changes, and sedimentation rates

To make valid estimations of the ice impact hazard to seabed installations, it is necessary to understand the effect of sea level changes, climatic changes, and sedimentation rates on the morphology and distribution of the ice-scour tracks that are seen today.

Sea level changes and climatic variations that pertain to the Beaufort Sea continental shelf are summarized in figure 4.10. The continental shelf is presumed to have been stable (i.e., no isostatic rebound has occurred) during the past 10 000 to 15 000 years (Lewis, 1977a). Therefore, the worldwide sea level curve can be applied to this area. It shows that until about 4000 years B.P. worldwide sea level rise was fairly rapid. Regions of the continental shelf that are now in fairly deep water (greater than 50 m) were presumably once

Figure 4.10 Climatic variations and the sea level curve that is applied to Beaufort Sea continental shelf sea level history. Sea level curve from Lewis (1977 a), based on several worldwide sea level curves, "...adapted from Curray and Shepard, 1972; Milliman and Emery, 1968; Shepard and Curray, 1967; Muller-Beck, 1966...".

in shallower water where average-sized ice keels could readily ground on the seabed.

Significant climatic changes have also affected the southern Beaufort Sea region in post-glacial times (Lamb, 1971; Hare and Thomas, 1974). This has probably affected wind speed and direction, floating ice distribution, sea ice thickness, and hence the magnitude of the ice impact hazard over time.

Sedimentation can affect the dimensions of ice-scour tracks as perceived on echograms and sonographs. Average sedimentation rates have to be considered with regard to the variable climate and rising sea level. The following analyses yield some estimates of sedimentation rates for the side-scan sonar mosaic areas. These rates can then be related to the degree of infilling of the ice-scour tracks that exist in the areas.

Two Geological Survey of Canada core sites which have yielded convincing physical estimates of the mud thickness above the basal sand and gravel surface (C.F.M. Lewis, pers. comm.) are indicated on figure 4.11. At the core site 185P in 17.5 m of water, the mud thickness is 1.6 ± 0.1 m.¹ This means that the basal sand/gravel 'transgression surface' is 19.1 m below present datum. From the sea level curve (figure 4.10) it can be estimated that inundation at -19.1 m (relative to

¹ uncertainty estimate based on core length versus penetration information, core radiograph analysis, and examination of opened core.

Figure 4.11 Locations of piston cores 169 E and 185 P.

present datum) commenced at 8600 $\begin{smallmatrix} +1200 \\ -2500 \end{smallmatrix}$ years B.P. (6100 to 9800 years B.P.). If one assumes that the 1.6 ± 0.1 m mud thickness has accumulated since the onset of transgression at that point, then an average sedimentation rate of $0.19 \begin{smallmatrix} +0.03 \\ -0.06 \end{smallmatrix}$ mm/yr (0.13 to 0.22 mm/yr) is obtained. But, Shearer (1971) and Lewis (1977a) pointed out that in the modern Beaufort Sea environment, mud deposition is only significant seaward of the 10 m depth contour. In shallower water, wave action sweeps fine sediments away. Therefore a more likely sedimentation rate calculation, based upon the time available for mud accumulation at the site subsequent to the transgression stage at about 6700 years ago when the sea level was -9.1 m below present datum gives a sedimentation rate of $0.24 \begin{smallmatrix} +0.04 \\ -0.09 \end{smallmatrix}$ mm/yr (0.15 to 0.28 mm/yr). Core site 169E in 32 m of water and a mud thickness of 2.2 ± 0.2 m¹ gives sedimentation rate values of 0.21 ± 0.05 mm/yr (0.17 to 0.26 mm/yr) if mud accumulation is presumed to have taken place since the onset of transgression at -34.2 m below present datum (about 10 400 years B.P.). If the time available for sedimentation is assumed to be that since innudation of the 24.2 m depth contour began (about 9300 years B.P.) the sedimentation rate calculation yields values of $0.24 \begin{smallmatrix} +0.05 \\ -0.06 \end{smallmatrix}$ mm/yr (0.18 to 0.29 mm/yr). The average sedimentation rates are similar for the two sites even though core site 169E lies outside of the present Mackenzie River sediment plume as

¹ uncertainty estimate based on core length versus penetration information, core radiograph analysis, and examination of opened core.

depicted by Pelletier (1975). The rates calculated here based on physical evidence are lower than the average 0.5 mm/yr ($\pm$?) rate quoted by Lewis (1977b). Furthermore, they are at odds with the generalized sedimentation rate curve presented by Lewis (1977b), based on mud thickness measurements from echograms, which predicts a sedimentation rate of about 1.3 mm/yr at the 17.5 m water depth and a rate of just over 0.6 mm/yr at the 32 m water depth. Sedimentation rates are expected to be highly variable between localities on the continental shelf. This conjecture is supported by the satellite imagery presented in Marko (1975). The surface turbidity distribution associated with suspended sediment input from the Mackenzie River is seen to be greatly variable over the three years for which images were available. Over a period of decades, this initial variability in sediment input to various offshore locations could cause significant differences in mud thickness even within areas of just a few square kilometres. Therefore, no attempt can be made in this report to resolve the discrepancies in sedimentation rates that are mentioned above. It should be pointed out, however, that the concept of 'average sedimentation rates', especially for time spans exceeding the past 4000 years, may not be entirely appropriate because of the variability of the post-glacial climate in the Mackenzie Delta - Beaufort Sea region (see figure 4.10). Nevertheless, for estimation purposes, derivation of this range of average sedimentation rates (0.13 to 1.3 mm/yr) does indicate that most ice-scour tracks in the

'Pullen Island' area and regions just to the north are likely to remain visible at the seabed surface for a few hundred years at least.

Many of the interpretations in the next chapter are based on information from ice-scour tracks that lie in water depths of 40 to 50 m in the 'East Mackenzie (North)' study area. An estimate of the sedimentation rate can be obtained using the following argument: The retreat of the glacial ice tongue which flowed down the Mackenzie Canyon is believed to have occurred 14 000 to 16 000 years ago (Shearer, 1972a). Seismic reflection work done by Shearer (1971) indicates that the surface of the deltaic sediments (which are probably associated with glacial outwash processes) lies about 24 m below the present seabed surface in the Mackenzie (submarine) Canyon. In the context of a very approximate calculation for the mosaic area, the addition of 24 m to, for example, the 42 m depth contour gives 66 m below present datum. According to the sea level curve, mud accumulation could have started about 13 500 years B.P. suggesting an average sedimentation rate of 1.7 mm/yr in this area. A higher sedimentation rate of 1.9 mm/yr is obtained if allowance is made for 10 m of seawater to have inundated the area first (12 700 years B.P.) before mud accumulation started.

Some of the ice-scour tracks observed in the 'East Mackenzie (North)' area are the surface expression of features

formed possibly several hundred years ago that have been blanketed with sediment. This sediment blanket is shown on a 30 kHz echogram excerpt from the 1974 survey (figure 3.8b) and also in figure 4.12 which is an excerpt from a 200 kHz/7 kHz sub-bottom profiling survey done in 1978 (see section 3.2.2).

In studying the 1978 echograms it was noticed that the survey line '78A' run in water depths of 43 to 46 m distinctly showed the presence of a 2 m thick uppermost sediment layer. The survey line '78B' which was run in water depths of 40 to 44 m did not show this layer very clearly. At first this was thought to be due to poor record quality on the second line because the weather was deteriorating at the time of the surveys. But, upon re-examining the 1974 echograms there is found evidence for a change in the character of the seabed sediment at the 42 m depth. On the 1974 echograms the sediment stratigraphy was only poorly defined and signal penetration was less than 5 m into the seabed in water depths less than 42 m. In deeper water, the sub-bottom reflector about 2 m below the seabed showed up clearly and signal penetration exceeded 5 m. No definite 'pinch-out' at the 42 m water depth of the 2 m thick surface layer could be observed, however.

Of further interest is the fact that of the fifty ice-scour tracks in the 'East Mackenzie (North)' area that have ice-scour depth information associated with them, sixteen show

Figure 4.12 The 2 m thick 'sediment blanket' in the 45.5 m water depth in the 'East Mackenzie (North)' mosaic area is clearly shown in this Raytheon RTT-1000 (200 kHz/7 kHz) echogram excerpt from the September 1978 C.C.G.S. Nahidik survey. The sediment layers to either side of the ice-scour track are actually flat-lying but the response of the ship to wave motion shows up on the record.

evidence of being infilled. Of these sixteen, fourteen lie in water depths exceeding 45 m. In summary, the 2 m thick sediment blanket only exists in water depths exceeding 42 to 45 m and most ice-scour tracks in shallower water can be regarded as showing their original dimensions on acoustic records. The reasons for the existence of a change in seabed character in the 42 m to 45 m water depth range must be linked to sea level changes, climatic changes, and sedimentation history. Unraveling the sequence of events (in order to date the various sediment layers seen in the echograms) is virtually impossible without the availability of more high resolution seismic reflection data from the mosaic area. This data would have to show the base of the post-glacial, post marine transgression mud layer. Then sedimentation rates could be estimated over a range of water depths.

A 1 m deep track (e.g., into surface 'B', figure 3.8b) would not disappear from the seabed ice impact record as observed on high frequency echograms and sonographs until 500 years had passed if the sedimentation rate was 2 mm/yr. This type of calculation conveniently assumes that ice-scour tracks are preferentially infilled (as a result of erosion of the lateral embankments, hydrodynamic considerations, etc.) such that the sedimentation rate within the track is exactly twice that of the undisturbed seabed to either side. Figure 4.13 depicts this idealized situation for preferential sedimentation.

* As long as preferential infilling rate is $2u$, the time taken for an ice-scour track to 'disappear' from record is $t_f = d/u$, where d is the ice-scour penetration depth and u is the sedimentation rate.

* If preferential infilling does not take place, then $t_f \rightarrow \infty$.

Figure 4.13 Idealized representation of an ice-scour track being infilled when it is assumed that the sedimentation rate within the track is twice that over the undisturbed seabed.

within a seabed trench. Reimnitz and Barnes (1974) suggested that infilling of ice-scour tracks is rapid. They mentioned processes such as slumping, grain flow, current action, wave action, and biological activity as being responsible for small-scale mass movements which contribute to erosion of the lateral embankments of ice-scour tracks. In addition to these processes, in Mackenzie Bay the suspended sediment concentration is relatively high as a result of inflow from the Mackenzie River.

Actual measurements (21 observations) of the ice-scour track sediment infilling ratio were made from the sixteen infilled tracks in the 'East Mackenzie (North)' mosaic area. The measurements (Table C.III), indicate a range of 0.9 to 2.9 for the infilling ratio. The mean ratio was 1.7 with a standard deviation of ± 0.4 . Although it is merely a mathematical convenience to assume that ice-scour tracks are covered with sediment twice as fast as the surrounding seabed (because then the time taken until no surface expression of the track remains (t_f) can be set equal to the keel penetration depth divided by the sedimentation rate), this assumption is empirically correct for the 'East Mackenzie (North)' study-area at least.

CHAPTER 5

CLASSIFICATION OF ICE-SCOUR TRACKS ACCORDING TO CHARACTERISTICS OF THE TRACK AS OBSERVED ON A SIDE-SCAN SONAR MOSAIC

5.1 Introduction

In this chapter, representative types of ice-scour tracks and planimetric forms of ice-scour tracks from the Beaufort Sea are illustrated. This writer has hypothesized that the planimetric form of the tracks must be dependent upon the various processes occurring during the motion of the ice that is contacting the seabed. The classification scheme presented in this chapter is used in the investigations of these processes.

5.2 Representative illustrations of the possible planimetric forms of ice-scour tracks

The following seven illustrations are all taken from the 1974 Beaufort Sea survey area mosaics. They are believed to represent the entire range of readily recognizable planimetric forms (straight, arcuate, sinuous, and crater) and some possible secondary characteristics (unmodified, abrupt change in direction, crater at one end). Although a continuum

of forms must exist, it is a fact that an interpreter can detect certain characteristics of an individual track which enable its assignment to a class. The tracing of planimetric form presented below each mosaic excerpt has been done according to the method described in section 3.3.2. No interpretation of processes is presented in this section, the intent is only to familiarize the reader with typical examples of form that provide a basis for a classification system. The existence of analogous track forms from the eastern continental shelf of Canada and the St. Lawrence estuary tidal flats will also be indicated.

The 'Pullen Island' area excerpts are all at a scale of 1:10 000 but the 'East Mackenzie' area excerpt (figure 5.3) is at a scale of 1:20 000. The horizontal resolution capabilities of the survey system (see Appendix A) are of no major consequence in the overall classification scheme, which is based on type of track and planimetric form, although narrower features (less than 5 m wide) such as scour furrows within an ice-scour track cannot be seen.

Figure 5.1 shows an ice-scour track with a single, straight track (about 20 m wide) having a pronounced crater and terminal embankment at the eastern end. A similar feature at a much smaller scale (about 1 m wide), caused by an ice floe scouring into a tidal flat on the St. Lawrence estuary, is shown in figure 6 of Dionne (1971). Icebergs offshore of

Figure 5.1 Single, straight ice-scour track with pronounced crater on east end. From 13.5 to 14 m water depth in 'Pullen Island' survey area, 1974. Scale 1: 10 000. Classification code for outlined track is S st d (see Table 5.1).

Newfoundland can apparently cause similar features but at a much larger scale (about 100 m wide) as a study of figure 2 in Harris and Jollymore (1974) shows (see especially their section of record labelled 'CD').

In figure 5.2 is seen a single ice-scour track having a sinuous planimetric form. This form of track is also illustrated by Dionne in his figure 5. Sinuous tracks are also created by icebergs grounding on the eastern continental shelf of Canada (see, for instance, figure 10 in van der Linden et al., 1976). The approximate order of magnitude for width is once again 1, 10, and 10^2 m for the St. Lawrence estuary tidal flat, Beaufort Sea, and east coast ice-scour tracks respectively.

The well-developed single arcuate ice-scour track illustrated in figure 5.3 is from the 'East Mackenzie' mosaic area. This form can also appear at a small scale as indicated by figures 2 and 4 of Dionne (1971). Large scale, iceberg-caused tracks can also have an arcuate form (van der Linden et al., 1976, figure 10).

A single ice-scour track showing evidence of an abrupt change in direction of the moving keel is illustrated in figure 5.4. Dionne (1969, figure 2) presents an analogous situation at the lower order of magnitude. That iceberg-scoured tracks can also have this form is indicated by figure 10b in van der Linden et al., 1976 (see top left corner of their figure b).

99a.

Figure 5.2 Single, sinuous, unmodified ice-scour track from 12.5 to 13 m water-depth in 'Pullen Island' survey area, 1974. Scale is 1: 10 000. Classification code for track is S si u (see also Table 5.1)

Figure 5.3 Single, arcuate, unmodified ice-scour track from the 44 to 45 m water depth interval in the 'East Mackenzie' survey area, 1974. Scale is 1:20 000. Classification code is S a u (see also Table 5.1).

Figure 5.4 Single, straight ice-scour track showing evidence of a relatively abrupt change in direction of the moving ice mass. This feature is from the 13.5 to 14 m water depth interval in the 'Pullen Island' mosaic area, 1974. Scale 1: 10 000. Classification code is 3 st 2 (see also Table 5.1).

Distinct craters (unconnected to tracks) caused by grounding of ice on bottom sediments also appear to be common at all scales. Figure 5.5 shows an example from the Beaufort Sea. Dionne (1969 and 1971) provides several examples from the tidal flats along the St. Lawrence estuary. The sonographs in Harris and Jollymore (1974) and in van der Linden et al., (1976) indicate that distinct circular depressions are associated with iceberg grounding as well.

Part of a several kilometres long multiple ice-scour track from the 'Pullen Island' survey area in the Beaufort Sea is shown in figure 5.6. An analogous small scale feature is illustrated in Dionne (1971, figure 3). It is not certain whether multiple ice-scour tracks caused by grounding icebergs exist although two sets of apparently parallel tracks appear on section 'I' of the sonographs illustrated by Harris and Jollymore (1974) in their figure 2.

Finally, the third distinctive type of track is typified by figure 5.7 showing a relatively broad, apparently, flat-bottomed double track. The small scale analogy is illustrated in figure 7 of Dionne (1971) which shows, "... very shallow erosional scars made by flat bottom ice blocks carried by ebb currents.". This type of track is also shown in section 'J' of the sonograph from northeast of Belle Isle shown as figure 2 in Harris and Jollymore (1974).

100a.

Pattern on
record
result of:
sound
refraction (?)
or
gas in
sediments (?)

Figure 5.5 A distinct crater (unconnected to any track) is shown in this mosaic excerpt from the 12.5 to 13 m water depth zone in the 'Pullen Island' survey area, 1974. Scale 1: 10 000. Classification code is 'c' (see also Table 5.1).

100b.

Figure 5.6 Part of a several kilometres long multiple, straight, unmodified ice-scour track from the 'Pullen Island' mosaic area, 1974. Scale 1: 10 000. Classification code is M at u (see also Table 5.1).

Figure 5.7 Broad, flat-bottomed ice-scour tracks that appear to be straight and unmodified. From 12.5 to 13 m water depth interval in 'Pullen Island' mosaic area, 1974. Scale 1: 10 000. Classification code: B st u (see also Table 5.1).

5.3 Ice-scour track classification

The classification scheme presented here (Table 5.1 and figure 5.8) is based on the following assumptions which seem justified in light of the observations described in section 5.2:

- (1) The type of track is at least partly dependent on the origin of the ice keel.
- (2) The planimetric form of ice-scour tracks is independent of the size of the ice mass that is ploughing into the bottom sediments.
- (3) The planimetric form is independent of sediment type (but not necessarily independent of variations in sediment strength in an area).
- (4) The planimetric form of the track is a result of processes involving wind, currents, adjacent ice pressure, seabed friction, coriolis force and rise and fall of tides acting during the motion of the ice that is in contact with the seabed.
- (5) Planimetric form is independent of bathymetry (evidenced by tidal flat observations of Dionne, 1969 and 1971).

These assumptions and figure 5.8 indicate that this classification method is based on several working hypotheses. This is intentional; because the classification scheme then is approaching a genetic classification (whose validity will, of course, depend upon the hypotheses that were chosen). Chapter six will examine these hypotheses in detail but the remarks in the following paragraphs, having regard to practical applications of the classification, are appropriate at this time.

It is believed that the classification will be of value in analyses of the ice impact hazard in a locality because the

Table 5.I Ice-scour track classification code.

<u>* Type of track</u>	<u>Symbol</u>	<u>Computer code</u>
Single ice-scour track	S	1
Multiple ice-scour track	M	2
Broad, flat-bottomed ice-scour track	B	3
<u>* Planimetric form of track</u>		
straight	st	4
arcuate	a	5
sinuous	si	6
ice-scour crater	c (this symbol always stands alone)	7
<u>* Modifications to planimetric form of track</u>		
unmodified	u	8
abrupt change in direction	z	9
crater at one end	d	0

ORIGIN OF ICE KEEL	ICE KEEL MORPHOLOGY	TYPE OF ICE-SCOUR TRACK	PROCESSES/ FORCES FOR GROUNDED ICE IN MOTION	MAGNITUDE OF FORCES ON ICE MASS	PLANIMETRIC FORM OF TRACK	ADDITIONAL MODIFICATION OF PLANIMETRIC FORM	
						PROCESS	FORM
first year pressured sea or lake ice multi-year	angular blocks of ice projecting from keel, one or several keels penetrate seabed	single track → multiple track	* wind stress * currents - ocean - tidal	constant one force steadily increasing or decreasing or effect of Coriolis force dominates	straight → arcuate	nil → unmodified	
	bowl-shaped, smooth	→ broad, flat-bottomed track	* rise and fall of tide			interaction with other ice? sediment resistance changes? change in direction of driving force?	abrupt change in direction
ice shelf → ice island	flat-bottomed		* ice floe interaction	variable forces	→ sinuous	settling of ice mass → consolidation of sediment?	crater at end of track
glacier → ice-berg	single angular keel multi-keel flat-bottomed	single track → multiple track → broad, flat-bottomed track	* Coriolis force * seabed friction (above based on Pounder, 1965, p. 40)	zero	→ crater		

Figure 5.8 Conceptual model of relationships between form and process on which the classification of ice-scour track form (Table 5.1) is based.

(R.V. Wahlgren, 1979)

primary division of ice-scour tracks into single tracks, multiple tracks, and broad, flat-bottomed tracks can be related to the probability of ice impacts per unit area of seabed. The origin of the ice mass (inferred from the type of track) that ploughs into the seabed is also significant. For example, an iceberg, which is derived from glacier ice, has the potential during its lifetime for damaging seabed installations in a wider range of water depths and possibly to greater depths beneath the seabed, than a relatively weaker pressure ridge keel composed entirely of first year sea ice.

The processes causing motion of the ice are also important in determining the degree of hazard. For example, winds rather than ocean currents are generally believed to be responsible for the motion of pressured sea ice in the Beaufort Sea. Therefore the risk of damage to seabed installations may increase during storms.

As shown in section 5.2 every ice-scour track can be categorized. This should be of value in the interpretation of mosaics of seabed which often show evidence of hundreds of ice impacts over time. Ultimately the classification scheme may be used in a statistical analysis of track morphology which may in turn aid in determining the ice impact hazard for a locality. Since the classification is not specific to a particular environment it can be used in the interpretation of 'fossil' ice-scour tracks in Glacial Lake Agassiz and modern

ice-scour tracks on the Siberian continental shelf to name just two interesting areas for future study.

The classification scheme should be amenable for computer storage of data since only ten symbols are involved. These can be represented by the digits 0 to 9 inclusive. Each track in a study area could be assigned a three digit number which would serve to describe the planimetric form in reasonable detail. Since the classification of form is based upon a consideration of process, information on the processes involved in the formation of a particular track is implicit in this three digit identification. Information on width, depth, length, and orientation could also be associated (e.g. on same punched card) with the three digit class identification.

CHAPTER 6

ANALYSES OF ICE-SCOUR TRACK INFORMATION GATHERED FROM ECHOGRAMS AND SONOGRAPH MOSAICS

6.1 Introduction

In this chapter, the results of this writer's quantitative study of ice-scour tracks are presented. The premise used is that the form of the ice-scour tracks is related to the processes which created them. The word 'form' as used here refers to collectively an ice-scour track's length, width, depth, azimuth, approach angle to a slope, volume, and amount of rise up a slope as well as to the type of track (single; multiple; broad, flat-bottomed) and the planimetric form of track (straight, arcuate, sinuous, crater). The conceptual model used in this study was presented earlier in figure 5.8 and showed that the final form of an ice-scour track could be always logically traced back to a certain type of grounding ice keel upon which various forces had acted. The process-response model of the Beaufort Sea physical environment (figure 4.1) also provides useful background information for the discussion of the results of the analyses.

Before presenting the actual results, comments on their validity and applicability must be made.

The validity of the results derived from analyses of depth measurements from the ice-scour track images in the 'East Mackenzie' mosaic area is affected because sedimentation rates in this area are rather high (probably greater than 2 mm/yr). This is because the area lies within the Mackenzie River sediment plume. Therefore, several of the ice-scour tracks included in the data set were partially infilled or buried.

The applicability of the results to other areas on the continental shelf may be affected by the rather deep water in the main 15 km² study area (40 to 50 m water depth). World-wide sea levels are believed to have remained constant during the past 2000 to 4000 years. The upper limit for ice island and pressure ridge keel drafts is believed to be about 50 m. Therefore, the ice-scour tracks that exist in this area may be the result of relatively rare ice impacts with the seabed. If sedimentation rate considerations are also added to this argument, it is likely that the evidence of even rarer events is being observed. That is, the buried scours would have required even deeper ice keels to form them if one assumes sea level has remained constant during the time of deposition of the 'mud blanket'. If the ice impacts with the seabed in this

area are indeed rare events it can be hypothesized that many of the ice-scour tracks are hundreds of years old. In any event, it is believed that most, if not all, the tracks seen in this area were created under climatic conditions similar to those which exist today in the Beaufort Sea region.

With the above cautionary statements in mind, the results can be presented. At the very least, it is believed that a practical methodology for analyzing ice-scoured seabeds on an areal basis has been developed which enables frequency distributions of ice-scour track dimensions to be found as well as enabling various correlations between variables to be made. Physically meaningful explanations can then be sought for the nature of the distributions and the strength and sign of the relationships between variables.

6.2 Frequency distributions

The nature of the frequency distributions for ice-scour track length, planimetric width, depth, azimuth, approach angle to α slope, and net rise of an ice keel up a seabed slope is best appreciated by referring to figures 6.1 (a), (b), and (c). As discussed in chapter three, difficulty was encountered in obtaining reasonably large data sets. Therefore, three data sets differing in detail between themselves, were used to provide as much flexibility as possible in the types of analyses that could be done. Data set 'A' (frequency distributions shown

(i) TRACK LENGTH (km)

(ii) PLANIMETRIC WIDTH (m)

(iii) ICE-SCOUR DEPTH (m)

(v) θ_{app} (degrees)

Figure 6.1 (a) The basic sample frequency distributions for ice-scour tracks: length, planimetric width, depth (with sub-bottom information included), azimuth, and approach angle in the 'East Mackenzie (North)' mosaic area (data set 'A').

(i) TRACK LENGTH (km)

(ii) PLANIMETRIC WIDTH (m)

(iii) ICE-SCOUR DEPTH (m)

(iv) ICE-SCOUR TRACK AZIMUTH

(v) θ_{app} (degrees)

Figure 6.1 (b) The basic sample frequency distributions for ice-scour track: length, planimetric width, depth, azimuth, and approach angle for data set 'B' (selected tracks from 'East Mackenzie' mosaic area).

Figure 6.1 (c) The basic sample frequency distributions for data set 'C' which is used in the 'net rise' analyses.

in figure 6.1 (a)) is from the 15 km² 'East Mackenzie (North)' mosaic area. This data set includes all the ice-scour tracks within an area of seabed from which the bathymetry is regular and water depths are in the relatively narrow range of 40 to 50 m. Data set 'B' is intended to provide a means of determining the influence of water depth and ice zonation on ice-scour track characteristics. It does not, however, include information on every ice-scour track within the data collection area. Measurements were made only on those tracks from which two or more depth measurements could be made. Therefore, the frequency distributions (figure 6.1 (b)) may be biased towards any particular characteristics that relatively long ice-scour tracks might have. Data set 'C' (figure 6.1 (c)) is that which is used in any discussion of the net rise of ice keels up a submarine slope. Twenty-nine of the tracks in data set 'C' are also in data set 'B' and three tracks are from data set 'A'. The actual data set 'C' contains forty cases (forty-five cases if infilled or buried tracks are included) because segments of tracks lying between the ship's survey lines are considered as separate cases. This was done to provide as much information as possible on 'net rise'.

In the analyses that follow, care is taken to present results based on at least two of the data sets in situations when bias in a data set could affect the interpretation of the results. The individual frequency distributions are discussed in detail in the following sections.

6.3 Response of grounding ice to forces

In this section, the forces that can act on a grounded ice keel moving through the seabed sediment will be discussed in terms of the ice-scour track azimuth, length, volume, net rise, net rise per unit length of track, and planimetric form of arcuate tracks. First, however, it is necessary to discuss the influence of bathymetry on these analyses (note that this is not a discussion of bathymetric control on grounded ice motion across the seabed which is considered in section 6.4).

6.3.1 Influence of bathymetry on the analyses

The relationship between the 'approach angles to a slope' of ice keels and the azimuths of ice-scour tracks is shown in figure 6.2 (a) for the 'East Mackenzie (North)' data and in figure 6.2 (b) for the 'East Mackenzie' mosaic area data used in the 'net rise' analyses. The former data shows a strongly developed linear relationship because the data are taken from within a relatively small area in which all the isobaths have the same alignment. More scatter is apparent for the data used in the 'net rise' analyses because the information is taken from a wider range of water depths and bathymetric configurations. Figure 3.4 (back pocket) shows the bathymetry of the study area.

The ice-scour track azimuth distribution probably is representative of the direction of ice keel movement before grounding occurred. Hence, the azimuth distribution should be

• two superimposed points

Figure 6.2 (a) The relationship between ice keel 'approach angles to a slope' and the azimuths of ice-scour tracks in the 'East Mackenzie (North)' mosaic area.

• two superimposed points

Figure 6.2 (b) The relationship between ice keel 'approach angles to a slope' and the azimuths of segments of selected ice-scour tracks in the 'East-Mackenzie' mosaic area.

highly correlated with the driving forces responsible for the motion of the ice keels. The approach angle distribution is seen to be mainly the result of the orientation of the seabed slope in the study area with respect to the prevailing driving forces (e.g., winds, currents, adjacent ice). The approach angle parameter is nevertheless useful in some analyses.

6.3.2 Driving forces

(a) Winds

The degree to which surface winds influenced the motion of the grounding ice keels which caused the ice-scour tracks in an area can be examined by considering the azimuth distribution of the tracks. The measurement of ice-scour track azimuth is described in section 3.3.3 (e) and the directional frequency distribution for the tracks in the 'East Mackenzie (North)' area is shown in figure 6.3 (a). The adjacent figure 6.3 (b) shows the annual directional frequency distribution for wind-speeds exceeding 14 m/sec over the Beaufort Sea.

There is a similarity between the two distributions insofar as the northwest storm winds are concerned. The rather high frequency of ice keels causing tracks with a north azimuth is possibly a result of the tendency of the drifting ice that is driven by the strong winds to turn to the right of the wind, because of Coriolis force. In fact, westerly winds are possibly responsible for many of the ice-scour tracks that lie within the

(from Berry et al.,
1975)

Figure 6.3 Frequency distributions for ice-scour track azimuth and for strong winds (speed greater than 14 m/sec) over the Beaufort Sea.

3

northwest track azimuth mode. Although westerly winds are relatively frequent, the proportion of ice-scour tracks indicating ice movement from the west is relatively low. This observation is compatible with the Coriolis effect turning the ice keels to the right of their direction of movement before grounding has occurred.

The relatively high frequency of ice keels that travelled from the SW to NE across the study area is difficult to explain in terms of the annual strong wind distribution given here. The distribution indicates a low frequency of strong winds blowing from the south or southwest. The southwest mode for track azimuth cannot be accounted for by moderate winds either (cf., Berry et al., 1975). This is possibly a result of the generalized nature of the distributions given by Berry et al. Local surface wind data from Shingle Point, about 70 km southwards of the 'East Mackenzie (North)' mosaic area indicates that 'strong' winds (7 to 13 m/sec) from the south-southwest are fairly common and that over a year, twenty-five per cent of all winds are from this direction (Wilson, 1974, p. 20-21). Because moving ice turns to the right before the wind it is expected that the south-southwest wind azimuth would be transformed into the southwest ice-scour track azimuth which is prominent in figures 6.1 (a.iv, b.iv, and c.iv).

Easterly scour azimuths are rare although strong winds from the east are fairly common. This is a result of the

bathymetric configuration of the study area (see figure 4.2). Easterly winds would drive ice keels into deeper water where grounding is less likely to occur.

It seems logical to use the length of ice-scour tracks as an index of the energy (e.g., transferred to the ice from wind) available in an ice keel that is scouring the seabed. The validity of such an index can be tested by plotting track lengths versus azimuths as is done in figure 6.4. A reasonably high threshold value for length is chosen so that the frequency distribution of the azimuths of the 'extreme lengths' can be found. The threshold value chosen here was 1500 m. The number of cases at or above this threshold which lie in a particular azimuth range must be weighted to remove the bias resulting from the azimuth distribution itself. The method of weighting is shown in Table 6.I. Basically, the weighting gives each of the eight azimuths an equal total number of ice-scour tracks (fourteen tracks in this case because the mode (NW) contains fourteen cases). The number of cases exceeding or equalling the threshold remains unaltered for the primary mode. For the other azimuths, however, the weighting serves to increase the absolute number of cases exceeding or equalling the threshold by the ratio of the total number of cases in the mode to the number of cases in a particular azimuth. For example, the north azimuth contains only eight cases. Therefore, the number of tracks (cases) 1500 m in length or more (which

Figure 6.4 Scattergram for ice-scour track length versus track azimuth.
Data from 'East Mackenzie (North)' area.

n = 43

Table 6.I Weighting of length versus azimuth data from the 'East Mackenzie (North)' mosaic area.

<u>Azimuth</u>	<u>no.</u>	<u>weight</u>	<u>no. ≥ 1500 m</u>	<u>wtd. no. ≥ 1500 m</u>	<u>wtd. %</u>
N	8	14/8	7	12.3	26.9
NE	1	14/1	1	14	30.6
E	0	0	0	0	0
SE	0	0	0	0	0
S	4	14/4	3	10.5	22.9
SW	10	14/10	2	3	6.6
W	6	14/6	0	0	0
NW	14	14/14	6	6	13.1

n = 43

n' = 19

n" = 45.8

100.1

Figure 6.5 The weighted frequency distribution for azimuths of ice-scour tracks in the 'East Mackenzie (North)' mosaic area that are greater than or equal to 1500 m in length.

is seven) is multiplied by the ratio 14/8 to give the weighted number of cases greater than or equal to 1500 m (which is 12.3).

Figure 6.5 shows the weighted frequency distribution for azimuths of ice-scour tracks greater than or equal to 1500 m in length. The distribution does not correspond very well with the strong wind distribution (figure 6.3b). This is probably a result of the northerly to southerly trend of the depth contours in the 'East Mackenzie (North)' area affecting the length of the ice-scour tracks. That is, ice keels heading more or less straight into the slope ($0^\circ \leq \theta_{app} \leq 45^\circ$, i.e., azimuth from the SW, W, and NW; see figure 6.2a) will usually leave shorter tracks than those grounding keels which travel along the slope (parallel to the depth contours). It is interesting to note that the two maximum lengths shown in figure 6.4 lie in the north and south azimuth ranges. Further discussion of this is deferred until section 6.4 on bathymetric control of grounded ice motion.

Although ice-scour track length failed to show any well developed relationship to the strong wind azimuth distribution, a consideration of ice-scour track volume may be more physically meaningful. The volume of seabed sediment excavated by a grounding keel should be proportional to the energy available in the moving ice keel. Perhaps one reason for the indefinite results of the length versus azimuth correlation is that only one dimension of the ice-scour tracks was being considered and

was not fully representing the sediment excavation process.

Using data set 'A', the volume versus azimuth relationship shown in figure 6.6 results. The weighted frequency distribution for azimuths of ice-scour tracks having volumes of $15\,000\text{ m}^3$ or more is shown in Table 6.II and figure 6.7. The weighting method is similar to that used in the length versus azimuth discussion. Figure 6.7 shows that relatively large sediment excavation volumes are most likely to occur when an ice keel approaches from a northerly direction. This can possibly be related to the storm winds but the overall nature of the distribution and the results of the length versus azimuth analysis suggest that the orientation of the seabed slope is masking the relationship. That is, ice-scour track lengths form a significant component of each volume value. The rather small data set used here ($n = 20$) consists only of those ice-scour tracks in the 'East Mackenzie (North)' area for which no sub-bottom reflector was obvious. These volume values should therefore represent true sediment excavation volumes.

To increase the scope of the volume versus azimuth analysis, data set 'C' was also used. The scattergram is shown in figure 6.8 while the weighted azimuth distribution for ice-scour track segments with volumes greater than or equal to $15\,000\text{ m}^3$ is presented in table 6.III and figure 6.9. This distribution bears fairly close resemblance to the strong wind distribution of figure 6.3b, particularly in terms of the north and northwest

Figure 6.6 Volume versus azimuth of ice-scour tracks in the 'East Mackenzie (North)' mosaic area.

Table 6.II Weighting of volume versus azimuth data from the
'East Mackenzie (North)' mosaic area.

<u>Azimuth</u>	<u>no.</u>	<u>weight</u>	<u>no. $\geq 15\ 000\ m^3$</u>	<u>wtd. no. $\geq 15\ 000\ m^3$</u>	<u>wtd. %</u>
N	2	6/2	2	6	27
NE	1	6/1	1	6	27
E	0	0	0	0	0
SE	0	0	0	0	0
S	3	6/3	1	2	9
SW	6	6/6	3	3	13.5
W	5	6/5	1	1.2	5.4
NW	3	6/3	2	4	18
<hr/>			<hr/>		
n = 20			n' = 10	n'' = 22.2	99.9

Figure 6.7 The weighted frequency distribution for azimuths of
ice-scraper tracks in the 'East Mackenzie (North)' mosaic
area that have volumes of $15\ 000\ m^3$ or more.

Figure 6.8 Volume versus azimuth of ice-scour track segments in data set 'C'.

Table 6.III Weighting of volume versus azimuth data from data set 'C'.

<u>Azimuth</u>	<u>no.</u>	<u>weight</u>	<u>no. $\geq 15\ 000\ m^3$</u>	<u>wtd. no. $\geq 15\ 000\ m^3$</u>	<u>wtd. %</u>
N	3	16/3	2	10.6	18.4
NE	4	16/4	2	8	13.9
E	0	0	0	0	0
SE	0	0	0	0	0
S	3	16/3	2	10.6	18.4
SW	16	16/16	1	1	1.7
W	1	16/1	1	16	27.8
NW	7	16.7	5	11.4	19.8
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n = 34			n' = 13	n'' = 57.6	100.0

Figure 6.9 The weighted frequency distribution for azimuths of ice-scour track segments in data set 'C' having volumes of $15\ 000\ m^3$ or more.

winds. The south azimuths can possibly be accounted for by the Shingle Point wind distribution.

Before making any final statements about the importance of wind as a driving force for the grounding ice keels, the relationship between net rise of ice keels up a seabed slope versus azimuth should be considered. The net rise of an ice mass may result from the conversion of kinetic energy to potential energy and as such should be proportional to the magnitude of the driving force. Data set 'C' is used exclusively in all discussions of 'net rise'. The frequency distribution for net rise of ice keels is shown in figure 6.1 (c, vi). Evidence of negative net rise and zero net rise was occasionally observed in cases where the depth of the ice-scour track increased as the ice keel moved upslope. Because net rise may partially depend on the length of ice-scour track that is being considered, it was thought best to use a parameter combining rise and length, namely 'net rise per unit length'. Figure 6.10 shows the plot of (net rise/length) versus azimuth. Table 6.IV and figure 6.11 show the azimuth frequency distribution obtained for those tracks for which (net rise/length) equalled or exceeded 10×10^{-4} . Comparison of figure 6.11 with figure 6.3 (b) shows fairly good correspondence between occurrence of westerly and northwesterly winds and high values of (net rise/length). Once again, a southwest azimuth component is evident which is possibly related to the Shingle Point wind regime.

Figure 6.10 Net rise per unit length versus azimuth of ice-scour track segments in data set 'C'.

Table 6.IV Weighting of net rise per unit length versus azimuth data from data set 'C'.

<u>Azimuth</u>	<u>no.</u>	<u>weight</u>	<u>no. $\geq (10 \times 10^{-4})$</u>	<u>wtd. no. $\geq (10 \times 10^{-4})$</u>	<u>wtd. %</u>
N	3	19/3	0	0	0
NE	4	19/4	1	4.8	12
E	0	0	0	0	0
SE	0	0	0	0	0
S	3	19/3	0	0	0
SW	19	19/19	8	8	20
W	4	19/4	4	19	48
NW	7	19/7	3	8.1	20

$n = 40$

$n' = 16$

$n'' = 39.9$

100

Figure 6.11 The weighted frequency distribution for azimuths of ice-scour track segments in data set 'C' having net rise per unit length of 10×10^{-4} or more.

To summarize the effect of wind on the morphology of ice-scour tracks the following points may be made:

- (1) The ice-scour track azimuth distribution generally corresponds to the azimuth distribution of strong winds (which is similar to the azimuth distribution for all winds in the Beaufort Sea). The correspondence is enhanced if the local Shingle Point surface wind information is considered.
- (2) Ice scour tracks with large volumes and large net rises upslope lie within the westerly, northwesterly, northerly, or southwesterly azimuths for strong winds although exceptions do occur.
- (3) Enough variability exists in these azimuth distributions to make it seem plausible that driving forces other than wind may also be acting on the ice keels. The motion of ice in a region is not necessarily a result of local winds and currents especially when a grounding ice keel is being driven by the force of the pack ice on it.

(b) currents

Data on currents, particularly bottom currents, are rather sparse for the 'East Mackenzie' mosaic area. Nevertheless, some qualitative assessments can be made of the role of currents in developing the observed ice-scour track azimuth distribution.

(i) tidal currents

Although tidal currents in Mackenzie Bay are weak, they may be significant in causing the planimetric forms of ice-scour tracks where the track crosses over itself and apparent downslope scouring has occurred (e.g., 'EMN 6' shown in figure C.2). Tidal effects are expected to be significant only if

surface winds are light. Cochkanoff et al., (1971), stated that tidal currents have a rotary form, swinging through 360° during each tidal cycle. This could account for changes in the direction of ice keel movement. Lowering of the water level coincident with offshore movement of a grounded ice keel could account for any downslope scouring that occurred. The length of the downslope scouring seen for track '6' falls within the vertical distance range of 0.3 to 0.5 m (the tidal range) when this length is compared to the bathymetric chart (figure 3.4).

(ii) surface currents

Surface current direction is about 30° to the right of the surface wind as indicated for the northwest (figure 4.6a) and east wind (figure 4.6b) regimes. The shallow water in the mosaic area (less than 50 m) means that the surface currents could be of major importance for driving ice keels. Because of the close relationship of surface current direction to the surface wind direction, it is difficult to separate the effects of surface currents from the effects of surface winds on ice keels. This is particularly so because 45° wide sectors had to be used to group wind and ice-scour track azimuth data. It is probably best to regard surface winds and surface currents as forces which always act simultaneously in driving an ice keel. The surface wind directional frequency distribution is presumed to approximate the directional frequency distribution of surface currents (in this case the currents are identified according to

the direction from which they are flowing, contrary to convention).

(iii) bottom currents

Bottom currents in the 'East Mackenzie' area may be strongly correlated with the wind azimuth distribution (all speeds). For instance, Herlinveaux and de Lange Boom (1975, p. 76) stated that southeastwards of Kay Point, "... close to the bottom there appears to be a general current set to the northwest, following the bottom contours. This flow probably extends throughout the water column below the surface layer and has a speed of about 5 cm/sec." This bottom current could be a result of the frequent south-southwest winds observed at Shingle Point during July to March. Wilson's (1974) data showed that during April to June winds from the SSW occur only fifteen per cent of the time while WNW winds occur forty-five per cent of the time. Interestingly, bottom current measurements at 69°43' N, 137°10' W in 40 m of water about 15 km north of the 'East Mackenzie' area agree partially with the Shingle Point wind observations. The current meter, which only operated from May 9 to June 30, 1974, yielded data which showed an average velocity of 0.024 m/sec at 143° true (approximately northwest to southeast flow) (Huggett et al., 1975, p. 27). Further current meter observations are needed but for now this writer presumes that the average bottom current direction is closely related to the average wind direction over a period of several days.

For the water depths in the mosaic area: the direction of the driving forces due to surface wind, surface current, and bottom current are probably all within the same quadrant of the azimuth distribution and may often lie within the same 45° sector. The proportion of the total ice keel driving force due to each component cannot be determined with the data that are available.

A complex interplay of several driving forces - possibly including ice floe interaction - may have been responsible for the unusual planimetric form of track 'EMN 34' whose image appears in figures 3.8 (a) and (c). The tracing of its planimetric form is shown in figure C.2 along with a notation as to the inferred direction of keel movement. The direction could be inferred from the continuity of lateral embankments at the crossover. Use of the bathymetric overlay shows that downslope scouring over a vertical distance of about 1.5 m must have occurred. The tidal range cannot account for this although perhaps a negative storm surge was associated with the downslope scouring process. It is noteworthy that when the M.V. Theta was allowed to drift in the Beaufort Sea ice in the summer of 1974, some of the recorded drift tracks (Herlinveaux and de Lange Boom, 1975, p. 46-47) showed 'crossovers' and somewhat contorted paths. The two examples that showed 'crossovers' indicate that light winds or calm conditions prevailed at the time of the 'crossover'. Ice interaction or tidal currents

then may have governed the path of the ship. The crossover seen in track 'EMN 34' may have occurred under similar conditions.

6.3.3 Storm surges

Storm surges in the Beaufort Sea are an example of winds and water currents acting together to set in motion objects in their path whether these be ice floes, ice islands, or portions of the shoreline. As mentioned in section 4.3.3, storm surges associated with strong northwesterly winds have been observed to cause rises in sea level of more than 2 m along the coast. During a severe storm in September 1970, the storm surge tide was 3 m (Kovacs and Mellor, 1974, p. 121). This range of rise in sea level accompanying a storm surge coincides with the range of net rise of grounding ice keels observed in the 'East Mackenzie' data. The range of total observed net rises along individual tracks is -0.3 m to 3.4 m (Table C.V(c)). The observed values are probably underestimates in most cases because the ship's echo-sounder transducer never conveniently crossed both the origin and the endpoint of a track. This writer hypothesized that storm surges might be the mechanism whereby grounding ice keels were uplifted and prevented from scouring deeper into the seabed sediments along the length of the ice-scour track.

The following analyses show, however, that despite the coincidence in the range of the two types of rise values, storm

surges cannot account for the majority of the ice keel net rises inferred from measurements on the ice-scour tracks in the 'East Mackenzie' area.

The net rise observed between ice-scour track cross-sections was plotted versus the mean water depth between cross-sections (figure 6.12). The scatter plot does suggest that net rises are usually larger in shallower water as should be the case for positive storm surges. Refinement of this analysis is possible by considering the net rise per unit length of track and by separating the data into two groups on the basis of the approach angle of the ice keel to the seabed slope. An approach angle of sixty degrees appears to provide a satisfactory boundary between the data sets. The plots shown in figures 6.13 and 6.14 show reasonably strong inverse relationships between net rise per unit length and water depth. The least squares regression lines shown on the graphs (see Appendix D, section D-2 for details of regression analyses) may be considered to estimate the functional relationship between net rise/length and mean water depth of an ice-scour track because the percentage errors associated with the values on the abscissa (independent variable) are much less than the percentage errors associated with the values on the ordinate (dependent variable) (cf., Agterberg, 1974, p. 258; Church and Kellerhalls, 1978, p. 1156). Error analyses are provided in Appendix E.

Figure 6.12 Net rise of ice keels between ice-scour track cross-sections versus mean water depth between the cross-sections. Information from data set 'C'.

Figure 6.13 Net rise per unit length versus mean water depth between ice-scour track cross-sections. Track segments have approach angles of 60° or less. Information is from data set 'C'. The data used here is listed in Table D.I, Appendix D.

Figure 6.14 Net rise per unit length versus mean water depth between ice-scour track cross-sections. Track segments have approach angles exceeding 60° . Information is from data set 'C'. The data used here is listed in Table D.II, Appendix D.

Because positive storm surges are known to be related to a northwest wind direction it was decided to repeat the plots shown in figures 6.13 and 6.14 but this time showing separately the data points for ice-scour track segments with northwest and southwest azimuths. The results are shown in figure 6.15 (a) and (b). For the seven track segments with northwest azimuth and θ_{app} less than 60° , the regression of y on x failed to be significant at the five per cent confidence level even when the negative (net rise/length) value was excluded. For the nine track segments with southwest azimuth (and θ_{app} less than or equal to 60°) the regression of y on x was highly significant, accounting for ninety-six per cent of the variance of y (leaving four per cent unexplained variance). But, the ten southwest azimuth track segments having a θ_{app} greater than 60° did not show a statistically significant relationship. The first two results are contrary to what would be expected if storm surges were responsible for preventing grounding ice keels from scouring deeper into the seabed as they moved into shallower water. It was expected that in the case of a NW azimuth, (net rise/length) would increase as the water depths decreased because storm surge magnitudes generally increase in shallower water particularly if ice floe concentrations are fairly low. Tracks with a SW azimuth should not have shown a relationship between (net rise/length) and water depth. Tracks with a SW azimuth would be expected to have been caused by ice keels driven by an offshore wind. Negative

Figure 6.15 (a) Net rise per unit length versus mean water depth of ice-scour track segments having NW azimuth. The data is listed in Table D.III, Appendix D.

Figure 6.15 (b) Net rise per unit length versus mean water depth of ice-scour track segments having SW azimuth. The data is listed in Table D.IV, Appendix D.

surges (temporary decreases in sea level) are the consequence of strong offshore winds (Henry, 1975, p. 34). Such decreases in sea level would be expected to cause ice keels (moving upslope) to dig deeper into the seabed at all water depths.

Based on the above analysis, it is concluded that storm surges by themselves are not responsible for the net rise phenomenon that is associated with many of the ice-scour tracks. Alternate hypotheses to explain the relationships shown in figures 6.13 to 6.15 will be examined later in this chapter.

6.3.4 Coriolis force

Coriolis force is not a driving force but is an effect on the motion of objects arising from the rotation of the Earth. It is an effect that must be considered in any discussion of ice motion (cf., Pounder, 1965; Murray, 1969; Cochkanoff, Graham, and Warner, 1971; Russell, Riggs, and Robe, 1977). The magnitude of Coriolis force is given by:

$$C = 2m \Omega (\sin \phi) V \quad (\text{eqn. 6.1})$$

where m is mass of an object

$\Omega = 7.29 \times 10^{-5} \text{ rad s}^{-1}$, the earth's angular velocity

ϕ is latitude

V is speed of an object

(Pounder, 1965, p. 41; McIntosh and Thom, 1972, p. 79-83).

The Coriolis effect per unit mass will be more evident at high latitudes and for higher ice speeds. The total effect will be

more pronounced for large ice bodies. It is expected that unconstrained objects travelling over relatively long distances (such as ice keels scouring into the seabed) should show the effect of Coriolis force. Therefore, a study of the planimetric form of ice-scour tracks in the context of Coriolis force effect may provide clues as to the concentration of ice floes associated with the creation of ice-scour tracks and speed of the ice keel moving through the sediment.

As a first step in the investigation, the direction of turning of arcuate ice-scour tracks is considered. Information on the direction of turning and consistency of turning with approach angle for twenty-four tracks in the 'East Mackenzie' mosaic area is given in Table C.VIII (see figure 3.13 for definitions of the information collected). In the northern hemisphere, moving objects are deflected to the right of their direction of motion because of the Earth's rotation. If one assumes that ice-scour tracks are the result of upslope movement of an ice keel, the direction of turning of the twenty-four tracks is as given in Table C.VIII. Surprisingly, there seems to be almost an equal chance of getting a turn to the right or to the left. There is also an equal chance of consistent or inconsistent turning on the slope. Statistical tests at the five per cent significance level show that the binomial probabilities are equal in each case (see Appendix C, section D.1).

Before considering the implications of these findings, it is interesting to consider the calculated values for the speed of the ice keel and the time taken to form an ice-scour track segment if indeed the effect of Coriolis force is made evident by the arcuate tracks. For example, measurements were made on ice-scour track 'EMN 33' shown in figure C.2. The types of measurements made are best understood by referring to figure 6.16. Under the assumption that Coriolis force was responsible for the form of track 'EMN 33', it is found that the time needed for an ice keel to scour the track would be 4217 seconds or 70 minutes. The average speed of the ice keel would have been 0.17 m/sec (0.34 knots). Following the empirical observation that ice drift speed is often about two per cent of the local wind speed (Herlinveaux and de Lange Boom, 1975, p. 11), it follows that windspeed would have been about 8.5 m/sec (17 knots, a strong southerly wind in the case of this track). These values for time, ice speed, and wind speed all seem to be reasonable. The results of similar calculations for thirteen other arcuate tracks are given in Table 6.V. The inferred wind speed values all seem reasonable except for the cases of tracks "EMN 27" and "EMN 29". These are relatively long tracks having only slight curvature to the right of the inferred direction of ice keel movement. For the eleven tracks yielding reasonable results for inferred wind speed it is interesting to compare Tables 6.VI (a) and (b) which are from Berry et al. (1975). These tables show the return periods for

Figure 6.16 Coriolis force analysis. The diagram shows a tracing of the visible segment of ice-scour track 'EMN 33' as it appears on the 1:20 000 scale 'East Mackenzie' mosaic.

Symbols: O is 'origin,

P₂ is point towards which ice keel was originally moving (on tangent line to initial part of curve),

P₁ is point to which ice keel actually moved because of the Earth's rotation.

Steps in Coriolis force analysis: * (based on McIntosh and Thom, 1972, p. 81-82)

(1) measure angle P₁OP₂ from the mosaic.

$$\angle P_1OP_2 = \Omega \sin \phi t$$

where $\Omega = 7.29 \times 10^{-5} \text{ rad s}^{-1}$, the Earth's angular velocity,

ϕ is latitude

t is time taken to form track

(2) calculate time taken to form track.

$$t = \frac{\text{angle } P_1OP_2}{\Omega \sin \phi} = \frac{\text{'deflection of object due to rotation of Earth while particle moves towards P'}}{\text{'magnitude of vertical component of Earth's angular velocity at latitude, } \phi \text{'}}$$

(3) calculate speed of ice keel during track formation using,

$V_{\text{ice}} = d/t$, where d is distance $\overline{OP_1}$ measured along the track (step off distance with dividers)

(4) enter values in Table 6.V.

* Assumptions: (1) upslope scouring (2) friction on ice keel negligible.

Table 6.V Data (track number, latitude, $\sin \phi$ of latitude, angle P_1OP_2) and results (time, t , taken to form track segment with length, d ; ice speed; and windspeed) for Coriolis force analysis.

Track	Latitude ϕ	$\sin \phi$	angle P_1OP_2 (radians)	t (min)	d (m)	V_{ice} (m/sec)	$V_{wind}^{(1)}$ (m/sec)
M-05	69° 27'	0.936	0.175	43	1160	0.45	22
M-07			0.419	102	2600	0.42	21
M-08			0.297	73	1200	0.27	14
M-14			0.175	43	1220	0.47	24
M-25			0.218	53	1600	0.50	25
EMN-4			0.209	51	1460	0.48	24
EMN-6			0.611	149	400	0.045	2
EMN-12			0.367	90	300	0.055	3
EMN-27			0.096	23	1680	1.2	61
EMN-29			0.070	17	1600	1.6	78
EMN-33			0.288	70	720	0.17	9
EMN-45			0.175	43	500	0.19	10
EMN-52			0.122	30	1000	0.55	28
EMN-62			0.157	38	1220	0.54	27

(1) assume $V_{ice} = 0.02 V_{wind}$

Table 6.VI Return periods for maximum wind speeds of certain durations over the Beaufort Sea. From Berry et al. (1975).

- (a) Maximum wind speeds (in knots)* for the June to October period in the Beaufort Sea

Duration (hrs)	Return Period (yrs)			
	2	5	20	100
1/60	58	65	74	84
1	46	52	59	67
6	40	45	51	58
12	36	41	47	53
24	34	38	43	49

- (b) Maximum wind speeds (in knots)* for the November to May period in the Beaufort Sea

Duration (hrs)	Return Period (yrs)			
	2	5	20	100
1/60	63	70	80	91
1	50	56	64	73
6	44	49	56	64
12	40	44	51	58
24	37	41	47	53

* 1 knot is approximately equal to 0.5 m/sec

maximum wind speeds (in knots) of certain durations. The maximum inferred windspeed in Table 6.V is 28 m/sec or 56 knots which must have had a minimum duration of thirty minutes in order to form the track (still assuming Coriolis force is wholly responsible for the planimetric form). The return period for such a wind is a bit less than twenty years in the June to October period in the Beaufort Sea and is only about five years in the November to May period. On the basis of this analysis, Coriolis force cannot be eliminated as an influencing factor in causing the arcuate planimetric form of ice-scour tracks. It should be noted, however, that friction forces due to ice interaction with the seabed, water drag, and lateral pressure from other ice floes were assumed to be negligible for this analysis. Upslope scouring was also assumed.

The fact that the direction in which the ice keels must have turned while forming ice-scour tracks is not always to the right nor always consistent with the angle of approach of the ice keels to a slope suggests that some process(es) is(are) disturbing the expected outcome of the planimetric form for many ice-scour tracks. The next sections consider bathymetric control on grounded ice motion across the seabed and the influence of ice floe interaction on the planimetric form of ice-scour tracks.

6.4 Bathymetric control on grounded ice motion across the seabed

The degree of bathymetric control on the motion of grounding ice keels is investigated by two methods. One method is to examine the frequency distribution for ice keel approach angles to a slope and the functional relationships between approach angle and the following variables: ice-scour track length, depth, volume, and net rise per unit length. The other method is to examine the direction of turning of ice-scour tracks with respect to the orientation of the slope and the approach angle.

The frequency distributions for the angle of approach of ice keels to the seabed slope are shown in figures 6.1 (a,v), 6.1 (b,v), and 6.1 (c,v) for data sets 'A', 'B', and 'C' respectively. Seabed gradient is presumed constant for these data sets. The measurement procedure for θ_{app} is discussed in section 3.3.2 (f). Most ice keels have travelled obliquely along the face of the seabed slope. The frequency distributions for θ_{app} are influenced by the orientation of the slopes in the study area with respect to the prevailing ice keel driving forces as is discussed in section 6.3.1.

The lengths of single ice-scour tracks having reasonably straight planimetric form in the 'East Mackenzie (North)' mosaic area are plotted versus θ_{app} in figure 6.17. The graph shows that the length of track is influenced by the approach angle

Figure 6.17 Ice-scour track length versus approach angle for 31 single tracks in the 'East Mackenzie (North)' mosaic area. The one standard error limits about the regression line are shown. The data is listed in Table D.V, Appendix D.

Figure 6.18 Ice-scour track length versus secant of the approach angle for the 31 tracks plotted in figure 6.17. The constants a , m , and $(m + a)$ are shown. Compare $(m + a)$ on this plot with that in figure 6.17. The data is listed in Table D.V, Appendix D.

of the ice keel. Keels heading straight into a slope ($\theta_{app} = 0^\circ$) are likely to create shorter tracks than those keels travelling parallel to a slope ($\theta_{app} = 90^\circ$). Of course, driving forces of unusually large magnitude would be expected to enable a longer track to be formed even at low approach angles. The scatter in the length versus θ_{app} relationship is probably a result of variability in the magnitude of the driving forces which caused each track.

The relationship between ice-scour track length and the approach angle (for constant seabed gradient) can be described by the equation:

$$L = m \secant (\theta_{app}) + a \quad (\text{eqn. 6.2})$$

where L is ice-scour track length

θ_{app} is approach angle

a is a constant analogous to the y-intercept in a standard linear regression. Its value is not physically meaningful by itself because it is associated with $x = \secant(\theta_{app}) = 0$ which is an undefined expression (because $1 \leq \secant(\theta_{app}) \leq +\infty$, always) (see figure 6.18)

m is a constant analogous to the slope in a standard linear regression. Its value is also not physically meaningful by itself.

$(m + a)$ is a constant which is directly proportional to the average strength of driving forces in a locality and is inversely proportional to the local gradient of the seabed. It is the minimum expected length of track created by an ice keel heading straight into a slope ($\theta_{app} = 0^\circ$).

When an ice keel travels parallel to a slope, the distance of travel (track length) is expected to be unconstrained

as long as the ice keel driving force is maintained and the seabed configuration along the ice keel path does not change.

A secant curve defined from 0° to 90° ,

$$y = \secant \theta \quad (\text{eqn. 6.3})$$

seems ideal for describing the length versus θ_{app} relation.

The dependent variable y has a positive minimum value at $\theta = 0^\circ$ and approaches infinity when $\theta \rightarrow 90^\circ$. If the angle exceeds 90° , the track should end abruptly as the ice keel floats free of the slope upon which it was grounding. Admittedly, a real ice keel could have θ_{app} exactly equal to 90° which is not provided for by the secant curve (the secant curve is asymptotic to 90°).

In all other respects, however, the secant curve can provide the basis for a physical interpretation of the relationship between length and θ_{app} . The errors at midrange of θ_{app} are $x \pm 2.5\%$ and $y \pm 10\%$. Therefore the non-linear regression line expressed in the form of the secant curve can be regarded as providing an estimate of the functional relationship between length and θ_{app} . The regression analysis is described in Appendix D, section D.3. Notice the change in character of the relationship at $\theta_{app} = 60^\circ$. This must be part of the reason that the (net rise/length) versus water depth relation was clarified when the data set was partitioned into those tracks with θ_{app} greater than 60° and those with θ_{app} less than or equal to 60° .

Mean ice-scour depths were plotted versus the approach angle of ice keels to a slope using measurements from data set 'A' (figure 6.19 (a)) and data set 'C' (figure 6.19 (b)). It is apparent that a relatively wide range of ice-scour depth values can occur with any approach angle. Therefore it is concluded that the two variables are independent of each other.

The approach angle of an ice keel to the seabed slope does not appear to influence the volume of sediment that is excavated along the path of the keel. This conclusion is based on the scattergrams in figure 6.20 (a) and (b). The influence of track length on volume does not appear to be important because no strong resemblance to the length versus θ_{app} relationship (figure 6.17) can be detected in figures 6.20 (a) and (b). Ice-scour depth is apparently independent of θ_{app} so depth values should not be influencing the relationship. The azimuths have been noted for those tracks or segments of tracks having volumes in excess of $20\,000\text{ m}^3$. The wide range of azimuths (i.e., N, NW, W, SW, and S) shows that driving forces alone are not responsible for the large volumes. The width of the keel may be important. It is noticed that those tracks having planimetric widths of thirty metres or more have the largest volumes. The main conclusion from the volume versus θ_{app} plots is that these two variables are independent of one another.

Figure 6.19 (a) Mean ice-scour depth versus approach angle for tracks in data set 'A'.

Figure 6.19 (b) Mean ice-scour depth versus approach angle for track segments in data set 'C'.

Figure 6.20 (a) Volume versus approach angle of twenty single tracks in data set 'A' for which volume could be calculated.

Figure 6.20 (b) Volume versus approach angle of track segments in data set 'C'.

The (net rise/length) versus θ_{app} scattergram shown in figure 6.21 leads to the conclusion that approach angle has no influence on the rise of an ice keel up a seabed slope. This is compatible with the conclusion reached in section 6.3.2 (a). That is, the magnitude of the driving forces must be primarily responsible for the (net rise/length) that is achieved along a track.

If a relatively gentle seabed gradient (1/400 to 1/500) such as that in the 'East Mackenzie' area is effective in 'steering' grounding ice keels, the effect should be noticeable in the planimetric form of ice-scour tracks. For example, arcuate tracks can be examined in relation to the local bathymetry as explained in figure 3.13. Data on the direction of turning and consistency of turning with the ice keel approach angle is given in Table C.VII. The analysis of the consistency of turning data shows that there is an equal chance for the turning to be consistent or inconsistent (see also Appendix D, section D.1.2 for details of the statistical analysis). The lack of a significant bias towards consistent turning suggests that a seabed gradient of 1/400 to 1/500 is not influencing the direction of motion of ice keels. Other influences on ice keel motion such as interaction between ice floes must be more important.

The analyses discussed above have shown that, for a given driving force magnitude, only ice-scour track length is affected

Figure 6.21 Net rise per unit length versus approach angle for 40 ice-scour track segments from data set 'C'.

by the direction at which an ice keel approaches the seabed slope. The depth and volume of an ice-scour track are independent of θ_{app} and are probably more dependent on characteristics of the ice keel itself. Net rise/length is also independent of θ_{app} and is determined by the magnitude of the ice keel's driving force. The seabed slope in the 'East Mackenzie' area does not 'steer' grounding ice keels.

6.5 Influence of ice type and ice zone

The ice types and ice zones that prevail above a certain seabed locality should be related to characteristics of the ice-scour tracks found in the area.

6.5.1 Type and form of track

In the 'East Mackenzie (North)' mosaic area, over eighty per cent of the ice-scour tracks are of the single track type with the remainder being broad and flat-bottomed or multiple tracks. The proportions were similar for the tracks included in data set 'B'. The proportions suggest that most ice floes containing pressure ridges have only one portion of the ice mass in contact with the seabed at any one time and that large scale pressure ridge systems or ice islands are responsible for only about one-fifth of the ice-seabed interactions in the 'East Mackenzie' area.

In terms of planimetric form, sixty per cent of the tracks in the 'East Mackenzie (North)' area were straight with the remaining forty per cent evenly divided between arcuate and sinuous forms. Roughly similar proportions were noted in data set 'B'. No ice-scour craters were noticed in the 'East Mackenzie' area.

Freely floating ice masses in open water (1/10 ice cover or less) or very open pack ice (1/10 to 3/10 ice cover); W.M.O. definitions, C.H.S., (1970, p. 89); would be expected to respond to Coriolis force and should form an arcuate track as they ground. The arc should be to the right of the direction of ice movement. As discussed in section 6.3.4, turning to the left of the direction of ice keel movement is fairly common. Ice floe interaction at the water surface was suggested as the process responsible for the leftward turning. This process could also explain the high proportion of straight ice-scour tracks. Presumably, ice floes are often so closely packed that as the whole ice field is driven forward by an applied stress, individual floes (only one of which may have an ice keel extending to the seabed), will be constrained in their lateral movement. Arcuate and sinuous tracks could presumably develop independently of Coriolis force in a pack ice situation when a grounding keel is at the leading edge of the pack and the individual floes are constantly shifting position in relation to each other.

6.5.2 Interaction of ice floes

The interaction of ice floes, only one of which need be associated with a grounding pressure ridge keel, can give rise to a variety of planimetric forms of tracks as shown by the hardware model described in section 3.3.4. The results of the experiment are illustrated in figures C.4 (a) to (d) in Appendix C.

Figure C.4 (a) shows that straight tracks were formed if the hex nuts that represented ice floes with grounding keels were located within the group of hex nuts that represented a pack of ice floes. During the time the force was applied to the 'floes', they rather quickly became locked into fixed positions relative to each other. The movement of the 'floes' was in the direction of the applied force and lateral movement was negligible.

Figures C.4 (b,c,d) all show a sinuous track at the left of the page and an arcuate track to the right. The arcuate tracks all show evidence of an abrupt change in direction after some time has passed. When the driving force was initially applied, the two 'grounding keel' hex nuts had a relatively large lateral freedom of movement because they were situated at the periphery or leading edge of the group of hex nuts that represented the pack ice. This lateral freedom of movement gradually decreased over the time of application of the driving force. This eventually resulted in straight tracks being formed

for the remainder of each trial. The important finding from this simple model is that when a driving force is applied to a group of hex nuts (ice floes) the paths of individuals can be, for short periods of time at least, straight, arcuate, or sinuous. Abrupt changes in direction also occur. These planimetric forms are also characteristic of ice-scour tracks on the Beaufort Sea seabed and elsewhere, as was discussed in chapter five. It seems reasonable to presume, therefore, that ice floe interaction is a process that coincides with the formation of ice-scour tracks. This in turn implies that the formation of the tracks is associated with storm winds or steady moderate winds that force ice floes into a pack. It also implies that the amount of kinetic energy available in a single grounding keel must be enormous because wind stress and current stress are being applied over an ice area much larger than that of the floe containing the grounding keel. The pressure ridge keel could be newly formed during the storm which is concentrating the pack ice or it could be a multiyear ridge - this is impossible to distinguish with the information that is available.

Arcuate tracks need not necessarily be attributed to Coriolis force effects and sinuous tracks need not necessarily be related to a complex interplay of wind, currents, and other driving forces as hypothesized in figure 5.8. This is not to say that these hypotheses incorporated into figure 5.8 can be eliminated. Ice floe interaction, however, does provide the most attractive explanation because all the planimetric forms

can be attributed to one process.

6.5.3 Length of tracks

The frequency distribution for length of ice-scour tracks in the 'East Mackenzie (North)' area is shown in figure 6.1 (a,i). The distributions based on data sets 'B' and 'C' are shown in figures 6.1 (b,i; c,i respectively). Track lengths were only measured from the mosaic if the beginning and end points of the track could be located. The 'East Mackenzie (North)' distribution is of the decaying exponential type (see results of the chi-square test, Appendix D, section D.4.1) suggesting that there is a greater chance of shorter tracks forming than long tracks. The length distributions for data sets 'B' and 'C' are not suitable for quantitative statistical analysis because the track sampling procedure will affect the length distribution for these two data sets.

Length of ice-scour tracks is a function of the following factors (at the minimum): magnitude of driving force, duration of driving force, pack ice concentration, θ_{app} , seabed gradient, and shear strength of the seabed sediment. The last two mentioned factors can probably be regarded as being constant for a certain area. It is believed that the effect of pack ice concentration acting alone over many years would be to generate a normal distribution for track length. The approach angle, θ_{app} , is determined by the driving force azimuth. Usually, a

locality would be subject to a prevailing driving force. The relationship between the prevailing force azimuth and the local bathymetry could produce a bias towards either short or long tracks if θ_{app} is either low or high respectively. So far, we have considered two constant factors, one randomly variable factor, and one deterministic factor. These are not likely to generate a decaying exponential length distribution. This leaves driving force magnitude and duration as the key factors responsible for the nature of the distribution. Figure 6.22 shows the decaying exponential type frequency distribution for windspeeds over the Beaufort Sea during an average August (Berry et al., 1975, p. III.5). Durations of strong winds are also likely to have a decaying exponential type distribution. Currents associated with the winds should also have this distribution.

A comparison of the observed and predicted length frequency distributions in the 'East Mackenzie (North)' area (see figure 6.1 (a,i)) suggests that there is a bias towards more long tracks occurring than would be expected. This is probably due to the relationship between prevailing driving forces and bathymetry which yields a relatively high mode for θ_{app} (60° to 70°). Figure 6.17 showed that higher approach angles are associated with longer tracks.

Figure 6.22 Relative frequency distribution for windspeeds over the Beaufort Sea during an average August (data from Berry et al., 1975).

6.5.4 Planimetric width of tracks

The planimetric width of ice-scour tracks is the width measured between the ridge lines of the ice-scour lateral embankments. The frequency distributions from data sets 'A' and 'B' are shown in figures 6.1 (a,ii) and 6.1 (b,ii) respectively. They are skewed towards the narrower track widths. In the 'East Mackenzie (North)' area, seventy per cent of the single ice-scour tracks have a planimetric width of 20 m or less. This distribution must be related to the sizes of the ice keels that have scraped the seabed in the study area. The ice keel dimensions should in turn be related to the overall size of the ice mass to which the keel belonged. The size of the ice body will depend upon the origin of the ice (pressure ridge or ice island) and also upon the ice zone and time of year.

Data set 'A' also includes some broad, flat-bottomed tracks having widths up to 140 m (see Table C.I). Most of these tracks are infilled by sediment. As suggested in figure 5.8, these unusually wide tracks may be the result of ice island scouring or pressured ice that has developed a very rounded profile. This track type appears to be an infrequent occurrence in the 'East Mackenzie' area.

6.5.5 Ice keel draft and ice-scour depth

(a) hypothesized relationship

Wadhams (1975) presented histograms of ridge height

distributions and an expression for predicting probability densities of ridge heights in the Beaufort Sea. The distributions and prediction equation are of the decaying exponential type. Because ridges are usually associated with a keel and there exists a mean empirical ratio of about 1:4.5 for ridge height to keel draft (Kovacs and Mellor, 1974) it is also expected that the keel draft population will have a distribution of the decaying exponential form. Wadhams' (1977) keel draft observations support this expectation. His observations are discussed in part (b) of this section.

The ice-scour depth distribution developed over many decades for a hypothetical, flat, square kilometre of seabed is necessarily related to the keel draft distribution by the nature of the ice-scouring process. If this square kilometre is in 40 m of water, for example, the decaying exponential distribution for keel draft suggests that each year a large number of shallow draft keels could pass overhead without marking the seabed. A lesser number of keels could conceivably barely skim the seabed surface in the area. Even fewer keels would be able to penetrate 1 m beneath the seabed and so on. Ice-scour tracks, say 4 m deep, would be extremely rare.

A decaying exponential type distribution for ice-scour depth should be generated over a long time period in any seabed location in the Beaufort Sea that is subject to ice-scouring. The next section examines how well the observed ice keel draft

and ice-scour depth distributions fit the hypothesized distributions.

(b) observed frequency distributions

The decaying exponential type of distribution referred to previously can be mathematically represented by the exponential density function. This is a special case of the gamma density which is given by:

$$G(X: r, \beta) = \frac{x^{r-1} e^{-x/\beta}}{\Gamma(r) \beta^r}, \quad X \geq 0 \quad (\text{eqn. 6.3})$$

where X is the independent variable

r is a location parameter

β is a scale factor

$\Gamma(r)$ is the gamma function evaluated for r (this value is obtained from published tables such as Table 20 in Spiegel, 1968)

(Krumbein and Graybill, 1965, p. 99-100 and 127-128.)

The exponential density results when $r = 1$ and $X \geq 0$. The scale factor β can be estimated by $\hat{\beta} = \bar{X}$, which is the arithmetic mean of all the values X_i (Krumbein and Graybill, 1965, Table 6.1, p. 121).

That is,

$$G(X: 1, \bar{X}) = \frac{e^{-X/\bar{X}}}{\bar{X}}, \quad X \geq 0 \quad (\text{eqn. 6.4})$$

gives the exponential density function. A chi-square test for goodness of fit was done on the sample frequency distributions that resembled the exponential density.

(i) keel draft

Information on ice keel drafts in the Arctic Ocean north

of Greenland was collected in October 1976 by the British nuclear submarine HMS Sovereign (Wadhams, 1977). Wadhams presented data concerning the distribution of deep keel drafts. These are plotted as figure 6.23. The predicted exponential density function derived by the present writer for this set is given by:

$$P(x) = \frac{e^{-(X-a)/(\bar{X}-a)}}{\bar{X} - a} \quad (\text{eqn. 6.5})$$

where $a = 30$ m to allow evaluation of the function from $x = 0$ to $x \rightarrow \infty$

$\bar{X} = 32.78$ m, the arithmetic mean of the sample population of keel drafts.

Therefore,

$$P(x) = \frac{e^{-(X-30)/2.78}}{2.78} \quad (\text{eqn. 6.5a})$$

A chi-square test for goodness of fit showed that at the five per cent level of significance, the sample distribution is consistent with the hypothesis that the population is distributed in a decaying exponential fashion (see Appendix D, section D.4.2 for details of the test). Weeks et al. (1971) also presented keel draft histograms which could most likely be described by equation 6.4. Those writers did not present their raw data so that this writer could not test this supposition.

The ice keels observed on the submarine traverses are presumed to have been formed in water depths much greater than the deepest keel draft. It is not known for certain whether or not this type of keel draft distribution can be regarded as

Figure 6.23 Relative frequency distribution for 45 independent deep keels observed on cruise of nuclear submarine H.M.S. Sovereign in October 1976 in Arctic Ocean north of Greenland (longitudes from 0° to 70° W). After information in Wadhams (1977).

being representative of the keel draft distribution one would typically obtain in the southern Beaufort Sea. The polar pack can, however, be driven against the coast such as during the severe storm of September 1970 (Kovacs and Mellor, 1974, p. 120-121). No keel draft distribution based on submarine measurements has been published for the southern Beaufort Sea as far as this writer is aware. Nevertheless, the observed keel draft distributions in the polar pack provide a strong case for the use of a negative exponential density function to characterize the keel draft population.

It seemed a reasonable idea to reconstruct the keel draft distribution in the 'East Mackenzie' mosaic area by adding the water depth above an ice-scour track to the ice-scour depth itself. In order to simulate the linear nature of a submarine traverse, data was collected from two north-south oriented echogram/sonograph lines from 1974 as described in section 3.3.3 (c). This data is listed in Table C.VIII. Histograms of inferred keel draft are shown in figure 6.24. Histogram (a) is based on a set of eighty-eight observations which excludes information from infilled tracks. Histogram (b) includes the sub-bottom information. In both cases the hypothesis that the sample populations are described by equation 6.4 was rejected at both the five and one percent significance levels. The normal and uniform distributions were also rejected by the goodness of fit tests (see Appendix D, sections D.4.3 and D.4.4). The failure to fit the decaying exponential

Figure 6.24 (a) Sample frequency distribution of inferred keel drafts in the 'East Mackenzie' area. Sub-bottom information excluded.

Figure 6.24 (b) Same as (a), except that sub-bottom information is included.

distribution is puzzling in the light of the keel draft distributions found by Weeks et al. (1971) and Wadhams (1977). Perhaps much more inferred ice keel draft data has to be collected before the sample frequency distribution becomes stable. It is also conceivable that the keel draft population in the 'East Mackenzie' area is different from that further offshore. Another consideration is that the net rise of ice keels may be affecting the keel draft distribution in an unknown way. The ice-scour depths were hardly ever measured near the origin of the track so that a bias towards shallower inferred keel drafts may be expected to occur.

The inferred keel draft distribution based solely on the ice-scour tracks that were not infilled in the 15 km² 'East Mackenzie (North)' mosaic area gave what appeared to be a surprising result at first. A goodness of fit test at the five per cent significance level indicated that this set of data came from a normally distributed population (see histogram in figure 6.25 and details of test in Appendix D, section D.4.5). The quality of this data is thought to be better than that in the preceding analysis because mean ice-scour depths could be added to the water depth at or near the origin of the track so that the net rise phenomenon should not be affecting the distribution. The apparent normality of the distribution is probably a result of the fact that there is no seabed record of the passage through the area of keels that did not contact the seabed. In fact, any reasonably small seabed area is

Figure 6.25 Inferred ice keel draft distribution based on 31 ice-scour tracks (not buried) that are visible in the 'East Mackenzie (North)' mosaic area.

probably subject to an exponential distribution of keel drafts at any one time when pack ice floats overhead. Those keels that actually contact the seabed within a small area will exhibit a normal distribution in terms of their draft. The indefinite results of the keel draft analysis based on data from the survey lines could also (in addition to the earlier speculations) be due to the fact that the lines did not include information from water depths less than about 30 m. Therefore, the 'lefthand' portion of the exponential decay curve remained poorly developed. Ideally, inferred keel draft information should be collected right up to the shoreline.

The above discussion shows that the best method of determining the keel draft distribution in an area is by submarine traverses. Admittedly this is difficult in shallow water. This writer believes that the keel draft population for an area always fits an exponential decay function although this cannot be proved with the information that is available.

(ii) ice-scour depth

Ice-scour depths are plotted versus water depth in the scattergram, figure 6.26. The overall impression is that a fairly wide range of ice-scour depths can occur at any water depth. The locus of observed extreme values of ice-scour depth (based only on the surface expression of tracks) is similar to that which Lewis (1977b) found for data from other

Figure 6.26 Scattergram of ice-scour depths versus water depth for 97 ice-scour tracks in the 'East Mackenzie' mosaic area.

regions of the southern Beaufort Sea. He used an extreme scour depth envelope as a basis for a model of ice-scouring and sedimentation on the Beaufort Sea shelf. The decrease of scour depths in the deeper waters to the right of the peak on the locus of extreme values was attributed by Lewis to sediment infilling of ice-scour tracks in a relict scouring zone where no new tracks are being formed. The 'East Mackenzie' data generally supports Lewis' model although some tracks that are not infilled appear to the right of the peak. It is seen that all the tracks seaward of 47 m are infilled. The break is remarkably abrupt. The break could be related to the maximum depth of ice keels that have traversed the area in the past few hundred years. Too much significance should not be placed on the actual depth values at this time because they are from a limited data base. The fact that Lewis' ice-scour depth data and the 'East Mackenzie' data both show the same characteristics when plotted versus water depth is important, however. It suggests that additional surveys at the active/relict scouring zone boundary may prove fruitful in estimating extreme keel drafts with a high degree of confidence.

Over a long period of time, probably a few hundred years, ice impacts with the seabed in the 15 km² 'East Mackenzie (North)' area have resulted in the ice-scour depth frequency distribution shown in figure 6.1 (a,iii). This distribution includes the ice-scour depths of infilled tracks, measured from the sub-bottom

information on the echograms. Clearly, the deeper penetrations of ice keels into the seabed are rarer events than shallower penetrations. The most suitable density function corresponding to the sample frequency distribution appears to be of the decaying exponential type as was found to be the case for keel drafts. A goodness of fit test showed that the 'East Mackenzie (North)' ice-scour depth data supported the hypothesis that the observations were drawn from a population distributed in a negative exponential fashion with $\hat{\beta} = \bar{X}$ (test at 5 % level; see also Appendix D, section D.4.6 for calculations).

Ice-scour depths from data set 'B' also fit the exponential density function (figure 6.1 (b.iii)) at the 5% significance level for rejection of the null hypothesis. The chi-square test is described in Appendix D, section D.4.7.

The ice-scour depth data from eighty-eight tracks (not buried) in the 'East Mackenzie' area also showed a decaying exponential form for the sample frequency distribution (rejected at 5% level but not rejected at 1% level using chi-square goodness of fit test). This distribution is shown in figure 6.27 and the statistical test is detailed in Appendix D, section D.4.8. To these observations should be added the exponential ice-scour depth distributions found by Lewis (1977b) for other regions of the Beaufort Sea.

In summary, the discussion at the beginning of this section appears to be valid: a decaying exponential keel draft

Figure 6.27 Sample frequency distribution for depths of 88 ice-scour tracks (not buried) in the 'East Mackenzie' mosaic area.

distribution does generate, over a long time period, a similar form of ice-scour depth distribution in the southern Beaufort Sea. The prevailing ice zone should not affect the general form of the distributions. The ice zone may, however, change the β parameter (i.e., arithmetic mean) in the exponential density function. Lewis (1977b) found that the parameters of ice-scour depth distributions varied with water depth zone.

6.5.6 A method for inferring size of ice floes

In the 'Pullen Island' mosaic area there is a four track arcuate scour system at UTM 521 000; 7 758 000. A tracing of this ice-scour track system is shown in figure 6.28. It is tempting to use this planimetric form to make inferences as to the possible size of the ice floe that created the track. On the basis of the earlier discussions of Coriolis force effects and ice floe interaction it is presumed that arcuate tracks are often formed as a result of ice floe interaction.

The concentric nature of the tracks suggests that all were formed at the same time by four keels frozen into a large ice floe. The minimum floe size can be estimated by measuring the distance between tracks '1' and '4' which is 440 m.

Another estimate of ice floe size is obtained by considering the 'pivot point' of the concentric tracks. This point can be located by geometry (see figure 6.28). The radius from the 'pivot point' to the outside track (number 4) is about

1.15 km. There is no apparent seabed disturbance visible on the mosaic at the 'pivot point'. It is hypothesized that ice floe interaction at the water surface was responsible for the rotation of the floe containing the four grounding keels. Most likely, a much larger, slower moving ice floe, or an already grounded, stationary floe served as the centre of rotation as the edges of the two floes met.

Only limited information is available on ice floe sizes in the Beaufort Sea but in general it is expected that floe sizes will be largest at spring breakup and will decrease throughout the summer (Markham, 1975). Invasions of polar pack ice could upset this pattern, however.

Data from the southern Beaufort Sea presented by Markham showed that on August 27, 1974, about eighty-one per cent of the floes were under 100 m in diameter. Eighteen per cent of the floes were 100 m to 500 m in diameter. The remaining one per cent of the floes exceeded 500 m in diameter. The track system shown in figure 6.28 is associated with relatively rare ice floe sizes in terms of Markham's data. The tracks could, however, have been formed in a season when large floes were more prevalent.

The value of a sonograph mosaic for ice-scour track analyses is evident here. The common origin of the four tracks would not have been apparent if only one echogram/sonograph line had been run across the area. A tally of tracks on a linear

basis would give an overestimate of the hazard per unit time of ice keels striking the seabed.

6.6 Ice-sediment interaction

6.6.1 Some effects of grounding ice on the seabed in the 'East Mackenzie (North)' area

In the 15 km² 'East Mackenzie (North)' mosaic area (figure C.2), which lies in water depths of 40 to 50 m, approximately eight per cent of the seabed has been disturbed by ice impacts. Taking into account only the surface expression of the ice-scour tracks in the area, it is estimated that $1.25 \times 10^6 \text{ m}^3$ of sediment has been displaced (estimation method detailed in Table C.II). The maximum age of the visible tracks is probably five hundred years. This estimate is based upon the amount of sediment accumulated above the buried tracks (see section 4.6).

The sample frequency distribution for the volume of single ice-scour tracks in the area is shown in figure 6.29. A chi-square test (Appendix D, section D.4.9) at the five per cent significance level did not support rejection of the hypothesis that the observed volume distribution is drawn from the population which has a mean volume of $30.9 \times 10^3 \text{ m}^3$. It has the density function:

$$P(x) = \frac{e^{-x/(30.9 \times 10^3)}}{30.9 \times 10^3} \quad (\text{eqn. 6.6})$$

It is not surprising that ice-scour track volume has a density

Figure 6.29 Sample frequency distribution for the volume of single ice-scour tracks in the 'East Mackenzie (North)' area. The sample population includes buried tracks. Four buried tracks with volumes exceeding $100 \times 10^3 \text{ m}^3$ are omitted from the histogram.

function of this form because, as seen earlier, both track length and ice-scour depth populations exhibit this form.

The amount of sediment displaced to form a track of $20\,000\text{ m}^3$ volume would fill a 50 m^2 pit that is 8 m deep. Each ice-scour track is therefore a significant seabed feature. No estimates can be made of the amount of sediment placed into suspension by the scouring process although this must surely occur. A fairly large proportion of the seabed material displaced by ice keels is simply 'bulldozed' to either side of an ice keel's path to form lateral embankments as noted in the echogram shown in figure 1.2 and as depicted in figure 3.9.

6.6.2 Ice-scour depth changes along tracks

Data for ice-scour depth changes along tracks is given in Table C.V (b) which is derived from data set 'C'. This data set includes information from buried tracks.

The ice-scour depths along a track can vary significantly over distances of several hundred metres. An example is provided by track 'M-07' (figure C.3 (b), Table C.V (b)). At the first, second, and third cross-sections, depths ($\pm 0.2\text{ m}$) were 0.2 m, 0.8 m, and 0.4 m respectively. These cross-sections are each a bit more than one kilometre apart.

The histogram in figure 6.30 shows the sample frequency distribution of forty-five ice-scour depth changes that were observed between cross-sections (400 m to 2800 m apart) in data

Figure 6.30 Sample frequency distribution of 45 ice-scour track depth changes observed in the 'East Mackenzie' area. The data set includes information from 5 buried tracks. The data is listed in Table C.V (b).

set 'C'. About seventy per cent of the cases show no significant depth change between cross-sections. Uncertainty in the calculated ice-scour depth change values was ± 0.3 m as represented by the width of the bars in the histogram. Fifteen per cent of the cases did show that deeper tracks were forming as the ice keel progressed upslope. Fifteen per cent of the cases showed that the ice keel penetration into the seabed decreased as the ice keel moved upslope. It is remarkable that about eighty-five per cent of the cases showed absolutely no tendency for the ice keel to plough deeper into the seabed slope as the keel moved forward. This is significant in terms of the ice impact hazard for objects buried beneath the seabed. Even a gentle seabed gradient such as that in the 'East Mackenzie' area appears to minimize the likelihood of ice keels causing extremely deep tracks. That is not to say that unusually deep tracks cannot occur but these appear to be the result of rare events for which the probability is less than 0.2 in the study area.

6.6.3 Ice-sediment interaction analysed in terms of an energy cascade model

(a) purpose of model

The creation of ice-scour tracks on the seabed can be visualized as a process in which sea ice is the medium by which energy is transferred from the atmosphere to the seabed. The modelling of such a process is done most efficiently by adopting

a systems analysis procedure. The procedure used here is based on Chorley and Kennedy (1971).

Tracing the energy flow through a system is a useful exercise because the logical linkages between components of the system become apparent. Sources of energy and energy sinks can be identified. The partitioning of energy amongst various sub-processes can be summarized. Sub-processes can be treated in as much or as little detail as desired, depending upon the level of understanding of the system or upon the importance of a sub-process. Later, quantitative modelling of all or part of the ice-scouring process can aid in estimating the amounts of energy required to create ice-scour tracks of specified dimensions. The quantification done here is based upon information from the sonographs and echograms.

(b) flowchart

The flowchart in figure 6.31 summarizes this writer's understanding of the ice-scouring process.

Energy is input to the system by wind, current, and ice floe forces acting either singly or in combination upon a moving ice floe which contains a pressure ridge/keel. These forces must have a non-zero component in the direction of motion of the ice mass for work to be done on the mass. The work done by a force can be expressed as:

Figure 6.31 Energy cascade model of the ice-scour track creation process.

$$W = (F \cos \theta) \cdot \Delta s \quad (\text{eqn. 6.7})$$

where F is the magnitude of a force

θ is the angle between the force vector and the ice mass motion

Δs is the distance travelled by the ice mass while the force is acting upon it.

Coriolis force does no work on the ice mass because this force always acts at right angles to the direction of motion. Therefore, no energy is lost or gained by the ice mass as a result of the Earth's rotation. The ice pressure ridge/keel will develop a certain kinetic energy

$$K_f = \frac{1}{2} M V_f^2 \quad (\text{eqn. 6.8})$$

where K_f is the final kinetic energy just before the keel first touches the seabed

M is the total mass of the ice pressure ridge/keel

V_f is the final speed of the ice mass just before the keel first touches the seabed.

The work done by the driving forces in achieving this kinetic energy is given by:

$$W = \frac{1}{2} M (V_f^2 - V_0^2) \quad (\text{eqn. 6.9})$$

where V_0 is the initial speed of the ice mass. The work done could also be expressed as

$$W = \Delta s (F_{\text{wind}} \cos \theta_{\text{wind}} + F_{\text{current}} \cos \theta_{\text{current}} + F_{\text{ice}} \cos \theta_{\text{ice}}) \quad (\text{eqn. 6.10}).$$

Eventually, the ice mass enters a water depth shallower than the keel draft. Now, significant energy losses result from forces having a non-zero vector component directed opposite to the direction of motion of the ice mass. These force components

are mainly the result of friction between the ice and seabed as the ice keel bulldozes through the sediment. Further energy loss occurs if the ice mass is uplifted as it travels along the slope. Then a portion of the kinetic energy will be converted to gravitational potential energy when the uplifted ice mass becomes negatively buoyant.

The uplift is a consequence of a reaction force which is always equal to the increasingly negative buoyancy of the ice mass as it is driven onto the seabed slope. This reaction force acts at right angles to the direction of keel movement and therefore does no work on the ice keel. The undrained shear strength of the silty-clay or clay sediment at the seabed surface is fairly low (1.7 to about 6 kN/m²; see Table 4.1). The shear strength is probably similar throughout the first two or three metres of sediment. This is the case for the soft clay seabed in the 76 m water depth off the Mississippi delta (Sangrey, 1972, p. 115). The reaction force is then not due to a solid sediment surface supporting the keel. Rather, the reaction force must be mainly due to excess pore water pressure in the seabed sediment. Table 4.1 showed that the clay concentration is 60% to 80% in the mosaic areas. The silt/clay ratio ranged from 0.25 to 0.75. Terzaghi and Peck (1967, p. 173-183) discussed the consolidation of compressible, saturated clay soils. When a load is initially applied to the surface of a compressible clay layer which can drain freely from its upper and lower surfaces, "... there is an initial

excess pressure in the water almost exactly equal to the consolidation stress" (p. 173).

The effective stress equation (Terzaghi and Peck, 1967) is written

$$\Delta p = \Delta \bar{p} + u \quad (\text{eqn. 6.11})$$

where Δp is the consolidation pressure at any point arising from the load on the sediment surface

$\Delta \bar{p}$ is the portion of the consolidation stress at any given time which is transmitted from grain to grain in the sediment

u is the excess hydrostatic pressure at the corresponding time.

It is clear that when $u = \Delta p$, as it must when the load is first applied, that the effective stress, $\Delta \bar{p}$, will be zero and the sediment will become 'quick'. Chari (1975, p. 141) observed this effect in his iceberg model. He found that a 'slurry' formed beneath the moving iceberg model and that there was an "... increase in normal static pressure on the bottom face [of the model]."

Because homogeneous clay sediments have a low permeability ($k < 10^{-6}$ cm/sec; Terzaghi and Peck, 1967, p. 55), a long time is required for the excess hydrostatic pressure, caused by the loading of the sediment, to dissipate. Sufficient time is not available in the case of a moving ice keel. Therefore the negative buoyancy of the keel will continue to be borne by the instantaneous increase in pore water pressure which occurs in response to the ice keel load on the seabed.

Because so little detailed information is available for the sediments in the mosaic areas, only a rough estimate can be made for the time it would take for a 10% degree of consolidation of the sediment to occur. The average water content, w , in the first 0.8 m of sediment in the 'Elf' mosaic area (figure 1.4) was found to be about 63% (Wahlgren and Lewis, 1977, figure 92.6). Terzaghi and Peck (1967, p. 68) stated that the water content of a normally loaded clay is similar to the liquid limit, L_w . Terzaghi and Peck also presented a graph (their figure 14.3) showing the relation between L_w and the coefficient of consolidation, c_v , for undisturbed clay samples. An L_w of 60% corresponds to a c_v of approximately $10^{-3} \text{ cm}^2/\text{sec}$. Now consider the consolidation of a 4 m thick sediment layer which is loaded by a 15 m wide ice keel. The sediment layer can drain freely from its upper and lower surfaces. The time, t , for a 10% degree of consolidation is given by Terzaghi and Peck (p. 180) as

$$t = T_v (H^2/c_v) \quad (\text{eqn. 6.12})$$

where time factor, $T_v = 0.01$. This value is obtained from Terzaghi and Peck (figure 24.5 (b)) using their curve C_1 because the keel width is much larger than the thickness of the consolidating layer. Therefore the consolidation pressure should be uniformly distributed in the layer. The other variables are

$$H = \frac{1}{2} (\text{layer thickness}) = 2 \text{ m or } 200 \text{ cm},$$

$$c_v = 10^{-3} \text{ cm}^2/\text{sec} \text{ as explained above.}$$

The time, t , is found to be 4×10^5 seconds or about 4.6 days. This is a conservative estimate of t in the case of the 'East Mackenzie' area where the mud layer is over 20 m thick (see section 4.5.2). There, drainage probably only occurs from the upper surface (the seabed) of a sediment layer. Hence, t should increase. A fairly long time is required for even a small amount of consolidation to occur. In comparison, the time taken for a 15 m diameter keel tip moving at 0.2 m/sec to move 15 m is only 75 seconds. Craters at the end of ice-scour tracks, such as those observed by McLaren (1977) east of Melville Island, are therefore expected to form only if an ice mass remains stationary for several days at the end of its track. The scarcity of ice-scour craters in the 'East Mackenzie' and 'Pullen Island' areas may imply that many grounded ice masses soon become mobile again. The resolution of the sonographs may also not always be good enough for distinguishing craters at the end of tracks.

The total kinetic energy of a grounding ice pressure ridge/keel is the sum of the translational kinetic energy, K_{trans} , and the rotational kinetic energy, K_{rot} , of the ice mass. The latter term has to be considered because of the torque imbalance experienced by a grounding, moving ice mass. Figure 6.32 shows this writer's conception of the forces acting to rotate an ice keel about its metacentre. The metacentre of a floating body is defined by Rawson and Tupper (1968, p. 19)

Figure 6.32. Forces acting on an ice keel which is grounded but still moving.

WL original waterline, centre of buoyancy at B

W_1L_1 final waterline, centre of buoyancy at B_1

M metacentre

ϕ 'small' angle of rotation about metacentre

Volume of emerged wedge = Volume of immersed wedge

b centre of buoyancy of wedge

Figure 6.33 Illustration of the concept of metacentre for a floating body (after Rawson and Tupper, 1968, p. 19).

as "... the point of intersection of the normal to a slightly inclined waterplane of a body, rotated without change of displacement, through the centre of buoyancy pertaining to that waterplane and the vertical plane through the centre of buoyancy pertaining to the upright condition ." Refer also to figure 6.33 which is based on Rawson and Tupper's figure 2.22.

As indicated on the flowchart, the net rise phenomenon may be a consequence of the keel rotation, the pore water reaction force, and amount of translational kinetic energy that is available for conversion to gravitational potential energy.

The work done by the ice keel moving through the sediment consists of:

- (1) Compression of sediment that lies immediately ahead of the keel and below the keel. The compression is the result of force from the front of the keel being transferred to the soil ahead and below via the shear plane in front of the keel (Chari, 1975, p. 139). Figure 6.34 illustrates Chari's conceptual model for sediment movement in front of a grounding ice keel. Chari found that the shear strength of the sediment inside the model iceberg scour track showed a "slight increase" compared to undisturbed sediment. Diving observations by McLaren (1977) also showed that the sediment in scour bottoms was compressed more than the surrounding sediment. Some consolidation must be taking place during the short time that an ice keel loads a certain area but the degree of consolidation is presumably much less than 10% (compare the calculation done earlier).
- (2) Work is done in overcoming the shear strength of the sediment in front of the ice keel. Chari (1975) derived the following equation to give the energy required to form an ice-scour track of specified length, width, and depth:

Figure 6.34 T.R. Chari's concept of sediment movement in front of a grounding ice keel (after Chari, 1975, p. 140).

$$E = \gamma' \frac{(H + D)^2}{6} B L + \tau D L B + \frac{2}{3} \tau D^2 L \quad (\text{eqn. 6.13})$$

where γ' is submerged unit weight of sediment $[N m^{-3}]$

H is height of the displaced soil in front of the ice keel [m]

D is ice-scour depth [m]

B is frontal width of ice keel [m]

L is total length of ice-scour track [m]

τ is shear strength of the sediment $[N m^{-2}]$.

Variables D, B and L can be obtained from echogram/sonograph information. It is presumed that H is approximately equal to B. The shear strength and unit weight of the sediment can be estimated from some limited observations in the Beaufort Sea. Chari found from his physical model study that both bottom and side resistance on the ice keel are likely to be negligible compared to the frontal resistance to movement.

- (3) Work is done in moving sediment to either side of the ice keel to form the lateral embankments which can be observed on both echograms and sonographs.
- (4) Finally, a certain amount of work is done moving sediment into suspension. This process has not been directly observed in the often turbid waters of the southeastern Beaufort Sea. But, observations of grounded icebergs have indicated that turbid water is usually associated with them (Tarr, 1897, p. 227) showing that sediment has been put into suspension by the grounding process.

(c) an energy flow analysis for ice-scour track M-25

(i) geometric model of ice pressure ridge/keel morphology based on ice-scour track dimensions

A better appreciation of the energy flow involved in the ice-scouring process can be gained if some estimate can be made of the size of the ice pressure ridge/keel that created a specific ice-scour track. Such an estimate is made here for

track M-25 in the 'East Mackenzie' area. The ink outline of this track is shown in figure C.3 (d) and its measurements are given in Table C.IV. The most important measurements to note are that its length, L , is 2500 m; planimetric width, B , is 25 m, and the mean scour depth, D , is 0.25 m. It will be assumed that B is roughly equal to the width of the ice keel tip. The water depth at the inferred origin of the ice-scour track is 39.9 m.

The geometric model chosen by this writer to represent the shape of the ice pressure ridge/keel is the frustrum of a right circular cone (figure 6.35). The 'sail' is represented by another 'inverted' frustrum placed on top of the lower one. A frustrum of a cone is a truncated cone in which the two plane sections are parallel.

This model is most representative of situations in which a fairly small diameter (less than 200 m) ice floe contains a pressure ridge sail and keel. The ice floe interaction discussion (section 6.5.2) suggested that the various planimetric forms of ice-scour tracks are a consequence of the interaction of discrete ice floes. It is also probable that many ice-scour tracks on the Beaufort Sea seabed are the result of extensive pressure ridge systems striking the seabed at various points along their length. These ice keels would not be satisfactorily represented by the model used here. The modelling of ice-scour track formation by complex ridge systems was not attempted at this time.

$$\text{Volume} = (1/3) \pi h (a^2 + a b + b^2)$$

Lateral surface area (area around whole cone, excluding areas of the two plane sections)

$$= \pi (a + b) (h^2 + (b - a)^2)^{\frac{1}{2}}$$

Figure 6.35 Frustum of a right circular cone of radii a , b and height h (from Spiegel, 1968, p. 9).

(i.a) keel geometry

The mosaic and bathymetric information indicates that the keel draft was about 40 m. Therefore, set $h_k = 40$ m. If the keel tip created a track 25 m wide, the radius of the keel tip must be $a_k = 12.5$ m. For a first year pressure ridge the average keel slope is $\alpha = 33^\circ$ (Kovacs and Mellor, 1974, p. 137). Now, the radius of the waterplane area is given by

$$b_k = h_k \tan (90^\circ - \alpha) + a_k \quad (\text{eqn. 6.14})$$

Substitution of the values for h_k and a_k in this equation gives $b_k = 74.1$ m.

(i.b) sail geometry

Because the geometric model assumes that the sail and keel are joined at the waterplane, the radius of the sail base b_s , must be equal to $b_k = 74.1$ m. For first year pressure ridges, the average keel draft to sail height ratio is 4.5 to 1 (Kovacs and Mellor, 1974, p. 136). Therefore, sail height

$$h_s = h_k / 4.5 \quad (\text{eqn. 6.15})$$

Sail height in this case is 8.89 m. Now the radius of the top of the sail can be found using

$$a_s = b_s - (h_s / \tan \beta) \quad (\text{eqn. 6.16})$$

where β is the average first year pressure ridge slope of 24° (Kovacs and Mellor, 1974, p. 137).

The value of a_s is found to be 54.1 m.

(i.c) volumes of sail and keel

The volume of a frustrum of a right circular cone is given by

$$\text{Volume} = 1/3 \pi h (a^2 + a b + b^2) \quad (\text{eqn. 6.17})$$

Substitution into this formula of the appropriate values found above gives a keel volume, $\text{Vol}_k = 2.75 \times 10^5 \text{ m}^3$ and a sail volume, $\text{Vol}_s = 1.16 \times 10^5 \text{ m}^3$. A scale drawing of the idealized pressure ridge/keel system which corresponds to the dimensions of ice-scour track M-25 is shown in figure 6.36. The cross-sectional shape of the idealized ice mass compares favourably to the cross-section of a first year pressure ridge/keel depicted by Kovacs and Mellor (1974, p. 137). The basic conical form and circular waterplane of the model has also been seen for at least one floeberg studied by Kovacs and Gow (1976; see their figure 1 which is a vertical aerial photograph of a grounded floeberg with a sail having a truncated cone shape).

(i.d) mass of sail and keel

The mass of a volume of solid sea ice can be computed as

$$M = \text{Vol} \cdot \rho_{\text{sea ice}} \quad (\text{eqn. 6.18})$$

$$\text{where } \rho_{\text{sea ice}} = 910 \text{ kg m}^{-3} \quad (\text{Pounder, 1965, p. 115})$$

The keel is presumed to be composed of solid ice so that the keel's structural strength definitely exceeds that of the seabed sediment. Enough time has passed since formation of the ridge so that the seawater in the voids between the ice blocks has frozen. Hence, $M_k = 2.50 \times 10^8 \text{ kg}$. Before computing the mass of ice in the pressure ridge sail, it is noted that the

Figure 6.36 Scale drawing of an idealized pressure ridge/keel system based on observed ice-scour track width of 25 m and water depth at initial seabed impact of 40 m. These dimensions pertain to ice-scour track M-25 in the 'East Mackenzie' area.

mass of water displaced by a keel with volume, Vol_k , is

$$M_{\text{water displ}} = \text{Vol}_k \cdot \rho_{\text{sea water}} \quad (\text{eqn. 6.19})$$

where $\rho_{\text{sea water}}$ is 1025 kg m^{-3} (Rawson and Tupper, 1968, p. xii).

The mass of water displaced by the keel is $2.82 \times 10^8 \text{ kg}$. A neutrally buoyant floating object has a mass equal to the mass of water it displaces. Therefore, to satisfy the condition for hydrostatic equilibrium of the ice pressure ridge/keel, the total mass of the sail plus keel must also be $2.82 \times 10^8 \text{ kg}$. This constrains the sail to a mass of $0.32 \times 10^8 \text{ kg}$. This in turn implies a sail porosity of 70%. This is a fairly high porosity value. Kovacs and Mellor (1974, p. 134) stated that newly formed pressure ridges may have porosities ranging from 10% to 40%. Although the geometric model gives an unrealistic sail porosity, it is decided to accept this drawback for now. The model can still give reasonable estimates of the mass and volumes of the pressure ridges which formed specific ice-scour tracks.

(ii) energy balance

The input of energy to the ice-scouring process must equal the energy losses involved in the process. Energy losses that occurred during the formation of track M-25 are now examined.

(ii.a) energy sinks

The energy used in excavation and compression of the sediments can be calculated using equation 6.13. Values for D, B, and L have already been stated. The average shear strength, τ , of the sediment in the 'East Mackenzie' area is estimated to be 5 kN/m^2 based on data given in Lewis (1977a). The submerged unit weight of the sediment, γ' , is estimated to be 6615 N/m^3 based on sediment core data (core 169 E) presented in Wahlgren and Lewis (1977). The energy, E, used in excavation is then found to be 9.59×10^7 joules. Chari (1975) stated that about one-third of the energy in a grounding keel is used up in compressing the sediment in front of and below the keel. This amount of energy is not directly accounted for in Chari's equation (equation 6.13). Therefore, the total energy, E', required to match the energy used in excavation (E) plus that used in compression ($0.33 E'$) is

$$E' = E + 0.33 E' \quad (\text{eqn. 6.20 a})$$

$$\text{or } E' = 1.49 E \quad (\text{eqn. 6.20 b})$$

It is found that E' is 1.43×10^8 joules. Hence, the energy used in sediment compression is 4.76×10^7 joules.

As the ice keel moves into shallower water and driving forces continue to act on it, the keel will be uplifted by the reaction force associated with excess pore water pressure in the sediment. This reaction force will always exactly balance any negative buoyancy developed by the pressure ridge when it

is uplifted and the volume of water displaced decreases. Hence, no work is done on the keel by the reaction force. Besides, this force always acts at right angles to the direction of keel motion. When the keel is uplifted, however, its kinetic energy will decrease by a certain amount. This loss of kinetic energy will appear as gravitational potential energy. The datum used here is sea level.

For ice-scour track M-25, the net rise per unit length of the track bottom was determined to be 0.0004. This means that over a total length of 2500 m, the total net rise should be 1 m. If it is assumed that no rotation of the ice mass about its metacentre took place (i.e., $K_{rot} = 0$) and that all of the uplift appeared above the initial water line (sea level) then the final gravitational potential energy at uplift, z , is given by

$$U_g(z) = \gamma_w \int_0^z A_w z \, dz \quad (\text{eqn. 6.21 a})$$

where γ_w is the unit weight of sea water, $10\,045 \text{ N/m}^3$

A_w is the area of the waterplane of the floating ice mass and z is the uplift.

For small values of net rise (not greater than 3 m) and the dimensions of the ice keel shown in figure 6.36, A_w may be regarded as a constant during the uplift process. Upon doing the integration,

$$U_g(z) = (\gamma_w A_w z^2)/2 \quad (\text{eqn. 6.21 b})$$

For the idealized pressure ridge/keel in figure 6.36 with $b_k = 74.1$, the area of the circular waterplane is $17\,250 \text{ m}^2$.

Evaluation of equation 6.21 (b) gives $U_g(1 \text{ m}) = 8.66 \times 10^7$ joules.

Now the debit side of the ice keel energy balance equation can be written (although K_{rot} is omitted because it is assumed to be negligible for now). That is,

$$\begin{aligned} \text{energy loss} = & (\text{energy used in sediment compression}) \\ & + (\text{energy used in sediment excavation}) \\ & + (\text{energy used in causing keel uplift}) \end{aligned}$$

$$\text{or, energy loss} = 0.33 E' + E + U_g(1 \text{ m}) \quad (\text{eqn. 6.22})$$

The energy required to create ice-scour track M-25 was 2.30×10^8 joules according to the above analysis.

(ii.b) ice keel speed before and after grounding related to changes in kinetic energy

The kinetic energy of the ice keel at the time of grounding cannot be directly calculated unless the keel's speed is estimated. Rather than making a poor or misleading estimate of the ice speed, it is better first to equate the translational kinetic energy of the keel at the time of grounding (K_f) to the required energy of 2.30×10^8 joules that was just calculated. A value for ice speed is found by calculating

$$V = (2(\text{energy required})/M)^{1/2} \quad (\text{eqn. 6.23})$$

where M is 2.82×10^8 kg, the total mass of the idealized ridge plus keel.

The ice speed at the time of grounding is found to be 1.3 m/sec or about 2.6 knots. This value is several times greater than that expected on the basis of ice drift studies (e.g., Markham,

1975; MacNeill and Garrett, 1975). Ice drift studies usually rely on observations that may be several hours or even days apart. Information on relatively short periods of ice movement at fairly high speeds would be expected to be lost if the 'rapid' movement occurs between observation times. Therefore, this writer believes that the ice speed just obtained for the ungrounded keel is realistic. In fact, MacNeill and Garrett reported a few drogue drift speeds of 0.5 to 0.9 m/sec.

Once the keel has grounded, the work done on the keel by the driving forces is presumed to be unchanged. But, the work ($W = K_f$) is now being divided between giving kinetic energy to the keel, compressing and excavating sediment, and uplifting the ice keel. Because the kinetic energy after grounding, K_{trans} , is less than K_f , the speed of the ice keel must decrease. Eventually, of course, the ice keel speed drops to zero as shown by the fact that the ice-scour track terminates (even though the driving forces may continue). A larger and larger proportion of the forces acting on the keel along its direction of motion must be used to overcome the increasing shearing resistance at the ice-sediment contact. The shearing resistance increases in direct proportion to the normal stress which is due to the increasing negative buoyancy of the rising ice mass. The ice mass is still supported by excess pore water pressure in the sediment. An analogous situation would be to pull a wooden block up a wooden incline.

The pulling force is kept constant and is initially strong enough to overcome friction, but weights are continually added to the wooden block. Eventually, the friction force (initial shearing resistance) plus the added shearing resistance will exceed the pulling force and the block will stop moving. Figure 6.37 shows the changes in forces during the formation of ice-scour track M-25.

The shearing resistance for an object with a 'smooth' base at rest on a 'smooth' incline is

$$T = (U_g/z) \sin \theta \quad (\text{eqn. 6.24})$$

where z is height above datum

U_g is gravitational potential at height z

θ is the angle of the slope.

The total resistance to ice keel movement up a seabed slope, at a certain uplift, z , is given by

$$R_t = \begin{aligned} &(\text{friction due to compression of sediment}) \\ &+ (\text{friction due to excavation of sediment}) \\ &+ (\text{shear resistance}) \end{aligned}$$

$$= E + 0.33 E' + T(z)$$

$$\text{or } R_t = E' + T(z) \quad (\text{eqn. 6.25})$$

where shearing resistance $T(z)$ depends upon the amount of uplift accomplished to a certain point. This is one dependent variable (scale on left hand side of graph) shown in figure 6.37.

The change in buoyancy of the keel is given by

$$\Delta \text{buoyancy} = \gamma_w A_w z \quad (\text{eqn. 6.26})$$

where γ_w and A_w are as defined earlier

z is the uplift or net rise of the keel. This value is defined to be negative when uplift occurs.

Figure 6.37 This graph pertains to ice-scour track M-25. The total resistance to keel movement through the seabed sediment increases linearly with the distance travelled in an upslope direction. The increase in total resistance is a result of decreasing keel buoyancy during uplift and consequent increase in shearing resistance between the keel base and the sediment. The ice keel speed decreases from 1.3 m/sec at the instant of initial grounding to zero when 2500 m has been traversed.

This variable, which is dependent on the distance the ice keel has travelled along a slope is also shown in figure 6.37 (use scale on right hand side of the graph).

Now the average speed of the ice keel while it is grounding can be considered. Using equation 6.23, the inferred ice speed at the instant of grounding was found to be $V_o' = 1.3$ m/sec. The final speed of the ice keel is $V_f' = 0$ m/sec. The average speed of the grounding keel is

$$\bar{V} = \frac{1}{2} (V_f' + V_o') \quad (\text{eqn. 6.27})$$

and $\bar{V}$ is computed to be 0.65 m/sec. The time taken to form track M-25 is given by

$$t = L/\bar{V} \quad (\text{eqn. 6.28})$$

and is found to be 3846 seconds or 64 minutes. Interestingly, the average speed value calculated here for the ice keel that formed track M-25 is close to the average speed of 0.5 m/sec calculated during the Coriolis force analysis for the same track (see Table 6.V). This is an encouraging result but it may only be coincidental. Numerous comparisons of the two methods of deriving ice keel speed should be done before any definite conclusions can be made as to whether they will always yield the same result for those arcuate tracks that turn to the right. Such an analysis was not attempted here because of the scarcity of data.

(ii.c) energy sources

The proportions of total energy contributed by each of wind, currents, and pack ice in creating ice-scour track M-25 are difficult to determine. Nothing is known for certain about the environmental conditions at the time of its formation. Indeed, the time of its formation is unknown. The fairly well developed arcuate form with turning to the right of the direction of keel movement, suggests, however, that pressure from adjacent ice floes was minimal. The wind and currents probably came from the south or south-southwest because the track azimuth is 202° . The fact that the turning of the track was not consistent with the approach angle shows that the seabed slope was not steering the ice keel.

An estimate of the wind force on the pressure ridge/keel system can be made. The lateral surface area of an idealized sail is given by

$$A_{\text{lat sfc}} = \pi(a_s + b_s) (h_s^2 + (b_s - a_s)^2)^{1/2} \quad (\text{eqn. 6.29})$$

where the variable values are as given in figure 6.36. Wind pressure would only act on one half of the lateral surface area so the area facing the wind is 4408 m^2 . The wind pressure on an object is given by

$$P = \frac{1}{2} C_f \rho_{\text{air}} u^2 \quad (\text{eqn. 6.30})$$

where ρ_{air} is the mass density of dry air, 1.2928 kg/m^3 at 0°C and 101.3 kPa (Yarwood and Castle, 1970, p. 29)

C_f is an average form drag coefficient for a typical ice pressure ridge. Arya (1973, p. 7096) estimated a value of 0.4 for C_f

u is wind speed

For a wind speed of 10 m/sec (20 knots), P is 25.9 N/m^2 .

Hence,

$$F_{\text{wind}} = P (A_{\text{lat sfc}}) / 2 \quad (\text{eqn. 6.31})$$

is $1.14 \times 10^5 \text{ N}$. This force acting over the 2500 m track length provides 2.85×10^8 joules of energy. Reference to figure 6.37 shows that this F_{wind} value is more than sufficient to overcome the initial seabed friction and exceeds the required total driving force. The minimum windspeed value that would meet the minimum requirement of a $9.2 \times 10^4 \text{ N}$ driving force acting over 2500 m (so that work done by wind, $W_{\text{wind}} = 2.30 \times 10^8$ joules) for the creation of track M-25 is $u = 9 \text{ m/sec}$ (18 knots). As noted in sections 4.3.1 and 6.3.2 (a), south-southwest winds of this magnitude are fairly common at Shingle Point, just south of the 'East Mackenzie' mosaic area.

Surface currents could also be driving the keel. The currents as discussed earlier, arise mainly in response to local wind stress. The scarcity of information on current speeds and uncertainty as to an appropriate form drag coefficient for the keel means that no detailed analysis of current influence on the ice keel can be done here.

An upper limit to the force that could be transmitted by one or more 2 m thick ice floes abutting the idealized pressure ridge/keel can be found. Kovacs and Mellor (1974, p. 154) estimated the crushing strength of 2 m thick ice to be about $2.8 \times 10^6 \text{ N/m}^2$. As per Kovacs and Mellor, the maximum

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transmitted force should be

$$F_{ice} \text{ (max.)} = (2.8 \times 10^6 \text{ N m}^{-2}) d B \quad (\text{eqn. 6.32})$$

where $d = 2 \text{ m}$

B = effective waterline width of the ice keel which is 148.2 m for our example.

The calculated $F_{ice} \text{ (max.)}$ is found to be $8.30 \times 10^8 \text{ N}$. This is a fairly high value which would prove more than adequate to create track M-25.

In summary, either strong winds alone or pack ice alone could provide enough energy input to the idealized ice keel to create track M-25 and meet the energy requirement of 2.30×10^8 joules over the 2500 m length of the track. The wind analysis and Coriolis force analysis seem to support each other. Ice floe interaction was probably not a factor in the formation of this particular track. The credit side of the ice keel energy balance equation can be written as

$$\begin{aligned} \text{energy gain} &= (\text{work done by wind on ice pressure ridge/keel}) \\ \text{or energy gain} &= W_{wind} \quad (\text{eqn. 6.33}) \end{aligned}$$

The complete energy balance equation for the grounded and now stationary ice keel that caused track M-25 is given by

$$(U_g + K)_{\text{initial}} + W_{wind} = (U_g + K)_{\text{final}} + 0.33 E' + E \quad (\text{eqn. 6.34 a})$$

where the right hand side is based on equation 6.22. The general form of the energy conservation equation is as given by Bueche (1969, p. 136). Identifying those terms with a value of

zero, the energy balance is

$$(0 + 0) + W_{\text{wind}} = (U_g(1 \text{ m}) + 0) + 0.33 E' + E \quad (\text{eqn. 6.34 b})$$

so
$$W_{\text{wind}} = U_g(1 \text{ m}) + 0.33 E' + E \quad (\text{eqn. 6.34 c})$$

where both sides of the equation equal 2.30×10^8 joules. A rigorous energy balance analysis requires that each term in the equation should be derived independently of the others which is not the case here. This can only be done if the various environmental variables are measured in the field at the time of creation of the track.

6.6.4 Discussion of the 'net rise' phenomenon

The fact that ice keels are often uplifted upon grounding rather than digging deeper into the seabed is of interest to engineers who must recommend safe burial depths for subsea equipment installations in the Beaufort Sea.

Kovacs and Mellor (1974, p. 143) stated that grounded ice islands are often observed to have been uplifted as much as 4 m when they are driven aground by the force of the pack ice behind them. They cited a report by Simpson (1890) who observed the grounding of a thick multi-year ice floe which was driven by pack ice. This floe was uplifted 12 to 13 m above its original waterline! A study of grounded floebergs near Prudhoe Bay by Kovacs and Gow (1976) indicated an uplift of 1.85 m in one case. Pack ice had been responsible for driving this floeberg aground. Another floeberg studied by Kovacs and Gow had

been uplifted by an undetermined amount and had been tilted from its original trim. Kovacs and Gow attributed this tilt to the piling up of broken ice floes on one side of the floeberg.

Figures 6.1 (c,iv) and 6.12 showed that net rise values observed in the 'East Mackenzie' data ranged from about -1 m to 3 m. Total observed net rise values range from -0.3 m to 3.4 m (Table C.V (c)). Positive rises generally occur inshore of the 45 m isobath while negative rise values generally occur in the deeper water (figure 6.38).

According to Lewis (1977b, figure 6), using data from other regions of the Beaufort Sea shelf, mean ice-scour depths increase from 0.3 m at the 10 m water depth to 0.9 to 1.0 m at the 50 m isobath. The trend thereafter shows a constant mean ice-scour depth of about 0.8 m out to the 70 m isobath. Most of the ice-scour tracks beyond the 50 m water depth are likely to be infilled. But, if infilling had not occurred it is expected that the general trend would be for mean ice-scour depths to increase with water depth. Lewis also presented a graph of seabed impact return period versus water depth (his figure 7) which showed that the hazard of deep (3 m) scours increases as water depth increases. These trends are supported by the net rise per unit length versus water depth curves shown in figure 6.38.

T.R. Chari's (1975) physical model for grounding icebergs used a rigidly mounted model iceberg which was not allowed to

Figure 6.38 Extrapolation of the net rise per unit length of track versus water depth relationships shown in figures 6.13 and 6.14. At water depths exceeding 45 m, 'negative rises' (i.e., ice keel digs deeper into seabed as it moves upslope) are predicted.

rise up the model slope. Because iceberg drafts usually exceed 45 m, his model was appropriate in view of the relationships shown in figure 6.38.

In an attempt to understand the physical basis for the net rise versus water depth relationship, figures 6.39 and 6.40 were drawn. The former figure shows (for an idealized pressure ridge/keel) how the mass of ice (M_{ice}) and the energy required for uplift (U_g) increase with keel draft. The latter figure shows how the moment of inertia, I , of a solid cone with a mass density of 1000 kg/m^3 varies with cone height. The slopes of the M_{ice} and I curves show marked increases for keel drafts exceeding 40 m. The $U_g(1 \text{ m})$ and $U_g(2 \text{ m})$ curves are almost linear over much of the 10 to 60 m keel draft range. The moment of inertia curve appears to fit best the observed net rise relationship to water depth (or keel draft).

To examine in more detail the influence of the moment of inertia of the ice mass, an estimate was made first of the angular speed at which a grounding ice mass would rotate away from its original axis. Figure 6.32 showed that such a rotation could arise because of an imbalance of torques. Some of the kinetic energy of the ice mass would have to be converted into rotational kinetic energy, K_{rot} , for the rotation to occur. In an extreme case, the 'net rise' could be envisaged as being entirely due to rotation with none of the 'rise' being due to uplift. A 40 m deep ice keel striking the seabed and proceeding

Figure 6.39 Total mass of ice in an idealized pressure ridge/keel and potential energy due to uplift of the ice mass along seabed slope versus keel draft. The above curves pertain to an ice keel which would cause a 15 m wide track.

Figure 6.40 Moment of inertia versus cone height for an hypothetical right circular cone having radius and height similar to those of an ice pressure ridge keel. The moment of inertia is about the axis through the centre of mass and perpendicular to the cone axis. Cone height is regarded as being analogous to keel draft.

up a 1/500 slope until 1 m 'net rise' had occurred would have to rotate $\phi = 12.8^\circ$ or 0.224 radians away from its original central axis in order to avoid digging into the seabed (see figure 6.41). If the keel travelled at 0.5 m/sec for 500 m (the distance at which rise is 1 m) the time taken would be $\Delta t = 1000$ seconds. The average angular speed

$$\bar{\omega} = \frac{\Delta\phi}{\Delta t} \quad (\text{eqn. 6.35})$$

would be 0.224×10^{-3} radians/sec. The total ice mass is assumed to be $M_{\text{ice}} = 2.82 \times 10^8$ kg as in the analysis for track M-25. The rotational kinetic energy is given by

$$K_{\text{rot}} = \frac{1}{2} I \bar{\omega}^2 \quad (\text{eqn. 6.36})$$

where I for the pressure ridge is approximated by the moment of inertia for a cone. The moment of inertia used in figure 6.40 is

$$I = (3/80) M_{\text{ice}} (4 a^2 + h^2) \quad (\text{eqn. 6.36})$$

where M_{ice} is 2.82×10^8 kg

$a = b_k = 74.1$ m as in figure 6.36

$h = h_k = 40$ m.

The approximate moment of inertia is $I = 2.49 \times 10^{11}$ kg m² so K_{rot} is approximately 6.25×10^3 joules. This is a small amount of energy relative to the other terms in the energy balance equation used in the M-25 track analysis. During that analysis, K_{rot} was regarded as being negligible. The K_{rot} value just found is in fact greater than that which would actually be obtained for the M-25 analysis because the latter involved a 1 m rise over 2500 m rather than over 500 m.

DEEPER WATER (negative rise):
Keel moves slowly enough
that excess pore water
pressure can dissipate (3)
while keel is still
loading area.

SHALLOWER WATER (positive rise):
Keel moves quickly enough
that excess pore water
pressure in sediment (3)
supports keel's negative
buoyancy for a few minutes

Figure 6.41

Possible explanations for the net rise phenomenon:
(1) uplift of ice keel because of reaction force in saturated clay sediment due to strength of sediment or to buildup of excess pore water pressure; (2) rotation of ice mass about its metacentre; (3) keel speed versus rate of dissipation of excess pore water pressure in sediment that is loaded by the keel; (4) a combination of these processes.

The finding that only a modest amount of energy is needed to cause substantial rotation of an ice keel about its metacentre does not fit the evidence cited earlier. That is, keel rotation apparently could occur easily at water depths in excess of 45 m with the energy inputs that are available. Uplifts of ice keels would never have to occur to enable the 'net rise' effect to happen. But uplifts of ice keels have actually been witnessed.

A possible explanation may be that the moments of inertia of ice keels do follow a curve such as in figure 6.40, but that the true curve is displaced more to the left. Moments of inertia (the force resisting rotation) and hence K_{rot} would then increase rapidly for keel drafts greater than 45 m. In water depths less than 45 m actual uplifts of the ice keels are expected to occur in conjunction with some amount of keel rotation. In deeper water, the large mass and large moment of inertia of a pressure ridge may make uplift and rotation both impossible in most cases. The ice keel would then dig deeper into the sediment the farther upslope it was driven.

Another explanation for the net rise versus water depth relation involves the speed of ice keels versus the rate of dissipation of excess pore water pressure in the sediment on which the keel acts as a load. If an ice keel is moving extremely slowly it may be able to consolidate the sediment beneath it as the excess pore water pressure has time to dissipate.

This process could cause ice-scour track depth to increase as the ice keel moves upslope.

It is possible that keel rotation, uplift, and varying degrees of sediment consolidation may all be influencing the observed distribution of ice-scour depth changes along tracks (figure 6.30) and the net rise versus water depth relationship. Variability in sediment shear strength and permeability may also be important factors.

In summary, ice keels in deeper water generally create deeper ice-scour tracks. A hazard determination should take the frequency distribution of keel drafts and the net rise versus water depth relationship into account.

CHAPTER 7

CONCLUSION

7.1 Summary

This paper has examined ice-scour tracks in the 10 to 50 m water depth range on the Beaufort Sea continental shelf that were caused by ice pressure ridges and ice islands grounding onto a seabed slope with a gradient of about 1/500. The ice keels can scour several metres into the seabed but most tracks are less than 2 m deep. Track width is usually in the 10 to 30 m range and tracks can be several kilometres long. Each ice keel impact with the seabed involves the excavation of thousands of cubic metres of sediment.

Ice-scour tracks are not unique to the Beaufort Sea. Seabed and lakebed surveys have shown that the tracks are a fairly common feature in the Northern Hemisphere. Some of the tracks are relict in the sense that no modern, suitably deep draft ice keels occur in the areas in which those tracks are found. The Beaufort Sea tracks inshore of the 50 m isobath are modern, however.

The study of ice-scour tracks is of practical interest to organizations involved in construction of seabed installations in ice-infested waters.

Information on the dimensions of ice-scour tracks from the Beaufort Sea was collected from echograms and sonograph mosaics. Published information on the physical environment (bathymetry, winds, currents, storm surges, floating ice, seabed sediments, sea level changes, climatic changes, and sedimentation rates) of the study area was used to try to understand the processes involved in the formation of the ice-scour tracks.

A fundamental task in this study was to use echograms to construct 1:10 000 and 1:20 000 scale bathymetric charts to overlay two sonograph mosaics of the seabed. The availability of processed bathymetric information in direct conjunction with the pattern of ice-scour tracks on the seabed provided a means of inferring the direction of ice movement during scouring events (hypothesized to be upslope in nearly all cases) and obtaining a better understanding of the relationship between gross seabed morphology and the microrelief created by ice keels scraping the seabed.

To aid in the interpretation of the seabed mosaics, a simple classification system was devised which involves the type of ice-scour track (single, multiple, broad and flat-bottomed), the planimetric form of ice-scour tracks (straight, sinuous, arcuate, ice-scour crater), and some possible secondary characteristics (unmodified, abrupt change in direction, crater at one end) and relates these forms to the processes occurring during the ice-scouring event.

The analyses of the ice-scour track data suggested the following generalizations which are listed in the order in which they were discussed in chapter six:

- (1) The force vectors for surface winds, surface currents, and bottom currents have approximately the same azimuth distribution in the shallow water of the Beaufort Sea continental shelf.
- (2) The relatively weak tidal currents are probably only important in causing the planimetric forms of ice-scour tracks wherein the track crosses over itself and downslope scouring has occurred.
- (3) The temporary rise in sea level accompanying storm surges cannot account for many cases of the net rise of ice keels observed in the 'East Mackenzie' area. Storm surges are not, however, ruled out as the cause of some cases of ice mass uplift upon grounding.
- (4) $(\text{net rise/length}) = m \ln (\text{water depth})/b$ (eqn. 7.1)
where m and b are constants.
- (5) Coriolis force is acting upon the moving ice keels but the effect is often not noticeable in the planimetric form of the ice-scour tracks because of the effect of ice floe interaction.
- (6) For a given driving force magnitude and seabed gradient,
 $L = m \secant (\theta_{\text{app}}) + a$ (eqn. 6.2)
where L is ice-scour track length
 θ_{app} is approach angle of ice keel to the seabed slope,
 m and a are constants.
- (7) The 1/400 to 1/500 gradient in the 'East Mackenzie' area does not steer grounding ice keels.
- (8) Most ice floes containing pressure ridges have only one portion of the ice mass in contact with the seabed at any one time.
- (9) The process of ice floe interaction can be used to explain the origin of all the observed planimetric forms of ice-scour tracks.
- (10) For a given θ_{app} , driving force magnitude and duration are probably the most important influences on the ice-scour track length distribution which is of the decaying exponential type.

- (11) The majority of ice keels are 20 m or less in width at the point at which they scrape the seabed.
- (12) The populations of ice keel drafts and ice-scour depths both follow a decaying exponential type of distribution which suggests that deep drafts and tracks are rare events.
- (13) Ice-scour depths may vary along a track but usually the depth remains fairly constant or decreases.
- (14) An exploratory calculation indicated that excess pore water pressure developed in the saturated clay sediment beneath a moving ice keel could support any negative buoyancy the ice keel might develop. This effect enables the ice keel to be uplifted as it moves into shallower water.
- (15) The ice-scouring process can be analysed in terms of an energy flow model which is adaptable to computer simulation. The simulation can be quantified by using an idealized geometric model for the ice pressure ridge/keel system that scoured the seabed.
- (16) In water depths less than 45 m, ice-scour depth in a track generally decreases with distance upslope whereas in water depths exceeding 45 m, ice-scour depth in a track generally increases with distance upslope. The physical basis for the net rise versus water depth relationship is not fully understood. It may be related to a combination of:
 - (a) uplift of the ice keel in response to the reaction force arising from the keel load on the sediment causing excess pore water pressure in the saturated clay sediment;
 - (b) rate of consolidation of the sediment;
 - (c) rotation of the ice mass about its metacentre.

7.2 Suggestions for further studies

Further studies of the ice-scour track creation process should preferably use high quality data from mosaic areas in which none of the tracks show evidence of infilling or burial by sediment. This should reduce ambiguities in measurements and interpretations of the data.

With the increased ship traffic and seabed exploration in the southeastern Beaufort Sea since 1974, researchers will have to be cautious in their interpretations of track-like seabed features. Anchor drag marks and dredge trails have undoubtedly been added to the 1974 population of seabed tracks. This is of particular concern in the 'Pullen Island' and 'Elf' mosaic areas.

Attempts should be made to correlate ice pressure ridge movements during a season with newly added ice-scour tracks in a mosaic area.

Computer simulation models of the ice-scouring process, tracing energy flow from atmosphere to seabed should be developed to increase theoretical understanding of the ice-scouring process. In conjunction with this, more physical modelling of the ice-sediment interaction is required. Such a physical model should be tailored to the ice and sediment characteristics of the Beaufort Sea environment.

New data should be obtained to check the general applicability of the length versus approach angle and net rise versus water depth relationships found in the 'East Mackenzie' mosaic area.

Historical studies of ice-scour tracks would benefit from the collection of additional mosaic type data from regions in which most of the tracks are buried or infilled. High resolution

seismic reflection profiling in conjunction with detailed long core information could help resolve controversies over sedimentation rates and the ages of ice-scour tracks.

It is hoped that the work presented in this paper can provide a basis for increasingly detailed, quantitative studies of the processes involved in the formation of ice-scour tracks.

APPENDIX A

RESOLUTION OF SEABED GEOMORPHOLOGICAL FEATURES BY
ECHO-SOUNDING AND SIDE-SCAN SONAR TECHNIQUES

A.1 Introduction

Several important relationships of underwater acoustics are reviewed in this appendix. Example calculations based on characteristics of the Krupp AD 10 echo-sounder and the EG&G side-scan sonar system are presented in order to assess the relative importance of certain survey equipment and environmental variables to the spatial resolution of seabed micro-relief (ice-scour tracks in particular). Figure A.1 shows the context in which these variables should be viewed. Table A.I shows the specifications of the equipment used during the survey of the 'East-Mackenzie' and 'Pullen Island' mosaic areas in August and September of 1974. A list of symbols that are used throughout this Appendix is provided in Table A.II.

A.2 Sound Waves

The transmission of sound through a medium can be expressed in terms of compressional waves (longitudinal waves) because the vibrations of particles in the medium are in a direction parallel to the direction of propagation of the wave. In

Figure A.1 Characteristics of equipment and environment which will affect resolution of seabed features on echograms and sonographs. Items marked with an asterisk (*) are discussed in more detail in text of Appendix A. 'Smoothing' refers to partial loss of information resulting mainly from signal averaging due to beamwidth at seabed and combination of ship's speed and paper speed.

TABLE A.I
EQUIPMENT SPECIFICATIONS

Krupp Atlas-Deso 10 echo-sounder (two transducers may be used simultaneously)

transducer (rectangular) - used throughout survey

- frequency: 30 kHz
- input power: 300 W
- longitudinal beam angle: 20° between half-power points
- transverse beam angle: 30° between half-power points

transducer (circular) - used occasionally in conjunction with 30 kHz transducer

- frequency: 210 kHz (30 kHz may be used simultaneously)
- input power: 150 W
- beam angle: 10° between half-power points

recorder paper

- type: 230 mm wide, dry electrosensitive
- speed: usually 2.5 cm/min; also can run at 1.25, 5.0 and 10.0 cm/min.

sounding rate with $c_{\text{sea water}} = 1500 \text{ m/sec}$

20 m range	10 soundings/sec
40 m range	5 soundings/sec
80 m range	2.5 soundings/sec

EG&G Mark 1B side-scan sonar system

transducer (rectangular slit)

- frequency: 105 kHz
- input power: 11.3 W
- horizontal beam angle: 1.2° between half-power points

recorder paper

- type: 280 mm wide, wet electrosensitive
- speed: 59 lines/cm (one line/pulse)

pulse rate:

200 m slant range	3.75 pulse/sec
250 m slant range	3.0 pulse/sec
500 m slant range	1.5 pulse/sec

pulse length: $0.1 \times 10^{-3} \text{ sec}$

tow speed: usually 3 m/sec (6 knots)

TABLE A.II

LIST OF SYMBOLS FOR UNDERWATER ACOUSTICS DISCUSSION

<u>Symbol</u>	<u>Description</u>	<u>Units</u>
b	length of rectangular transducer	m
c_x	speed of sound in material x	m/sec
d	distance	m
D	diameter of a circular transducer	m
E	bulk modulus ¹	N/m ²
I	intensity of compressional wave	N/m ²
i	angle of incidence of plane wave	degrees
l_a	length of arc	m
P_d	pulse duration	sec
R_r	range resolution	m
r	angle of reflection	degrees
S	salinity	‰
T	temperature	C
t	time	sec
V_s	ship's speed	m/sec
w	beamwidth	m
z	water depth	m
θ	true slope of seabed	degrees
θ_n	angle of approach/depart of wavefront at a sound speed discontinuity	degrees
θ_{Res}	approximate angular resolution (beam angle)	degrees
λ	wavelength	m
ν	frequency	sec ⁻¹
ρ	density of material	kg/m ³
ϕ	measured slope of seabed	degrees

¹ bulk modulus, $E \equiv \frac{P}{\Delta V/V}$, where ΔV is the decrease in volume, V , resulting from application of pressure, P .

contrast, many aspects of the behaviour of electromagnetic waves (radio, visible light, x-rays, etc.) are best modelled by transverse waves for which vibrations are perpendicular to the propagation direction. Nevertheless, the principles and laws of reflection, refraction, and diffraction apply equally well to both types of waves (see for example, Bueche, 1969).

A.3 Speed of sound

A.3.1 Introduction

The speed of sound waves in a material is a function of the bulk modulus and density of the material. That is:

$$c_x = \sqrt{E/\rho} \quad (\text{eqn. A.1, list of symbols in Table A.II})$$

The relationship between speed of sound, wavelength, and frequency is

$$c_x = \lambda v \quad (\text{eqn. A.2})$$

In ocean water, the speed of sound can be empirically related to salinity, temperature, and depth below the surface. The speed of sound is most sensitive to water temperature. A generally accepted empirical relationship is as follows:

$$c_{\text{sea water}} \text{ (m/sec)} = 1449.2 + 4.6 T - 0.055 T^2 + 0.00029 T^3 + \\ (1.34 - 0.010 T) (S - 35) + 0.016 z \\ (\text{eqn. A.3})$$

This equation is given by Clay and Medwin (1977, p. 3).

A.3.2 Effect of speed of sound errors on records obtained by echo-sounder and side-scan sonar

For many oceanographic acoustic instruments, a constant speed of sound is assumed. This is the case for the EG&G side-scan sonar system for which speed of sound in seawater is taken to be 1500 m/sec. The Krupp echo-sounder can be adjusted for the speed of sound in a locality so that true depths are recorded (from a flat seabed). Usually, the speed adjustment is checked by suspending a metal bar at a known depth below the transducer but this was not done for the particular survey discussed here. A compilation of the Krupp AD 10 speed of sound settings for the mosaic area surveys is shown in Table A.III. The settings ranged from 1470 to 1510 m/sec. The average speed of sound at the time of the survey (late August to early September) was calculated for both the 'East Mackenzie' and 'Pullen Island' survey areas (using eqn. A.3 and information on salinity and temperature contained in figures 16 and 18 of Herlinveaux and de Lange Boom, 1975). The average speed of sound was found to be 1435 m/sec for water depths greater than 10 m (that is, below the thermocline). Therefore both the side-scan sonar and echo-sounder were set for a speed of sound that was too fast. This resulted in recorded depths being too deep (for echograms) and slant ranges being exaggerated (for sonographs).

First, consider the amount of error in recorded depth resulting from the Krupp AD 10 sounder being set at 1510 m/sec

TABLE A.III
 SPEED OF SOUND SETTINGS ON KRUPP AD 10 ECHO-SOUNDER
 DURING M. V. PANDORA II 1974 SURVEY IN BEAUFORT SEA
 MOSAIC AREAS¹

Date	Time	Speed of sound setting (m/sec)	Error in recorded depth ² (%)
25 Aug.	0006	1510	+ 5
26 Aug.	2000	1480	+ 3
26 Aug.	2200	1480	+ 3
28 Aug.	from seismic refraction work in vicinity, but this setting not used on echo-sounder. $c_{\text{sea water}} = 1448 \text{ m/sec} \pm ?$		
28 Aug.	1516	1470	+ 2.5
30 Aug.	0800	1470	+ 2.5

Notes: 1. Information taken from M.V. Pandora II Aug./Sept. 1974 field notebook.

2. Error in recorded depth is based on $c_{\text{sea water}} = 1435 \text{ m/sec}$ (see text, section A.3.2)

when the true speed was 1435 m/sec. The time taken for a pulse from the transducer to reach a seabed, say 50 m below, be reflected, and return to the transducer would be $t = 2z/c_{s.w.} = 100 \text{ m}/(1435 \text{ m/sec}) = 69.69 \text{ millisec}$ (assuming vertical incidence) if the average speed of sound in this 50 m column of water was 1435 m/sec. The distance between the transmission mark and the 50 m mark on the sounder record is also traversed by the recording stylus in $t' = t$ when the speed of sound control is adjusted correctly. But, the sounder was adjusted for an incorrect speed of sound, $c'_{s.w.} = 1510 \text{ m/sec}$ and t' would therefore be set too fast at $t' = 2z/c'_{s.w.} = 100 \text{ m}/(1510 \text{ m/sec}) = 66.23 \text{ millisec}$ for the record scale between 0 and 50 m. A pulse travelling at an average speed¹ of 1435 m/sec would return to the transducer $(69.69 - 66.23) \text{ millisec} = 3.46 \text{ millisec}$ too late to be recorded at the 50 m mark and would be recorded at a depth of $z' = \frac{t' \cdot c'_{s.w.}}{2} = \frac{(69.69 \times 10^{-3} \text{ s}) (1510 \text{ m/sec})}{2} = 52.5 \text{ m}$. The recorded depth is therefore seen to be 5% too deep with respect to the true depth. Similar calculations for speed of sound settings on the sounder of 1480 m/sec and 1470 m/sec show that errors in recorded depth of +3% and +2.5% respectively occurred.

¹Reference to Table A.V shows that the per cent difference in speed of sound at the sea surface and at the seabed is only 0.6% in Mackenzie Bay on 11 August 1974. Note also that the 1435 m/sec average speed was not based on the data shown in Table A.V.

The two surveys referred to in this study are in water depths ranging from approximately 10 to 50 m. If the echosounder was misadjusted for a speed of sound such that recorded depths could be 5% greater than the true depth, the errors in recorded depths for the survey areas could range from + 0.5 m to +2.5 m. Table A.III shows, however, that during most of the survey, errors in recorded depth would be +3% or less. This translates to absolute errors of +0.3 m to +1.5 m for the depth range given above.

The effect of speed of sound misadjustments on relief information from the echograms is minimal. Even when the speed of sound was incorrectly set at 1510 ms^{-1} (+5% error in depth indication) any scale interval on the chart would only be expanded by a factor of $52.5/50 = 1.05$. A typical feature on the seabed with actual relief of 2 m would therefore appear to have a relief of 2.1 m. For most of the survey, the echo-sounder scale was set so that the smallest chart divisions corresponded to a depth of either 0.2 or 0.4 m. The smallest possible uncertainty in depth measurements from the records is therefore $\pm 0.1 \text{ m}$. A +0.1 m discrepancy in relief measurement caused by speed of sound misadjustment is not regarded as being significant in this study.

In the case of the side-scan sonar transducer, a +5% error in slant range (based on the system assuming $c_{s.w.} = 1500 \text{ m/sec}$), gives an absolute error of + 10 m at the 200 m scale line on the

record. This is almost half of a 25 m wide scale division. Most of the records obtained during the survey, however, only contain images out to the middle portion of the slant range so the maximum error in this case becomes + 5 m. This is acceptable because on a 1:10 000 scale mosaic, ice-scour track length measurements can only be made to ± 100 m (see section 3.3.2b). Measurements of ice-scour track width would not be greatly affected because any scale interval on the sonograph would only be expanded by a factor of 1.05 (as in the case of the echograms). For example, a 30 m wide track parallel to the ship's survey line would be recorded as being 31.5 m wide. This 1.5 m discrepancy is well within the width measurement uncertainty of ± 5 m on the mosaics (see section 3.3.2c).

In summary, speed of sound corrections were not applied when making relief measurements on echograms and planimetric measurements on a mosaic of side-scan sonar records. For bathymetric studies, the errors just discussed become important only when data collected at the 1510 m/sec setting is combined with data collected at the 1480 m/sec or 1470 m/sec settings. Studies involving comparison of relative water depths from echograms all collected using the same speed of sound setting will not be seriously affected by the errors.

A.4 Beam angle and beamwidth of a transducer

A.4.1 Definition of beam angle

The beam angle of an ultrasonic transducer is conventionally defined by the total angle between the half-power or -3 dB points² of the main beam (see figure A.2).

From optics, the limiting angle of resolution,

$$\theta_{\text{Res}} = \lambda/b \quad (\text{Bueche, 1969}) \quad (\text{eqn. A.4})$$

This relationship can be applied to a rectangular transducer such that as that on a side-scan sonar towfish.

For a circular aperture,

$$\theta_{\text{Res}} = 1.220 \lambda/D \quad (\text{Bueche, 1969}) \quad (\text{eqn. A.5})$$

This relationship can be used for a circular ultrasonic transducer.

It is found that the transducer beam angle defined on the basis of the -3 dB points is similar to the limiting angle of resolution defined using the Rayleigh criterion for resolution as in optics (viz, equations A.4 and A.5). This is demonstrated in Table A.IV for some transducers in common use. The results of this analysis makes the selection of the -3 dB points (at a specific power output) to describe a transducer's beam angle and angular resolution seem reasonable.

²For $I_1/I_2 = 1/2$, $10 \log_{10} (I_1/I_2)$ decibels = $10 (-0.301)$ dB = -3 dB

Figure A.2 "The graph of intensity (vertical axis) against bearing (horizontal axis) known as a polar diagram, indicates the degree of sharpness of a directional sound beam. The beam width is usually defined by the total angle between half-power points, ie, the sector over which the intensity is over half the peak value at right-angles to the transducer face" (Haines, 1974). Diagram after Haines, 1974.

TABLE A.IV

COMPARISON OF MANUFACTURER'S SPECIFIED BEAM ANGLE BETWEEN
-3 dB POINTS AND LIMITING ANGLE OF RESOLUTION CALCULATED
USING OPTICAL FORMULAE

(a) circular transducers

Manufacturer /model	Diameter (cm)	Frequency (kHz)	Wavelength λ (cm)	Mfg. spec. beam angle	$\theta_{Res} =$ radians	$1.22 \lambda / \text{Dia.}$ degrees
Raytheon 2445AD	6.985	200	0.732 ^a	8°	0.1278	7.3
Raytheon 7245	18.574	200	0.732 ^a	2.5°	0.0480	2.8
Raytheon TC-7	43.18	7	20.9 ^a	36°	0.5905	34
Kelvin Hughes MS 26 B	35.56	14.25	10.5 ^b	28°	0.3611	21
Krupp SW6014	7.5	210	0.714 ^b	10°	0.1162	6.7

(b) rectangular transducers

Manufacturer /model	b=length (cm)	Frequency (kHz)	Wavelength λ (cm)	Mfg. spec. beam angle	$\theta_{Res} =$ radians	$1.22 \lambda / b$ degrees
Klein 402S- 001 towfish	65	100	1.5 ^b	0.75°	0.02308	1.3
EG&G towfish model 272	43.5	105	1.4 ^b	1.2°	0.03284	1.9
Krupp SW56	18.26 ^c	30	5.0 ^b	20° (long.)	0.2739	16°
	11.43 ^d	30	5.0 ^b	30° (trans)	0.4374	25°

Notes: a: Raytheon uses $c = 4800 \text{ ft/sec} = 1463 \text{ m/sec}$ for equipment calibration.
Therefore, $\lambda = \frac{1463 \text{ m/sec}}{\text{Freq (Hz)}}$

b: $\lambda = \frac{1500 \text{ m/sec}}{\text{Freq (Hz)}}$

c: longitudinal

d: transverse

A.4.2 Beamwidth and horizontal resolution

Kraus (1966, p. 158) stated that, "The resolution of an antenna in one plane is about equal to the half-power beamwidth in that plane." In the present work, the minimum horizontal distance between two objects (at a given depth) that can be resolved using a given beam angle is defined to be the beamwidth (see figure A.3). The beamwidth, w , will of course be proportional to the distance, z , from the transducer face to the objects. That is,

$$w = 2z \tan (\theta_{\text{Res}}/2) \quad (\text{eqn. A.6})$$

For an echo-sounder the distance, z , is the water depth below the transducer whereas for the side-scan sonar system this distance is the slant range. These relationships are depicted graphically in figure A.4 for the equipment used. For example, with 40 m of water beneath the face of the Krupp AD 10 30 kHz transducer with 20° longitudinal beam angle, objects on the seabed must be at least 14.1 m apart before echoes from them will just begin to be received separately. For the 210 kHz transducer with 10° beam angle, this critical distance is 7 m. In 20 m water depth, horizontal resolution of objects at least 7 m apart is possible insofar as the 30 kHz transducer characteristics are concerned. In this water depth the critical distance is 3.5 m for the 210 kHz transducer.

The side-scan transducer used has a beam angle of 1.2°. At mid slant range (100 m), acoustic resolution of objects at

z = depth of water beneath transducer face

w = beamwidth at depth z ; $w = 2 z \tan(\theta_{Res}/2)$; θ_{Res} in radians

Figure A.3 Beam angle and beamwidth for an echo-sounder transducer. Transducer draft can be compensated for on most echo-sounders, thereby allowing depths to be read directly from the record.

A-8b.

Figure A.4 Beamwidth* on a flat surface as a function of distance from the transducer face.

least 2 m apart should be possible (see figure A.4).

A.4.3 Smoothing of recorded microrelief

In the study of seabed microrelief the beamwidth characteristic of the transducer that is used can substantially alter the appearance of the profile across the seabed (see figure A.5). Ridges appear wider whereas troughs appear narrower even when there is no vertical exaggeration involved. In cases where the floor of a trough is not as wide as the beamwidth, information on the true depth of the trough will be lost as in the example shown in figure A.5. On an actual echogram depth measurements cannot be made with any certainty for depressions that are distinctly V-shaped. As a general rule, any depression on an echogram that is less than a beamwidth wide across the top is probably not showing the true depth of the floor of the trough. This rule is based on the observation that the recorded width for a depression will always be narrower than the depression's true width anywhere along its vertical dimension. Measurement of depth on relatively flat-bottomed furrows on an echogram should yield a true average depth (taking into account the possibility that smoothing of microrelief within the larger feature may be occurring).

At this point it is appropriate to comment on those furrows that have an 'infilled' appearance. The infilling effect (see for instance figure A.6) may be an artifact of the

A-9a.

Figure A.5 Graphical demonstration of the smoothing that occurs in the representation of seabed microrelief by an echo-sounder transducer with a 10° beam angle. Note that there is no vertical exaggeration in this diagram. Hence, the loss of information that occurs is due entirely to the limiting angle of resolution of the transducer.

A-0b

Figure A.6 Examples of ice-scour tracks having an 'infilled' appearance in profile. Echogram from 'East Mackenzie' mosaic area, just north of fix number 228 (UTM coordinates at fix are 710 960; 7 697 700).

echo-sounding process, particularly on relatively narrow furrows. The thin dark traces extending below the surface of the sediment and which could be taken to represent the sides of an infilled ice-scour track may only be the extensions of hyperbolic traces from the sides of the actual furrow. This writer believes that a furrow cannot be labelled as being infilled with sediment simply on the basis of its appearance on an echogram. Supporting evidence from coring, diver observations, or seismic reflection data should be used to substantiate the 'infilled' interpretation.

A.5 Validity of plane wave approximation

Usually it is assumed that the spherical wavefronts which are farther away from a transducer than a certain critical distance will behave as plane waves. This assumption is important because plane waves have unchanging intensity with distance away from the source (Bueche, 1969, p. 626) and are relatively simple to deal with geometrically in wave refraction analysis such as is done in the next section.

The shallowest water depth encountered in the Beaufort Sea surveys discussed here is about 10 m. Is it reasonable to assume that the echo-sounder signal acts as a plane wave between the -3 dB points of the Krupp AD 10 transducer, 10 m away from the transducer face? The geometry of the situation is shown in figure A.7.

Calculation of Δt for 40 m water depth and 30° beam angle:

$$\begin{aligned} \text{difference, } y &= \left(\sqrt{\left(\frac{w}{2}\right)^2 + z^2} \right) - z \\ &= \left(\sqrt{\left(\frac{21.4 \text{ m}}{2}\right)^2 + (40 \text{ m})^2} \right) - 40 \text{ m} \\ y &= 1.41 \text{ m} \end{aligned}$$

$$\text{now, } \Delta t = y / c_{\text{sea water}} = 1.41 \text{ m} / (1500 \text{ m/sec}) = 0.9 \text{ millisec.}$$

Figure A.7 Length of arc of a spherical wavefront compared to beamwidth, w . Also, difference in arrival times (Δt) at centre and edge of 'sound cone' (refer to text, section A.5).

The analysis for the 'worst case' of the 30° transverse beam angle of the 30 kHz transducer involves a comparison of the beamwidth to length of arc at 10 m depth where radius of curvature will be greater than in deeper water.

$$\text{Length of arc} = l_a = 2 \pi z \theta_{\text{Res}} / 360^\circ \quad (\text{eqn. A.7})$$

$$l_a = 2 \pi (10 \text{ m}) (30^\circ) / 360^\circ = 5.236 \text{ m}$$

$$\text{Beamwidth} = w = 2x = 2z \tan (\theta_{\text{Res}}/2) \quad (\text{eqn. A.8})$$

$$w = 2 (10 \text{ m}) \tan (30^\circ/2) = 5.359 \text{ m}$$

These values, l_a and w are equivalent within 12.3 cm even relatively close to the transducer face. Therefore, the plane wave approximation is regarded as being valid for the beamwidth and horizontal resolution. But, it is noted that there is a significant difference between the arrival times to the seabed of the central part of the spherical wavefront and a sound ray corresponding to the -3 dB point on the wavefront (see inset diagram figure A.7 and sample calculation). That is, the plane wave approximation is not valid in this case and the vertical resolution of the echo-sounder is degraded. For the side-scan sonar with a 1.2° horizontal beam angle the plane wave approximation is valid across all of the slant range.

A.6 Refraction effects on transducer beamwidth

A.6.1 Echo-sounding

Speed of sound variations in the water column, resulting from temperature, salinity, and pressure differences (with depth)

TABLE A.V

• DEPTH, SALINITY, TEMPERATURE, AND CALCULATED SPEED OF SOUND*
IN MACKENZIE BAY, 11 AUGUST 1974

Depth (m)	Salinity (‰)	Temperature (C)	Speed of sound (ms ⁻¹)
0	3	4.8	1429
5	3	4.8	1429
5.5	6	4.8	1433
7	27	-1.0	1434
10	29	-1.2	1436
15	30	-1.5	1436
35	31.5	-1.5	1438

$$\bar{c} = 1434 \pm 4 \text{ m/sec}$$

* speed of sound calculated using equation A.3

Data for S and T is from Herlinveaux and de Lange Boom, 1975,
figure 18.

BB. $a = w/2 = \text{beamwidth}/2$

A-11b.

$da = \text{incremental increase in 'a'}$
at lower boundary of water layer

SPEED OF SOUND (ms^{-1})

$da_n (\text{thickness of water layer}) \tan \theta_n$

1430 1435 1440

$$da_1 = 0.437 \text{ m}$$

$$da_2 = 0.0438 \text{ m}$$

$$da_3 = 0.132 \text{ m}$$

$$da_4 = 0.264 \text{ m}$$

$$da_5 = 0.440 \text{ m}$$

$$da_6 = 1.76 \text{ m}$$

$$\sum da = 3.077 \text{ m}$$

DEPTH (m)

Figure A.8 Analysis of beamwidth increase resulting from refraction as sound waves pass into denser layers of seawater. The analysis is based on Snell's law (eqn. A.7). The data for sound speeds is from Mackenzie Bay, 11 August 1974 (see also Table A.V).

in various water layers can increase the effective beamwidth of a transducer. To establish the significance of these effects for the 1974 Beaufort Sea mosaic area surveys the data on salinity and temperature for August 11 to September 2, 1974, in Mackenzie Bay published as figure 18 in Herlinveaux and de Lange Boom (1975) were referred to. Information extracted from the figure is tabulated in Table A.V. Figure A.8 shows this writer's division of the water column into layers based on the speed of sound differences observed in Table A.Y.

$$\text{Using Snell's law, } \frac{\sin \theta_2}{\sin \theta_1} = \frac{c_2}{c_1} \quad (\text{eqn. A.7})$$

the spreading of the sound ray corresponding to the -3 dB points and limit of resolution was analyzed. The effect was found to be negligible for both the 30 kHz, 20° longitudinal, 30° transverse beam angle transducer and the 210 kHz, 10° beam angle transducer (see figure A.8) for the salinity and temperature conditions shown in Table A.V which are assumed to be typical of conditions at the time of both the surveys that are of concern in this report.

A.6.2 Side-scanning

As long as the side-scan towfish was scanning within a homogeneous mass of water, refraction effects would not be a problem. If the sound rays had to pass through various water layers with differing densities then sound refraction patterns would have appeared on the sonograph. The horizontal resolution

would be affected in that it often becomes difficult to distinguish the seabed image from the sound refraction pattern. Fortunately, refraction effects are absent from most of the sonographs used in this study.

A.7 Effect of average slope of seabed on recording of microrelief

The steepest undisturbed seabed in the study area has a slope of almost two degrees (East Mackenzie area). An analysis can be made to determine the discrepancy in recorded and actual depths when an echo-sounding transducer advances perpendicular to the slope (see figure A.9). Even in a water depth of 50 m, a 2° slope will yield an error in recorded depth of only (-0.03 m), well within the best resolution possible (± 0.1 m) on the echogram. Therefore this effect need not be of concern when measuring ice-scour tracks in the two study areas.

A.8 Problems in measurement of slope of microrelief features on echograms

The ice-scour tracks that are the subject of this study are not likely to be properly represented in cross-profile on echograms. Since most of the tracks are not crossed at right angles by the ship's survey line the cross-profiles are distorted by varying degrees. In addition, note that it is an area of seabed that is being insonified, not merely a thin line. Therefore, seabed features to the port and starboard of a survey line that lie within the circle or ellipse having a

For this example (not drawn to scale):

- using sine law, $z/\sin 90^\circ = 50 \text{ m}$, and $x/\sin 88^\circ = 50 \text{ m}$.
- length of transmitted and reflected ray is, $x = 50 \text{ m} (\sin 88^\circ) = 49.97 \text{ m}$

Figure A.9 Diagram to illustrate that on a slope, recorded depth will be less than true depth because sound ray perpendicular to slope arrives back at transducer first (because this ray has shortest path to travel).

v.e. = 3

A-13b.

$$\theta = 45^\circ ; \phi = 71.5^\circ$$

$$\tan 71.5^\circ = 3$$

v.e. = 2

$$\theta = 45^\circ ; \phi = 63.5^\circ$$

$$\tan 63.5^\circ = 2$$

v.e. = 1

$$\theta = 45^\circ ; \phi = 45^\circ$$

$$\tan 45^\circ = 1$$

Figure A.10

An illustration of the effect of vertical exaggeration on the slope recorded on an echogram. In general, one can state that, $\tan \phi = (\text{v.e.}) \times \tan \theta$, where ϕ is recorded slope and θ is actual slope.

diameter (or major and minor axis) equal to the transducer beamwidth will also contribute to the acoustic pulse that returns to the transducer. In other words, an averaged seabed relief is depicted on the echograms.

The considerable vertical exaggeration (30 - 40 times) of the echograms distorts the width-depth relationship in terms of visual impressions. Measurements from the echograms indicate that usually width is much greater than depth. The vertical exaggeration has the additional effect of recording any real slope greater than 10° as a slope of 80° or more. This effect is independent of the transducer beam angle, being given by the equation

$$\tan \phi \text{ (v.e.)} = \tan \theta \quad (\text{eqn. A.8})$$

where v.e. is the vertical exaggeration on the echogram

ϕ is the recorded slope

θ is the actual slope

A simple example of the effect of vertical exaggeration on recorded slope is shown in figure A.10.

Another problem in obtaining information on the slopes of the ridges and furrows created by ice impacts is that theoretically one cannot expect to get signals returned from slopes greater than 15° for a transducer having a beam angle of 30° (slopes greater than 5° for 10° beam angle transducer). This is illustrated in the ray path diagram, figure A.11. In reality, the occurrence of diffuse reflection means that a certain amount of signal return can be expected from slopes greater than half

Figure A.11 Ray path diagram for 10° beam angle and 5° slope and an arbitrary seabed slope greater than 5° .

the beam angle value, particularly in relatively shallow water (cf. Krause and Kanaev, 1970, p. 30). As stated earlier, though, slopes greater than 10° become difficult to quantify on the echogram. This is unfortunate because reliable cross-profiles of ice-scour tracks can therefore not be reconstructed for use in studies of their morphology even if smoothing, as discussed in section A.4.3 did not occur. Information compiled from scuba diver observations of the microrelief on the Beaufort Sea seabed (Lewis, 1977a) indicates that slopes in the range of 10° to 45° are fairly common albeit this data pertains to fairly narrow (less than 10 m wide) ice-scour tracks.

A.9 Effect of orientation and dominance of seabed microrelief

A.9.1 Orientation

The problem of the orientation of ice-scour tracks and their representation on echograms has already been dealt with in section A.8. On the side-scan sonar records the orientation of the features is important in that ice-scour tracks parallel to the ship's survey line are well defined by acoustic shadows but tracks perpendicular to the survey line usually appear to be wider with relatively smooth bottoms because the sound waves can 'see' along their axes. This effect is not removed during the construction of a mosaic in which only the planimetric distortions are removed from the sonographs. Therefore it is unwise to rely too much on the overall appearance of the 'interior' of an ice-scour track when attempting to infer details

of the processes that created the track.

A.9.2 Dominance

The echo-sounding records indicate that the amplitude of the microrelief caused by ice impacts is relatively constant in any one locality. This may be a result of the signal averaging process discussed in section A.8. Given the relatively high width to depth ratio of those features that can be resolved on the echograms it is unlikely that much acoustic masking of other resolvable features by any other resolvable feature occurs. That is, most features appear to be wider than the transducer's 20° longitudinal beam angle at a certain depth.

Although quantitative measurements of relief on sonographs can be made of objects standing above a flat seabed by measuring the length of the acoustic shadow, height of the transducer above the seabed, and slant range at which the object was recorded (EG&G, 1974, p. 3-33), the method does not work when the acoustic shadow falls in a depression of indeterminate depth as is usually the case when ridges lie parallel to furrows in ice-scoured seabed areas.

A.10 Effect of ship's speed and recorder paper speed on horizontal resolution of seabed features

In shallower water depths the combination of ship's speed and recorder paper speed can be of more importance than the transducer beam angle in determining the precision to which

horizontal dimensions can be measured on both the echograms and sonographs.

Speed of the survey vessel was normally 3 m/sec (6 knots) and echo-sounder paper speed was usually 2.5 cm/min. The ratio of these values, (paper speed/ship's speed) = $1/7200$ is the horizontal scale of the echogram. Therefore 1 mm on the record is equivalent to 7.2 m on the seabed. Since measurements on the record can only reasonably be made with an uncertainty of, ± 0.5 mm (using a millimetre scale), the echogram horizontal resolution in this instance would be about ± 4 m. Each stylus mark on the chart is about 0.3 mm wide.

From figure A.4 it is found that the transducer longitudinal beamwidth is less than or equal to 4 m only in water depths less than or equal to 12 m (for the 30 kHz transducer) and water depths less than or equal to 25 m (for the 210 kHz transducer). With respect to the 30 kHz transducer, therefore, the transducer beam angle will be of more importance than the relationship between ship's speed and recorder speed in determining the horizontal resolution for all of the echograms used in this study.

In the East Mackenzie survey area the echo-sounder pulse repetition rate was usually 5 soundings/sec. With a ship's speed of 3 m/sec, 4 m on the seabed is traversed in 1.33 seconds. At least 6 pulses would be emitted over this distance and 6

adjacent marks would be printed by the stylus. This indicates that the smallest resolvable feature on the seabed is defined by several pulses, with the peak pressure of each pulse being associated with $4 \text{ m}/6 \text{ pulses} = 0.67 \text{ m}$ of seabed along the ship's track. This relatively small insonified area will be reflecting back an infinite number of sound rays, many of which will lie within the beam angle of the transducer. It is upon return of the signal to the transducer that loss of information or 'smoothing' first occurs as a result of the transducer's limiting angle of resolution, within which averaging of the returning signals takes place. The next major loss of information occurs when the signal is transferred to the recorder paper.

The side-scan sonar recorder was set at a paper feed speed of 59 lines per cm with a pulse rate of 3.75 pulses/sec (on the 200 m range scale). This combination of values can be expressed as a paper speed of 3.8 cm/min. The ratio (paper speed/ship's speed) is $1/4737$ when ship's speed is 3 m/sec. Therefore 1 mm on the record (parallel to ship's track) is equivalent to 4.7 m on the seabed. Practical horizontal resolution is therefore $\pm 2.5 \text{ m}$ on the side-scan sonar record. This distance would be traversed by the ship in 0.83 s during which time at least 3 pulses would have been emitted. Each pulse would be associated with $2.5 \text{ m}/3 \text{ pulses} = 0.83 \text{ m}$ of seabed along the ship's track. In the case of the sonographs, therefore, the limiting conditions for horizontal resolution are

imposed by the particular combination of ship's speed and recorder paper speed that is used during the survey and not by the rate of trigger of the pulse or the transducer beam angle (see section A.4.2 for discussion of latter).

A.11 Range resolution on sonographs

The horizontal resolution perpendicular to the ship's track must be considered in the case of sonographs. In terms of the electronic capability of the system, range resolution, R_r , is equal to half the pulse length, P_d , at a certain speed of sound, c (EG&G, 1974, p. 3-33). That is

$$R_r = (P_d \cdot c)/2 \quad (\text{eqn. A.9})$$

For the EG&G Mark 1B system, $P_d = 0.1 \times 10^{-3}$ s and during the survey $c_{\text{sea water}} = 1435$ m/sec. Hence R_r is 7.2 cm. But, on the actual sonograph (200 m slant range, 125 mm wide) practical resolution using a millimetre scale is only about ± 1 m. In this case, the dimensions of the recorder paper dictate the degree of resolution that is possible.

A.12 Effect of ship's speed on horizontal displacement of features on record from true position on seabed

Because the transducer is in motion the echo pulse will not be received at exactly the same location at which the original pulse was transmitted (see figure A.12). The effect will be most pronounced in deeper water because the travel time of the pulse will be increased.

A-19a.

Figure A.12 Effect of ship's speed on horizontal displacement of features on record from their true position on the seabed.

As a numerical example of the displacement effect, consider a water column with a speed of sound of 1500 m/sec and a water depth of 50 m. The time taken for a pulse to return to the transducer will be approximately $t = 2z/c_{s.w.}$. $= 2(50 \text{ m})/1500 \text{ m/sec} = 66.7 \text{ millisec}$ (we are ignoring slightly longer path length of the returning ray). In the same time interval, a ship steaming at 3 m/sec (6 knots) will have advanced $d = V_s t = (3 \text{ m/sec}) (66.7 \times 10^{-3} \text{ s}) = 0.20 \text{ m}$. The laws of reflection must be taken into account so the actual displacement of a feature will be $d/2 = 0.1 \text{ m}$ (see ray paths shown on figure A.12). This distance is several times less than the length of seafloor along the ship's track that is insonified by each pulse (see section A.10). Therefore the central part of each pulse is actually providing overlapping coverage of a line along the seabed and no gaps in coverage occur at normal survey speeds in the range of water depth considered in this study. When one considers the actual beamwidth of the transducer signal it is even more apparent that no gaps in coverage occurred when the echo-sounder was recording a profile of the seabed. The foregoing analysis method can also be applied to the side-scan sonar system with the same result - no gaps in coverage resulting from excess ship speed in relation to the pulse trigger rate will occur.

A.13 Conclusions

In terms of the study of ice-scour tracks on the seabed, the main conclusions that can be drawn from this review of some aspects of underwater acoustics are the following (refer also to figure A.1):

- (1) There is a major loss of information (including information on slopes of ridges and depressions) for seabed microrelief when the returning sound waves are processed by a transducer with a certain limiting angle of resolution. This effect becomes increasingly important in deeper water.
- (2) A second signal averaging process occurs when signals are transferred to the recorder paper. This effect becomes more important than effect of transducer beam angle when working in shallower water.
- (3) Speed of sound settings on equipment should preferably be kept constant so that comparisons of bathymetry within a survey area are made easier.
- (4) Some effects that must be accounted for in deep ocean surveys may be safely neglected in this study of microtopography in water depths less than 50 m (e.g. slope of seabed, refraction effect on beam-width, dominance of features, and ship's speed).

Ideal conditions for a survey of ice-scour tracks, using echo-sounding and side-scanning techniques, would involve the following prerequisites:

- (1) Slow ship's speed (less than 2 m/sec).
- (2) Relatively fast paper speed along with increased pulse rate.
- (3) Very narrow beam angle with a transducer stabilized against ship roll and pitch or use of a transducer towed close to the seabed.
- (4) Calm or lightly rippled sea.

- (5) Use of a bar check to determine speed of sound in water.

In practice of course, these conditions are seldom met. Therefore it is important to be aware of the limitations of the data, particularly when relatively small scale features such as ice-scour tracks are being studied.

APPENDIX B

NOTES REGARDING ASSEMBLY OF BATHYMETRIC OVERLAYS

B.1 Introduction

With the addition of processed bathymetric information, the side-scan mosaics (figures 3.2a,b (East Mackenzie area) and 3.3a,b (Pullen Island area) - in front pocket) can give a generalized three-dimensional representation of the seabed. The ice-scour tracks themselves are not represented on the bathymetric overlay. The intent is, rather, to show by means of contours the seabed surface as it would appear if no ice impacts with the seabed had occurred. The bathymetric charts, figures 3.4 and 3.5 (in back pocket), are at the same scale as the mosaics, this being 1:20 000 for the East Mackenzie area and 1:10 000 for the Pullen Island area. The original bathymetric charts were drawn on transparent plastic film which can be laid over the mosaics, thereby providing a convenient method of investigating ice-scour track characteristics and spatial distribution in the light of knowledge about the local seabed morphology.

B.2 Procedure

Initially, all of the fix marks appearing on the mosaics had to be identified and labelled. Reference was made to ship's track plots compiled before the mosaics had been made and a cross-check was done by referring to the original sonographs. The record fix numbers do not appear on the final copies of the mosaics provided here.¹ Fix numbers do not appear on the bathymetric charts either, in order to avoid confusion with depth information.

B.2.1 Collecting the depth data

The actual plotting procedure that was adopted is outlined below:

- Step 1: Select a fix interval from the mosaic and refer to the corresponding original sonograph and echogram sections.
- Step 2: Measure the distance (in mm) between the fix marks on the mosaic and calculate actual distance on seabed. e.g. for the 1:20 000 scale mosaic,
Actual distance on seabed = (distance on mosaic in mm) x (20 m/mm).
- Step 3: Record this distance neatly in pencil between appropriate fixes on the original sonograph. Notations on records should not interfere with the actual image that is displayed but should be written in an unobtrusive location. This enhances the appearance of the record if it is desired to photograph it for publication. It may be desirable to write on the original records only in certain colours which will not show on a reproduction.

¹ Reproduction difficulties prevented this. Complete information is on file with: Environmental Marine Geology, Atlantic Geoscience Centre, Bedford Institute of Oceanography, P.O. Box 1006, Dartmouth, Nova Scotia, B2Y 4A2

- Step 4: Measure the distances in cm between fixmarks on the echogram and sonograph and write these values on the records.
- Step 5: Calculate the horizontal scale along the ship's track for the fix interval on the echogram and sonograph and write this value on the records.
- Step 6: Select a prominent feature within the fix interval that can be reliably identified on both types of record. Compute the distance along the seabed from the left hand fix mark on the sonograph to this feature on the sonograph. Then compute the distance along the seabed from the left hand fix mark on the echogram to the same feature (as was used on the sonograph) on the echogram. By subtracting the latter value from the former, the distance can be found between the echosounder transducer (mounted on the ship) and the side-scan transducers mounted in the towfish which is towed some distance astern.
- e.g. sonograph fix #619 to deepest part of track 'X' 481 m
 echogram fix #619 to deepest part of track 'X' 427 m
 distance between transducers equals difference ... 54 m
- In the 'East Mackenzie' area, this distance ranged from 35 to 180 m, while in the 'Pullen Island' area the distance varied from 30 to 73 m.
- Step 7: Referring once again to the mosaic, plot the locations of the echogram fixes on the mosaic. Note that these must appear forward of the corresponding sonograph fix marks.
- Step 8: Referring to the echogram, select plotting points for water depth (integer values at 1 m intervals for the 'East Mackenzie' area; 0.5 m intervals for the 'Pullen Island' area). The analyst must make a decision regarding the level of undisturbed seabed if the seabed is highly dissected by ice impacts.
- Step 9: Using a large set of ten-point dividers (proportional dividers), scale off the depth plotting points between the fix marks on the echogram.
- Step 10: Fit the ten-point dividers to the newly plotted echogram fix interval on the mosaic and plot the depth values at the appropriate distances relative to the fix marks as determined in step 9. The transducer draft of 2.4 m was always compensated for in the depth values so that each depth value is the distance from the ocean surface to the seabed.

Steps 2 to 7 may be omitted after having been done once if no change to ship to towfish distance occurs along a survey line.

The location of a depth value was plotted on the plastic overlay as an ink dot with the depth value printed to the left (e.g., 40.). Sometimes the location of a depth value was approximate, particularly if the value was obtained from the beginning or end of a record where the location did not lie within a pair of fix marks. Such approximate locations are indicated by a bracketed depth value beside the location dot (e.g., (40) .).

B.2.2 Tidal corrections

In the regions of the Beaufort Sea that are of concern in this report, the tidal range is small. At Herschel Island the tidal range for mean tides is 0.21 m while at Cape Parry the range is 0.37 m (Logan et al., 1975). Even for large tides, the same source quotes tidal ranges of only 0.58 m at Herschel Island and 0.70 at Cape Parry. These values can be expressed as mean sea level $\pm$ 0.29 m and m.s.l. $\pm$ 0.35 m respectively. Therefore, no tidal corrections have been applied to the bathymetric information in either the 'East Mackenzie' or 'Pullen Island' areas.

B.2.3 Contouring

Once the depths had been plotted as points on the bathymetric

overlay, freehand contouring was done. This was an iterative process with the chief aim being to preserve the continuity of ridges and troughs. The final contours represent the surface of the seabed as it would appear if no ice impacts had disturbed the smoothness of the seabed.

There were problems with the radio positioning system that the survey vessel was using. The ship's track plot can, however, be established with a relatively high degree of certainty that it is correct once the sonograph mosaic has been assembled because visual matching of the ice-scour track patterns on the seabed could be done to align the sonograph strips. Examination of the mosaics shows relatively good continuity between the features, although for detailed work, minor mismatches can be troublesome. Since the seabed mosaic serves as the horizontal control for the bathymetric compilation, there should be little possibility of echo-sounding lines being laterally displaced with respect to each other. This is an important consideration in establishing the validity of the prominent ridge and trough system that appears in the southeastern corner of the 'East Mackenzie' mosaic area and the two mounds that show up on the 'Pullen Island' chart.

B.3 Special notes regarding the 'East Mackenzie' mosaic area overlay

The general alignment of the depth contours is in agreement with a bathymetric compilation done by D. Monahan of the

Canadian Hydrographic Service in 1973 at the 1:50 000 scale from spot soundings (D. Monahan, pers. comm.).

B.3.1 Prominent ridge and trough system in southeast corner

In the prominent ridge and trough system that appears in this area, the 33 m and 25 m contours were double checked using an echo-sounding line that ran between the side-scan lines shown on the mosaic. Between these contours, interpolation becomes difficult because fix mark locations of the 'extra' echo-sounding line cannot be unequivocally established. Therefore, only a general trend, as observed on the echograms, can be indicated on the chart. These contours are dashed to indicate that they are approximate and are not based on actual data points compiled from echograms.

B.3.2 Speed of sound adjustments to depth values

During the survey in the 'East Mackenzie' area, three different speed of sound settings on the echo-sounder were used, namely 1510, 1480, and 1470 metres/sec (see also Table A.III, Appendix A). With a one metre depth contour interval, the + 5% error in recorded depth at the 1510 metres/sec setting was not compatible with the + 2.5 to + 3% errors in recorded depth at the 1470 to 1480 metres/sec settings.¹ It was decided to reduce all the depths collected at the 1510 metres/sec

¹ The error in recorded depth is based upon the actual speed of sound in the survey areas being approximately 1435 metres/sec (see Section A.3.2, Appendix A).

setting by 2% so that in effect, all of the depths shown on the 'East Mackenzie' bathymetric overlay have values as if they had all been collected with speed of sound settings of 1470 to 1480 metres/sec.

The 2% reduction was applied to all the depth values collected from echograms lying between fixes 1 and 188. These were mostly from locations in the northern half of the mosaic area. Because the adjusted depths were not integral depth values, interpolation was done (assuming that slope of undisturbed seabed was constant) to determine the approximate location of the integral depth value. These values are specially identified on the overlay by the symbol (⊙). Similar contouring procedures could then be applied to the entire mosaic area.

B.3.3 List of echograms and sonographs used

A list of the echograms and sonographs used in the 'East Mackenzie' area bathymetric compilation is provided in Table B.I..

B.4 Special notes regarding the 'Pullen Island' mosaic area overlay

B.4.1 Notes

During the survey of the 'Pullen Island' area, the chart drive mechanism on the echo-sounder broke down intermittently leading to the occurrence of major gaps in the echo-sounding

TABLE B.1

ECHO-SOUNDING AND SIDE-SCAN SONAR RECORDS FOR
 'EAST MACKENZIE' MOSAIC AREA - RECORDS FROM AUGUST AND
 SEPTEMBER 1974.

ECHO-SOUNDING RECORDS* (30 kHz; 210 kHz used simultaneously
 & occasionally)

<u>Roll number</u>	<u>Date/Time</u>	<u>Fixes on roll</u>
1	25 Aug/0111 - 25 Aug/0405	5 - 19
2	25 Aug/0428 - 25 Aug/1630	30 - 95
3	25 Aug/2121 - 26 Aug/1645	-
4	26 Aug/1700 - 27 Aug/0240	158 - 261
5	4 Sept/1140 - 4 Sept/1350	270 - 295
6	4 Sept/1400 - 4 Sept/1542	298 - 317
7	4 Sept/1555 - 4 Sept/1648	-
8	4 Sept/1650 - 4 Sept/1930	331, 333(?)
9	4 Sept/1935 - 4 Sept/2205	364 - 383
10	4 Sept/2207 - 4 Sept/2247	389(?)

SIDE-SCAN SONAR RECORDS*

<u>Roll number</u>	<u>Date/Time</u>	<u>Fixes on roll</u>
1	25 Aug/0200 - 25 Aug/2045	1 - 142
2	26 Aug/1545 - 27 Aug/0230	145 - 261
3	4 Sept/1140 - 4 Sept/1701	266 - 333
4	4 Sept/1705 - 4 Sept/2247	334 - 393

* Original records are filed at: Environmental Marine Geology,
 Atlantic Geoscience Centre, Bedford Institute of Oceanography,
 P.O. Box 1006, Dartmouth, Nova Scotia, B2Y 4A2

records. This is the reason why only part of the 1:10 000 scale mosaic area is covered by a bathymetric overlay. In the actual overlay area, only every second line has echograms associated with it. Fortunately though, the bathymetry in this area is quite regular so that contours could be drawn without too much difficulty. A 0.5 m contour interval was used for this area because of the rather small range in water depth (16 m to 12 m). This 0.5 interval is still greater than the tidal range for mean tides of 0.21 m to 0.37 m as mentioned earlier in this Appendix.

B.4.2 List of echograms and sonographs.

A list of the echo-sounding and side-scan sonar records used in the 'Pullen Island' area bathymetric compilation is provided in Table B.II.

TABLE B.II
 ECHO-SOUNDING AND SIDE-SCAN SONAR RECORDS USED IN THE
 'PULLEN ISLAND' AREA MOSAIC COMPILATION - RECORDS
 FROM AUGUST 1974.

ECHO-SOUNDING RECORDS* (30 kHz; 210 kHz used simultaneously
 occasionally)

<u>Roll number</u>	<u>Date/Time</u>	<u>Fixes on roll</u>
1	28 Aug/1515 - 28 Aug/1700	409 - 412
2	30 Aug/0638 - 30 Aug/0935	570 - 605
3	30 Aug/1005 - 30 Aug/1210	612 - 638
4	30 Aug/1510 - 30 Aug/1605	670 - 680
5	30 Aug/1925 - 30 Aug/2030	719 - 720
6	30 Aug/2300 - 31 Aug/0205	762 - 796
7	31 Aug/0205 - 31 Aug/0350	804 - 816

SIDE-SCAN SONAR RECORDS*

<u>Roll number</u>	<u>Date/Time</u>	<u>Fixes on roll</u>
1	28 Aug/1500 - 28 Aug/1535	-
2	28 Aug/1535 - 30 Aug/0105	407 - 506
3	30 Aug/0110 - 30 Aug/1310	507 - 646
4	30 Aug/1315 - 31 Aug/0025	647 - 776
5	31 Aug/0035 - 31 Aug/0350	778 - 816
6	31 Aug/1725 - 31 Aug/1835	821 - 835
7	31 Aug/1842 - 31 Aug/2006	836 - 852

* Original records are filed at: Environmental Marine Geology,
 Atlantic Geoscience Centre, Bedford Institute of Oceanography,
 P.O. Box 1006, Dartmouth, Nova Scotia, B2Y 4A2.

APPENDIX C

DATA

Figure C.1 Key to tracing overlay locations in the 'East Mackenzie' mosaic area for outlines of ice-scour tracks shown on figure C.2 and figures C.3 (a) to (e).

Figure C.2 Reproduction of the ice-scour track tracing overlay for the 'East Mackenzie (North)' study area. Track 'EMN 34' was excluded from the measurement data set because of its unusual characteristics. It is discussed as an individual case in chapter 6.

Table C.1 Data set 'A'. Measurements from ice-scour track images in the 'East Mackenzie (North) mosaic study area. The tracing overlay for this set of tracks is shown in figure C.2.

Case number (prefix 'EMN') Type of track Planimetric form Modifications to form	see Table 5.1	Total length (m) *	Mean width (m)	Mean depth (m) * #	Azimuth (degrees)	Approach angle (degrees)	Water depth (origin) (m) *	Water depth (end) (m) *
1	3 4 8	2300	40	(2.10)	212	063	0.0	0.0
2	3 4 8	2160	60	(3.70)	305	020	0.0	0.0
3	3 4 8	2400	90	(1.80)	305	020	0.0	0.0
4	3 5 8	1480	50	(2.50)	305	022	0.0	0.0
5	1 4 8	1840	15	(2.00)	018	065	0.0	0.0
6	1 5 9	0	35	0.00	335	042	0.0	48.3
7	1 4 8	200	25	(2.00)	287	000	0.0	0.0
8	1 6 8	1880	5	0.00	350	060	49.1	48.2
9	3 6 8	2960	140	0.00	350	060	49.3	47.9
10	1 4 8	0	15	0.00	250	030	49.6	0.0
11	1 4 8	1100	15	0.00	327	047	49.8	48.5
12	1 5 8	0	10	0.00	355	073	0.0	0.0
13	1 4 8	220	10	0.00	293	010	48.5	48.2
14	1 4 9	0	5	0.40	202	070	48.5	0.0
15	1 5 8	0	5	0.20	202	070	48.4	0.0
16	1 4 8	460	15	0.20	278	000	48.0	47.2
17	1 4 8	180	10	0.00	208	068	48.1	48.1
18	1 4 8	280	5	0.00	349	061	48.0	47.8
19	3 4 8	0	50	(1.00)	290	015	0.0	0.0
20	1 4 8	800	40	0.40	308	026	46.7	45.0
21	1 4 8	140	5	0.00	305	026	46.5	46.0
22	1 4 8	3120	10	0.60	025	050	46.6	45.9
23	3 6 8	600	60	(2.40)	318	035	0.0	0.0
24	1 6 9	0	25	(0.60)	295	090	0.0	0.0
25	1 6 8	5100	15	0.40	200	025	46.8	43.6
26	1 4 9	0	20	(1.90)	340	070	0.0	0.0
27	1 5 9	3460	15	0.00	357	082	46.1	44.5
28	1 4 8	400	15	0.40	271	005	46.9	46.0
29	1 5 8	0	35	(1.20)	206	070	0.0	0.0
30	1 4 8	0	10	0.30	225	050	47.1	0.0
31	1 5 8	1420	30	(1.80)	333	057	0.0	0.0
32	3 4 8	0	70	0.00	000	084	0.0	0.0
33	1 5 8	0	15	0.00	200	075	0.0	0.0
34	1 6 9	3600	10	0.40	180	090	46.8	47.4
35	1 6 8	2400	15	0.20	202	076	48.1	47.1

* missing values
indicated by '0'.

ice-scour depth values
in brackets are from
infilled or buried
tracks.

cont'd. next page...

Table C.I (cont'd.)

Case number (prefix 'NN')	Type of track	Planimetric form	Modifications to form	Total length (m) *	Mean width (m)	Mean depth (m) * #	Azimuth (degrees)	Approach angle (degrees)	Water depth (origin) (m) *	Water depth (end) (m) *
36	1	4	8	1280	20	1.00	210	064	47.5	46.0
37	1	4	8	0	40	(0.70)	330	055	0.0	0.0
38	1	4	8	0	50	(2.80)	330	055	0.0	0.0
39	1	4	8	0	15	0.00	347	071	0.0	0.0
40	1	4	8	0	20	1.00	321	047	0.0	0.0
41	1	4	8	600	15	1.60	270	008	47.7	46.1
42	1	4	8	220	35	0.00	309	033	47.7	47.4
43	1	4	8	0	5	0.00	206	067	0.0	0.0
44	1	4	8	380	25	2.00	290	013	45.6	44.6
45	1	5	8	940	25	2.80	229	048	45.6	44.1
46	1	4	8	0	15	0.80	210	067	45.2	0.0
47	1	4	8	900	30	2.00	313	038	45.4	43.7
48	1	6	8	1820	40	1.40	315	036	45.5	43.7
49	1	4	8	360	10	1.00	270	008	44.6	43.8
50	1	4	8	880	5	0.30	213	062	44.8	43.9
51	1	4	8	0	5	0.30	213	062	0.0	0.0
52	1	5	8	1020	10	0.70	214	060	45.4	44.1
53	1	4	8	0	10	0.00	343	066	0.0	44.3
54	1	6	8	2200	10	0.00	350	076	45.4	43.9
55	1	6	8	1300	30	1.00	217	057	45.0	43.5
56	2	4	8	880	30	0.20	203	070	44.2	43.6
57	1	6	8	0	10	0.40	340	064	44.5	0.0
58	1	5	8	1620	10	0.30	200	078	44.5	43.4
59	1	4	8	0	20	0.00	201	070	0.0	43.1
60	2	4	8	940	40	0.40	224	050	44.6	43.0
61	1	4	8	1480	10	(1.20)	334	053	0.0	0.0
62	1	5	8	1240	20	0.60	216	058	44.5	42.6
63	1	6	8	2250	15	0.80	338	063	44.6	41.4
64	2	6	8	3000	280	1.00	210	060	42.8	40.7
65	1	5	8	0	10	0.00	189	086	0.0	0.0
66	1	4	8	0	10	0.30	209	065	44.3	0.0
67	1	4	8	0	10	0.00	216	055	0.0	42.7
68	1	4	8	0	30	0.80	326	049	44.6	0.0
69	2	6	8	1800	35	1.00	335	060	44.2	40.8
70	1	6	8	2250	35	1.00	342	065	44.0	40.6
71	1	4	8	0	25	0.00	320	045	0.0	0.0
72	1	4	8	0	30	0.00	336	060	0.0	47.7
73	1	5	8	0	10	(1.20)	315	037	0.0	0.0

* missing values
indicated by '0'.

ice-scour depth values
in brackets are from
infilled or buried
tracks.

Table C.II Volume and planimetric area values for ice-scour tracks within the 'East Mackenzie (North)' mosaic area. Total volume values for single tracks that are not infilled or buried.

Case number (prefix 'EMN')	Total length (m) *	Length within study area (m)	Mean width (m)	Mean depth (m) #	within study area		Total volume (m ³)
					Planimetric area (m ²)	Volume (10 ³ m ³)	
1	2300	2100	40	0.40	84000	33.6	
2	2160	360	60	1.40	21600	30.24	
3	2400	820	90	1.00	73800	73.8	
4	1480	1480	50	0.30	74000	22.2	
5	1840	1840	15	0.60	27600	16.56	
6	0	1200	35	0.00	42000	21.0	
7	200	200	25	0.80	5000	4.0	
8	1880	1880	5	0.00	9400	4.7	
9	2960	2960	140	0.00	414400	207.2	
10	0	760	15	0.00	11400	5.7	
11	1100	980	15	0.00	14700	7.35	
12	0	600	10	0.00	6000	3.0	
13	220	220	10	0.00	2200	1.1	
14	0	2000	5	0.40	10000	4.0	
15	0	2200	5	0.20	11000	2.2	
16	460	460	15	0.20	6900	1.38	1380
17	180	180	10	0.00	1800	0.90	
18	280	280	5	0.00	1400	0.70	
19	0	500	50	0.20	25000	5.0	
20	800	240	40	0.40	9600	3.84	12800
21	140	140	5	0.00	700	0.35	
22	3120	500	10	0.60	5000	3.0	18720
23	600	600	60	0.60	36000	21.6	
24	0	1800	25	0.20	45000	9.0	
25	5100	4620	15	0.40	69300	27.72	30600
26	0	1000	20	0.30	20000	6.0	
27	3460	1700	15	0.00	25500	12.75	
28	400	400	15	0.40	6000	2.4	2400
29	0	1640	35	0.30	57400	17.22	
30	0	920	10	0.30	9200	2.76	
31	1420	1420	30	0.40	42600	17.04	
32	0	700	70	0.00	49000	24.5	
33	0	900	15	0.00	13500	6.75	
34	3600	3600	10	0.40	36000	14.4	14400
35	2400	2400	15	0.20	36000	7.2	7200

* missing values indicated by '0'.

if '0', use 0.5 m depth for 'volume within study area' calculation. No account taken of sediment infilling or burial of tracks. Depth values are for surface expression of tracks only.

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Table C.II (cont'd.)

Case number (prefix 'EMN')	Total length (m) *	Length within study area (m)	Mean width (m)	Mean depth (m) * #	within study area		Total volume (m ³)
					Planimetric area (m ²)	Volume (10 ³ m ³)	
36	1280	1280	20	1.00	25600	25.6	25600
37	0	460	40	0.60	18400	11.04	
38	0	900	50	1.40	45000	63.0	
39	0	1440	15	0.00	21600	10.8	
40	0	500	20	1.00	10000	10.0	
41	600	600	15	1.60	9000	14.4	14400
42	220	160	35	0.00	5600	2.8	
43	0	80	5	0.00	400	0.2	
44	380	380	25	2.00	9500	19.0	19000
45	940	500	25	2.80	12500	35.0	65800
46	0	560	15	0.80	8400	6.72	
47	900	900	30	2.00	27000	54.0	54000
48	1820	1820	40	1.40	72800	101.92	101920
49	360	360	10	1.00	3600	3.6	3600
50	880	880	5	0.30	4400	1.32	1320
51	0	400	5	0.30	2000	0.60	
52	1020	1020	10	0.70	10200	7.14	7140
53	0	420	10	0.00	4200	2.1	
54	2200	420	10	0.00	4200	2.1	
55	1300	1300	30	1.00	39000	39.0	39000
56	880	880	30	0.20	26400	5.28	
57	0	600	10	0.40	6000	2.4	
58	1620	1620	10	0.30	16200	4.86	4860
59	0	340	20	0.00	6800	3.40	
60	940	940	40	0.40	37600	15.04	
61	1480	1480	10	0.60	14800	8.88	
62	1240	1140	20	0.60	22800	13.68	14880
63	2250	1920	15	0.80	28800	23.04	27000
64	3000	200	280	1.00	56000	56.00	
65	0	540	10	0.00	5400	2.7	
66	0	140	10	0.30	1400	0.42	
67	0	240	10	0.00	2400	1.2	
68	0	900	30	0.80	27000	21.6	
69	1800	520	35	1.00	18200	18.2	
70	2250	800	35	1.00	28000	28.0	78750
71	0	200	25	0.00	5000	2.5	
72	0	340	30	0.00	10200	5.1	
73	0	500	10	0.20	5000	1.0	

SUMS: 1954400 1244.8

* missing values indicated by '0'.

if '0' use 0.5 m depth for 'volume within study area' calculation. No account taken of sediment infilling or burial of tracks. Depth values are for surface expression of tracks only.

Table C.III Sediment infilling ratio measurements for ice-scour tracks in the 'East Mackenzie (North)' mosaic area. Please see figure 3.14 for an explanation of the measurement procedure.

<u>Track identification</u>	<u>a (m)</u>	<u>b (m)</u>	<u>RATIO = b/a</u>
EMN-1 (cross-section A-A')	1.8	3.8	2.1
1 B-B'	2.3	2.8	1.2
2 A-A'	1.9	4.0	2.1
2 B-B'	1.9	3.8	2.0
3 A-A'	1.6	3.1	1.9
3 B-B'	1.9	2.5	1.3
4 A-A'	1.8	5.2	2.9
4 B-B'	2.0	3.0	1.5
5	2.0	3.6	1.8
7	1.8	3.0	1.7
19	2.3	3.4	1.5
23	1.8	3.6	2.0
24 A-A'	1.8	-	-
24 B-B'	2.0	3.2	1.6
26 A-A'	1.8	3.3	1.8
26 B-B'	2.0	3.2	1.6
29	2.0	2.4	1.2
31	1.7	2.3	1.4
37	2.0	1.8	0.9
38	1.8	3.2	1.8
61	2.0	2.8	1.4
73	2.0	3.2	1.6

n = 21; range for RATIO value is 0.9 to 2.9.

Mean ratio = 1.68; standard deviation = $\pm$ 0.42

Therefore, RATIO = 1.7 ± 0.4

Figure C.3 (a) Reproduction of an ice-scour track tracing overlay from the 'East Mackenzie' mosaic area. Cross-sections where ice-scour depth measurements could be made from an echogram are indicated. The cross-sections are labelled alphabetically from deeper to shallower water.

Figure C.3 (b) Reproduction of an ice-scour track tracing overlay from the 'East Mackenzie' mosaic area. Scale is 1: 20 000.

Figure C.3 (c) Reproduction of an ice-scour track tracing overlay from the 'East Mackenzie' mosaic area. Scale is 1:20 000.

Figure C.3 (d) Reproduction of an ice-scour track tracing overlay from the 'East Mackenzie' mosaic area. Scale is 1: 20 000.

Figure C.3 (e) Reproduction of an ice-scour track tracing overlay from the 'East Mackenzie' mosaic area. Scale is 1: 20 000.

Table C.IV Data set 'B'. Measurements from ice-scour track images in the 'East Mackenzie' mosaic area for which two or more ice-scour depth determinations could be made. Tracing overlays for this set of tracks are shown in figures C.3 (a-e).

Case number	see Table 5.1			Total length (m) *	Mean width (m)	Mean depth (m) *	Azimuth (degrees)	Approach angle (degrees)	Water depth (origin) (m) *	Water depth (end) (m) *
	Type of track	Planimetric form	Modifications to form							
101	1	6	8	2200	20	0.45	033	050	28.4	25.8
102	1	4	8	900	15	0.45	230	045	29.6	25.5
103	1	4	8	900	35	0.40	230	045	29.7	25.7
104	1	6	8	3520	10	0.60	219	080	33.0	31.4
105	1	5	8	1240	30	0.70	314	000	37.3	34.6
106	1	4	8	2240	20	0.40	213	066	37.2	36.9
107	1	5	8	4300	20	0.50	012	059	39.0	36.4
108	1	5	8	0	30	1.90	350	020	0.0	0.0
109	1	6	8	0	35	0.40	028	063	0.0	41.0
110	1	4	8	0	40	1.70	300	008	0.0	0.0
111	1	4	8	1620	25	0.40	230	062	42.1	41.7
112	2	4	8	2260	160	0.50	290	007	41.3	36.0
113	1	6	8	3100	15	0.80	196	085	38.9	38.6
114	1	5	8	1300	35	1.35	230	047	39.1	36.6
115	1	4	8	1180	25	0.80	244	042	37.6	35.0
116	1	4	8	3420	20	0.40	207	081	36.9	34.9
117	1	5	8	3300	15	0.40	203	059	42.8	42.4
118	1	5	8	0	40	2.70	318	027	0.0	0.0
119	1	4	8	0	20	1.25	321	020	0.0	0.0
120	1	5	8	1200	40	2.35	273	008	42.8	40.5
121	1	4	8	1100	15	0.25	234	047	42.3	40.9
122	1	6	8	1750	25	0.90	318	038	42.8	39.8
123	2	4	8	1500	300	1.40	233	046	40.6	38.1
124	1	4	8	0	15	0.20	308	034	0.0	0.0
125	1	5	8	2500	25	0.25	202	077	39.9	38.6
126	1	6	8	3700	5	0.63	210	068	39.5	35.9
127	1	5	8	0	30	1.40	205	000	36.9	0.0
128	2	5	8	1400	60	0.60	230	068	44.6	43.1
129	1	4	9	0	20	0.50	220	075	0.0	45.2
130	1	5	8	0	15	0.10	295	000	0.0	45.1

* missing values indicated by '0'

Table C.V (a) Data set 'C'. Measurements from segments of ice-scour track images in the 'East Mackenzie' mosaic area.

Track	Type of track (see Table 5.1) Cross-sections between which segment lies	Length between xs. (m)	Mean width within xs. (m)	Mean depth within xs. (m)	Azimuth (degrees)	Approach angle (degrees)	Water depth at first xs. (m)	Water depth at second xs. (m)
M-01	1 A-B	800	20	0.45	042	070	28.0	26.0
	02 1	400	15	0.45	235	043	28.3	25.7
	03 1	420	35	0.40	229	046	28.4	25.8
	04 1	940	10	0.80	225	090	33.2	33.2
	05 1	760	30	0.70	310	010	37.2	35.7
	06 1	1140	20	0.40	214	090	37.3	37.2
	07 1	1200	20	0.50	000	077	37.8	37.1
	08 1	600	30	1.90	000	037	41.1	40.4
	09 1	1500	35	0.40	026	058	41.7	41.2
	10 1	680	40	1.50	300	012	41.6	41.0
	11 1	800	25	0.40	230	068	42.1	41.9
	12 2 a-A	620 (160)		0.35	290	005	41.2	40.2
	13 1 A-B	960	15	0.70	211	067	38.5	37.5
	14 1	700	35	1.35	227	049	38.8	37.5
	15 1	700	25	0.80	245	034	37.0	35.3
	16 1	1380	20	0.40	207	090	36.4	35.3
	17 1	1400	15	0.40	205	090	43.1	43.1
	18 1	800	40	2.70	313	010	43.7	42.7
	19 1	960	20	1.25	322	031	44.0	42.9
	20 1	500	40	2.35	275	007	42.2	41.1
	21 1	620	15	0.25	236	047	42.1	41.2
	22 1	660	25	0.90	310	027	42.1	40.6
	23 2	800 (300)		1.40	234	042	40.1	38.6
	24 1	omitted; one cross-section shows infilling, other does not.						
	25 1	1820	25	0.25	200	081	39.8	39.1
	26 1	960	5	0.55	217	060	39.0	38.0
	27 1	1400	30	1.40	202	090	35.9	35.9
	28 2	580 (60)		0.60	245	045	44.4	43.8
	29 1	640	20	0.50	240	058	45.3	45.0
	30 1	740	15	0.10	315	000	46.4	45.7
M-04	1 B-C	1180	10	0.60	219	081	33.2	32.3
	07 1	1320	20	0.60	030	083	37.1	36.9
	10 1	660	40	2.10	300	010	41.0	40.0
	12 2 A-B	740 (160)		0.25	287	005	40.2	38.8
M-12	2 B-C	520 (160)		0.60	287	005	38.8	37.2
M-13	1 B-C	1050	15	1.00	000	090	37.5	38.2

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Table C.V (a) (cont'd.)

Track	Type of track (see Table 5.1) Cross-sections between which segment lies	Length between xs. (m)	Mean width within xs. (m)	Mean depth within xs. (m)	Azimuth (degrees)	Approach angle (degrees)	Water depth at first xs. (m)	Water depth at second xs. (m)
M-26	1 B-C	1240	5	0.60	208	072	38.0	36.4
M-26	1 C-D	1000	5	0.70	210	075	36.4	35.9
EMN-22	1 A-B	1400	10	0.60	025	085	47.0	46.5
EMN-25	1 A-B	2800	15	0.50	199	075	46.2	44.4
EMN-64	2 A-B	920	(280)	1.00	222	075	41.5	40.9

For multiple tracks (type '2'), width values are bracketed.

Table C.V (b). Data set 'C'. Ice-scour depth measurements at cross-sections and calculated change in ice-scour depth.

Notes: (1) Cross-sections are labelled alphabetically from deeper to shallower water.

(2) For multiple track scours, depth of the deepest track is recorded.

Track	Ice-scour depth at cross-section (m)					Ice-scour depth change (Δd) (m)			
	<u>a-a'</u>	<u>A-A'</u>	<u>B-B'</u>	<u>C-C'</u>	<u>D-D'</u>	<u>a to A</u>	<u>A to B</u>	<u>B to C</u>	<u>C to D</u>
M-01		0.4	0.5				0.1		
M-02		0.6	0.3				-0.3		
M-03		0.5	0.3				-0.2		
M-04		0.8	0.8	0.4			0.0	-0.4	
M-05		0.6	0.8				0.2		
M-06		0.4	0.4				0.0		
M-07		0.2	0.8	0.4			0.6	-0.4	
M-08		1.8	2.0				0.2		
M-09		0.4	0.4				0.0		
M-10		1.0	2.0	2.2			1.0	0.2	
M-11		0.3	0.5				0.2		
M-12	0.4	0.3	0.2	1.0		-0.1	-0.1	0.8	
M-13		0.4	1.0	1.0			0.6	0.0	
M-14		1.3	1.4				0.1		
M-15		0.8	0.8				0.0		
M-16		0.4	0.4				0.0		
M-17		0.3	0.5				0.2		
M-18		2.4	3.0				0.6		
M-19		1.0	1.5				0.5		
M-20		2.3					0.1		

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Table C.V (b) (cont'd.)

Track	Ice-scour depth at cross-section (m)					Ice-scour depth change (Δd) (m)			
	<u>a-a'</u>	<u>A-A'</u>	<u>B-B'</u>	<u>C-C'</u>	<u>D-D'</u>	<u>a to A</u>	<u>A to B</u>	<u>B to C</u>	<u>C to D</u>
M-21		0.3	0.2				-0.1		
M-22		0.8	1.0				0.2		
M-23		1.4	1.4				0.0		
M-24	omit								
M-25		0.3	0.2				-0.1		
M-26		0.5	0.6	0.6	0.8		0.1	0.0	0.2
M-27		1.4	1.4				0.0		
M-28		0.3	0.9				0.6		
M-29		0.4	0.6				0.2		
M-30		0.1	0.1				0.0		
EMN-22		0.8	0.4				-0.4		
EMN-1		(2.8)	(1.4)				(-1.4)		
EMN-3		(2.0)	(1.6)				(-0.4)		
EMN-4		(3.6)	(1.4)				(-2.2)		
EMN-25		0.4	0.6				0.2		
EMN-26		(2.2)	(1.6)				(-0.6)		
EMN-64		1.0	1.0				0.0		
EMN-2		(3.6)	(3.8)				(0.2)		

() brackets indicate information from a buried or infilled track.

Uncertainties: ice-scour depth * 0.2 m; ice-scour depth change * 0.3 m
(see calculations, Appendix E)

Table C.V (c) Data for analyses of the net rise of an ice keel up a slope. This table is based on data set 'C' (Table C.V (a)) and information in Table C.V (b).

Track	Net rise [*] between cross-sections (m)				Total observed net rise (m)
	a to A	A to B	B to C	C to D	
M-01		1.9			1.9 ± 0.3
M-02		2.9			2.9 ± 0.3
M-03		2.8			2.8 ± 0.3
M-04		0.0	1.3		1.3 ± 0.4
M-05		1.3			1.3 ± 0.3
M-06		0.1			0.1 ± 0.3
M-07		0.1	0.6		0.7 ± 0.4
M-08		0.3			0.3 ± 0.3
M-09		0.5			0.5 ± 0.3
M-10		-0.4	0.8		0.4 ± 0.4
M-11		0.0			0.0 ± 0.3
M-12	1.1	1.5	0.8		3.4 ± 0.5
M-13		0.4	-0.7		-0.3 ± 0.4
M-14		1.2			1.2 ± 0.3
M-15		2.3			2.3 ± 0.3
M-16		1.1			1.1 ± 0.3
M-17		-0.2			-0.2 ± 0.3
M-18		0.4			0.4 ± 0.3
M-19		0.6			0.6 ± 0.3
M-20		1.0			1.0 ± 0.3

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* uncertainty in net rise is ± 0.3 m (please see Appendix E)

Note also that: Net rise = (water depth_A - water depth_B) - Δd

Table C.V (c) (cont'd.)

Track	Net rise* between cross-sections (m)				Total observed net rise (m)
	a to A	A to B	B to C	C to D	
M-21		1.0			1.0 ± 0.3
M-22		1.3			1.3 ± 0.3
M-23		1.5			1.5 ± 0.3
M-24	omit				
M-25		0.8			0.8 ± 0.3
M-26		0.9	1.6	0.3	2.8 ± 0.5
M-27		0.0			0.0 ± 0.3
M-28		0.0			0.0 ± 0.3
M-29		0.1			0.1 ± 0.3
M-30		0.7			0.7 ± 0.3
EMN-22		0.9			0.9 ± 0.3
EMN-1	infilled tracks; omit net rise calculations because original water depth not known with high degree of certainty				
EMN-2					
EMN-3					
EMN-4					
EMN-25		1.6			1.6 ± 0.3
EMN-26		infilled track			
EMN-64		0.6			0.6 ± 0.3

range of values for
total observed net
rise is -0.3 m to 3.4 m.

* uncertainty in net rise is ± 0.3 m (please see Appendix E)

Note also that: Net rise = (water depth_A - water depth_B) - Δd

Table C.VI Volume, net rise, net rise per unit length, and mean water depth values for segments of ice-scour track images listed in data set 'C'.

Track	Segment	Volume (m ³)*	Net rise (m)	Net rise/length	Mean water depth (m)
M-01	A to B	7200	1.9 ± 0.3	0.0024 ± 0.0004	27.0 ± 0.1
M-02		2700	2.9	0.0073 ± 0.0008	27.0
M-03		5880	2.8	0.0067 ± 0.0009	27.1
M-04		7520	0.0	0.0	33.2
M-05		15960	1.3	0.0017 ± 0.0004	36.5
M-06		9120	0.1	0.0001 ± 0.0003	37.2
M-07		12000	0.1	0.0001 ± 0.0003	37.5
M-08		34200	0.3	0.0005 ± 0.0005	40.8
M-09		21000	0.5	0.0003 ± 0.0002	41.5
M-10		40800	-0.4	-0.0006 ± 0.0004	41.3
M-11		8000	0.0	0.0	42.5
M-12	a to A	-	1.1	0.0018 ± 0.0005	40.7
M-13	A to B	10080	0.4	0.0004 ± 0.0003	38.0
M-14		33075	1.2	0.0017 ± 0.0004	38.2
M-15		14000	2.3	0.0033 ± 0.0004	36.2
M-16		11040	1.1	0.0008 ± 0.0002	35.9
M-17		8400	-0.2	-0.0001 ± 0.0002	43.1
M-18		86400	0.4	0.0005 ± 0.0004	43.2
M-19		24000	0.6	0.0006 ± 0.0003	43.5
M-20		47000	1.0	0.0020 ± 0.0006	41.6
M-21		2325	1.0	0.0016 ± 0.0005	41.7
M-22		14850	1.3	0.0020 ± 0.0005	41.4
M-23		-	1.5	0.0019 ± 0.0004	39.4
M-24	omit				
M-25	A to B	11375	0.8	0.0004 ± 0.0002	39.5
M-26		2640	0.9	0.0009 ± 0.0003	38.5
M-27		58800	0.0	0.0	35.9
M-28		-	0.0	0.0	44.1
M-29		6400	0.1	0.0002 ± 0.0005	45.2
M-30		1110	0.7	0.0009 ± 0.0004	46.1
M-04	B to C	7080	1.3	0.0011 ± 0.0003	32.8
M-07		15840	0.6	0.0005 ± 0.0002	37.0
M-10		55440	0.8	0.0012 ± 0.0005	40.5
M-12	A to B	-	1.5	0.0020 ± 0.0004	39.5
M-12	B to C	-	0.8	0.0015 ± 0.0006	38.0
M-13		15750	-0.7	-0.0007 ± 0.0003	37.9
M-26		3720	1.6	0.0013 ± 0.0002	37.2
M-26	C to D	3500	0.3	0.0003 ± 0.0003	36.2
EMN-22	A to B	8400	0.9	0.0006 ± 0.0002	46.8
EMN-25		21000	1.6	0.0006 ± 0.0001	45.3
EMN-64		-	0.6	0.0007 ± 0.0003	41.2

*Volume values are not given for multiple ice-scour tracks.

Table C.VII Direction of curvature for arcuate ice-scour tracks. Tracings of these tracks, which are from the 'East Mackenzie' mosaic area, are shown in figure C.2 and figures C.3 (a to e).

Notes: (1) Refer to figure 3.13 for definitions of information collected.

(2) Symbols: L = left Y = yes
R = right N = no

Arcuate track identification		Direction of turning	Is turning consistent with approach angle?
On overlay	For computer input		
M-05	105	R	Y
M-07	107	R	Y
M-08	108	R	Y
M-14	114	R	N
M-17	117	L	N
M-18	118	L	N
M-20	120	L	Y
M-25	125	R	N
M-27	127	L	Y
M-28	128	L	Y
M-30	130	L	Y
EMN-4	4	R	Y
EMN-6	6	R	Y
EMN-12	12	R	Y
EMN-15	15	L	Y
EMN-27	27	R	Y
EMN-29	29	R	N
EMN-31	31	L	N
EMN-33	33	R	N
EMN-45	45	R	N
EMN-52	52	R	N
EMN-58	58	L	Y
EMN-62	62	R	N
EMN-73	73	L	N

Summary: Total L 10
R 14
n = 24

Total Y 13
N 11
n = 24

Table C.VIII (a) Ice keel draft and ice-scour depth data from 1974 survey fixes 37 (UTM 408 920; 7 718 480) to 51 (UTM 409 240; 7 703 340) in the 'East Mackenzie' area.

<u>Track number</u>	<u>Track identification</u>	<u>Water depth (m)</u>	<u>Ice-scour depth (m)</u>	<u>Inferred ice keel draft (m)</u>
fix 225	(UTM 410 820; 7 694 560)			
1		31.6	0.8	32.4
2		31.7	0.6	32.3
3		32.0	0.2	32.2
4		32.0	0.6	32.6
5		32.3	0.2	32.5
6		32.4	0.6	33.0
7		32.4	0.1	32.5
8		32.4	0.3	32.7
9		32.6	0.1	32.7
10	M-04 C-C'	32.7	0.7	33.4
11		32.8	0.6	33.4
12		32.8	0.7	33.5
13		32.8	0.6	33.4
14		33.2	0.8	34.0
15		33.4	0.4	33.8
16		33.8	0.6	34.4
17		34.0	0.4	34.4
18		34.4	0.2	34.6
19		34.0	0.2	34.2
20		34.4	0.3	34.7
21		34.8	0.6	35.4
22		34.8	0.4	35.2
23		35.0	0.2	35.2
24		35.2	0.8	36.0
25		35.6	0.3	35.9
26	M-05 B-B'	35.8	1.0	36.8
27		36.1	0.2	36.3
28		36.2	0.6	36.8
fix 228	(UTM 410 960; 7 697 700)			
29		36.4	0.1	36.5
30		36.4	0.2	36.6
31		36.7	0.9	37.6
32		36.4	0.2	36.6
33		37.0	0.4	37.4
34		36.9	0.7	37.6
35		37.2	0.2	37.4
36	M-06 A-A'	37.2	0.3	37.5
37		37.3	0.1	37.4
38		37.4	0.3	37.7
39		37.6	0.3	37.9
40		37.8	0.6	38.4

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Table D.VIII (a) (cont'd.)

Track number	Track identification	Water depth (m)	Ice-scour depth (m)	Inferred ice keel draft (m)
41		37.8	0.4	38.2
42	M-07 A-A'	38.2	0.2	38.4
43		38.1	0.9	39.0
44		38.1	0.7	38.8
45		38.3	0.3	38.6
fix 230	(UTM 411 020; 7 700 600)			
46		38.4	1.7	40.1
47		38.4	0.4	38.8
48	M-13 A-A'	38.5	0.4	38.9
49	M-12 B-B'	38.8	0.2	39.0
50	M-14 A-A'	38.8	1.2	40.0
51	M-26 A-A'	39.0	0.6	39.6
52		39.1	0.9	40.0
53		39.1	0.2	39.3
54		39.3	0.9	40.2
55		39.5	1.4	40.9
56		39.8	0.4	40.2
57	M-25 A-A'	40.0	0.3	40.3
58		40.0	0.2	40.2
59	M-23 A-A'	40.4	1.4	41.8
fix 233	(UTM 410 860; 7 703 460)			
60		40.4	0.2	40.6
61		40.4	0.1	40.5
62		40.5	0.6	41.1
63		40.6	0.3	40.9
64		40.9	0.5	41.4
65	M-22 B-B'	40.9	0.8	41.7
66		41.2	0.8	42.0
67	M-20 B-B'	41.4	2.4	43.8
68	M-21 B-B'	41.4	0.1	41.5
69		41.4	1.0	42.4
70		41.6	1.9	43.5
71		41.7	0.3	42.0
72		41.8	0.7	42.5
fix 235,	(UTM 410 860; 7 706 420)			

Table C.VIII (b) Ice keel draft and ice-scour depth data from 1974 survey fixes 225 (UTM 410 820; 7 694 560) to 235 (UTM 410 860; 7 706 420) in the 'East Mackenzie' area.

Track number	Track identification	Modern water depth (m)	'Paleo' * water depth (m)	Ice-scour depth (m)		Inferred ice keel draft (m)	
				from surface expression	from sub-bottom	from surface expression	from sub-bottom info. and 'paleo' w.d.
fix 51	(UTM 409 240; 7 703 340)						
1		43.0		0.4		43.4	
2		43.5		1.2		44.7	
3		43.5		0.4		43.9	
4		43.5		0.8		44.3	
5		43.7		2.4		46.1	
6		44.0		0.9		44.9	
7		44.1		0.2		44.3	
8		44.3		0.4		44.7	
9		44.5		0.6		45.1	
10		44.5		0.6		45.1	
fix 49	M-28 A-A' (UTM 409 240; 7 706 400)						
11		45.3		0.2		45.5	
12		45.5		0.4		45.9	
fix 48	(UTM 409 200; 7 707 540)						
13		45.9		0.3		46.2	
fix 47	(UTM 409 180; 7 708 460)						
14		46.3		0.2		46.5	
15		46.4		0.1		46.5	
16	M-30 A-A'	46.6		0.4		47.0	
fix 46							
fix 45	(UTM 409 160; 7 710 500)						
17		47.5	49.5	1.3	3.2	48.8	52.7
18		47.7	49.7	0.8	1.8	48.5	51.5
19		48.1	50.1	0.4	1.9	48.5	52.0
fix 44	(UTM 409 140; 7 711 340)						
20		48.0	49.8	0.2	3.6	48.2	53.4

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Table C.VIII (b) (cont'd.)

Track number	Track identification	Modern water depth (m)	'Paleo' * water depth (m)	Ice-scour depth (m)		Inferred ice keel draft (m)	
				from surface expression	from sub-bottom	from surface expression	from sub-bottom info. and 'paleo' w.d.
21		48.2	50.0	0.6	2.6	48.8	52.6
22		48.3	50.1	0.7	2.1	49.0	52.2
fix 43	(UTM 409 130; 7 712 360)						
fix 42	(UTM 409 120; 7 713 200)						
fix 41	(UTM 409 090; 7 714 400)						
fix 39	(UTM 409 040; 7 716 320)						
23		49.4	51.4	0.6	1.2	50.0	52.6
24		49.6	51.6	1.0	0.2	50.6	51.8
fix 38	(UTM 408 960; 7 717 960)						
fix 37	(UTM 408 920; 7 718 480)						
25		50.2	52.2	0.4	1.6	50.6	53.8
end of line - ship turning							

* 'Paleo' water depth = modern water depth + thickness of sediment blanket on top of buried undisturbed seabed (cf., figure 3.14)

Figure C.4(a) Hardware model for interaction of floating ice masses. The two 'marked' hex nuts (having pens attached) were initially located within the group of remaining hex nuts. As the force was applied the 'marked' hex nuts quickly became locked into fixed positions with the whole moving group and produced the relatively straight tracks shown below at actual scale.

MODEL: Ice masses with grounding keels
are situated amongst other floes
in pack ice.

direction of
movement

Figure C.4(b-d) Hardware model for interaction of floating ice masses. For the three trials shown here, the two 'marked' hex nuts were initially located at the periphery of the main group of hex nuts. At the beginning of each trial, the 'marked' hex nuts had a relatively large freedom of movement. This progressively decreased throughout the duration of the trial as the hex nuts gradually became locked into fixed relative positions. The tracks shown on this and the next two pages are reproduced at true scale.

Figure C.4 b Trial 1

MODEL: Ice masses with grounding keels are situated at pack ice - open water boundary.

direction of movement

Figure C.4 c Trial 2

MODEL: Ice masses with grounding
keels are situated at
pack ice- open water
boundary.

↓
direction of
movement

Figure C.4 d Trial 3

direction of
movement

MODEL: Ice masses with grounding
keels are situated at
pack ice - open water
boundary.

APPENDIX D
STATISTICAL TESTS

5

D.1 Arcuate tracks -direction of curvature

D.1.1 Direction of turning (this test referred to in section 6.3.4)

The direction of turning is either to the left or right of the direction of ice keel motion (see figure 3.13).

From Table C.VII find that:

$$P(\text{left}) = 10/24 = 0.42 = p_0,$$

$$\text{and } P(\text{right}) = 14/24 = 0.58 = p.$$

Hypotheses:

$$H_0: P(\text{left}) = P(\text{right}); \text{ i.e., } p = p_0.$$

$$H_1: P(\text{right}) > P(\text{left}); \text{ i.e., } p > p_0.$$

Significance level, $\alpha = 0.05$; one-tailed test.

Compute statistic,

$$z = \frac{r - n p_0 - \frac{1}{2}}{(n p_0 (1 - p_0))^{\frac{1}{2}}} \quad (\text{eqn. D.1})$$

where r is number of right turns ($r = 14$)

n is sample population ($n = 24$)

Reject H_0 if $z > z_a$

where $z_a = 1.645$ (from Crow et al., 1960, their Appendix, Table 2,

for $F(z) = 1 - \alpha = 0.95$).

Upon substituting appropriate values in equation D.1, find that

$z = 1.41$. Therefore, accept H_0 at $\alpha = 0.05$. The statistical test

indicated that there is equal probability of a moving ice keel

turning to the right or to the left of its direction of motion.

D.1.2 'Consistency' of turning (this test referred to in section 6.4)

As an ice keel approaches a seabed slope, the direction of turning of the ice keel will be either consistent ('yes') or inconsistent ('no') with the ice keel's angle of approach to the slope (see figure 3.13).

From Table C.VII find that:

$$P(\text{yes}) = 13/24 = 0.54 = p,$$

$$P(\text{no}) = 11/24 = 0.46 = p_0.$$

Hypotheses:

$$H_0: P(\text{yes}) = P(\text{no}); \text{ i.e., } p = p_0.$$

$$H_1: P(\text{yes}) > P(\text{no}); \text{ i.e., } p > p_0.$$

Significance level, $\alpha = 0.05$; one-tailed test.

Compute statistic z (equation D.1) using r equal to the number of consistent turns ($r = 13$) and n is 24 again. It is found that $z = 0.6$. This is less than $z_\alpha = 1.645$ so accept H_0 at $\alpha = 0.05$. The statistical test indicated that there is equal probability of an ice keel's turning being 'consistent' or 'inconsistent' with its θ_{app} .

D.2 Regression of net rise per unit length versus mean water depth between ice-scour track cross-sections

A suitable form of curve for the non-linear regression of net rise per unit length versus mean water depth is given by

$$y = -m \ln \frac{x}{a} \quad (\text{eqn. D.2 a}).$$

This equation may be rewritten as

$$y = -m (\ln x - \ln a)$$

$$\text{or } y = -m \ln x + m \ln a \quad (\text{eqn. D.2 b}).$$

Equation D.2 b is of the form

$$Y = M X + b \quad (\text{eqn. D.3})$$

which is the expression describing a linear relationship between X and Y. It is seen that,

$$Y = y \quad (\text{eqn. D.4 a})$$

$$M = -m \quad (\text{eqn. D.4 b})$$

$$X = \ln x \quad (\text{eqn. D.4 c})$$

$$\text{and } b = m \ln a \quad (\text{which is the same as } a = e^{b/m}) \quad (\text{eqn. D.4 d}).$$

The data points plotted in figure 6.13 are tabulated in Table D.I.

The tracks listed there all have approach angles of 60° or less.

The linear regression yields:

$$\text{slope} = M = -0.013002$$

$$y - \text{intercept} = b = 0.049478$$

$$s_X = \pm 0.133$$

$$s_Y = \pm 0.00187$$

The correlation coefficient, given by

$$r = \frac{M s_X}{s_Y} \quad (\text{eqn. D.5; from Crow et al., 1960, p. 158})$$

is equal to -0.92 .

Table D.I Data used in regression analysis of (net rise/length) versus mean water depth for tracks with $\theta_{app} \leq 60^\circ$. See also figure 6.13.

Track	Segment	Mean water depth (m) x	ln x X	(net rise/length) Y = y
M-02	A to B	27.0	3.30	0.0073
M-03		27.1	3.30	0.0067
M-05		36.5	3.60	0.0017
M-08		40.8	3.71	0.0005
M-09		41.5	3.73	0.0003
M-10		41.3	3.72	-0.0006
M-12		40.7	3.71	0.0018
M-14		38.2	3.64	0.0017
M-15		36.2	3.59	0.0033
M-18		43.2	3.77	0.0005
M-19	A to B	43.5	3.77	0.0006
M-20		41.6	3.73	0.0020
M-21		41.7	3.73	0.0016
M-22		41.4	3.72	0.0020
M-23		39.4	3.67	0.0019
M-26		38.5	3.65	0.0009
M-28		44.1	3.79	0.0
M-29		45.2	3.81	0.0002
M-30		46.1	3.83	0.0009
M-10		40.5	3.70	0.0012
M-12	A to B	39.5	3.68	0.0020
M-12	B to C	38.0	3.64	0.0015

n = 22

* the uncertainties associated with these variables are given in Table C.VI.

The number of degrees of freedom is

$$\text{d.f.} = N - n_r \quad (\text{eqn. D.6; from Arkin and Colton, 1963, p.24})$$

where N is the number of pairs of observations ($N = 22$)

and n_r is the number of variables ($n_r = 2$).

Hence $\text{d.f.} = 20$.

Reference to Table 22 in Arkin and Colton shows that the linear correlation between X and Y is significant at both the 5 % and 1 % levels.

Using the values of M and b and equation D.4 (b) and (d), equation D.2 (a) is now written as

$$y = -0.013 \ln\left(\frac{x}{44.9}\right) \quad (\text{eqn. D.7}).$$

The standard error of estimate for the regression line

is given by

$$s_{Y|X} = \pm \sqrt{\left[\frac{n-1}{n-2} (s_Y^2 - M^2 s_X^2) \right]}$$

(eqn. D.8; from Crow et al., p. 156)

and is calculated to be $\pm 7.5 \times 10^{-4}$.

The data used in figure 6.14 is listed in Table D.II.

The regression analysis gave:

$$\text{slope} = M = -0.0025906955$$

$$\text{y-intercept} = b = 0.0098778862$$

$$s_X = \pm 0.1237143764$$

$$s_Y = \pm 0.0006530319$$

$$r = M \frac{s_X}{s_Y} = -0.49 \quad \text{which is barely significant at the 5 \% level} \\ \quad \quad \quad (16 \text{ d.f.}).$$

Table D.II Data used in regression analysis for (net rise/length)
versus mean water depth for tracks with $\theta_{app} > 60^\circ$.
See also figure 6.14.

Track	Segment	Mean water * depth (m)	ln x	(net rise/length) *
		x	X	Y = y
M-01	A to B	27.0	3.30	0.0024
M-04		33.2	3.50	0.0
M-06		37.2	3.62	0.0001
M-07		37.5	3.62	0.0001
M-11		42.5	3.75	0.0
M-13		38.0	3.64	0.0004
M-16		35.9	3.58	0.0008
M-17		43.1	3.76	-0.0001
M-25		39.5	3.68	0.0004
M-27		35.9	3.58	0.0
M-04	B to C	32.8	3.49	0.0011
M-07		37.0	3.61	0.0005
M-13		37.9	3.63	-0.0007
M-26		37.2	3.62	0.0013
M-26	C to D	36.2	3.59	0.0003
EMN-22	A to B	46.8	3.85	0.0006
EMN-25		45.3	3.81	0.0006
EMN-64		41.2	3.72	0.0007

n = 18

* the uncertainties associated with these variables are given in Table C.VI.

The equation of the regression line is

$$y = - 0.0026 \ln \frac{x}{45.3}$$

with $s_{Y|X} = \pm 6 \times 10^{-4}$.

The data used in figure 6.15 (a) is listed in Table D.III. A linear regression of y on x with the negative rise value excluded, gave:

slope = m = - 0.0001171758

y - intercept = b = 0.0060557586

$s_x = \pm 2.98$

$s_y = \pm 0.00055$.

The correlation coefficient is $r = - 0.635$ (4 d.f.) which is not significant. The non - linear regression of (net rise/length) versus $\overline{W.D.}$, using all 7 pairs of observations, gave:

slope = M = - 0.0043633126

intercept = b = 0.0171813891

$s_x = \pm 0.0677028324$

$s_y = \pm 0.0007964206$.

The correlation coefficient, $r = - 0.371$ (5 d.f.) which is also not significant.

The data used in figure 6.15 (b) is listed in Table D.IV. For the 9 points with $\theta_{app} \leq 60^\circ$, the regression analysis yielded the following results:

slope = M = + 0.0138246283

intercept = b = 0.0525137697

$s_x = \pm 0.1781038677$

$s_y = \pm 0.00251872$

Table D.III Data used in regression analysis for (net rise/length)
versus mean water depth for tracks with NW azimuth.
See also figure 6.15 (a).

Track	Segment	Mean water [*] depth (m)	ln x	(net rise/length) [*]
		$\bar{x}$	$\bar{X}$	$\bar{Y} = \bar{y}$
M-05	A to B	36.5	3.60	0.0017
M-10		41.3	3.72	-0.0006
M-18		43.2	3.77	0.0005
M-19		43.5	3.78	0.0006
M-22		41.4	3.72	0.0020
M-30		46.1	3.83	0.0009
M-10	B to C	40.5	3.70	0.0012

n = 7

Table D.IV Data used in regression analysis for (net rise/length)
versus mean water depth for tracks with SW azimuth.
See also figure 6.15 (b).

Track	Segment	θ_{app} [*] (degrees)	Mean water [*] depth (m)	ln x	(net rise/length) [*]
			$\bar{x}$	$\bar{X}$	$\bar{Y} = \bar{y}$
M-02	A to B	043	27.0	3.30	0.0073
M-03		046	27.0	3.30	0.0067
M-04		090	33.2	3.50	0.0
M-06		090	37.2	3.62	0.0001
M-11		068	42.5	3.75	0.0
M-13		067	38.0	3.64	0.0004
M-14		049	38.2	3.64	0.0017
M-15		034	36.2	3.59	0.0033
M-16		090	35.9	3.58	0.0008
M-17		090	43.1	3.76	-0.0001
M-21		047	41.7	3.73	0.0016
M-23		042	39.4	3.67	0.0019
M-26		060	38.5	3.65	0.0009
M-28		045	44.1	3.79	0.0
M-29		058	45.2	3.81	0.0002
M-04	B to C	081	32.8	3.49	0.0011
M-26	C to D	072	37.2	3.62	0.0013
M-26		075	36.2	3.59	0.0003
EMN-64	A to B	075	41.2	3.72	0.0007

n = 9 for $\theta_{app} \leq 60^\circ$

n = 10 for $\theta_{app} > 60^\circ$

* the uncertainties associated with these variables are given in Table C.VI.

$$r = \frac{M s_X}{s_Y} = -0.978 \quad (7 \text{ d.f.})$$

The association between Y and X is significant at the 5 % and 1 % levels (Table 22, Arkin and Colton).

Note that $m = -M = 0.0138$

$$a = e^{b/m} = e^{3.798566483} = 44.6.$$

Therefore, $y = -0.014 \ln \left(\frac{x}{44.6} \right)$.

The standard error of estimate is

$$s_{Y|X} = \pm 6 \times 10^{-4}.$$

For the 10 points with $\theta_{\text{app}} > 60^\circ$, the regression analysis gave:

$$\text{slope} = M = -0.001897519$$

$$\text{intercept} = b = 0.0073423015$$

$$s_X = 0.0895600357$$

$$s_Y = 0.0004673329$$

$$r = \frac{M s_X}{s_Y} = -0.364 \quad (8 \text{ d.f.}).$$

The association between X and Y is not significant at the 5 % level.

Table D.V Data used in ice-scour track length versus θ_{app} analysis
(figures 6.17 and 6.18 in text)

Track		θ_{app} (degrees)	$\secant(\theta_{app})$	track length (m)
		<u>x</u>	<u>X</u>	<u>Y = y</u>
EMN	5	065 $\pm$ 1	2.37	1840 $\pm$ 100
	7	000	1.00	200
	8	060	2.00	1880
	11	047	1.47	1100
	13	010	1.02	220
	16	000	1.00	460
	17	068	2.67	180
	18	061	2.06	280
	20	026	1.11	800
	21	026	1.11	140
	22	050	1.56	3120
	25	075	3.86	5100
	27	082	7.19	3460
	28	005	1.00	400
	31	057	1.84	1420
	35	076	4.13	2400
	36	064	2.28	1280
	41	008	1.01	600
	42	033	1.19	220
	44	013	1.03	380
	45	048	1.49	940
	47	038	1.27	900
	49	008	1.01	360
	50	062	2.13	880
	52	060	2.00	1020
	54	076	4.13	2200
	58	078	4.81	1620
	61	053	1.66	1480
	62	058	1.89	1240
	63	063	2.20	2250
	70	065	2.37	2250

n = 31

D.4 Goodness of fit tests (using chi-squared method)

D.4.1 Test (referred to in section 6.5.3) if ice-scour length data from the 'East Mackenzie (North)' area can be said to be drawn from population with exponential density

$$f(x) = \frac{e^{-x/\bar{x}}}{\bar{x}} ; \bar{x} = 1496.82 \text{ m}$$

Size of sample, n, is 44.

Use χ^2 test for goodness of fit; $\alpha = 0.05$.

Hypothesis: Data is exponentially distributed (decaying exponential)

If $U > \chi^2_{0.95}$ (9 degrees of freedom) then reject hypothesis with 5% chance of rejecting true hypothesis.

class interval (m)	relative theoretical freq., p_i	expected frequency $n p_i$	observed frequency n_i	$\frac{(n_i - n p_i)^2}{n p_i}$
0- 500	0.2839	12.49	10	0.496
500-1000	0.2033	8.95	8	0.101
1000-1500	0.1456	6.41	8	0.394
1500-2000	0.1042	4.59	5	0.037
2000-2500	0.0746	3.28	7	4.219
2500-3000	0.0535	2.35	2	0.052
3000-3500	0.0383	1.68	2	0.061
3500-4000	0.0274	1.21	1	0.036
4000-4500	0.0196	0.86	0	0.860
4500-5000	0.0141	0.62	0	0.620
5000-5500	0.0101	0.44	1	0.713

$$U = 7.589$$

Number of classes, k = 11.

Degrees of freedom, d.f. = k - (m + 1); m = 1 because the population mean, θ , must be estimated. That is, $\hat{\theta} = \bar{x}$.
Hence, d.f. = 9.

$$\chi^2_{0.95} (9 \text{ d.f.}) = 16.9 \text{ (from Table 49, Spiegel, 1968).}$$

Therefore, data does not support rejection of hypothesis.

D.4.2 Goodness of fit test for Wadhams' (1977) Keel draft data.
This test is referred to in section 6.5.5 (b.1).

H_0 : keel draft has decaying exponential distribution

$$f(x) = \frac{e^{-(x-a)/(\bar{x}-a)}}{(\bar{x}-a)}$$

where $a = 30$ m to allow evaluation of the function from $x = 0$ to $x \rightarrow \infty$.

$$\begin{aligned} \text{d.f.} &= k - 1 - m \\ &= 6 - 1 - 1 \\ &= 4. \end{aligned}$$

$$\begin{aligned} \bar{x} &= 32.78 \text{ m} \\ n &= 45 \end{aligned}$$

If $U > \chi^2_{0.95}$ (4 d.f.), reject H_0 with $\alpha = 0.05$.

$$\chi^2_{0.95} \text{ (4 d.f.)} = 9.49 \text{ (Table 49, Spiegel, 1968).}$$

Adjusted class interval (x - a) (m)	relative theoretical frequency p_1	expected frequency $n p_1$	observed frequency n_1	$\frac{(n_1 - n p_1)^2}{n p_1}$
0-2	0.5130	23.09	24	0.036
2-4	0.2498	11.24	11	0.005
4-6	0.1217	5.48	4	0.400
6-8	0.0593	2.67	4	0.663
8-10	0.0289	1.30	1	0.069
10-12	0.0141	0.63	1	0.217

$$U = 1.39$$

Because $U < \chi^2_{0.95}$ (4 d.f.), can accept H_0 .

Note also that because $\chi^2_{0.05} = 0.711$ which is less than U ,
the fit is not too good to be acceptable.

D.4.3 (a) Goodness of fit test (decaying exponential distribution) for inferred keel draft distribution (sub-bottom information excluded). This test is referred to in section 6.5.5 (b.1).

H_0 : keel draft distribution is of decaying exponential form

$$f(x) = \frac{e^{-(x-a)/(\bar{x}-a)}}{(\bar{x}-a)}$$

where $a = 32$ m to allow evaluation of function from $x = 0$ to $x \rightarrow \infty$.

$$\begin{aligned} \text{d.f.} &= k - 1 - m \\ &= 8 - 1 - 1 \\ &= 6 \end{aligned}$$

$$\begin{aligned} \bar{x} &= 38.9 \text{ m} \\ n &= 88 \end{aligned}$$

If $U > \chi^2_{0.95}$ (6 d.f.), reject H_0 with $\alpha = 0.05$.

$$\chi^2_{0.95} \text{ (6 d.f.)} = 12.6 \quad \text{and} \quad \chi^2_{0.99} \text{ (6 d.f.)} = 16.8 \quad (\text{Table 49, Spiegel, 1968}).$$

Adjusted class interval (x - a) (m)	relative theoretical frequency p_1	expected frequency $n p_1$	observed frequency n_1	$\frac{(n_1 - n p_1)^2}{n p_1}$
0-2	0.2516	22.14	15	2.30
2-4	0.1883	16.57	10	2.61
4-6	0.1409	12.40	14	0.21
6-8	0.1055	9.28	13	1.49
8-10	0.0789	6.94	16	11.83
10-12	0.0591	5.20	6	0.12
12-14	0.0442	3.89	9	6.71
14-16	0.0331	2.91	5	1.50

$$U = 26.77$$

Because $U > \chi^2_{0.95}$ (6 d.f.), reject H_0 at 5% level.

Also, $U > \chi^2_{0.99}$ (6 d.f.). Therefore reject H_0 at 1% level.

D.4.3 (b) Goodness of fit test (normal distribution) for inferred keel draft distribution (exclude sub-bottom information). This test is referred to in section 6.5.5 (b.1).

H_0 : keel draft has normal distribution.

$$\bar{x} = 38.9 \text{ m}; \quad s = \pm 4.2 \text{ m}; \quad n = 88$$

$$\text{d.f.} = k - 1 - m = 8 - 1 - 2 = 5,$$

where $m = 2$ because both mean and variance of population are estimated. That is, $\mu = \bar{x}$ and $\sigma^2 = s^2$.

$$\chi^2_{0.95} (5 \text{ d.f.}) = 11.1 \quad \text{and} \quad \chi^2_{0.99} (5 \text{ d.f.}) = 15.1 \quad (\text{Table 49, Spiegel, 1968}).$$

Reject H_0 if $U > \chi^2_{0.95} (5 \text{ d.f.})$

keel drafts (m)	class boundaries (m)	z	area 0 to z	class area	e_j	o_j	$\frac{(o_j - e_j)^2}{e_j}$
	32	-1.64	0.4495				
32 - 34				0.0705	6.20	15	12.49
	34	-1.17	0.3790				
34 - 36				0.1241	10.92	10	0.08
	36	-0.69	0.2549				
36 - 38				0.1717	15.11	14	0.08
	38	-0.21	0.0832				
38 - 40				0.1858	16.35	13	0.07
	40	0.26	0.1026				
40 - 42				0.1678	14.59	16	0.14
	42	0.74	0.2704				
42 - 44				0.1184	10.42	6	1.87
	44	1.22	0.3888				
44 - 46				0.0657	5.78	9	1.79
	46	1.69	0.4545				
46 - 48				0.0305	2.68	5	2.01
	48	2.17	0.4850				

$$U = 18.53$$

Because $U > \chi^2_{0.95} (5 \text{ d.f.})$, reject H_0 at 5 % level.

Also reject H_0 at 1 % level because $U > \chi^2_{0.99} (5 \text{ d.f.})$.

Symbols: $z = (x - \bar{x})/s$
 e_j = expected frequency
 o_j = observed frequency

D.4.4 (a) Goodness of fit test (decaying exponential distribution) for inferred keel draft distribution (including sub-bottom information). This test is referred to in section 6.5.5 (b.1).

H_0 : keel draft has decaying exponential distribution

$$f(x) = \frac{e^{-(x-a)/(\bar{x}-a)}}{(\bar{x}-a)}$$

where $a = 32$ m to allow evaluation of function from $x = 0$ to $x \rightarrow \infty$.

$$\begin{aligned} \text{d.f.} &= k - 1 - m & \bar{x} &= 40.163 \text{ m} \\ &= 11 - 1 - 1 & n &= 97 \\ &= 9. \end{aligned}$$

If $U > \chi^2_{0.95}(9 \text{ d.f.})$, reject H_0 with $\alpha = 0.05$.

$$\chi^2_{0.95}(9 \text{ d.f.}) = 16.9 \quad (\text{Table 49, Spiegel, 1968}).$$

Adjusted class interval (x - a) (m)	relative theoretical frequency p_1	expected frequency $n p_1$	observed frequency n_1	$\frac{(n_1 - n p_1)^2}{n p_1}$
0-2	0.2173	21.08	14	2.38
2-4	0.1701	16.50	10	2.56
4-6	0.1331	12.91	15	0.34
6-8	0.1042	10.11	11	0.08
8-10	0.0815	7.91	16	8.27
10-12	0.0638	6.19	8	0.53
12-14	0.0500	4.85	9	3.55
14-16	0.0391	3.79	5	0.39
16-18	0.0306	2.97	0	2.97
18-20	0.0240	2.33	2	0.05
20-22	0.0188	1.82	7	14.74

$$U = 35.86$$

Because $U > \chi^2_{0.95}(9 \text{ d.f.})$ must reject H_0 .

D.4.4 (b) Goodness of fit test (normal distribution) for inferred keel draft distribution (including sub-bottom information). This test is referred to in section 6.5.5 (b.i).

H_0 : keel draft has normal distribution.

$\bar{x} = 40.163 \text{ m}$; $s = \pm 5.6 \text{ m}$; $n = 97$

d.f. = $k - 1 - m = 11 - 1 - 2 = 8$.

$\chi^2_{0.95}(8 \text{ d.f.}) = 15.5$ (Table 49, Spiegel, 1968).

If $U > \chi^2_{0.95}(8 \text{ d.f.})$, reject H_0 with $\alpha = 0.05$.

keel drafts (m)	class boundaries (m)	z	area 0 to z	class area	e_j	o_j	$\frac{(o_j - e_j)^2}{e_j}$
32 - 34	32	-1.45	0.4265	0.0622	6.03	14	10.53
34 - 36	34	-1.10	0.3643	0.0939	9.11	10	0.09
36 - 38	36	-0.74	0.2704	0.1224	11.87	15	0.83
38 - 40	38	-0.38	0.1480	0.1360	13.19	11	0.36
40 - 42	40	-0.03	0.0120	0.1413	13.71	16	0.38
42 - 44	42	0.33	0.1293	0.1225	11.88	8	1.27
44 - 46	44	0.68	0.2518	0.0990	9.60	9	0.04
46 - 48	46	1.04	0.3508	0.0669	6.49	5	0.34
48 - 50	48	1.39	0.4177	0.0422	4.09	0	4.09
50 - 52	50	1.75	0.4599	0.0227	2.20	2	0.02
52 - 54	52	2.11	0.4826	0.0105	1.02	7	35.06
	54	2.46	0.4931				

$U = 53.01$

Because $U > \chi^2_{0.95}(8 \text{ d.f.})$ must reject H_0 .

D.4.4 (c) Goodness of fit test (uniform distribution) for inferred keel draft distribution (including sub-bottom information). This test is referred to in section 6.5.5 (b.1).

H_0 : keel draft has uniform distribution.

$\bar{x} = 40.163 \text{ m}$; $s = \pm 5.6 \text{ m}$; $n = 97$.

d.f. = $k - 1 - m$; $m = 0$
 $= 11 - 1$
 $= 10$

$\chi^2_{0.95}(10 \text{ d.f.}) = 18.3$ (Table 49, Spiegel, 1968).

If $U > \chi^2_{0.95}(10 \text{ d.f.})$, reject H_0 with $\alpha = 0.05$.

keel drafts (m)	relative theoretical frequency p_1	expected frequency $n p_1$	observed frequency n_1	$\frac{(n_1 - n p_1)^2}{n p_1}$
32 - 34	0.0909	8.82	14	3.04
34 - 36			10	0.16
36 - 38			15	4.33
38 - 40			11	0.54
40 - 42			16	5.84
42 - 44			8	0.08
44 - 46			9	0.02
46 - 48			5	1.65
48 - 50			0	8.82
50 - 52			2	5.27
52 - 54			7	0.38

$$p_1 = 1/k$$

$$= 1/11 = 0.0909$$

$$U = 30.13$$

Because $U > \chi^2_{0.95}(10 \text{ d.f.})$ must reject H_0 .

D.4.5 Test goodness of fit of 'East Mackenzie (North)' area inferred keel draft distribution to normal distribution. This test is referred to in section 6.5.5 (b.ii).

H_0 : sample population is normally distributed.

$n = 31$

Estimated parameters are: (1) $\hat{\mu} = \bar{x} = 46.548$ m.
(2) $\hat{\sigma} = s = \pm 1.5$ m.

d.f. = $k - 1 - m = 7 - 1 - 2 = 4$.

$\chi^2_{0.95}(4 \text{ d.f.}) = 9.49$ (Table 49, Spiegel, 1968).

If $U > \chi^2_{0.95}(4 \text{ d.f.})$, reject H_0 with $\alpha = 0.05$.

keel drafts (m)	class boundaries (m)	z	area 0 to z	class area	e_j	o_j	$\frac{(o_j - e_j)^2}{e_j}$
43 - 44	43	-2.37	0.4911	0.0357	1.11	1	0.0109
44 - 45	44	-1.70	0.4554	0.1069	3.31	4	0.1438
45 - 46	45	-1.03	0.3485	0.2042	6.33	9	1.1262
46 - 47	46	-0.37	0.1443	0.2622	8.13	2	4.6220
47 - 48	47	0.30	0.1179	0.2161	6.70	8	0.2522
48 - 49	48	0.97	0.3340	0.1155	3.58	6	1.6359
49 - 50	49	1.64	0.4495	0.0401	1.24	1	0.0465
	50	2.31	0.4896				

$U = 7.8375$

Because $U < \chi^2_{0.95}(4 \text{ d.f.})$ can accept H_0 .

D.4.6 Test (referred to in section 6.5.5 (b.11)) if ice-scour depth data from the 'East Mackenzie (North)' area can be said to be drawn from population with decaying exponential density

$$f(x) = \frac{e^{-x/\bar{x}}}{\bar{x}} ; \bar{x} = 1.1 \text{ m}$$

H_0 : sample population has decaying exponential distribution.

$n = 50$ is size of sample.

$$\text{d.f.} = k - (m + 1) = 8 - (1 + 1) = 6.$$

$$\chi^2_{0.95}(6 \text{ d.f.}) = 12.6 \text{ (Table 49, Spiegel, 1968).}$$

If $U > \chi^2_{0.95}(6 \text{ d.f.})$, reject hypothesis that the 50 observations were drawn from an exponentially distributed population with $\hat{\theta} = \bar{x}$ (rejection at 5% level).

class interval (m)	relative theoretical frequency p_i	expected frequency $n p_i$	observed frequency n_i	$\frac{(n_i - n p_i)^2}{n p_i}$
0 - 0.5	0.3656	18.28	14	1.002
0.5 - 1.0	0.2319	11.60	12	0.014
1.0 - 1.5	0.1471	7.36	10	0.947
1.5 - 2.0	0.0934	4.67	4	0.096
2.0 - 2.5	0.0592	2.96	6	3.122
2.5 - 3.0	0.0376	1.88	3	0.667
3.0 - 3.5	0.0238	1.19	0	1.190
3.5 - 4.0	0.0151	0.76	1	0.076

$$U = 7.114$$

Find that data does not support rejection of hypothesis because

$$U < \chi^2_{0.95}.$$

D.4.7 Test (referred to in section 6.5.5 (b.11)) if ice-scour depth data from data set 'B' is drawn from population with exponential density

$$f(x) = \frac{e^{-x/\bar{x}}}{\bar{x}} \quad ; \quad \bar{x} = 0.823 \text{ m}$$

H_0 : population has decaying exponential distribution.

$$n = 30$$

$$\text{d.f.} = k - (m + 1) = 6 - (1 + 1) = 4.$$

$$\chi^2_{0.95}(4 \text{ d.f.}) = 9.49 \quad (\text{Table 49, Spiegel, 1968}).$$

If $U > \chi^2_{0.95}(4 \text{ d.f.})$ reject H_0 with $\alpha = 0.05$.

class interval (m)	relative theoretical frequency p_i	expected frequency $n p_i$	observed frequency n_i	$\frac{(n_i - n p_i)^2}{n p_i}$
0 - 0.5	0.7033	21.10	15	1.764
0.5 - 1.0	0.2481	7.44	7	0.026
1.0 - 1.5	0.1348	4.04	4	0.000
1.5 - 2.0	0.0733	2.20	2	0.018
2.0 - 2.5	0.0398	1.19	1	0.030
2.5 - 3.0	0.0216	0.65	1	0.188

$$U = 2.026$$

Because $U < \chi^2_{0.95}$ can accept H_0 .

D.4.8 Goodness of fit test (decaying exponential distribution) for the ice-scour depth distribution derived from two lines in the 'East Mackenzie' area (omit sub-bottom information). This test is referred to in section 6.5.5 (b.11).

H_0 : ice-scour depth has decaying exponential distribution,

$$f(x) = \frac{e^{-x/\bar{x}}}{\bar{x}} \quad ; \quad \bar{x} = 0.5602 \text{ m}$$

$$n = 88$$

$$\text{d.f.} = k - 1 - m = 5 - 1 - 1 = 3.$$

$$\chi^2_{0.95}(3 \text{ d.f.}) = 7.81 \quad \text{and} \quad \chi^2_{0.99}(3 \text{ d.f.}) = 11.3$$

(Table 49, Spiegel, 1968).

If $U > \chi^2_{0.95}(3 \text{ d.f.})$ reject H_0 with $\alpha = 0.05$.

If $U > \chi^2_{0.99}(3 \text{ d.f.})$ reject H_0 with $\alpha = 0.01$.

ice-scour depth (m)	relative theoretical frequency p_i	expected frequency $n p_i$	observed frequency n_i	$\frac{(n_i - n p_i)^2}{n p_i}$
0 - 0.5	0.5904	51.95	49	0.17
0.5 - 1.0	0.2418	21.28	31	4.44
1.0 - 1.5	0.0991	8.72	4	2.55
1.5 - 2.0	0.0406	3.57	2	0.69
2.0 - 2.5	0.0166	1.46	2	0.20

$$U = 8.05$$

Find $U > \chi^2_{0.95}(3 \text{ d.f.})$. Therefore reject H_0 at 5 % level.

But, $U < \chi^2_{0.99}(3 \text{ d.f.})$. Therefore do not reject H_0 at 1 % level.

D.4.9 Goodness of fit test for the ice-sour track volume distribution in the 'East Mackenzie (North)' area. Single tracks only are considered and the data set includes buried tracks. This test is referred to in section 6.6.1.

H_0 : distribution is of the decaying exponential form,

$$f(x) = \frac{e^{-x/\bar{x}}}{\bar{x}} \quad ; \quad \bar{x} = 30.91 \times 10^3 \text{ m}^3.$$

$$n = 26$$

$$\text{d.f.} = k - 1 - m = 9 - 1 - 1 = 7.$$

$$\chi^2_{0.95}(7 \text{ d.f.}) = 14.1 \quad (\text{Table 49, Spiegel, 1968}).$$

If $U > \chi^2_{0.95}(7 \text{ d.f.})$, reject H_0 with $\alpha = 0.05$.

class interval ($\text{m}^3 \times 10^3$)	relative theoretical frequency p_i	expected frequency $n p_i$	observed frequency n_i	$\frac{(n_i - n p_i)^2}{n p_i}$
0 - 10	0.2764	7.19	7	0.01
10 - 20	0.2000	5.20	7	0.62
20 - 30	0.1447	3.76	3	0.15
30 - 40	0.1047	2.72	1	1.09
40 - 50	0.0758	1.97	1	0.48
50 - 60	0.0548	1.42	2	0.24
60 - 70	0.0397	1.03	1	0.00
70 - 80	0.0287	0.75	2	2.08
80 - 90	0.0207	0.54	2	3.94

$$U = 8.61$$

Because $U < \chi^2_{0.95}(7 \text{ d.f.})$ do not reject H_0 at 5 % level.

APPENDIX E
ERROR ANALYSES

E.1 Error in 'net rise' variable

$$\text{Net rise} = \text{NR} = (\text{water depth}_A - \text{water depth}_B) - (\text{ice scour depth}_B - \text{ice scour depth}_A) \quad (\text{eqn. E.1 a})$$

$$\text{or NR} = \Delta \text{W.D.} - \Delta d \quad (\text{eqn. E.1 b})$$

The error analysis is as follows:

$$E_{\text{NR}}^2 = e_{\Delta \text{WD}}^2 + e_{\Delta d}^2 \quad (\text{eqn. E.2})$$

$$\text{but } e_{\Delta \text{WD}}^2 = e_{\text{WD}_A}^2 + e_{\text{WD}_B}^2 \quad (\text{eqn. E.3})$$

where $e_{\text{WD}} = \pm 0.1 \text{ m}$ (see section 3.3.2 (g)). Therefore it is found that $e_{\Delta \text{WD}} = \pm 0.14 \text{ m}$.

$$\text{Find } e_{\Delta d}^2 = e_{d_B}^2 + e_{d_A}^2 \quad (\text{eqn. E.4})$$

where $e_d = \pm 0.2 \text{ m}$ because of resolution on echogram.

$$\text{Therefore, } e_{\Delta d} = (0.08 \text{ m}^2)^{\frac{1}{2}} = \pm 0.28 \text{ m}.$$

$$\text{Now, } E_{\text{NR}}^2 = (0.14 \text{ m})^2 + (0.28 \text{ m})^2 = 0.1 \text{ m}^2.$$

$$\text{Therefore, } E_{\text{NR}} = \pm 0.3 \text{ m}.$$

E.2 Error in net rise per unit length

$$E_{\text{net rise/length}}^2 = (\text{net rise/length})^2 \left[\left(\frac{e_{\text{NR}}}{\text{NR}} \right)^2 + \left(\frac{e_{\text{length}}}{\text{length}} \right)^2 \right] \quad (\text{eqn. E.5})$$

The error term depends upon value of the ratio, (net rise/ length).

E.3 Error in mean water depth between cross-sections

$$\text{Mean water depth} = \text{MWD} = \frac{\text{WD}_A + \text{WD}_B}{2} \quad (\text{eqn. E.6})$$

$$\text{Note that, } E_{\text{MWD}} = e_{\Delta \text{WD}} = \pm 0.14 \text{ m}.$$

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700000

700000

for

- Notes:
- 1) Bathymetry obtained during Geological Survey of Canada cruise, M.V. Pandora II, August 25-27 and September 4, 1974.
 - 2) Depths adjusted to 1480 metres/sec speed of sound setting (see Appendix B).
 - 3) No tide corrections made.
 - 4) Transducer draft compensated for.
 - 5) UTM grid approximate.
 - 6) overlay onto Figure 3.2 a and b.
 - 7) refer also to Appendix B: Notes regarding assembly of bathymetric overlays.

771500

773000

48

49

48

48

47

approximate track of line 78A

46

43 @ 43.1

44 @

44.1

78A (start)

42

approximate track of line 78B

43

(40)

(41)

41.4

775000

775000

775000

50

50

49

49.1

(49)

49

48

47

47.8

47

45.5

46

45

45.1

45

44

43

788 (end)

43

42

70F

773000

772000

407000

408000

410000

50

50

(49)

49

48

45.5

46

45

44

788 (end)

7655000

7657000

40. spot depth from echogram (based on speed of sound = 1450 metres/sec)

(40). approximate location of spot depth

40. interpolated spot depth after speed of sound adjustment made (assume even slope)

————— depth contour

----- approximate depth contour

c)

**Bathymetry of 'Undisturbed Seabed' for
EAST MACKENZIE
SIDE-SCAN SONAR
MOSAIC AREA,
BEAUFORT SEA**

t of true north)

for

- Notes:
- 1) Bathymetry obtained during Geological Survey of Canada cruise, M.V. Pandora II, August 25-27 and September 4, 1974.
 - 2) Depths adjusted to 1480 metres/sec speed of sound setting (see Appendix B).
 - 3) No tide corrections made.
 - 4) Transducer draft compensated for.
 - 5) UTM grid approximate.
 - 6) overlay onto Figure 3.2 a and b.
 - 7) refer also to Appendix B: Notes regarding assembly of bathymetric overlays.

77000

77500

Figure 3.4, to accompany Report
THE BEAUFORT SEA CONTINENTAL
interpretation of the process
R.V. Wahlgram, Ottawa, 1978.

Figure 3.4 Bathymetry of
mosaic area

Figure 3.4, to accompany report: ICE SCOUR TRACKS, ON
THE BEAUFORT SEA CONTINENTAL SHELF - their form and an
interpretation of the processes creating them; by
R.V. Wahlgren, Ottawa, 1978.

Figure 3.4

Bathymetry of East Mackenzie
nomic area

759000 516000

577000

776000

574000

772000

772000

571000

13.0

13.0

12.5 12.5

10

520 000

7 762 000

521 000

X

X

X

X

14.0 ——— 14.0

X

13.5

X

13.5

X

7 163 000 572000

52

X

X

X

14.5

14.5

X

14.2

X

(140)

X

523 000

524 000

524 000

X

X

X

X

15.0

15.0

X

14.5

14.5

14.5

X

50F

14.5

7765000

7766000

7766000

X

15.5

14.8

15.0

15.0

X

14.0

14.0

13.8

14.5

X

14.0

14.0

14.5

14.5

15.0

15.0

60F

12.5

12.5

12.5

775000

51000

775000

12.0

12.0

140

13.0

12.5

12.5

12.0

12.0

12.0

13.5

13.5

13.0

13.0

12.5

100

14.0

14.0

13.5

13.0

grid north (00° 36' east)

1106

120

77000

50000

20000

150F

12.0

12.5

12.0

12.0

521,000

7735,000

522,000

7736,000

160F

13.0 spot depth from echogram

depth contour

approximate depth contour

0.5

170 F

**Bathymetry of 'Undisturbed Seabed' for
a part of the
PULLEN ISLAND SIDE - SCAN SONAR
MOSAIC AREA, BEAUFORT SEA**

Depth contour interval 0.5 m

180F

- Notes: 1) Bathymetry obtained during Geological Survey of Canada cruise, M.V. Pandora II, August 28-31, 1974.
- 2) Echo-sounder speed of sound setting kept constant at 1470
- 3) No tidal corrections made.
- 4) Transducer draft compensated for.
- 5) UTM grid and geographical coordinates are approximate.
- 6) overlay onto Figure 3.3 a and b.
- 7) refer also to Appendix B: Notes regarding assembly of bat

km 1:10 000

190F

15.0

14.5

14.0

13.5

13.0

12.5

X

X

X

X

52000

176000

375000

31, 1974.

stant at 1470 metres/sec.

proximate.

sembly of bathymetric overlays.

200F

Figure 3.5, to accompany report: ICE SCOUR TRACKS
ON THE BEAUFORT SEA CONTINENTAL SHELF - their form
and an interpretation of the processes creating them;
by R.V. Wahlgren, Ottawa, 1978.

Figure 3.5 Bathymetry of 'Pullen Island'
mosaic area

210F21

GEOLOGICAL SURVEY OF CANADA

PULLEN ISLAND (Beaufort sea)

MARINE PHOTOMAP

Scale : 1/10,000

BEICIP-MARINE

March 1975

SHEET 1

Figure 3.3 (a)

Side-scan sonar mosaic used with
permission of the Geological
Survey of Canada and A.P.C.A.

124° 32'

778000

82000

810 000 70° 00' 134° 30'

7700 000

820 000

134° 28'

820 000

7700 000

70° 00'

134° 26'

7700 000

820 000

134° 36'

7769 000

696 000

69° 56'

7769 000

134° 34'

7787 000
877 000

69° 55'

7788 000

104° 52'

88100

7789 000

7758 000

134° 32'

522 000

7758 000

69° 54'

522 000

7758 000

69° 28'

GEOLOGICAL SURVEY OF CANADA

PULLEN ISLAND (Beaufort sea)

MARINE PHOTOMAP

Scale : 1/10,000

BEICIP-MARINE

March 1975

SHEET 2

Figure 3.3 (b)

Side-scan sonar mosaic used with
permission of the Geological
Survey of Canada and A.R.O.A.

7780000

830000

134' 14"

7780000

70' 0"

830000

7780000

7701000

824000

13° 22'

69° 57'

7780000

628000

L

+

+

)

6

601

7865 000

887 000

134° 22'

69° 57'

7780 000

830 000

7780 000

134° 20'

69° 56'

407 000

7 688 000

7 689 000

GEOLOGICAL SURVEY OF CANADA
EAST MACKENZIE (Beaufort S
MARINE PHOTOMAP

Scale : 1/20,000

BEICIP MARINE

March 1

408 000

SHEET 1

Figure 3.2 (a)

Side-scan sonar mosaic used with
permission of the Geological
Survey of Canada and A.P.O.A.

7 886 000

7 887 000

7699000

7701000

7703000

7708000

407000

408000

41000

Side-scan sonar mosaic used with
permission of the Geological
Survey of Canada and A.F.C.A.

411000

413000

415000

7883000

7881000

7883000

50F

+

+

)

W

60F

7685 000

7687 000

[Redacted]

[Redacted]

70F

7

491000

493000

495000

7705000

7705000

80F8

407000

7708000

7707000

7709000

408000

411000

77081000

7710000

7713000

7715000

7717000

140F

7718 000

772000

407 000

✓

+

408 000

+

41000

40F

150F

411000

413000

415000

708000

707000

700000

50F

160F16

60F

10F

+

+

1000

17000

70F

GEOLOGICAL SURVEY OF CANADA
EAST MACKENZIE (Beaufort Sea)

MARINE PHOTOMAP

Scale : 1/20,000

BEICIP MARINE

March 1975

Figure 3:2 (b)

SHEET 2

Side-scan sonar mosaic used with permission of the Geological Survey of Canada and A.P.O.A.

END

06 03 80

FIN