Environmental
Studies
Revolving
Funds

037

Evaluation of Sea Bottom Ice Scour Models

Canada

June 1986

ENVIRONMENTAL STUDIES REVOLVING FUNDS
REPORT NO. 037

JUNE, 1986

EVALUATION OF SEA BOTTOM ICE SCOUR MODELS

G. Comfort

B. Graham

Arctec Canada Limited
16-6325 11th Street S.E.
Calgary, Alberta, T2H 2L6

Scientific Adviser: Dr. Bruce Dunwoody

Comfort, G. and B. Graham. 1986. Evaluation of sea-bottom ice scour models. Environmental Studies Revolving Funds Report No. 037. Ottawa, 71p.

Published under the auspices of the Environmental Studies Revolving Funds
ISBN 0-920783-36-8

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Appendices

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the efforts of John Zevenhuisen, who was instrumental in assembling the individual sea-bed scour ground truth data sets.

The assistance provided by M. Lewis of the Bedford Institute of Oceanography and V. Barrie of C-CORE is also acknowledged.

SUMMARY

Seabed scouring by large draft ice features, such as icebergs and ice ridges, is of concern to the safety and integrity of proposed subsea petroleum transportation systems for the frontier regions. The determination of a "safe" pipeline protection system is required to allow development to proceed. An assessment of risk level versus pipeline protection specification is a necessary part of the economic pre-development prospect evaluation process.

Consequently, much research has recently been conducted on ice scours. Field measurement programs have been conducted to establish regional data bases on scour depth and frequency, as well as to provide detailed mapping of individual scours. In parallel, analytical studies have been undertaken to produce predictors of ice-scour depth using both statistical and deterministic analyses.

The primary objectives of this study were threefold:

- to evaluate available deterministic analytical models;
- to compare observed scours with model results; and
- to document ongoing ice scour research and to make recommendations on future research priorities.

The available field data were found to be incomplete from the viewpoint of supplying calibration data for deterministic models. Consequently, it was necessary in some cases to use baseline environmental data and to make assumptions to establish ranges which bounded the required data set. Data were compiled from the Bedford Institute of Oceanography for the Karlsefni K007, Caroline, and Frances groundings. Data were also available from Mobil Oil Canada for bergs #95 and #104 but could not be compiled in time to meet the project schedule.

Currently available deterministic models were reviewed, programmed and exercised with the compiled ground truth data sets. FENCO'S (1975) dynamic model and the work-energy models of Chari (1979) and FENCO (1975) (with modifications to include wind and current drag energies) were calibrated.

The available work-energy models are simplistic, one-degree-of-freedom treatments of the scouring process. Scour depths were generally overpredicted by these models, typically by a factor of two. The Chari (1979) model predicted greater scour depths, by a factor of about 20%, than did the FENCO (1975) model.

The FENCO (1975) dynamic model is a three-degree-of-freedom force balance analysis. This program is the most complete and sophisticated deterministic treatment that is currently available publicly. However, it contains numerous errors that need to be addressed before the model can be used with confidence. (These are described in the report). In some cases, the dynamic model predicts lift-off from the sea bed of the leading corner of the berg (which results in the prediction of a negative scour depth). Calibration studies done with the dynamic model are considered inconclusive for this reason.

Sensitivity analyses were conducted for both of these model types. The following parameters greatly affect the scour depth:

- iceberg kinetic energy
- iceberg motions during scouring
- soil resistance
- sea-bed bathymetry
- scour breadth
- pack-ice forces

Environmental loads applied to the berg during scouring from the actions of winds, waves, and currents are relatively small and hence relatively insignificant. Pack-ice forces, however, may be of much larger magnitude and require more careful consideration.

Continuing research was documented by surveying agencies known to be active in ice-scour research. Current work consists primarily of the establishment of regional repetitive survey ice scour data bases, the cataloguing of existing information on ice scour, the study of scour infill rates, the estalishment of risk levels for various burial depths, and the development of a sophisticated six-degree-of-freedom analytical model.

Research is required to understand the following problems related to ice scour:

- the establishment of risk levels for damage resulting from ice scour for various pipeline protection specifications;

- the prediction of soil pressures beneath the scour on buried installations; and

- the prediction of the scour potential for "special-cast" ice-soil interactions (such as the scouring of protective glory holes).

Deterministic models are considered to have a limited role to play towards the first objective whereas they are essential for the remaining two.

The available deterministic models suffer from inadequate treatment of the processes involved and from inadequate sets of field data for calibration. Therefore, research efforts need to be concentrated in these areas. A number of field-dedicated grounding experiments, ranging from studies of active and passive iceberg grounding to the conduct of a large-scale scour test by winching an ice feature into the sea bed are described for consideration.

RESUME

This report describes an analytical study which was undertaken to evaluate currently available deterministic ice scour models.

Ground truth data were compiled from the Bedford Institute of Oceanography for the Karlsefni K-007, Frances and Caroline groundings. It was necessary to complement all of these data sets with baseline environmental data in order that runs could be made with the deterministic models.

Currently available deterministic models were reviewed. FENCO'S (1975) dynamic model and the work-energy models of Chari (1979) and FENCO (1975) were calibrated.

The available work-energy models are simplistic one-degree-of-freedon treatments of the scouring process. Scour depths were generally overpredicted by these models, typically by a factor of two.

The FENCO (1975) dynamic model is a three-degree-of-freedom force balance analysis. This program is the most complete and sophisticated deterministic model that is currently available publicly. However, it contains numerous errors which need to be addressed before the model can be used with confidence. Calibration studies done with the dynamic model are considered inconclusive for this reason.

Sensitivity analysis were conducted for both model types. The scour depth is highly sensitive to the initial energy of the iceberg, the iceberg motions during scouring, the soil resistance and the seabed bathymetry. Environmental loads applied to the berg during scouring from the actions of winds, waves and currents are relatively insignificant. Pack-ice forces, however, may be of much larger magnitude and require more careful consideration.

The available deterministic models suffer from inadequate knowledge of the process involved and from inadequate sets of field data for calibration. Consequently, further research efforts are recommended towards these objectives. A number of field grounding experiments are described for consideration.

RÉSUMÉ

Le présent rapport fait état d'une étude analytique effectuée dans le but d'évaluer les modèles déterministes d'érosion des glaces présentement connus.

Des données confirmées avec le sol provenant de l'Institut d'océanographie de Bedford ont été compilées dans le cas des icebergs échoués Karlsefni K-007, Frances et Caroline. Toutefois, il a fallu les compléter par des données environnementales de base afin de pouvoir mettre à l'essai les modèles déterministes.

Les modèles déterministes présentement connus ont été analysés; le modèle dynamique de FENCO (1975) et les modèles travail-énergie de Chari (1979) et de FENCO (1975) ont été étalonnés.

Les modèles énergie-travail connus sont des traitements à un degré de liberté du processus d'érosion. Avec ces modèles, la profondeur de l'érosion a généralement été surévaluée, du double dans la plupart des cas.

Le modèle dynamique de FENCO (1975) est une analyse de l'équilibre des forces à trois degrés de liberté. Il s'agit du modèle déterministe le plus complet et le plus au point qui soit connu officiellement à l'heure actuelle. Toutefois, il comporte de nombreuses erreurs qui doivent être redressées avant de pouvoir l'utiliser en toute confiance. C'est pourquoi les études d'étalonnage effectuées avec ce modèle ont été jugées insatisfaisantes.

Les deux modèles ont été soumis à des analyses de sensibilité. La profondeur de l'érosion est extrêmement sensible à l'énergie cinétique initiale de l'iceberg, à son mouvement pendant l'érosion, à la résistance du sol et à la bathymétrie du fond

marin. Certaines charges environnementales appliquées aux icebergs pendant l'érosion provoquée par l'action du vent, des vagues et des courants, revêtent peu d'importance. Cependant, la force de la banquise peut être beaucoup plus importante et doit être considérée avec soin.

En somme, la connaissance de ces modèles déterministes portant sur les processus en jeu et l'ensemble des données d'étalonnage recueillies sur place est limitée. Par conséquent, des recherches supplémentaires sont recommandées afin d'atteindre ces objectifs. Un certain nombre d'expériences sur place portant sur les icebergs sont décrites à des fins de considération.

INTRODUCTION

Continued oil and gas exploration efforts in the offshore frontier regions have brought into focus the need for effective and economic transportation and production systems.

The presence in these regions of mobile, deep-draught ice features, such as icebergs and ice ridges, make protection of production system subsea pipelines and collector manifolds necessary. To carry out engineering design work on such production systems, and to assess the risk of damage associated with various pipeline protection specifications, it is necessary to understand probable scour depths in particular regions of interest. In addition, an understanding of the subsea installations by icebergs or ice ridge keels scouring process of is necessary to determine stresses on buried pipelines and to assess the likelihood of scouring in protective glory holes.

To gain knowledge in this area, a number of field measurement programs, laboratory tests, and analytical studies have been conducted in recent years. Field surveys have been undertaken to establish regional scour depth and scour frequency data bases, as well as to provide detailed mapping of individual scours. In parallel, several numerical predictors of risk have been proposed based on probable interaction senarios between ice feature and sea bed. Analytical treatments of the ice-scouring process, numerical statistical analyses, and laboratory test data have been used to fulfil this objective. To date, no attempt has been made to correlate field observations with the analytical model predictions.

The objectives of this study were threefold:

- to evaluate available deterministic analytical models;
- to compare observed scours with model predictions; and
- to document current ice-scour research and to make recommendations on future research priorities.

Some attention was given to the statistical methods found in a review of the relevant literature to provide a more comprehensive overview of the approaches in use. However, the study effort was concentrated on the assessment of currently available deterministic models, which were exercised and compared with a few available field measurements. Conclusions about the direction of future research were drawn based on this assessment and an evaluation of needs identified by current researchers and end users.

LITERATURE REVIEW

A literature review was conducted to document the public material available on analytical ice-scour modelling. It was initiated by searching the relevant data bases within the Canadian Institute of Science and Techology Index (CISTI library. The Arctic Institute of North America (AINA) library was also searched. Table 1 summarizes the data bases searched and the keywords used.

TABLE 1

LITERATURE SEARCH

Libraries and Databases Searched

Library	Database
CISTI	National Technical Information Service (NTIS) Engineering Index (EI) Canadian and International Government Documents (CODOC) University Research (IEC) Current CISTI Catalogue (OON)
AINA	Complete database

Search Keywords and Phrases

ICE GOUG*	MODEL*
ICE SCOR*	PLOUGH*
ICE SCOUR*	MATH*
ICEBERG GOUG*	NUMER*
ICEBERG SCOR*	ANALYT*
ICEBERG SCOUR*	PHYISICAL*
	SCALE*

* Indicates that any references with keyword in title will be flagged.

In general, the available material falls into the following broad categories:

- statistical analyses of probable ice-scour depths and spatial and temporal frequencies--this information is based upon field mappings of ice scours, and, in some cases, information over several years is available;

- deterministic of ice scour predictors that are based on theoretical assessments of the considered primary components of the scouring process--in some cases, small-scale laboratory test data have been used for calibration; and

- laboratory and field test data which have been used to assess soil behaviour and resistance in other interaction scenarios--these include the action of agricultural and earth-moving implements which plough or bulldoze the soil, and earthen embankments that resist retaining walls by passive pressure.

Relevant paper were reviewed, and summaries for selected papers are provided in Appendix A.

STATISTICAL ANALYSES

Statistical analyses of probable ice-scour depths and spatial frequencies have been produced by several investigators (e.g. Pilkington and Marcellus 1981 ; Weeks et al. 1983); based on measured scour-depth distributions. Extreme-value methods generally have been used to assess probable scour depths and frequencies. This information is valuable for understanding the levels of scour risk and for the specification of "safe" burial depths for pipelines. As discussed later, these analyses suffer from a number of limitations, including uncertainties regarding short-and long-term infill rates, and difficulties in differentiating between new and relict scours. Also, field data on scour have not been systematically gathered over time to apply with confidence. For the purposes of this study, the available analyses are useful only as a gross verification of the scours predicted by the available deterministic ice-scour models.

DETERMINISTIC SCOUR MODELS

Several relevant analytical treatments of ice scour were located in the literature. These models are reviewed in some detail in the section 4 "Review of avilable ice-scour models."

In support of the development of these models, some small-scale laboratory tests of ice scour have been carried out (E.G., Chari 1979, Abdelnour et al. 1981;) to investigate soil resistance during scouring events. During these tests, cross-sectional shapes representative of the keel of an ice ridge or an iceberg were used. Large soil deformations occurred during the tests, and the surcharge deposition geometry was evaluated. Also, some of these tests were carried out in submerged conditions.

Chari and co-workers (Chari 1979; Chari and Green 1981) conducted laboratory tests in an attempt to calibrate their theoretical formulation by verifying the nature and type of soil resistance forces. Tests were conducted in cohesive and cohesionless soils to assess the applicability of the theory of rigid- and pastic-limit equilibrium in passive soil resistance. In cohesive soils, this theory underpredicted the laboratory results by about 30%. For cohesionless soils, there was better agreement, as the theoretical values were found to underpredict the measured forces by about 10%. Chari's model is discussed in "Revew of available ice scour models.".

The test results of Abdelnour et al. (1981) have not yet been incorporated into an analytical model. Their tests data showed the soil resistance in sand to be proportional to the soil density, scour depth, and scour width. In silt and clay, the soil cohesion was an additional parameter. In sand, the scour force increased with increasing velocity, whereas the reverse was true for silt and clay. The measured soil resistances in sand were higher, by a factor of about two, than those predicted by Kovacs (1974), who used a rigid- and plastic-limit equilibrium analysis to estimate the frontal bulldozing soil resistance in.

The significance of the physical model studies conducted to date is difficult to assess. As soil behaviour is dependent upon the effective state of stress in the soil, scaled model tests are difficult and generally impractical. Towards this end, centifuge testing has been used at small scales to investigate soil behaviour. However, this testing is difficult to perform at large scales. Also, for purely cohesive soils,useful small-scale tests may be conducted by scaling the stress path, provided this is known. However, in general, scaled physical model tests in soils are not possible. Therefore, laboratory testing must be viewed as small-scale field tests. Laboratory tests, along with field data, have been used in other soil mechanics applications (e.g., retaining walls) to guide the development of soil resistance formulations. However, in the case of ice scour, there are insufficient field data to corroborate the laboratory test results.

FAILURES OF SOILS AND INTERACTING MATERIALS

Scenarios in which interaction has led to the progressive failure of soil material or, where pastic, failures of other materials were considered to have potential for providing insight into the scouring process. Consequently, consideration was given to a large number of interactions for which field and laboratory tests data have been collected.

Many studies have been conducted on cutting, grinding, and ploughing actions in soils as related to agricultural equipment, maring anchors, and coal ploughing, for example. These results are considered to be of limited application to the ice-scour problem, because these tests involve lifting and cutting of the soil by various ram shapes that are significantly different from those of an ice feature.

Laboratory test results of soil passive resistance on retaining walls have more application, although soil deformations are typically significantly less for a retaining wall than for the ice-scour case. In addition, laboratory test results for the retaining wall do not provide information on soil surcharge deposition and resistance. However, these data are of interest for the large wall-movement case, which is the most analogous to the ice-scour interaction. For large deformations, the test results (e.g., Lee and Herrington 1972) correlate well with theoretical, passive pressure, coefficient values and with theoretical, rigid plasticity solutions. This indicates that rigid pasticity analyses may be applicable, provided the ultimate state is reached along the rupture surface, as would be the case for an iceberg scouring the ocean floor. Furthermore, it is noted that progressive failures are likely because of non-uniform strain conditions in the soil mass, and, hence, it would be unacceptable in practice to use peak values for shear resistance in determining the passive resistance of the soil.

Finally, the Mohr Hardness test for metals was considered as a possible source of insight. Approximate plasticity solutions are available to describe the mechanics of this scratch hardness test and to predict the force on the tip of the ram. However, soild behaviour in the ice-scour case is more complex because of a number of factors. For example, the application of shear stresses will cause changes in soil volume. As well, most soils experience strain-softening behaviour after peak strength has been obtained. Consequently, these analytical treatments were considered of limited value.

REVIEW OF AVAILABLE ICE-SCOUR MODELS

Several types of analytical ice scour predictors are available in the literature. These may be broadly categorized as:

- statistical or probabilistic predictors based on field measurements--to date, these have been used to estimate risk levels associated with various submarine corridor protection specifications.

- Deterministic analytical treatments of the iceberg-soil interaction process.

Both of these treatments have inherent limitations. Consequently, it is desireable to seek a convergence of methodologies to establish risk levels for various specified burial depths with some confidence.

Several probabilistic predictors have been proposed (e.g., Pilkington and Marcellus 1981; Weeks et al. 1983) which are based on measured scour-depth distributions, and sometimes a combination of measured ice feature statistics and scourdepth distributions. Allen (pers. comm., 1984) has used berg flux and iceberg keel distribution data to assist in verifying and establishing risk levels obtained from measured ice-scour statistics. This approach is similar to that of Pilkington and Marcellus (1981), who proposed a method based on measured distributions of ridge keel depths and measured ice scours to establish risk levels for the Canadian Beaufort Sea. These treatments suffer from a number of uncertainties.

a) Ice-scour data have not been systematically gathered over time, making statistical analyses difficult to apply with confidence.

b) There are uncertainties regarding short- and long-term infill rates, which causes difficulties in interpretation of the field survey data. This is especially true for the Beaufort Sea, where infill rates may be high because of the presence of relatively weak surficial soils and shall water depths. Infill rates for the Hibernia area off Canada's east coast are expected to be low (Barrie 1985). For the Beaufort Sea, infilling is expected to be primarly a periodic phenomenon, occurring during major storms. The rate of infilling is also expected to depend on the water depth.

c) There are uncertainties in differentiating between new and relict scours.

Thus, statistical predictors based solely on measured scour depth distributions need to be used with caution. The use of complementary statistical data on ice features improves the reliability of this approach and seeks a convergence of methodologies. Unfortunately, there are also uncertainties in our knowledge of ice feature distributions and flux rates which limit the reliability of the combined ice keel/scour statistics method.

On the other hand, deterministic models are rleatively simplistic at present, and suffer from inadequate knowledge of the processes involved. The application of deterministic models to provide probabilistic estimates of scour depth is further hindered by inadequate knowledge of the distribution of required input parameters (e.g., ice feature sizes and shapes, winds, waves, currents, and pack-ice driving forces).

In general, deterministic models consider the interaction of three factors:

- environmental driving forces
- soil reactive forces
- energy sinks related to the hydrodynamics and hydrostatics of the ice feature creating the scour

Figure 1 described schematically the interaction of these factors.

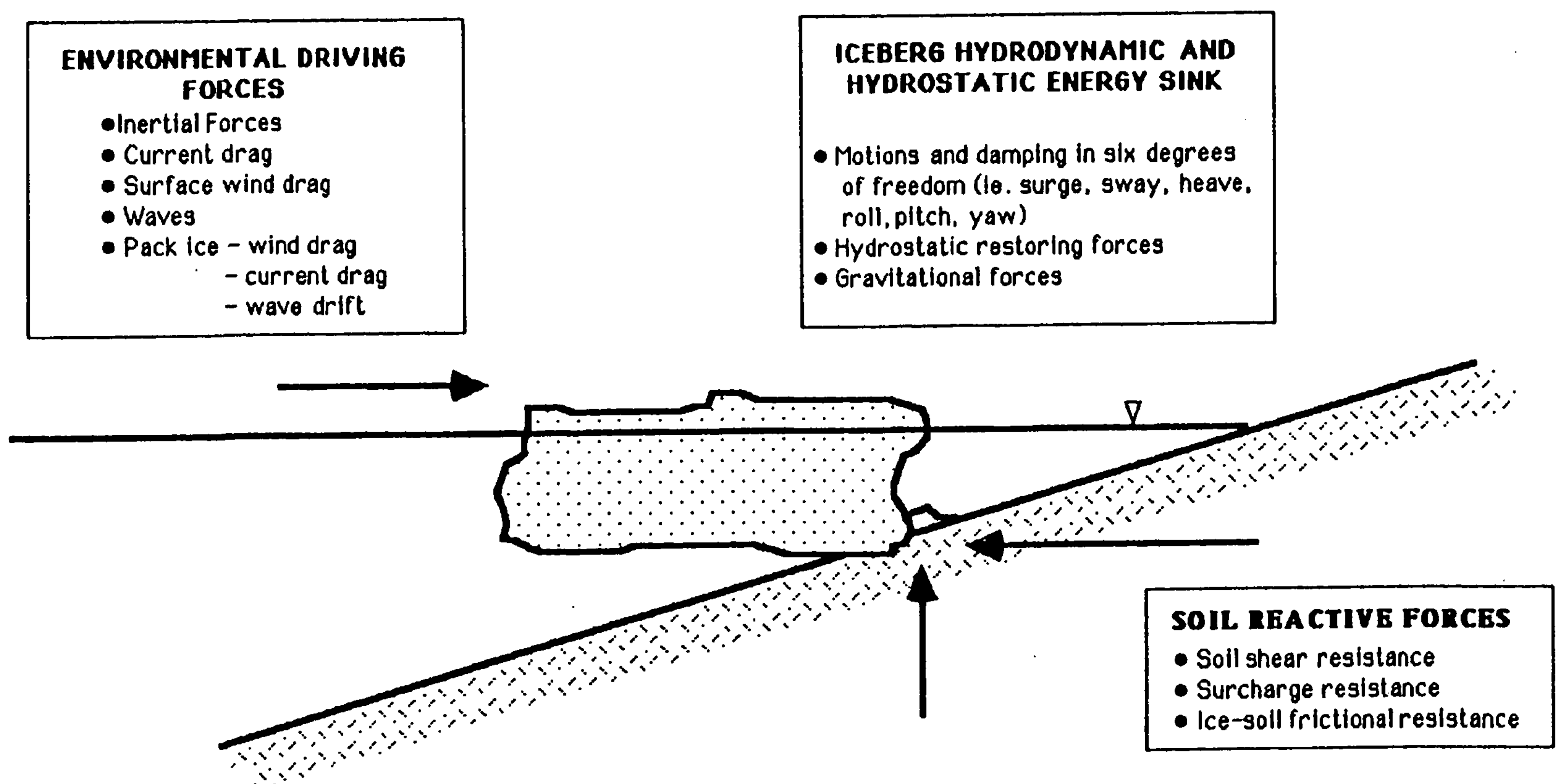
A detailed analysis of the interaction of these factors is beyond the scope of this project. However, a brief overview is presented here.

Environmental driving forces may be considered to originate from the actions of winds, waves, currents, and pack ice (if present). Resultant forces, in most cases, depend upon the interaction and upon the relative directions and magnitudes of these components. Surface wind-generated currents may oppose deep-water currents, which include an oscillatory tidal flow component. Pack ice will signficantly affect the applied environmental driving forces, as these loads may be of high magnitude in relation to the others. Also, pack ice will attenuate wave forces acting on the ice feature.

For the purposes of deterministic modelling, environmental driving forces may be considered to impose the following two general types of loads:

- inertial forces necessary to decelerate the ice feature
- forces applied to the ice feature during the scouring event.

FIGURE 4.1
SCOUR INTERACTION SCHEMATIC



The reactive forces are commonly assumed to be limited by the strength of the ocean sediments. However, for linear ice features, such as multi-year ice ridges, the force applied to the sea bed may be limited by flexural failure of the ice.

Soil reactive forces are complex because of the dynamic nature of the interaction. The soil penetration resistance is dependent on the geometry of the keel, the soil properties under short-term loading, and the soil failure plane. The resistance contributed by the soil surcharge is a function of the surcharge geometry and the remolded stregnth of the soil. Also, the frictional component of the soil resistance along the bottom and sides of the ice feature depends upon the soil properties and the nature and magnitude of the contact stresses (which are related to the environmental driving forces and the motions of the iceberg).

The hydrostatic and hydrodynamic restoring forces resisting iceberg motions are another energy sink which affects the ice scour produced. These forces depend on the shape of the ice feature and on the location and magnitude of the applied forces.

Presently available deterministic models may be generally categorized by technical approach, as follows:

- force-balance treatments
- work-energy treatments
- limiting scour-depth approaches.

These deterministic model types are reviewed in the following sections.

FORCE-BALANCE MODELS

Model Description

Two force-balance models are available in the literature, and are described in APOA 69 (FENCO 1975). These are the "dynamic solution" and the "minimization solution".

Dynamic solution. The "dynamic solution" is a dynamic equilibrium analysis that solves the differential equation of motion numerically for the berg in a time series manner, using a Runge Kutta fourth-order method, for all applied external forces (i.e., wind, wave, soil, pack ice, and currents). Further description of this model folows:

a) Two models for predicting the vertical soil reaction are presented. The plastic model assumes that the soil reaction is the product of the soil's ultimate bearing capacity and the effective area. The elastic model estimates the soil's spring constant, which is a function of penetration depth, and obtains the reaction. It is further noted that the elastic model should be considered to be valid for a settlement up to 0.6m (2 ft.), and the plastic model should be employed beyond 0.6m (2 ft.).

b) The horizontal soil reaction is determined by assuming the soil passive pressure to be fully mobilized. It is calculated using a trial wedge solution with a plane failure surface (Coulomb's assumption). Friction between the ice--soil interface is neglected. The surcharge is assumed to contribute to the overall passive resistance, but is considered to have no shear resistance as it is remolded.

c) Wind, wave, current, and pack-ice force are calcuated term by term in the model. However, when the pack-ice force is taken into consideration, wind and wave forces are ignored (assumed to be zero), as waves are attenuated by the pack--ice, and the magnitude of these forces is significantly less than the pack-ice force. Pack-ice force, when included, is taken to the 720 kN/m (50 kps/ft.).

d) Noting that current drag and wind drag forces build during the grounding to a maximum value at the end of the event, the model calculates these forces at intermediate time steps by reducing the maximum value by a factor which varies as the square of the velocity of the feature relative to that of the current or the wind speed, respectively.

e) Three degrees of freedom are allowed for the ice feature: surging, heaving, and pitching. The added masses and moment of inertia resulting from hydrodynamic effects are included in the equations of motion.

f) The model is two-dimensional, with the iceberg shape assumed to be rectangular and the scour width taken as being equal to the berg width. Some general suggestions are provided in the report for consideration of bergs with limited keel width. However, no provision is made in the program for ice features of limited keel width.

g) Soil friction at the sides of the ice feature is mentioned but not considered.

h) Constant sea-bottom slope is assumed, and changes in sea--bed topography are not considered. One way to take this into account with the model is to divide the sea-bed into a series of secants, and consider the scouring process section by section, with initial conditions (e.g., velocity location) taken as the conditions at the end of the previous section.

Minimization solution. The minimization solution is a static equilibrium analysis. It assumes that the berg is always in static equilibrium, and that the scour path cut by the berg is the one requiring the least driving force. This model solves the three equations of equilibrium with the environmental forces being treated as a variable, and hence calculates the equilibrium scour depth for a constant sea-bed slope for a given environmental force magnitude. The passive resistance across the face of the iceberg is computed in a manner similar to the dynamic model described previously. The base reaction is computed using either elastic subgrade reaction theory or an elasto-plastic representation of the soil's load-deflection curve. The equations of equilibrium are solved iteratively, and have been programmed for computer solution to obtain the minimum force required to displace the iceberg over a given amount of penetration. The path of the iceberg represents the path of least resistance during grounding.

This model is difficult to apply to a dynamic grounding event (in which a berg comes to rest in the sea bed), because analysis may be applied only for a specified environmental force nagnitude. Also, the minimization solution neglects inertial forces necessary to decelerate the berg. As these were found to be highly significant, (see "Dynamic Model Sensitivity Analysis)", the minimization solution is considered to be an overly simplistic treatment of the scouring process. Consequently, it was decided to program and exercise the dynamic solution only for subsequent calibration studies.

Dynamic Model Programming Problems

A number of problems were encountered in programming and exercising the dynamic model. The program is not well documented, and the user is forced to enter the source code to understand the program's operation and output.

Modifications were made to the program as required, and are summarized below. A complete listing of the program used, with the modifications made to the program listed in FENCO (1975), is available from Arctec Canada on request.

a) For the program to execute and to duplicate the sample results listed in APOA 69 (FENCO 1975), it was necessary to add statements limiting the value of the intermediate time step wind drag and current drag forces (see item (d) in "Force-balance models--Dynamic solution" to the maximum value at the end of the souring event. The numerical instability that occurred with the original program may have resulted from differences in round-off and truncation procedures between the two computers used.

b) Modifications were also made to allow the program to be run for the case when pack ice was not present. (The original version internally set the pack-ice force at 720kN/m (50 kips/ft) and the forces for wind drag and current drag to zero in all cases.) Statements were added that allowed the pack-ice force to be read in, and that built in program logic to use the correct values of wind--drag and current-drag force when pack ice was not present (i.e., the pack-ice force was equal to zero). The original program logic was maintained for the case when pack ice was present.

c) Both an elastic and a plastic soil model are presented in FENCO (1975) for the computation of vertical soil reactions, and are built into the dynamic model program. However, it was possible to run the dynamic model only with the elastic soil model. Documentation provided in APOA 69 indicates that the plastic soil model may be selected by setting input parameter KM equal to 2; however, no input parameter labelled as KM was found in the program listing.

   Attempts were made to run the plastic soil model by relabelling the appropriate call statements from "CALL SOREL" (which is the subroutine name for the elastic model) to "CALL SOREC" (which is the subroutine name for the plastic model), with the same parameter list. This change was unsuccessful, as the program stopped execution after two iterations with a "mode error."

d) The force polygon on page 90 of APOA 69 has been formulated on the assumption that downward relative motion between the iceberg and the soil occurs. The angle between force P and the horizontal plane was labelled as "90-(+)" where - is the inclination of the front face of the iceberg to vertical and - is the ice-soil friction angle. This angle should be "90-(- - -)". Correction of this error involved several programming changes. This modification is only of significance for cohesionless soils where Delta is non-zero.

Despite the above problems, the FENCO dynamic model is the most sophisticated, deterministic, sea-bed scour model now available in the public domain.

However, as will be detailed in "Model calibration studies", several inconsistencies were noted in the results obtained with the dynamic model. In some cases (e.g., the Frances grounding and the K007 grounding), the berg was predicted to lift off the sea bed, and, consequently, a negative scour depth was predicted. In other cases (e.g., the K007 and the Caroline grounding), the model predicts results that are inconsistent with intuition and with the results obtained from senstivity runs (discussed in the next section). As an example, lower scour depths are predicted for increased berg drift rates and for increased bed+slopes relative to those used in the base case for the K007 grounding.

As a detailed analysis and debugging of the FENCO model could not be undertaken in this project, it is not possible to provide definite reasons for these inconsistencies. However, it is recommended that the following areas be checked by subsequent users and investigators.

The program uses a Runge-Kutta fourth-order approximation method to solve the equations of motion for each time step. FENCO (1975) notes that numerical instabilities and inaccuracies may occur with this method for time steps greater than about 2 s. Consequently, a value of 2 s is built into the FENCO program. A reduced time step may be advisable.

As well, the program outputs the values of the berg displacements and velocities only at every tenth time step. The berg displacements at the final time step (which occurs when the berg velocity is less than 2% of the initial value) are not output. Because berg velocities are typically low at the last output time step, the magnitude of this error is expected to be small and within the range of other calibration data errors. Consequently, the program output was not changed. However, this may contribute to some of the inconsistencies observed in runs done for sensitivity analysis purposes, in which all of the predicted scour-depth magnitudes were relatively low.

Because no intuitive inconsistencies were noted in the runs made only to test the model's sensitivity to various input parameters, it was decided to consider these results to be reliable. The sensitivities are discussed in detail in the following section.

Dynamic Model Sensitivity Analysis

<u>Sensitivity analysis base case</u>. To study the relative significance of each input variable on the predicted scour depth, a total of 15 sensitivity runs was performed.

The base case was chosen to represent an average condition on the Canadian east coast. The mass of the iceberg was selected as 1.3 million tonnes. As required by the dynamic model, the berg was assumed to be a rectangular block. The correlations developed by Hotzel and Miller (1982) for tabular bergs were used to predict berg dimensions for the selected iceberg mass.

Sea-bed conditions are highly variable. For the base case, a sea-bed slope of 1.2° was assumed. The soil was assumed to be a pure sand. Lambe and Whiteman (1969) suggested a range of friction angles of 26 - 36° for loose to dense sand, with an elastic modulus (E) between 2,000 and 5,000 psi. For the base case, a median friction angle of 30° was chosen, with E linearly interpolated between 2,000 and 5,000 psi. The friction angle between ice and soil was taken as 4° less than the soil friction angle. A value of 0.33 was used for Poisson's ratio.

The wind speed was taken as 20.5 fps, which is the average value from available MAST information and the wave height of 11.5 ft. was taken from an analysis of MEDS information from AES. The initial iceberg drift rate was taken as being equal to the current velocity, and fixed at 1.69 fps (1 kt).

<u>Sensitivity analysis results summary</u>. Table 2 describes the sensitivity analysis conducted for the dynamic model. Table 3 summarizes the observed sensivitities. Appendix B provides a complete listing of the sensitivity analysis results. For the base case, a scour depth of 4.8 ft is predicted. It is important to note that this model assumes a rectangular berg cross-section (in both the longitudinal and transverse planes), and therefore the breadth of the predicted scour is equal to the berg width (which has been taken to be 320 ft. The following discussion further details the observed sensitivities.

TABLE 2
FENCO Dynamic Model Sensitivy Runs

Run Description	Parameter value	Base Case value	Changed value	Predicted output: Scour length (ft)	Berg lift (ft)	Scour depth (ft)
Base case	-	-	-	224.2	-0.1	4.8
Loose sand	Soil friction angle (°)	30	26	245.0	-0.1	5.2
	Ice-soil friction angle (°)	26	22			
	Soil sub. wt. (pcf)	51	46			
	Soil elastic mod. (psf)	460,000	288,000			
Dense sand	Soil friction angle (°)	30	36	188.3	0.0	3.9
	Ice-soil friction angle (°)	26	32			
	Soil sub. wt. (pcf)	51	61			
	Soil elastic mod. (psf)	460,000	720,000			
Weak cohesive	Soil friction angle (°)	30	0	69.6	-0.8	1.5
	Ice-soil friction angle (°)	26	0			
	Ice-soil adhesion (psf)	0	150			
	Soil cohesion (psf)	0	150			
	Soil elastic mod. (psf)	460,000	14,400			
Strong cohesive	Soil friction angle (°)	30	0	24.6	-0.3	0.8
	Ice-soil friction angle (°)	26	0			
	Ice-soil adhesive (psf)	0	500			
	Soil cohesion (psf)	0	500			
	Soil elastic mod. (psf)	460,000	28,800			

TABLE 2 (Cont'd)

Run Description	Parameter value	Base Case value	Changed value	Predicted output: Scour length (ft)	Predicted output: Berg lift (ft)	Predicted output: Scour depth (ft)
Changed bedslope	Bedslope (°)	1.2	5	87.3	-0.1	7.7
Pack ice Force included	Pack ice (lb/ft)	0	50,000	393.4	-0.7	8.3
Current and berg drift rate increased	Current (ft/s)	1.69	3.38	355.3	-0.2	7.6
	Initial berg velocity (ft/s)	1.69	3.38			
Increased wave height	Wave height (ft)	11.5	49	315.9	-0.4	7.0
Increased wind speed	Wind speed (ft/s)	20.5	175	225.2	-0.1	4.8
Decreased berg width	berg width (ft)	320	80	225.2	0.0	4.7
Decreased berg mass	Berg length (ft)	400	315	191.3	-0.1	4.1
	Berg width (ft)	320	232			
	Berg depth (ft)	360	269			
Increased soil roughness	Soil surface coeff.	0.002	0.004	224.2	-0.1	4.8
	Ridge intensity factor	0.02	0.04	224.2	-0.1	4.8
	Soil form roughness drag coeff.	0.4	0.6	224.2	-0.1	4.8
Increased current drag	Keel drag coeff.	0.5	1.0	224.2	-0.1	4.8
Increased soil Poisson's ratio	Poisson's ratio	0.33	0.5	224.5	-0.1	4.8

TABLE 3
Dynamic Model Sensitivy Analysis Summary

PARAMETER VARIED	INPUT PARAMATER VARIATION	PREDICTED SCOUR DEPTH VARIATION (ft)
Sea-bed properties		
Sand: loose - dense	See Table 2	3.9 - 5.2
Clay: weak - strong	See Table 2	0.8 - 1.5
Bedslope	1.2 to 5.0	4.8 - 7.7
Poisson's ratio	0.33 to 0.5	No change from base case
Environmental forces		
Pack-ice force (kip/ft)	0 - 50,000	4.8 - 8.3
Current speed and berg (ft/s) drift rate	1.69 to 3.38	4.8 - 7.6
Wind speed (ft/s)	20.5 - 175	No change from base case
Wave height (ft)	11.5 - 49	4.8 - 7.0
Current drag coefficient	0.5 - 1.0	No change from base case
Sail form drag coefficient	See Table 2	No change from base case
Iceberg dimensions		
Berg width (ft)	320 - 80	4.8 - 4.7
Berg mass (million tons)	1.3 - 0.5	4.8 - 4.1

Notes: All input parameter variations listed above are with respect to the base case, except for the runs done to investigate the effects of sand friction angle and clay cohesion. The base case was taken as a medium sand with an internal friction angle of 30°.

As outlined previously, deterministic ice-scour models consider the interaction of three basic factors:

- soil-reactive forces applied to the ice feature that resist the scouring motions;

- driving forces that push the ice feature into the sea bed; and

- hydrodynamic and hydrostatic restoring forces resulting from ice feature motions that act as an energy sink.

The sensitivity analysis has provided information on both the relative importance of these interaction factors and the relative significance of the individual components comprising the above factors.

Soil reactive forces limit the scours produced in the sea bed. As will be quanitified subseuqnetly, the predicted scour depth was found to be approximately inversely proportional to the magnitude of the total horizontal soil resistance. Ranges of loose-to-dense cohesionless soils and weak-to-strong cohesive soils were considered. Deeper scours were predicted for cohesionless soils. The soil shear strength (i.e., cohesion and/or friction angle) was found to significantly affect the total soil resistance and, hence, the scour depth. Also, the total soil resistance is dependent upon the with of scour. However, the scour width cannot be independently varied from the iceberg width in the FENCO dynamic model, and, consequently, the sensitivity analysis conducted cannot provide quantitative information. From the sensitivity analyses conducted for the work-energy models and an analysis of the soil passive-resistance equation, an approximate inverse square relationship is expected between the scour depth and the scour breadth.

As would be expected, the predicted scour depth increased for increasing driving force levels. Driving forces are composed in general terms of inertial forces necessary to decelerate the ice feature and environmental loads (e.g., wind, wave, current, and possibly pack-ice forces) applied to the ice feature during scouring. Of these two components, the inertial forces were concluded to be more significant for the typical iceberg scour case. The inclusion of pack-ice forces and wave forces was also found to be important, as these forces may significantly increase the environmental loads and, hence, the total driving force.

The motion ice features during scouring also significantly affects the scour depth. The FENCO dynamic model allows the ice feature three degrees of freedom (i.e., heave, pitch, and surge). This cannot be varied in the program.

Consequently, only a qualitative understanding of the significance of berg motion energy sinks could be obtained. This was done by comparing the scour depths predicted by the dynamic model with those predicted by the work-energy models (which allow the berg to translate in the horizontal plane only). Scour depths predicted by the FENCO dynamic model were about 30% of those predicted by the work-energy models.

Detailed discussion of sensitivity analysis results.

(A) Sea-bed Properties

a) Soil shear strength and resistance - The shear strength of the soil significantly affects the predicted depth of scour. Scour depth variations of about 33 and 50% are predicted for cohesionless and cohesive soils, respectively, over the range of shear strengths tested. (See Table 2 for range of values.)

The total soil resistance to scouring is composed of several components, including the shearing resistance, the gravity component associated with the material's density, and the frictional resistance along the sides and base of the iceberg. As well, the surcharged material contributes to the total soil resistance.

Hence, the results of this analysis cannot be used directly to determine the sensitivity of the predicted scour depth to the total soil resistance. For the above-described sensitivity runs, the variations in soil resistance shown in Table 4 resulted.

TABLE 4
Variations in Soil Resistance: Dynamic Model Sensitivity Analysis

Case Description	Horizontal Soil Resistance (kip): Passive Pressure Component	Base Reaction Component	Total	Vertical Soil Resistance (kip): Passive Pressure Component	Base Reaction Component	Total
Base case	1,269	1.589	2,858	-616	+3,274	+2,658
Loose sand	1,392	1,323	2,605	-559	+3,021	+3,580
Dense sand	1,063	2,307	3,370	-661	+3,710	+3,049
Weak Cohesive	897	4,345	5,242	-252	+3,927	+3,675
Strong Cohesive	2,318	23,150	25,468	-765	+20,890	+20,125

Notes: 1. See Table 2 for case description parameter listings.
2. The above forces are the maximum values (which occurred at the end of the interaction).

The predicted scour depth is expected to be related inversely to the total soil resistance. The sensitivity analyses support this expectation, and the relationship between scour depth and soil resistance is shown in Table 5.

TABLE 5
Scour Depth Versus Horizontal Soil Resistance Sensitivity for Dynamic Model

Case Description	Predicted scour: Depth (ft)	Predicted scour: % change from base	Total horizontal soil resistance: Magnitude (kip)	Total horizontal soil resistance: % change from base case
Base case	4.8	-	2,858	-
Loose sand	5.2	+8	2,605	-9
Dense sand	3.9	-19	3,370	+18
Weak Cohesive	1.5	-69	5,242	+83
Strong Cohesive	0.8	-83	25,468	+790

b) Bedslope -- For shallow bedslopes, the frictional components of the soil resistance may become large, whereas the shearing resistance and gravity components will become more predominant for steeper slopes. In general, however, the scour depth is expected to increase for increasing bedslope. During the sensitivity analysis, the bedslope was varied only for the base case (which is a median cohesionless soil). This analysis showed that the scour depth is expected to increase by a factor of 1.6 for an increase in bedslope of about fourfold.

(B) Driving Forces

As noted previously, driving forces are another major component of deterministic models, and act to push the ice feature into the sea bed. For modelling treatment purposes, these forces may be generally divided into inertial forces (which are necessary to bring the ice feature to rest) and environmental loads imposed during the scouring event (which occur as a result of wind, wave, current, and pack-ice forces). All these components were varied to obtain some understanding of their relative significance. Environmental loads were varied as shown in Table 6.

TABLE 6
Environmental Load Variation During Sensitivity Analyses

Case Description	Magnitude of Parameter Variation	Wind Force on Top (kip)		Wind Force on Side (kip)		Current Drag Force (kip)		Wave Force (kip)		Pack-Ice Force (kip)		Total Driving Force (kip)	
		Horiz.	Vert.	Horiz.	Vert.	Horiz.	Vert.	Horiz.	Vert.	Horiz.	Vert.	Horiz.	Vert.
Base	-	0.75	0	6.25	0	143	0	543	0	0	0	693	0
Pack-ice force increase	0 - 50 kip/ft	0.73	0.01	6.96	0	0	0	0	0	16,000	0	16,008	0.01
Increased current and drag drift rate	1 - 2 kts	0.75	0	6.45	0	575	0	547	0	0	0	1,129	0
Increased wave height	11.5 - 49 ft	0.73	0	6.61	0	139	0	9,675	0	0	0	9.821	0
Increased wind speed	12 to 104 kts	55.4	0.1	465	0	145	0	551	0	0	0	1,216	0.1
Increased current drag coefficient	0.5 - 1.0	0.75	0	6.28	0	287	0	545	0	0	0	839	0

Notes: 1. See Table 2 for case parameter values.

2. Magnitude of parameter variations are with respect to the base case.

3. Above forces are those at final time step.

As would be expected, the predicted scour depth increases with increasing environmental load levels, as shown in Table 7.

TABLE 7

Total Environmental Load Levels: Dynamic Model Sensitivity Analysis

	Predicted Scour Depth		Total Environmental Load Level (kip)	
Case	Magnitude (ft)	% Change from base case	Magnitude (kip)	% Change from base case
Base	4.8	-	693	-
Pack-ice force increase	8.3	+73	16,008	+2,200
Increased current and berg drift rate	7.6	+58	1,129	+ 63
Increased wave height	7.0	+46	9,820	+1,400
Increased wind speed	4.8	0	1,216	+ 75
Increased current form drag coefficient	4.8	0	839	+ 21

However, the sensitivity analysis results have shown that the predicted scour depth is relatively insensitive to the total environmental load level. (An increase in driving force of more than 22-fold is necessary to double the scour depth.)

The sensitivity analysis has also provided information on the relative significance of the components that make up the driving force during scouring.

a) Currents and berg drift rate - A relatively large increase in scour depth (i.e., +58%) was predicted for the increased current and berg drift rate case, although the increase in total environmental driving force was relatively small i.e., +63%). However doubling the current form drag coefficient produced no change in predicted scour depth. Because the berg was assumed to drift at the current speed, the effect of doubling the current speed was both to increase dramatically the inertial force component of the driving forces (as the berg's initial kinetic energy was quadrupled) and to quadruple the current drag force. When the current-drag coefficient was doubled, only the current drag forces were increased proportionately.

As may be seen from Table 6, both of these sensitivity runs produced relatively small increases in the total environmental loads applied to the berg during scouring. Thus, it is concluded that the relatively large increase in scour depth predicted in the case of increased current and berg drift rate stems predominantly from an increase in the inertial force component of the total driving forces. This indicates that, for this case, inertial forces are a much greater component of the total driving force than are the environmental loads applied during scouring.

This observation is expected to change somewhat for the multi-year ice-floe scour case. In this interaction, the current-drag (and also wind-drag) forces act over a larger area, and hence reach considerably greater magnitudes. The inertial forces would also increase, as the ice mass would generally be increased. However, icebergs are typically thicker in relation to their horizontal cross-sectional area than are ice floes. For a multi-year floe of 10-km diameter and 15-m thickness, the current-drag and wind-drag forces would act over about 6,700 times more surface area than for the iceberg base case used in the sensitivity analysis. This multi-year floe would have only about 900 times more mass than would the iceberg base case. Thus, it can be seen that the environmental loads during scouring would constitute a larger proportion of the driving force in this case.

b) Wave height - The analysis shows that the scour depth is relatively sensitive to the wave height. This is to be expected, as the environmental driving forces were significantly increased by an increase in wave height. The scour depth is predicted to increase by 46% for an increase in wave height of about fourfold. This increased the total environment loads by about 13-fold.

c) Wind speed - The wind speed was increased by a factor of about 9. As would be expected from analysis of the change in total environmental loads that resulted, this had negligible effect on the predicted scour depth. Hence, the scour depth was also insensitive to the range of values selected for the form-drag and skin-drag coefficients (see Table 2).

As discussed previously, this observation is expected to change somewhat for the case in which scours are created by multi-year ice floes. In this interaction, wind stresses act over a larger area and reach larger magnitudes. Consequently, the scour depth is expected to be more sensitive to the wind speed in this case.

d) Pack-ice forces - The magnitude of ridge-building forces is very poorly understood at present, and the range of estimated values spans two orders of magnitude, from about 0.01 to 1 MN/m (Croasdale 1984). The value selected for the sensitivity analysis was 50 kip/ft (0.7 MN/m). Thus, the analysis is expected to be somewhat conservative in that the observed sensitivity to pack-ice forces is expected to be close to the maximum value. As shown in Table 4, pack-ice force magnitudes may represent a very large proportion of the total environmental loads, and, consequently, the scour depth is very sensitive to the presence of pack ice. Therefore, it is expected that scouring in the greatest conditions would produce the design condition. This has the greatest implication for the Beaufort Sea area, where pack-ice movements are common.

(C) Ice feature dimensions

Sensitivity runs were made to investigate the effects of ice feature breadth and mass on the scour depth. From these runs, attempts have been made to infer the significance of scour breadth and inertial force magnitudes on the scour depth.

a) Iceberg breadth and scour breadth - The iceberg breadth appears to have negligible effect on the predicted scour. (A scour depth decrease of 2% was predicted for a berg breadth reduction of 7%.) This is not unexpected, as the dynamic model is two-dimensional, and, consequently, the line load, environmental, driving forces and soil reaction forces have not been significantly changed.

However, the effect of scour breadth on scour depth is known to be more significant. Unfortunately, the scour breadth and the iceberg breadth cannot be independently varied in the program. Presently the dynamic model can only analyze a rectangular ice feature shape and the resulting scour breadth is assumed equal to the berg breadth. This is considered to be a major shortcoming of the model. In order to obtain some gross understanding of the probable relationship, the equation of soil passive pressure was considered. From this predictor, the following approximate relationship between the scour breadth (B) and the scour depth (D) is expected:

$$B \quad \frac{1}{D^2}$$

The sensitivity analyses carried out later for work-energy models (which also use rigid- and plastic-limit equilibrium theory to predict the soil passive pressure) indicate the following sensitivity of scour depth to scour breadth as shown in Table 8.

TABLE 8

Scour Depth Versus Scour Breadth

Model	Scour Breadth (m)	Scour Depth (m)	Proportionality Proportionality Exponent for D
FENCO (1975) including wind and current-drag energy	100 30	1.3 2.2	-2.3
Chari (1979) including wind and current-drag energy	100 30	2.6 2.5	-2.7

Thus, it can be seen that the scour depth is significantly affected by the scour breadth.

b) Iceberg mass and inertial effects - The previously described sensitivity run for the increased berg drift case showed that inertial forces are a very significant factor affecting the predicted scour depth. Therefore, the predicted scour depth is also expected to be relatively sensitive to the berg mass. A reduction in iceberg mass decreases the initial kinetic energy of the berg and, hence, the magnitude of the inertial forces required to decelerate it.

Unfortunately, the results of this sensitivity analysis cannot be used directly, as the iceberg mass could not be independently varied in the program. For this run, the iceberg mass was reduced by decreasing all iceberg dimensions by the same approximate ratio. This was done to maintain the same relationship between the hydrostatic and hydrodynamic restoring forces in the three degrees of freedom considered, as for the base case. This resulted in a berg of reduced cross-sectional area, and, hence, the applied environmental loads are decreased. Also, the scour breadth was decreased (as the berg's breadth was reduced).

During this run, the following variations from the base case shown in Table 9 resulted.

TABLE 9

Influence of Berg Mass on Scour Depth:
Dynamic Model Sensitivity Analysis

Model	Berg Mass (ton)	Total Horizontal Environmental Loads (kip)	Scour Breadth (ft)	Predicted Scour Depth (ft)
Base	1.3 million	693	320	4.8
Reduced Berg mass	0.5 million	485	232	4.1

The predicted scour depth was reduced by 15% from the base case, whereas the total environmental loads applied to the berg during scouring were reduced by 30%. Referring to Table 6 and the previous discussion on environmental loads, a reduction of only 30% is expected to have a negligible effect on the predicted scour depth. Consequently, it is believed that variations in total environmental load between these two runs may be safely neglected when evaluating the predicted sensitivities.

However, the scour breadth reduction inherent in this sensitivity run is significant. As discussed previously, an inverse relationship between scour depth and breadth is expected. Because the scour breadth cannot be independently varied, the sensitivity run results are not able to provide information directly on this relationship. As discussed earlier, an approximate inverse square relationship between scour breadth and scour depth is expected. Using this predictor, the model would predict a considerably larger scour depth for the reduced berg mass case. Thus, it can be seen that the effect of reduced iceberg mass on the scour depth has been masked by the effects caused by a reduced scour breadth.

(D) Influence of hydrostatic and hydrodynamic forces

The dynamic model allows the ice feature degrees of freedom in the heave, surge, and pitch directions. Work done against the hydrostatic and hydrodynamic restoring forces acting on the ice feature (as the berg is displaced) reduces the magnitude of the total work done in deforming the soil. Thus, the scour depth is expected to be reduced when these energy sinks are considered.

The degrees of freedom available to the ice feature cannot be varied in the dynamic model. Consequently, the effect of including these in the analysis on the predicted scour depth cannot be evaluated directly. However, some understanding of the effect of these forces can be gained from a comparison of the results obtained for the dynamic model and for the work-energy models (which allow the berg to move only in the horizontal plane). These models are described in the next section.

TABLE 10
Influence of Hydrostatic and Hydrodynamic Forces on Scour Depth

	Berg Size L(m) W(m) H(m)	Scour Breadth (m)	Soil Cohesion (kpa)	Wind Speed (m/s)	Current Speed (m/s)	Wave Height (m)	Predicted Scour Depth (m)
Dynamic equilibrium model							
FENCO (1975)	120x100x110	100	7	6	0.5	3.5	0.5
			28	6	0.5	3.5	0.2
Work-energy models							
FENCO (195)	120x100x110	100	7	6	0.5	Not included in model	1.3
			28	6	0.5		0.8
Chari (1979	120x100x110	100	7	6	0.5	Not included in model	1.6
			28	6	0.5		1.1

The above table demonstrates that the hydrostatic and hydrodynamic forces on the berg have a significant influence on the predicted scour depth.

WORK-ENERGY MODELS

Model Description

These models use an energy-balance approach to describe the iceberg-scouring process and to predict the scour depth. In general terms, they equate the initial kinetic energy of the berg, along with the work done by the current-drag and wind-drag forces during scouring, to the work done in deforming the soil.

FENCO (1975) and Chari (1979) both proposed simple models using this approach. Both of these models allow the berg only one degree of freedom (i.e., surge), and consider it to be rectangular. The contribution of the berg's hydrodynamic added mass to the overall initial kinetic energy of the berg may be included with an added mass factor. Noting that icebergs typically have greater strength than the sea-bed sediments, these models assume that soil failure governs the interaction process. Icebergs of limited keel width may be considered by these models.

The soil is considered to be a rigid-plastic material, and limit equilibrium analysis is used to estimate the soil resistance. The passive soil resistance is assumed to be fully mobilized, and is given by Coulomb's earth-pressure theory. The surcharged material is assumed to contribute to the passive resistance, but is considered to have no strength as the soil is remolded. Soil friction along the base of the iceberg is neglected, as the berg is considered to be free-floating throughout the interaction. The work done in accelerating the soil wedge in front of the grounding iceberg is also neglected, as it is typically less than 1% of the initial kinetic energy of a 200-GN iceberg.

All the available models are formulated to consider only cohesive soils at present. The basic differences between the two models are the determination of the surcharge height and the treatment of side friction. Chari (1979) leaves the ratio of surcharge height to scour depth as an operator input, whereas the FENCO (1975) model assumes that the surcharge material is deposited at the bedslope (which fixes the ratio at 1.4). As well, the Chari model neglects side friction, whereas the FENCO model considers a shear force equal to the active lateral earth pressure multiplied by the soil-ice friction coefficient to act on the sides of the iceberg.

Chari's (1979) model may be expressed by the following relation:

$$\frac{MV^2}{2} = \frac{(H+D^2}{6} \quad BL + \quad DLB + \frac{2}{3} \quad D^2L$$

where:

M = mass of iceberg
V = drift rate of iceberg
= submerged unit weight of sediment
H = surcharge height
D = scour depth
B = breadth of scour
L = length of scour
= soil shear strength

FENCO's (1975) model is expressed as:

$$\frac{MV^2}{2} =$$

$$L^2B\ (1= \quad 2) \quad \tan \quad \frac{(1 - \quad 2)}{6} \quad \tan \quad + \quad \frac{\tan^2}{12} \ \underline{L}^4$$

where:

= bedslope
= ice-soil friction coefficient

The work done by current-drag and wind-drag forces during scouring may be significant in some cases. For wind, this is express as:

where: F = wind drag force

Current-drag forces build to a maximum value at the end of the interaction when the berg comes to rest. The time history of the current-drag force is unclear, and it is necessary to make simplifying assumptions to allow the current-drag energy to be included in the models. By assuming the floe velocity or its deceleration to vary linearly over the interaction, the following relationships are determined, respectively, for the current-drag energy during scouring:

where: F = current-drag force.

Because the latter relationship is considered more likely to be reliable, it has been used in subsequent analyses. As will be shown later, the current-drag energy is a relatively small proportion of the total energy, and, consequently, the study results are not sensitive to this assumption.

Both FENCO and Chari models, as well as the modified models (to include the above wind-drag and current-drag energies), were used in subsequent analyses.

Sensitivity Analysis of Work-Energy Models

Sensitivity analysis base case description. As for the dynamic model, sensitivity analysis was conducted to understand the relative influence of the predicted scour depth on the various input parameters.

For the most part, the same base case used for the dynamic model sensitivity analysis was assumed. Because the available work-energy models are presently formulated based on the passive resistance of only cohesive soils, the base case soil was taken as cohesive. (The base case soil used for the dynamic model was cohesionless.) This difference is not significant for the purposes of evaluating the sensitivity of the predicted scour depth to the soil reaction magnitude.

Table 11 lists the base case parameters used for the sensitivity analyses.

TABLE 11

Work-Energy Model Sensitivity Analysis Base Case

Base case input parameters	Value
Iceberg dimensions	
length	120 m
width	100 m
depth	110 m
Ice density	8,950 N/m^3
Water density	9,850 N/m^3
Submerged soil density	8,000 N/m^3
Soil cohesion	7 kPa
Bedslope	1.2 degrees
Scour breadth	30 m
Windspeed	6 m/s
Current speed	0.5 m/s

Notes:

1. The added mass coefficient was taken as 0.5.

2. Drag coefficients were taken as:

	FORM	SKIN
Wind	1.0	0.005
Current	1.0	0.05

3. For Chari's (1979) model, H/D was taken as 1.4.

4. For all models, the ice-soil friction angle was taken as 0.

<u>Sensitivity analysis results summary</u>. Table 12 summarizes the observed sensitivities. Appendix B lists the complete sensitivity analysis results.

TABLE 12

Work-Energy Model Sensitivity Analysis Summary

		Predicted Scour-Depth (M) Variation			
Input Parameter Varied	Input Parameter Variation	FENCO (1975) Model	Modified FENCO Model	Chari (1979) Model	Modified Chari Model
Berg mass	1.2 to 0.15 million tons	2.16 to 0.19	2.18 to 0.91	2.44 to 1.11	2.47 to 1.13
Scour breadth	30 to 100 m	2.16 to 1.32	2.18 to 1.33	2.44 to 1.56	2.47 to 1.58
Soil strength	7 to 28 kPa	2.16 to 1.41	2.18 to 1.43	2.44 to 1.89	2.47 to 1.91
Bedslope	1.2 to 5 degrees	2.16 to 3.77	2.18 to 3.78	2.44 to 4.09	2.47 to 4.10
Windspeed	6 to 60 m/s	No change	2.18 to 2.51	No change	2.47 to 2.85
Current speed	0.5 to 1 m/s	2.16 to 3.71	2.18 to 3.76	2.44 to 4.03	2.47 to 4.09

Notes:
1. All variations above are with respect to the base case.
2. The berg mass was reduced by assuming the following dimensions for the berg:

length: 60 m
width: 50 m
depth: 55 m

As for the dynamic model, the scour depth is predicted to be almost inversely proportional to the total soil resistance. The soil resistance was varied by considering a range of soil shear strengths (i.e., 7 to 28 kPa). This produced variations from the base case in the total soil resistance of about 30 and 10% for the FENCO (1975) and the Chari (1979) models, respectively. The following section provides a quantitative discussion of the analysis conducted. In addition, the scour breadth was varied during the sensitivity analysis, as it also affects the total soil resistance. The scour depth was found to be very sensitive to the scour breadth. (The scour depth was predicted to be inversely proportional to the scour depth to the exponents 2.3 and 2.7 for the FENCO and Chari models, respectively.)

As would be expected, the scour depth is predicted to increase for increasing driving forces and total environmental energies. The sensitivity analysis shows that the total environmental energy is governed by the inital kinetic energy of the berg. The work done by current-drag and wind-drag forces during scouring is a relatively small component, and is not expected to exceed 15% of the total environmental energy for typical iceberg scour scenarios.

Detailed discussion of sensitivity analysis results.

(A) Sea-bed parameters.

a) Soil resistance - As mentioned previously, the total soil resistance is dependent upon several parameters, including the soil density, cohesion and/or friction angle, ice-soil friction angle, and the surcharge geometry. To vary the soil resistance, the soil cohesion was changed from 7 to 28 kPa. This produced the following changes in soil resistance and scour depth shown in Table 13.

TABLE 13

Scour Depth versus Soil resistance sensitivity: Work-energy Models

		Predicted Scour Depth (m)		Total soil resistance (MN) at maximum scour depth		
Model	Base case	Increased soil strength	% change from base case	Base Case	Increased soil strength	% change from base case
FENCO (1975)	2.16	1.41	-35	5.46	7.17	+31
FENCO (1975) including wind and current-drag energy	2.18	1.43	-34	5.53	7.25	+31
Chari (1979)	2.44	1.89	-23	5.22	5.77	+11
Chari (1979) including wind and current-drag energy	2.47	1.92	-22	5.34	5.81	+ 9

As would be expected, the scour depth is predicted to be reduced with increasing soil resistance. The predicted scour depth is more sensitive to the soil strength for the FENCO (1975) model than for the Chari (1979) model. This is reflected by a comparison of the total soil resistances (at the maximum scour depth) for the two models. The soil resistance in the FENCO model is more sensitive to the soil shear strength than is that in the Chari model. This occurs because the FENCO Model assumes that the surcharge material contributes to the total shear resistance, whereas the Chari model neglects this contribution on the basis that the surcharge material is remolded.

b) Bedslope – The scour depth is sensitive to the bedslope for both models. An increase in bedslope angle from 1.2 to 5° resulted in predicted increases in scour depth ranging from 42 to 75% over the base case.

This is to be expected, as the bedslope greatly affects the length of scour and, hence, the work done in deforming the soil.

(B) Environmental driving forces

As discussed previously, the environmental driving forces may be broadly divided into inertial forces associated with decelerating the berg and environmental loads applied to the berg during scouring. The energies associated with doing work against these forces were varied as shown in Table 14.

TABLE 14

Environmental Energies: Work-Energy Model Sensivity Analyses

Case	Parameter Variation with respect to base case	Initial Kinetic Energy (Mn.m)	Applied Current Drag Energy (Mn.m)		Applied Wind Drag Energy (Mn.m)		Total Energy (Mn.m) applied to Sea bed	
			FENCO Model	Chari Model	FENCO Model	Chari Model	FENCO Model	Chari Model
Base		227.3	5.3	6.0	0.23	0.26	232.8	233.6
Berg weight	1.2 to 0.15 million tons	28.4	0.5	0.7	0.03	0.03	28.9	29.1
Wind speed	6 to 60 m/s	227.3	6.1	6.9	24.4	27.6	257.8	261.8
Current speed and berg drift rate increased	0.5 to 1 m/s	909.2	36.3	39.5	0.40	0.44	945.9	949.1

Table 14 clearly shows that the inertial component of the driving energy is much larger than that resulting from the environmental loads imposed during scouring. Therefore, the scour depth is expected to be much more sensitive to the berg's initial kinetic energy than to the other components. As discussed previously, environmental loads during scouring would assume more importance for the multi-year ice-floe scour case.

The predicted scour depth is sensitive to the total environmental energy, and increases with increasing energy levels as shown in Table 15.

TABLE 15

Scour Depth versus Environmental Energy Sensitivity: Work-Energy Models

	Predicted Scour				Total Energy (Mn.m) Applied to Sea Bed			
	FENCO Model		Chari Model		FENCO Model		Chari Model	
Case	Depth (m)	% Change from base	Depth (m)	% Change from base	Depth (m)	% Change from base	Depth (m)	% Change from base
Base	2.18	-	2.47	-	232.8	-	233.6	-
Berg mass reduced	0.91	-58	1.13	-54	28.9	-88	29.1	+87
Wind speed increased	2.28	+5	2.58	+5	257.8	+11	261.8	+12
Current speed and berg drift increased	3.76	+72	4.09	+66	945.9	+300	949.2	+310

(C) Ice feature dimensions

Sensitivity runs were made to investigate the influence of the ice-feature size and the scour breadth on the predicted depth of scour.

a) Scour breadth - As discussed earlier in "Dynamic model sensitivity analysis" the scour depth was found to be highly sensitive to the scour breadth. The scour depth to be inversely proportional to the scour breadth to the exponents 2.3 and 2.7 for the FENCO and Chari models, respectively.

b) Iceberg mass - The influence of iceberg mass on the predicted scour depth has been outlined in the previous section on environmental driving force sensitivities. For the iceberg scour case, the predicted scour depth is very sensitive to the initial kinetic energy of the berg (as the other components of the total environmental energy are small) and, thus, to the berg mass.

LIMITING SCOUR-DEPTH APPROACH

A number of analytical treatments have been proposed to model the case where failure of the ice feature, rather than soil failure, governs the interaction.

FENCO (1975) considered scour by an unconsolidated first--year ridge to be governed by the shear resistance of the ridge (which is treated as a Mohr-Coulomb material). Comfort et al. (1982) proposed a scour-depth predictor based on the limited flexural strength of an unconsolidated first-year ridge to explain observed scours in Lake Erie (which were created by unconsolidated first-year ridges).

For both of these models, the soil passive resistance was treated using the limit equilibrium analysis method proposed by Chari (1979) and FENCO (1975). Comfort et al. (1982) calculated vertical forces on the ice ridge based on a resolution of the applied horizontal forces to the soil and the frictional forces at the sloped interface. The ice ridge was treated as a beam on an elastic foundation for this model.

Neither model has been directly calibrated. However, the FENCO model produced results which are considered reasonable in view of observed Beaufort Sea sea-bed scours. As well, the Comfort et al. (1982) model showed good correlation with observed scours in Lake Erie. Consequently, both models are considered to provide useful insight into the scouring process. However, the limiting scour-depth approach is limited to cases where failure of the ice feature as opposed to failure of the soil, represents the critical failure criterion. Consequently, this approach cannot be applied to cases in which scours are created by icebergs or multi-year floes and ridges.

A further limitation of these models is that some of the required input parameters (e.g., ridge flexural and shear strength, ice-soil friction factor) are poorly understood. However, the scour-depth magnitudes can be bounded using this approach through the selection of a range of input parameter values.

Because scours created by "hard" ice features are considered to represent the design case for areas of interest, it was decided not to attempt to further calibrate these models.

MODEL CALIBRATION STUDIES

AVAILABLE FIELD DATA

The previously described ice-scour model review gave an understanding of the field parameters significant for model calibration studies. Table 16 lists these factors.

TABLE 16

Model Calibration Parameters

Category	Parameter
Ice feature	•Dimensions and geometry of feature (i.e., length, width, depth, shape classification)
	•Keel geometry
	•Mass of ice feature
Sea-bed properties	•Bathymetry along scour track
	•Strength of soild (e.g., cohesion and/or friction angle, density) along track, and their variation
	•Classification of surficial soils
Environmental	•Wind – average speed and direction during grounding
	•Current – average speed and direction during grounding
	•Drift rate and direction of ice feature
	•Pack ice (if present) – ice type, floe size distribution, average thickness, speed, temperature, and direction of movement
Scour track	•dimensions of scour along track: -length, width, depth, embankment height, embankment slop -single or multiple track

The available literature was searched, and various organizations were contacted with the aim of assembling a data base of known iceberg scouring events that could provide calibration data.

It was not possible to assemble a complete data set for any scouring event, because field data have not been systematically gathered towards this objective. However, five groundings, as listed in Table 17, were identified as being sufficiently documented to allow approximate model calibration. Of these events, only data relating to the K007, Caroline, and Frances groundings could be assembled in time for inclusion in this report. For each of these groundings, it was necessary to use baseline data from other sources to provide typical values and ranges of critical interaction parameters to complete the data set.

TABLE 17

Documented Iceberg Groundings

Events	Grounding Date	Sea-bed Scour Data Source Agency
Karlsefni K007 berg	15 September, 1976	BIO/C-CORE
Caroline berg	Summer 1979	BIO/C-CORE
Frances berg	1 August, 1979	BIO/C-CORE
Berg #95	1983	Mobil Oil Canada
Berg #104	1983	Mobil Oil Canada

Table 18 summarizes the available field data by source for each grounding event.

Tables 19, 20 and 21 provide quantitative data for K007, Caroline, and Frances groundings, respectively. Raw ground truth data are listed in Appendix C for each of these events.

TABLE 18

Available Field Data by Source

Parameter	Grounding Event		
	K007	Caroline	Frances
Ice Feature			
Berg shape or classification	1976 Karlsefni well-site log	Photos of grounded berg	Photos of grounded berg
Berg dimensions	Side-scan sonar survey recorded in Karlsefni well-site log	Estimated by scaling from available photos using helicopter as a basis. Berg depth calculated from the measured freeboard and water depth	Estimated by scaling from available photos using helicopter as a basis. Berg depth calculated from the measured freeboard and water depth
Keel shape	Not available	Not available	Not available
Sea-bed properties			
Bathymetry along scour track	Local bathymetric surveys using 12-KHz fathometer	Local bathymetric surveys using 12-KHz fathometer	Local bathymetric surveys using 12-KHz fathometer
Surficial soils classification	Lab tests of core samples	Huntec sub-bottom profiler	Huntec sub-bottom profiler
Soil strength properties	Lab tests of core samples	Typical soil properties for observed soil type taken from Lambe and Whitman (1969)	Lab test results on similar soil types used to establish soil properties
Environmental Conditions			
Berg velocity prior to grounding	Velocity calculated from measured berg positions recorded in Karlsefni well-site log	No data available (taken as equal to current velocity)	No data available (taken as equal to current velocity)
Wind velocity	Karlsefni well-site log	Range of wind speeds measured at Gilbert well-site for August used	Range of wind speeds measured at Gilbert well-site for August used

TABLE 18 (Cont'd)

Parameter	Grounding Event L007	Caroline	Frances
Current velocity	Karlsefni well-site log (for 50-m depth)	Max. and mean current speeds measured at 58°53'N; 62°10'W over July-Oct. 1980 period used (after Petro-Canada Exploration Ltd. 1982)	Max. and mean current speeds measured at 58°53'N; 62°10'W over July-Oct. 1980 period used (after Petro-Canada Exploration Ltd. 1982)
Wave height	Karlsefni well-site log	Max. and most probable significant wave heights measured at Gilbert well-site used	Max. and most probable significant wave heights measured at Gilbert well-site used
Pack-ice conditions	Karlsefni well-site log	Inferred from knowledge of typical ice conditions	Inferred from knowledge of typical ice conditions
<u>Sour Track</u>			
Scour cross-sectional geometry depth breadth single or multiple track	1979 side-scan sonar survey 1982 side-scan sonar survey 1979 Huntec sub-bottom survey	1979 side-scan sonar survey 1982 side-scan sonar survey 1982 Huntec sub-bottom survey	1982 side-scan sonar survey 1982 Huntec sub-bottom survey

TABLE 19

Field Data Summary: K007 Grounding

PARAMETER	QUANTITATIVE DATA
Ice feature	
Berg shape or classification	Weathered tabular
dimensions	
length	230 m
width	180 m
depth	265 m
Keel shape	Not available
Sea-bed Properties	
Water depth (m)	155–165 (see Note 2)
Along-track bedslope	0.05° to 0.75°; 0.32° in predominant scour direction (see Note 2)
Soil type	Poorly stratified glaciomarine silt
Soil parameters	
Submerged weight	5.6 KN/m^3
Soil cohesion	5.8 kPa
Soil friction angle	0
Environmental conditions	
Initial berg velocity	0.08 m/s (see Note 3)
Current velocity	0.08 m/s (see Note 3)
Wind velocity	11.2 m/s (see Note 4)
Wave height	1 m (see Note 5)
Pack-ice conditions	None present
Scour track	
Scour length	300–2200 m (see Note 2)
Scour width	15–65 m (see Note 2)
Scour depth	0.5–6 m (see Note 2)
Scour geometry	See appendix C

Notes:

1. Scour position: 58°54'N; 61°45'W
   Grounding date: 15 September 1976
   Surveys conducted by type:
   Side-scan sonar: 1978, 1979, 1981, 1982
   Huntec sub-bottom 1979

2. The K007 sea-bed scour cannot be positively identified from the side-scan sonar mosaics (Barrie 1984). Consequently, the distribution and range of scour depths and widths were measured over a grid cell 1' in latitude by 2' in longitude known to contain the K007 scour (see Appendix C for raw data). The bedslope was also highly varied because the sea-bed scours were oriented in several directions. The bedslope angle was measured to range typically between 0.05 and 0.75°. The average bedslope in the predominant scour direction was 0.32°.

3. This was the initial berg drift rate and the current speed over the 0200- to 0400-hours period on 15 September 1976. The time at which the berg started to scour is unclear.

4. This was the average wind speed over the 0400- to 1700-hours period on 15 September 1976. The berg came to rest over this period (see Appendix C).

5. This was the average significant wave height over the 0300- to 1500-hours period on 15 September 1976. The berg came to rest over this period (see Appendix C).

TABLE 20

Field Data Summary: Caroline Grounding

PARAMETER	QUANTITATIVE DATA
Ice feature	
Berg shape or classification	Tabular
dimensions	
length	180 m
width	180 m
depth	230 m
Keel shape	Not available
Sea-bed Properties	
Water depth	117-119 (m)
Along-track bedslope	0.37°
Soil type	Overconsolidated glacial fill
Soil parameters	
Submerged weight	6,300 N/m^3
Soil cohesion	4- 10 kPa (range of values given in Lambe and Whitman (1969)
Soil friction angle	0
Environmental conditions	
Initial berg velocity	Not available (taken as equal to current velocity)
Current velocity	0.14-0.47 m/s (see Table 17)
Wind velocity	0-42 m/s (see Table 17)
Wave height	1.1 - 4.6m (see Table 17)
Pack-ice conditions	None present
Scour track	
Scour length	Not available (incomplete side-scan sonar record - (see Appendix C)
Scour width	22-45 m (see Appendix C)
Scour depth	0.3 - 0.7 m (see Appendix C)
Scour geometry	See appendix C

Note 1. Scour Position: 59°21'N; 62°34'W
Grounding date: Summer 1979
Surveys conducted by Type:
Side-scan sonar: 1979, 1982
Huntec sub-bottom: 1982

TABLE 21

Field Data Summary: Frances Grounding

PARAMETER	QUANTITATIVE DATA
Ice feature	
Berg shape or classification	Tabular
Dimensions	
length	360 m
width	360 m
depth	159 m
Keel shape	Not available
Sea-bed Properties	
Water depth	131-137 m
Along-track bedslope	0-0.15°
Soil type	Overconsolidated glacial fill
Soil parameters	
Submerged weight	8,300 N/m^3
Soil cohesion	14-24 kPa (range of probable shear strengths)
Soil friction angle	0
Environmental conditions	
Initial berg velocity	Not available (taken as equal to current velocity)
Current velocity	0.11-0.34 m/s (see Table 17)
Wind velocity	0-42 m/s (see Table 17)
Wave height	1.1 - 4.6m (see Table 17)
Pack-ice conditions	None present
Scour track	
Scour length	Not available
Scour width	30-42 m (see Appendix C)
Scour depth	1.0 - 1.0 m (see Appendix C)

Note 1. Scour Position: 57°38'N; 60°14'W
Grounding date: 1 August 1979
Surveys conducted by Type:
Side-scan sonar: 28 October 1982
Huntec sub-bottom: 28 October 1982

From the sensitivity analyses conducted and described in the section "Review of available ice scour models", the following general parameters were identified as having the greatest significance for scours created by an iceberg:

- initial kinetic energy of the iceberg
- soil resistance
- sea bed bathymetry
- berg motions during scouring.

The K07 event is the best-documented grounding in the first two areas listed above. The mass of this berg was estimated from side-scan sonar surveys of the berg, and the initial velocity from radar tracks of its drift path. For the Frances and Caroline groundings, only hand-held photographs (with a helicopter in view at the berg for scale) are available. No information on dirft rate is available for these events, and it is necessary to use baseline current data to obtain some understanding of the probable rate drift.

Soil samples were taken and laboratory-tested for the K007 grounding to give information on soil strength. For the Frances and Caroline groundings, only sub-bottom profiler information is available to classify the surficial soils. Hence, it is necessary to use baseline soil data ranges for these groundings. No information on the motions of the berg is available for any of these scouring events.

Thus, it can be seen that the K007 grounding is much better documented than the other two. Unfortunately, information on the scour created by this berg is ambiguous, as there are numerous scours on the sea bed, and the K007 scour cannot be positively identified despite numerous surveys (V. Barrie, pers. comm.). Consequently all scours within the general area (i.e., with a 1' in latitude fo 2' in longitude grid cell) where the K007 scour occurred were measured to provide a range of values. Unfortunately, this introduces uncertainties in both the scour geometry and the bedslope into the calibration data set.

Relatively good scour information is available for the Caroline and Frances groundings as the scours created during these events have been positively identified from the side-scan records.

Because of these uncertainties in the field calibration data, only an approximate calibration is possible.

DETERMINISTIC MODEL PREDICTIONS

The available deterministic ice-scour models were programmed and exercised with the field data summarized in the previous section. The following models, as described earlier were excercised with the field data:

- the dynamic ice-scour model of FENCO (1975)
- the work-energy model of FENCO (1975)
- the work-energy model of Chari (1979)
- both of the above work-energy models with modifications to include the work done by wind-drag and current-drag forces during scouring.

Appendix B.1 summarizes the results of the work-energy model runs for the K007, Caroline, and Frances groundings. Appendix B.2 summarizes the FENCO dynamic model scour-depth predictions for these groundings.

Work-Energy Model Predictions

The following parameters were varied, over the base case, in the work-energy model runs made for the K007 grounding:

a) •Berg dimensions (1 x w x h) were increased from the values of 230 m x 180 m x 265 m to 460 m x 360 m x 265 m. This quadrupled the berg mass and is believed to bound the probable value.

b) •Berg drift rate and current speed were increased from the base case value of 0.077 m/s to 0.17 m/s reflecting the range of field data.

c) •Bedslope was varied from the minimum measured bedslope (i.e., 0.05°) to the maximum measured bedslope (0.75°), along which scouring occurred.

For work-energy model runs made for the Frances and Caroline groundings, the soil cohesion, wind speed, and current speed were varied over the expected range of field values (see "Available field data"), as follows:

•soil cohesion: (Caroline groundings) 4 to 10 kPa
(Frances groundings) 14 to 24 kPa

•wind speed: 0 to 42 m/s

•current speed (and berg drift rate):
0.14 to 0.46 m/s (Caroline grounding)
0.11 to 0.34 m/s (Frances grounding).

Table 22 compares the range of predicted scour depths with the range of measured values.

The work-energy model scour-depth predictions are in general agreement with the ranges of measured values. For the K007 groundings, both models predict scour depths in the lower range of the measured values. For the Caroline and Frances groundings, the measured values lie within the range of predicted values. The FENCO model predicts lower scour depths than does the Chari model.

TABLE 22

Comparison of Work-Energy Model Scour Depth with Measured Values

Range of work-energy model scour depth predictions (m)

Iceberg grounding event	FENCO (1975) Model	Modified FENCO Model	Chari (1979) Model	Modified Chari Model	Range of Measured Scour Depth(m)
K007	0.29-1.37	0.45-1.47	0.40-1.64	0.67-1.78	0.5-6.0
Caroline	0.86-2.91	0.86-3.07	1.13-3.15	1.14-3.99	0.3-0.7
Frances	0.38-1.35	0.38-2.01	0.55-1.70	0.55-2.58	1.0

Notes:

1. Work-energy models of FENCO (1975) and Chari (1979) were modified to include work done by wind-drag and current-drag forces during scouring, as discussed in "Review of available ice-scour models".

2. See appendix B.1 for ranges of input parameters.

3. Scour breadth taken as 30, 30, and 35 m for the K007, Caroline, and Frances groundings respectively.

Dynamic Model Predictions

As for the work-energy model runs, input parameters were also varied over a range of values for the dynamic model runs, reflecting uncertainties in the field-calibration data set. Input parameters were varied over the same ranges of values previously described for the work-energy model runs. For the Caroline and Frances groundings, the wave height was also varied (from 1.2 to 4.6 m, reflecting the range of probable field values). For the K007 grounding, the influence of ice-soil adhesion was also investigated by setting it to zero from the soil cohesion value assumed in the base case.

Table 23 compares the range of predicted scour depths with the range of measured scour depths. As discussed in "Review of available ice-scour models", the dynamic model assumes that the berg creates a scour equal in breadth to the berg width. The sensitivity analyses have shown that the scour depth is significantly affected by the scour breadth. To obtain some understanding of the scour depth that would be prdicted for a known scour breadth, the correction for the predicted scour depth has been estimated using an inverse square relationship based on the midpoint of the scour breadth ranges that were measured and assumed by the model. (See "Dynamic model sensitivity analysis" for justification.)

Table 23 shows that the dynamic model appears to overestimate the field scours.

As outlined in "Dynamic model programming problems" the dynamic model are considered unreliable because of a number of anomalies.

a) Work-energy versus dynamic model results comparison - During the sensitivity runs (see "Dynamic model sensitivity analysis" and "Sensitivity analysis of work-energy models"), significantly lower scour depths were predicted by the dynamic model compared with the work-energy models. This is to be expected, because the work-energy models do not consider hydrostatic and hydrodynamic restoring forces as an energy sink, which would reduce the work done in deforming the soil. The results obtained for the calibration runs are in disagreement with this trend.

b) Comparison of individual dynamic model runs for specific grounding event - Several anomalous results were predicted by the dynamic model. For example, the Caroline grounding runs sometimes predict deeper scours for lower wave heights. (The model predicts a scour depth change from 0.5 to 0.9 m for a wave height reduction from 4.6 to 1.2 m. See Appendix B for tabulation of results.)

TABLE 23

Comparison of FENCO Dynamic Model Scour Depth Predictions with Measured Values

Iceberg Grounding Event	Range of Predicted Values: Scour depth (m)	Range of Predicted Values: Scour breadth (m)	Range of Measured Values: Scour depth (m)	Range of Measured Values: Scour breadth (m)	Range of Measured Values: Corrected scour depth (m) Predictions (for scour breadth[b]
K007	017[a] to 1.3	180 to 230	0.5 to 6.0	15 to 65	0 to 32.5
Caroline	0.5 to 0.9	180	0.3 to 0.7	22 to 45	14 to 26
Frances	0 to 0.5	360	1.0	30 to 42	0 to 50

[a] This predicted value is considered unrelable. See text for discussion.

[b] See text for basis used for corrections.

Notes: 1. Scour depth calculated as outlined in FENCO (1975 as: scour length : tangent bed-slope angle) - berg lift.

2. See Appendix B.2 for ranges of input parameters.

In addition, the berg is predicted to lift off the sea bed in a number of cases. For the K007 grounding, the berg was predicted to lift 17 m off the sea bed for the case where the berg length and width were switched as input parameters (see Appendix B).

As a final example, the dynamic model predicts reduced scour depths for the increased berg drift rate and current speed case for the K007 grounding (see Appendix B for values).

The reasons for these anomalies are unclear, and should be investigated further. As a detailed analysis and debugging of the dynamic model were not within the scope of this study, only general recommendations can be made. Because the dynamic model sensitivity results show a reasonable relationship with input parameter variations, it is suspected that the calibration run anomalies may stem from numerical inaccuracies associated with the Runge-Kutta method of solution. FENCO (1975) recommended a time step of 2 s and, consequently, built this value into the program. A reduced time step may be advisable.

In addition, the model is only programmed to output the results of every tenth time step. The final berg displacements are not output. For large displacements, this error is small. However, for small penetrations, this error may be significant, and has no doubt contributed somewhat to the observed anomalies.

Therefore, the calibration run results for the dynamic model must be considered inconclusive.

ONGOING RESEARCH AND PRIORITIES

Ongoing research

Questionnaires were widely distributed with the aim of documenting ongoing research into ice-scour problems. In total, 32 representatives of industry, government, research centres, and involved consulting firms were contacted. In addition, the authors had personal communications with several selected individuals and organizations.

Table 24 summarizes the ongoing research (as of November 1984) by project type and scope, and funding source. In general, current research is directed towards two main areas:

- the development of observational-based numerical statistical risk level predictors; and

- the development of deterministic analytical treatments of the iceberg-soil scour process.

As may be seen from Table 24, ice-scour research is presently being concentrated on the first area. However, some research effort is also being expended towards the development of deterministic models.

In addition, it can be seen that the bulk of the present research effort is being funded by the offshore oil industry.

TABLE 24

Ongoing Research

Ice scour characterizations and <u>Data base development</u>	
Compile regional data bases of ice-scour occurrences and their character	ESRF: PERD, EMR
Scour-dating studies using cross-cutting analyses and geologic layer dating	PERD: EMR
Establishment of regional, repetitive mapping grids for the east coast and Canadian Beaufort Sea	ESRF
Repetitive ice-scour mapping survey for the Alaskan Beaufort Sea	Joint industry project

TABLE 24

Ongoing Research

<u>Ice scour infill rates</u>	
Analytical modelling using sediment transport theory	U.S. DOE
Repetitive ice-scour mapping survey for the Alaskan Beaufort Sea	Joint industry project
<u>Analytical model development</u>	
Development of deterministic six-degree-of-freedom model	Joint industry project
<u>Risk level assessment</u>	
Risk-level assessment study using available iceberg flux, draft distribution, and scour-depth distribution data	In-house Petro-Canada project
Application of extreme value statistics of pressure-ridge keel data towards an estimation of the ages of deep-water scours	Scott Polar Research Institute

Numerical, Statistical, Risk-Level Predictors

Research efforts for the development of statistical risk-level predictors are being focussed in the following three areas:

- ice-scour characterization and data-base development
- ice-scour infill rates
- risk-level assessments.

The greatest efforts are presently being expended in the area of ice-scour characterization and data-base development. Regional, repetitive field-mapping grids have been established and are being updated. To a considerably lesser extent, attempts are being made to date scours using cross-cutting and geologic dating analyses.

Lesser efforts are being expended on understanding ice-scour infill rates and estimating risk levels for various protection specifications and layouts for flowlines and collector manifolds.

This emphasis reflects a basic need for improved ice-scour distribution information to increase confidence in the statistical approach. The collection of systematic field data over the long term will improve the accuracy of the distributions fitting for extrapolation purposes. In addition, past information has not been generally archived or analysed in detail. Thus, efforts are being made to catalogue and understand presently available ice-scour information.

Scour-dating studies relfect a need to differentiate between new and relict scours on the sea bed. These techniques are now in the developmental stage. Cross-cutting techniques will provide information on the relative ages of scours, but cannot be relied upon for the differentiation of relict scours. Geologic dating analyses are an expensive approach for widespread use. Thus, efforts are reduced in this area at present.

The scour infill rate is another critical parameter affecting the reliability of the measured field scour dimensions. Thus, efforts are being made to understand probable infill rates. This research is directed towards Beaufort Sea locations (where infill rates are expected to be significant due to the presence of relatively shallow water depths and weak surficial soils). Infill rates for east coast locations are not being researched, as previous studies (e.g., Barrie 1985) have shown that they are expected to be low.

Risk-level assessments are also being conducted, based on a combination of the probable distribution of ice scours and on the probable distribution of the ice features creating the scours. This is considered to provide a significant advance in relability over risk-level predictors, based on only the distribution of the measured scours. Although this method suffers from inadequate knowledge of ice-feature parameters (e.g., iceberg flux rate and draft distribution, multi-year ridge keel geometry), it is an important first step in verifying the relability of statistical risk-level predictors.

The work on the statistical description of the ice features is also of importance in allowing the eventual evaluation of risk levels using the deterministic models.

Deterministic Modelling

Research efforts are also being expended at present towards improved deterministic modelling, altough to a lesser extent.

Work in this area is centred on the development of a three-dimensional numerical model which can be used to predict both iceberg motions and scour geometry in a time series manner. The non-linear iceberg keel - soil interaction model is fully coupled with a hydrodynamic model. Soil resistance functions and environmental loadings are described as input by the user. Force and motion calculations are performed at discrete time steps. (S. Foo, pers. comm.)[1]

RESEARCH PRIORITIES

Research efforts are required to assist in solving the following ice scour-related problems:

- to define the risk levels associated with various subsea structure protection specifications;

- to understand "special-case" interaction scenarios for which there is little field data (such as the scouring of protective glory holes by ice features of limited size, or downslope scouring); and

- To define the stresses on buried pipelines during scouring.

Figure 2 outlines a suggested research plan organization aimed at meeting these objectives.

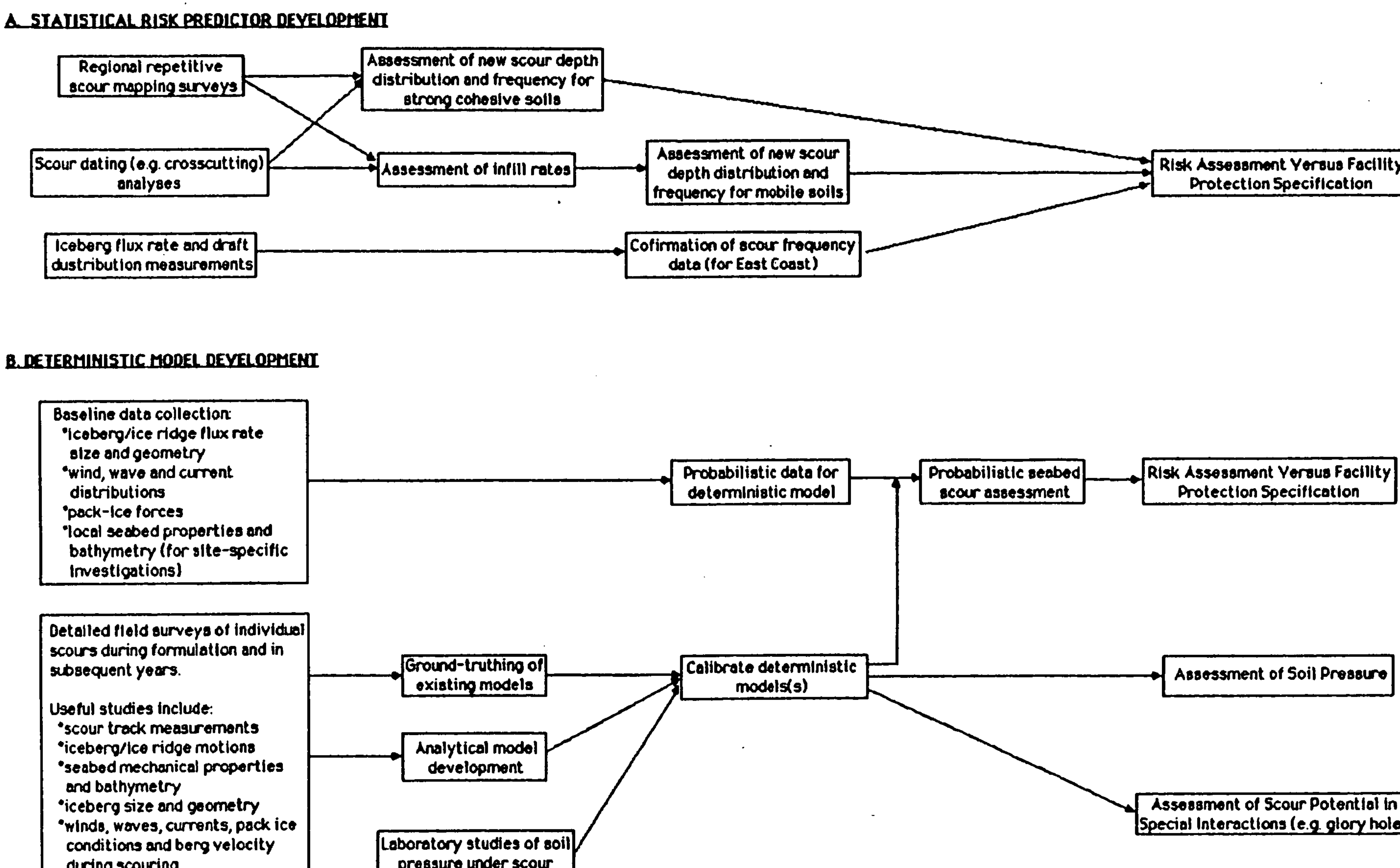
Deterministic models are considered to have a limited role to play in the first problem area whereas they are esential for the solution of the other two.

The use of deterministic models to verify or establish scour-damage risk levels is likely to be limited in the near term to gross verification of statistical predictors. Present knowledge of essential input parameters (e.g., iceberg drafts and shapes, flux rates, multi-year ridge geometries, pack-ice forces) is considered inferior to that available for ice-scour distributions. Also, the ice feature - soil interaction process is complex, and it is necessary to make simplying assumptions to produce a tractible model. As the present state-of-the-art in deterministic modelling is improved, the uncertainties introduced into the model by these assumptions will become better defined, and deterministic models will, hence, be more reliable as design tools. However, we believe that they have the greatest role to play in the last two problem areas listed above.

1 S. Foo, Mobil Research and Development Corp., personal communication (quessionnaire reply) 1985.

FIGURE 6.1

RESEARCH PLAN ORGANIZATION



Five areas were identified and prioritized in the survey as targets for future research towards improved deterministic modelling:

- corroboration of existing models with field or laboratory data.
- improvement of overall understanding of the scour process.
- incorporation of hydrodynamic aspects of process
- improvements in treatment of soil resistance
- predictions of soil pressures beneath the scour.

The majority of survey responses indicated that the first two areas listed above need to receive highest priority for further deterministic model development. The remaining three were considered to be of lesser priority, and need to be assessed after the development of a calibrated model. We would add, however, that the incorporation of hydrodynamic effects appears to be essential to satisfying the second point, especially for icebergs.

The responses generally reflect as very rudimentary understanding of the scour process and a lack of field data suitable for full model calibration at present. The present study has initiated work in these areas which may be used as a basis for further planning.

The collection of more complete field data is considered to be the first step towards an improvement in deterministic modelling.

The sensitivity analyses can provide guidance for the design of the required field-data collection program. For the iceberg-scour case, emphasis should be placed on defining the following parameters:

- initial kinetic energy of the berg (i.e., its mass and its drift rate)
- local sea-bed bathymetry
- soil strength (e.g., cohesion and/or friction angle, density)
- iceberg keel geometry and dimensions
- scour geometry (i.e., width, depth, surcharge height, and breadth)
- iceberg motions during scouring.

Data on other parameters, such as wind velocity, current velocity, and wave conditions, should also be collected for completeness. However, the analyses have indicated that the scour depth is not sensitive to these parameters, and, consequently, significant efforts to define these variables are not recommended.

The analyses have also indicated that the scour depth may be highly sensitive to the presence of pack ice, as this may impose high loads on the iceberg. However, pack-ice force magnitudes are poorly understood at present. Consequently, field programs at this time should avoid the scenario where pack ice presents and contributes to the environmental driving forces creating the scour.

Sea-bed scours of concern may also occur as a result of the action of multi-year ridge keels. As discussed in the section "Review of available ice scour models", input parameter sensitivities will vary somewhat for this case over the iceberg scour case; however, it is believed that the basic interaction features for this case are simliar to those for the iceberg scour case. Consequently, the field observation of iceberg scours is expected to provide relevant developmental data for the multi-year ridge-scour case as well.

Because the iceberg-scour case is simpler to document and is also less likely to involve pack ice, it is recommended that dedicated grounding experiments focus on this case.

Tables 25 to 28 describe a range of possible field programs, from the observation of groundings of opportunity to a dedicated grounding experiment. As would be expected, these provide a range of benefits and span a range of risks and costs.

It is believed that the dedicated grounding experiments (see Tables 25 to 27 for description) are necessary for the provision of the required field data.

In conjunction with these efforts, improvements need to be incorporated into the mathematical models. The best candidate for further work, on the basis of this study, is the FENCO (1975) dynamic model. Mobil Oil Canada, as mentioned previously, is developing a more comprehensive model which may satisfy this objective.

TABLE 25

Project Summary: Active Grounding Experiment

Objective	To document the scouring process of icebergs and to supply a full set of field calibration data for deterministic models.
Approach	At a location where iceberg-in-open-water conditions are common (e.g., Nain Bank in summer), tugboats would be used to guide icebergs into the sea bed. Upon contact with the sea bed (as evidenced by a towline tension increase), the towlines would be released and the berg would continue to scour into the sea bed. The iceberg mass and geometry would be measured prior to grounding. Iceberg motions and drift rates would be measured during scouring, whereas sea-bed soil properties, bathymetry, and scour geometries would be measured after the event.
Benefits and Risks	This approach has a high probability of supplying a complete set of field data, as the field crew will be able to have some control over the grounding time and location. Also, grounding is more likely to occur with this approach. Therefore, there is a high probability that data will be collected. Difficulties include iceberg location and towing problems. (Experience has shown that only relatively small bergs up to about 50,000 tons may be definitively towed.) This is also the most expensive approach.
Estimated cost	$3 million
Project duration	1-2 yr.

TABLE 26

Project Summary: Passive Grounding Experiment

Objective	To document the scouring process of icebergs and to supply a full set of field calibration data for deterministic models.
Approach	This field program is similar in scope to the active grounding experiment (see Table 25 for description). However, in this case, the field crew would stand by only in an area where groundings are expected. If a grounding event were considered probable, then the crew would collect iceberg-size and keel-geometry data and deploy motions-sensing packages on the iceberg using a helicopter. The experiment would then proceed by documenting iceberg motions and drift rate during scouring. Sea-bed soil property, bathymetry, and scour geometry information would be collected after the event.
Benefits and Risks	The major benefit of the passive grounding experiment over the active grounding experiment is that it has the potential to supply the same data at significantly less cost. On the negative side, the crew has no control over the grounding time and location. In addition, there are uncertainties regarding the time at which scouring commences. Finally, fewer grounding events are expected to be documented with this approach. Therefore, the risks include a decreased probability of collecting complete field data sets and a likely decrease in the number of grounding events.
Estimated cost	$1 million
Project duration	2-3 yr.

TABLE 27

Project Summary: Large-scale Scour Tests

Objective	To investigate the scouring process and to obtain deterministic model calibration data.
Approach	Large-scale scour tests would be conducted by winching an ice feature into the sea-bed using piles and anchors as reaction points. Possible locations include abandoned Beaufort Sea exploration islands, present-day exploration structures, and beaches. Field observations would include tow forces, ice-feature geometry, scour geometry, sea-bed bathymetry, and strength and ice-feature motions during scouring.
Benefits and Risks	This approach offers the greatest experimental control and, hence, the greatest probability that a complete data set will be gathered. The field crew will have good control over the scouring time and location, and will have a good understanding of the experimental variables, including the time at which scouring commences. This approach is likely to provide the best overall understanding of all aspects of the scour process. This approach has fewer data collection risks than the active or passive grounding experiments (see Tables 24 and 25). Problems with this approach include difficulties in towing or winching the ice feature and difficulties in providing sufficient sea-bed reaction for the towing forces.
Estimated cost	$1 million
Project duration	1-2 yr.

TABLE 28

Project Summary: Documentation of Groundings-of-Opportunity

Objective	To document ice-soil interaction parameters for grounding cases.
Approach	Grounded icebergs and multi-year ridges will be located using either aerial or reconnaissance missions or rig-based ice observer's reports. Surveys will then be conducted to document the ice feature (e.g., size and keel geometry) that created the scour. Sea-bed soil property, bathymetry, and scour-geometry data would also be collected.
Benefits and Risks	The major benefit of this approach is that a large quantity of data may be collected in a relatively economic manner. However, the field data set will be incomplete, as the berg motions will be unknown. Also, the berg drift rate is likely to be unknown or poorly documented, and there will be uncertainties regarding the berg or floe mass because of the effects of ablation and calving or splitting. These uncertainties are expected to be more significant for iceberg scours. Thus, the value of this information will be limited, although it will be useful for gross verification of deterministic model predictions. Other difficulties with this approach include the identification of grounded ice features.
Estimated cost	Beaufort Sea multi-year ridge ice scours -- $500,00. East coast iceberg scours -- $300.000.
Project duration	1-2 yr.

CONCLUSIONS

The available literature has been reviewed. Available ice-scour deterministic models are relatively simplistic at present, and range from three-degree-of-freedom equilibrium analyses to single-degree-of-freedom work-energy treatments. A great deal of field and laboratory study has been done on soil failure as related to other applications (e.g., agricultural equipment, marine anchors and ploughs, retaining walls). However this research is considered to be of limited value to the ice-scour problem, as these tests involve relatively small soil deformations and also lifting and cutting of the soil by profile shapes that are significantly different from those of scouring ice features.

Sensitivity analyses were conducted for the available deterministic ice-scour models. The predicted scour depth is most sensitive to the following parameters:

- initial kinetic energy of the ice feature
- motions of the ice feature during scouring
- soil resistance
- sea-bed bathymetry
- scour breadth
- pack-ice forces.

The environmental loads applied to the iceberg during scouring (resulting from the actions of winds, waves, and currents) are relatively small and, consequently, have little effect on the predicted scour depth. The action of pack ice loads may, however, be significant, as these forces may be much larger than the other applied environmental loads.

The available field data were found to be incomplete from the viewpoint of supplying deterministic model calibration data. It was necessary to use baseline data to establish ranges for several essential input parameters.

Attempts were made to calibrate the work-energy models of FENCO (1975) and Chari (1979) and the FENCO (1975) dynamic equilibrium analysis. The range of scour depths predicted by the work-energy models is typically higher than the range of measured field values. Predicted scour depths are typically within a factor of two of the measured values.

Calibration analyses done with the FENCO dynamic model are considered inconclusive because of anomalies in the predicted scour depths. It is believed that the program output has been affected by numerical instabilities and inaccuracies inherent in the prediction of small scour depths.

Research efforts are currently focussed on the establishment of long-term regional ice-scour data bases. Considerably less effort is being devoted to the development of deterministic models. Deterministic models are considered to have the following roles in understanding ice-scour problems:

- gross verification of the ice-scour damage versus pipelines protection specifications risk levels established from field ice-scour observations;

- prediction of soil pressures beneath the scour on buried installataions; and

- prediction of the scour potential for ice-soil interactions for which there are few field data (such as the scouring of protective glory holes).

The current application of deterministic models is hindered by a lack of understanding of the overall scour process and by a lack of field calibration data. Therefore, research efforts need to be focussed on the collection of a complete set of field ice-scour data for a number of grounding events (i.e., scour geometry, berg mass and geometry, berg drift rate, berg motions during scouring, soil strength parameters, and sea-bed bathymetry). A dedicated grounding experiment is recommended as the next step in advancing the state-of-the-art in deterministic modelling.

In conjunction with this work, an improved deterministic model should be developed, incorporating a full treatment of the hydrodynamic aspects of the problem and the ability to handle an assortment of shapes. Mobil Oil Canada is currently developing a more comprehensive model which may satisfy this objective.

RECOMMENDATIONS

This study has investigated the reliability of deterministic models for predicting scours, and makes recommendations regarding future research priorities.

REFERENCES

Abdelnour et al. 1981

Barrie, V. 1985. Sediment transport and iceberg scour preservation and degradation, Eastern Canadian Shelf. proc. ESRF Ice Scour Workshop, Calgary.

Chari, T. 1979. Geotechnical aspects of iceberg scours on ocean floors. Canadian Geotechnical Journal 16.

Chari, T.R. and H.P. Green, 1981. Iceberg scour studies in medium dense sands. proc. POAC, Quebec City.

Comfort, G., R. Abdelnour, B. Trak, B. Menon, and B. Graham. 1982. Lake Erie ice scour investigation. Presented at the NRC Workshop on Ice Scouring, Montebello, Quebec.

Croasdale, K.R. 1984. A logical approach to ice loads. Proc. Arctic Offshore Symposium, Paper TP-040584, Houston.

FENCO. 1975. Edited by R. Pilkington and H. Iyer. An analytical study of ice scour on the sea bottom. APOA Project 69.

Hotzel, S., and J. Miller. 1982. Relationships between measured iceberg dimensions. Presented at the NRC Workshop on Ice Scouring, Montebello, Quebec.

Kovacs 1974.

Lambe, W. and R. Whitman. 1969. Soil mechanics. Massachusetts Institute of Technology Press.

Lee, I.K. and J.R. Herrington. 1972. A theoretical study of pressures acting on a rigid wall by a sloping earth or rock fill. Geotechnique 22: 1-26.

Petro-Canada Exploration Ltd. 1982. Edited by G. Glazier, Offshore Labrador initial environmental assessment.

Pilkington, R. and R. Marcellus. 1981. Methods of determining pipeline trench depths in the Canadian Beaufort Sea. Proc. POAC, Quebec City.

Weeks, W.F. et al. 1983. Statistical aspects of ice gouging on the Alaskan Shelf of the Beaufort Sea. CRREL Report 83-21.

APPENDIX A

ABSTRACTS OF RELEVANT PAPERS

SUMMARY OF REFERENCE MATERIAL

SOURCE

NO.

Comfort, G., Abdelnour, R., Trak, B., Menon, B., and Graham, B., Lake Erie Ice Scour Investigation, NRC Ice Scour Workshop Proceedings, 1982.

SUMMARY

An analytical study was undertaken to obtain a better understanding of safe burial depths for a proposed submarine electric cable corridor in Lake Erie.

Ice scours up to 1.8 m deep in 15 to 25 m of water were measured by Ontario Hydro along a proposed submarine electrical cable corridor in Lake Erie from Nanticoke, Ontario to Erie, PA. This paper compares the results of ice scour predictions made by available deterministic work-energy ice scour models with the observed field data. In general, relatively poor correlation was found. Noting that these models assume soil failure to be the critical criterion and that relatively weak unconsolidated first year ridges are the primary scouring agents in Lake Erie, the authors proposed a simple analysis based on the limited flexural strength of a first year ridge. The proposed limiting scour depth approach provided better understanding of and correlation with the observed scours.

KEYWORDS

DATE

REVIEWED BY

SUMMARY OF REFERENCE MATERIAL

SOURCE

NO.

Abdelnour, R., and Lapp, D., 1980, Model Tests of Sea Bottom Ice Scouring, APOA # 150, submitted by Arctec Canada Limited.

SUMMARY

A series of laboratory tests of seabed scour were conducted to acquire experimental data on resistance force and pressure in the soil and at the model surface. In addition the tests examined the soil failure mechanisms and documented the characteristics of the scour profile. The test matrix included two model geometries and sizes, (i.e a pyramid and a prismatic), and three soil materials (i.e. sand, silt and clay). Each of these test matrix points was tested at three cut depths in a levelled soil bottom at three towing velocities.

Soil resistance was found to be directly proportional to the scour depth and width. In sand, the scour force increased with increasing velocity, while the reverse was true for clay soil. High local pressures were measured on the indentor face. Significant pressures were also measured in the soil beneath the indentor.

KEYWORDS

DATE

REVIEWED BY

SUMMARY OF REFERENCE MATERIAL

SOURCE

NO.

A.B. Dunwoody, J.A. Losch
Ice/Berm Interaction
O.T.C. 1984, pp. 223

SUMMARY

A physical model study was undertaken to develop a better understanding of ice-berm interactions. After reviewing the important considerations in the problem, a simple apparatus was constructed to model the main physical phenomena involved. Thirty-four tests were run over a range of floe face geometries and vertical stiffnesses of the leading edge of the floe. The main conclusions from the model tests were that the horizontal load is proportional to the stiffness for low values of stiffness and that the floe face geometry has minimal influence on the loads.

KEYWORDS

DATE

REVIEWED BY

SUMMARY OF REFERENCE MATERIAL

SOURCE

NO.

Lortz, W. (1979)

A Model of Cutting Mechanism in Grinding

Wear, March, 1979, 53(1), pp. 115-128

SUMMARY

In order to achieve optimum working results during grinding, information regarding both the kinematic relations and the structure of the multiple cutting-edge tool is necessary. In addition, the physical and metallurgical properties of the workpiece material and the specific influence of the inter-facial frictional effects must be taken into account.

This paper presents a contribution to the understanding of the cutting mechanisms in grinding. An analysis of the grinding mechanism is made on the basis of the cutting-edge geometry and the kinetics involved. One physical model has been developed to explain all the phenomena from friction to ploughing and cutting under plane strain conditions.

Starting from the velocity relation at an averaged penetrating cutting-edge and characterizing frictional conditions at the interface between the cutting-edge and the workpiece material, it is possible to calculate a slip-line field which satisfies all the existing boundary conditions. The flow pattern of the material can be drawn taking the corresponding hodograph into account. This results in a distortion of the square grid characterizing the material on passing through the region of plastic deformation. Agreement with cross-sections of actual chip formation zones during grinding is observed. The significance of this analysis lies in the fact that it establishes a relation between chip formation and the resultant surface integrity.

KEYWORDS

DATE

REVIEWED BY

SUMMARY OF REFERENCE MATERIAL

SOURCE

Roxborough, F.F and S. Eskikaya
Investigation into Some Aspects of Coal Plough System Design Using a ¼ Scale Dynamic Model

Mining Engineer (London), V.134, November, 1971, pp. 55-68

NO.

SUMMARY

THE paper describes the design and application of a one-quarter scale operational model of a coal plough installation as a further step in research in the field of coal ploughing in progress at the University of Newcastle upon Tyne. This work had confirmed the value of the "Variable Geometry" concept in coal ploughing and the next requirement was to design an equally efficient production system using the variable geometry cutting head as its principal production component. To experiment with a full production system would have been unrealistic in terms of financial and technical resources. The one-quarter scale model described in the paper enabled a study of the large number of variables involved and obviated the manufacture of duplicate items of costly equipment.

KEYWORDS

DATE

REVIEWED BY

SUMMARY OF REFERENCE MATERIAL

SOURCE | **NO.**

E radat Oskoui, K

Determination of Plough Draught-1. Prediction from soil and meteorological data with cone index as the soil strength parameter.
Journal of Terramechanics, V.19 n.2, June 1982, pp. 97-106

SUMMARY

Using cone index as an indication of soil strength, empirical equations are developed in accordance with soil mechanics theory to relate soil moisture content to plough draught. The plough draught equation comprises a quasi-static component dependent on cone index and a dynamic component which is a function of the soil specific weight, plough speed and mouldboard tail angle. It is further argued that the cohesive and frictional components of the cone penetration resistance can be predicted by means of a simple equation comprising a reciprocal function of the square of the soil moisture content and a linear function of the soil specific weight. The cone index equation explained 98% of the experimental data for three soils over a wide range of moisture contents. These empirical equations, together with a soil moisture model, provide a method of predicting plough draught directly from soil and meteorological data.

KEYWORDS

DATE

REVIEWED BY

SUMMARY OF REFERENCE MATERIAL

SOURCE

NO.

Gilormini, P. and E. Felder

Theoretical Experimental Study of the Ploughing of a Rigid-Plastic Semi-Infinite Body by a Rigid Pyramidal Indentor
Wear (Switzerland), July 1, 1983, 88(2), pp. 195-206

SUMMARY

Surface ploughing of a rigid-plastic semi-infinite body by a rigid pyramidal indentor is modelled by using a velocity field calculated by minimizing the dissipated power. The theoretical predictions are compared with the results of simulation tests using a model material. Good agreement is found for the tangential force, but the prediction of the flow pattern is less satisfactory. A simplified version of this model gives good results for forces and geometry when compared with tests on a low carbon steel.

KEYWORDS

DATE

REVIEWED BY

SUMMARY OF REFERENCE MATERIAL

SOURCE

Chari, Hydrodynamic Effects on Iceberg Gouging
Cold Region Science & Engineering, V.4, N.1
January, 1981, pp. 55-61

NO.

SUMMARY

A model of a grounding iceberg which takes into account the soil resistance and the hydrodynamic drag is formulated. Based on analytical investigations and numerical results, a simple and accurate estimator for gouge length is proposed. The calculations reveal that the hydrodynamic drag on grounding icebergs may have significant influence on the total gouge length. A numerical criterion which defines the range of iceberg parameters and ocean bottom characteristics for which drag effect cannot be neglected is established.

KEYWORDS

DATE

REVIEWED BY

SUMMARY OF REFERENCE MATERIAL

SOURCE

A Analytical Study of Ice Scour on the Sea Bottom, April 75, APOA 69 - 1

NO.

SUMMARY

The study covers all aspects of scouring: a review of literature; environmental factors required for study; types of ice formations; marine sediments; plus several idealistic mathematical models to predict scour for different situations. In particular, a dynamical model has been developed (by solving the basic equations of motion of a body being driven into a sloping sea-bed) and the solutions compared with other simpler model solutions which use either energy conservation or static equilibrium conditions. Finally, suggestions for model tests are given which could be used to verify the mathematical solutions presented here.

KEYWORDS

DATE

REVIEWED BY

APPENDIX B

DETERMINISTIC MODEL CALIBRATION AND SENSITIVITY STUDY RESULTS SUMMARY

APPENDIX B.1

WORK ENERGY MODEL SCOUR DEPTH PREDICTIONS

TABLE B.1

WORK-ENERGY MODEL SENSITIVITY ANALYSIS

	COMMENTS						
	BASE CASE	BERG MASS REDUCED	SCOUR BREADTH INCREASED	SOIL STRENGTH INCREASED	BEDSLOPE INCREASED	WIND SPD INCREASED	CURRENT & BERG DRIFT RATE INCREASED
INPUT PARAMETERS							
Berg length-m	120	60	120	120	120	120	120
Berg width -m	100	50	100	100	100	100	100
Berg depth -m	110	55	110	110	110	110	110
Scour breadth-m	30	30	100	30	30	30	30
Ice density-N/m ^{3}	8950	8950	8950	8950	8950	8950	8950
Water density-N/m^3	9850	9850	9850	9850	9850	9850	9850
Sub. soil dens N/m	8000	8000	8000	8000	8000	8000	8000
Bedslope -deg	1.2	1.2	1.2	1.2	5	1.2	1.2
Soil cohesion-Kpa	7	7	7	28	7	7	7
Wind speed -m/s	6	6	6	6	6	60	6
Current spd -m/s	0.5	0.5	0.5	0.5	0.5	0.5	1.0
OUTPUT PREDICTED SCOUR DEPTH (M)							
Fenco Model	2.16	0.91	1.32	1.41	3.78	2.16	3.71
Modified Fenco Model	2.18	0.91	1.33	1.43	3.79	2.28	3.76
Chari model	2.44	1.11	1.56	1.89	4.09	2.45	4.03
Modified Chari Model	2.47	1.13	1.58	1.92	4.11	2.58	4.09

Notes: 1. Work-energy models of Fenco (1975) and Chari (1979) modified to include work done by wind drag and current drag forces during scouring.

2. Added mass coefficient taken as 0.5

3. Drag coefficients taken as:

	Form	Skin
Wind	1.0	0.005
Current	1.0	0.05

4. For Chari model, H/D taken as 1.4.

5 For all models, the ice-soil friction angle was taken as 0

TABLE B.2

WORK-ENERGY MODEL SCOUR DEPTH PREDICTIONS : K-007 GROUNDING

	COMMENTS				
	BASE CASE	BERG MASS INCREASED BY 4	BERG DRIFT RATE & CURRENT VELOCITY INCREASED	MAXIMUM BEDSLOPE	MINIMUM BEDSLOPE
Berg length– m	230	460	230	230	230
width – m	180	360	180	180	180
depth – m	265	265	265	265	265
Scour Breadth–m	30	30	30	30	30
Ice Density n/m	9000	9000	9000	9000	9000
Water density n/m	10000	10000	10000	10000	10000
Soil density n/m	5635	5635	5635	5635	5635
Wind velocity m/s	11.1	11.1	11.1	11.1	11.1
Current vel– m/s	.077	.077	.17	0.077	0.077
Cohesion pa	5800	5800	5800	5800	5800
Ice soil friction angle – degrees	0	0	0	0	0
Initial vel–m/s	.077	.077	.17	0.077	0.077
Bed slope degrees	.32	.32	.32	.75	.05
<u>OUTPUT PREDICTED SCOUR (M)</u>					
Fenco Model (1975)	0.69	1.26	1.38	1.00	0.29
Mod Fenco Model	0.72	1.33	1.42	1.03	0.34
Chari Model (1979)	0.88	1.53	1.64	1.24	0.40
Mod. Chari Model	0.94	1.61	1.70	1.28	0.49

Notes:
1. See tables 5.2 and 5.4 for ranges of input parameters.
2. Drag coefficients taken as:

	Form Roughness	Skin Friction
Wind	1.0	0.005
Current	1.0	0.05

3. Added mass coefficient taken as 0.5.
4. For Chari model, surcharge height/scour depth taken as 1.4.
5. Work-energy models of FENCO (1975) and Chari (1979) modified to include work done by wind drag and current drag forces scouring as discussed in Section 4.

APPENDIX B.2

DYNAMIC MODEL SCOUR DEPTH PREDICTIONS

TABLE B3

WORK-ENERGY MODEL SCOUR DEPTH PREDICTIONS: CAROLINE GROUNDING

COMMENTS								
WINDSPEED :	MINIMUM	MINIMUM	MAXIMUM	MAXIMUM	MINIMUM	MINIMUM	MAXIMUM	MAXIMUM
CURRENT :	MEAN	MAXIMUM	MEAN	MAXIMUM	MEAN	MAXIMUM	MEAN	MAXIMUM
SOIL STRENGTH :	LOW	LOW	LOW	LOW	HIGH	HIGH	HIGH	HIGH
Input Parameters								
Berg length (m)	180	180	180	180	180	180	180	180
depth (m)	180	180	180	180	180	180	180	180
width (m)	232	232	232	232	232	232	232	232
Scour breadth (m)	30	30	30	30	30	30	30	30
Ice density (N/m3)	9000	9000	9000	9000	9000	9000	9000	9000
Water density (N/m3	10000	10000	10000	10000	10000	10000	10000	10000
Soil density (N/m3	6300	6300	6300	6300	6300	6300	6300	6300
Wind velocity (m/s)	0	0	42	42	0	0	42	42
Current velocity (m/s)	0.14	0.46	0.14	0.46	0.16	0.46	0.14	0.46
Cohesion (Pa)	4000	4000	4000	4000	10000	10000	10000	10000
Ice soil friction angle (deg.)	0	0	0	0	0	0	0	0
Initial velocity (m/s)	0.14	0.46	0.14	0.46	0.14	0.46	0.14	0.46
Bed slope (deg.)	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Output Predicted Scour Depth (m)								
Fenco Model (1975)	1.14	2.92	1.14	2.93	0.86	2.45	0.86	2.45
Modified Fenco Model	1.16	2.98	1.58	3.22	0.87	2.51	1.14	2.69
Chari Model (1979)	1.33	3.15	1.33	3.16	1.13	2.89	1.13	2.89
Modified Chari Model	1.35	3.23	1.85	3.48	1.14	2.96	1.55	3.18

Notes: 1. See tables 5.2 and 5.4 for ranges of input parameters
2. Drag coefficients taken as:

	Form Roughness	Skin Friction
Wind	1.0	0.005
Current	1.0	0.05

3. Added mass coefficient taken as 0.5
4. For Chari model, surcharge height/scour depth taken as 1.414.
5. Work-energy models of FENCO (1975) and Chari (1979) modified to include work done by wind drag and current drag forces during scouring as discussed in section 4.

TABLE B.4

WORK-ENERGY MODEL SCOUR DEPTH PREDICTIONS: FRANCES GROUNDING

	COMMENTS							
Windspeed :	MINIMUM	MINIMUM	MAXIMUM	MAXIMUM	MINIMUM	MINIMUM	MAXIMUM	MAXIMUM
Current :	MEAN	MAXIMUM	MEAN	MAXIMUM	MEAN	MAXIMUM	MEAN	MAXIMUM
Soil strength :	LOW	LOW	LOW	LOW	HIGH	HIGH	HIGH	HIGH
Input Parameters								
Berg length (m)	360	360	360	360	360	360	360	360
width (m)	360	360	360	360	360	360	360	360
depth (m)	159	159	159	159	159	159	159	159
Scour breadth (m)	35	35	35	35	35	35	35	35
Ice density (N/m^3)	9000	9000	9000	9000	9000	9000	9000	9000
Water density (N/m^3)	10000	10000	10000	10000	10000	10000	10000	10000
Soil density (N/m^3)	8325	8325	8325	8325	8325	8325	8325	8325
Wind velocity (m/s)	0	0	42	42	0	0	42	42
Current velocity (m/s)	0.11	0.34	0.11	0.34	0.11	0.34	0.11	0.34
Cohesion (Pa)	14000	14000	14000	14000	24000	24000	24000	24000
Ice soil friction angle - (deg)	0	0	0	0	0	0	0	0
Initial velocity (m/s)	0.11	0.34	0.11	0.34	0.11	0.34	0.11	0.34
Bed slope (deg)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Output Predicted Scour Depth (M)								
Fenco Model (1975)	0.48	1.35	0.48	1.35	0.38	1.11	0.38	1.11
Modified Fenco Model	0.48	1.39	0.78	1.60	0.38	1.13	0.56	1.28
Chari Model (1975)	0.66	1.71	0.66	1.71	0.55	1.49	0.55	1.49
Modified Chari Model	0.67	1.75	1.17	2.05	0.55	1.54	0.93	1.78

Notes:
1. See tables 5.2 and 5.5 for ranges of input parameters
2. Drag coefficients taken as:

	Form Roughness	Skin Friction
Wind	1.0	0.005
Current	1.0	0.05

3. Added mass coefficient taken as 0.5
4. For Chari model, surcharge height/scour depth taken as 1.4.
5. Work-energy modesl of FENCO (1975) and Chari (1979) modified toinclude workdone by wind drag and current drag forces during scouring as discussed in section 4.

TABLE B.5

FENCO DYNAMIC MODEL SENSITIVITY RUNS

	BASE CASE	LOOSE SAND	DENSE SAND	WEAK COHESIVE	STRONG COHESIVE	CHG BEDSLOPE	PACK ICE FORCE INCL.	INCRE'D CURRENT	INCRE'D WAVE HT	INCRE'D WIND SPD	DECRE'D WIDTH	DECRE'D MASS	INCRE'D SAIL ROUGH*	INCRE'D CURRENT DRAG	INCRE'D POISSON'S RATIO
INPUT PARAMETERS															
Berg length-ft	400	400	400	400	400	400	400	400	400	400	400	315	400	400	400
width -ft	320	320	320	320	320	320	320	320	320	320	80	232	320	320	320
depth -ft	360	360	360	360	360	360	360	360	360	360	360	269	360	360	360
Bedslope -deg.	1.2	1.2	1.2	1.2	1.2	5	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Ice pack thick-ft	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0
Soil frict angle-deg	30	26	36	0	0	30	30	30	30	30	30	30	30	30	30
Ice soil frict-deg	26	22	32	0	0	26	26	26	26	26	26	26	26	26	26
Soil adhesion-psf	0	0	0	150	500	0	0	0	0	0	0	0	0	0	0
Soil cohesion-psf	0	0	0	150	500	0	0	0	0	0	0	0	0	0	0
Soil sub. wt-pcf	51	46	61	51	56	51	51	51	51	51	51	51	51	51	51
Soil elastic mod at bed surface-psf	460000	288000	720000	14400	28800	460000	460000	460000	460000	460000	460000	460000	460000	460000	460000
Poisson's ratio	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.5
Mod change with depth - psf/ft	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400
Air dens.-slugs/ft3	0.00237	0.00237	0.00237	0.00237	0.00237	0.00237	0.00237	0.00237	0.00237	0.00237	0.00237	0.00237	0.00237	0.00237	0.00237
Wind speed-ft/sec	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	175	20.5	20.5	20.5	20.5	20.5
Sail surf drag coeff	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	*	0.002	0.002
Ridge intensity factor	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	*	0.02	0.02
Sail form rough drag coeff.	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	*	0.4	0.4
Sail fbd.drag coeff	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Water density -pcf	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64
Ice density -pcf	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57
Current -ft/sec	1.69	1.69	1.69	1.69	1.69	1.69	1.69	3.38	1.69	1.69	1.69	1.69	1.69	1.69	1.69
Keel drag coeff.	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1.0	0.5
Wave height -ft	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	49	11.5	11.5	11.5	11.5	11.5	11.5
Pack ice force - lb/ft	0	0	0	0	0	0	50000	0	0	0	0	0	0	0	0

Table B.5 continued

	BASE CASE	LOOSE SAND	DENSE SAND	WEAK COHESIVE	STRONG COHESIVE	CHG BEDSLOPE	PACK ICE FORCE INCL.	INCRE'D CURRENT	INCRE'D WAVE HT	INCRE'D WIND SPD	DECRE'D WIDTH	DECRE'D MASS	INCRE'D SAIL ROUGH*	INCRE'D CURRENT DRAG	INCRE'D POISSON'S RATIO
INITIAL VALUES:															
Init.x-displ-ft	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Init.z:displ-ft	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Init.pitch disp-deg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Init.x-vel. -fps	1.69	1.69	1.69	1.69	1.69	1.69	1.69	3.38	1.69	1.69	1.69	1.69	1.69	1.69	1.69
Init.z-vel. -fps	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Init.pitch velocity-deg/s	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OUTPUT VALUES															
Scour length -ft	224.2	245.0	188.3	69.6	24.6	87.3	393.4	355.3	315.9	225.2	225.2	191.3	224.2	224.2	224.5
Berg lift - ft	0.1	0.1	0.0	-0.8	-0.3	-0.1	-0.7	-0.2	-0.4	-0.1	0.0	-0.1	-0.1	-0.1	-0.1
Scour depth -ft	4.8	5.2	3.9	1.5	0.8	7.7	8.3	7.6	7.0	4.8	4.7	4.1	4.8	4.8	4.8

* The sail surface drag coefficient, ridging intensity factor, and sail freeboard form roughness drag coefficients were each varied separately, (from 0.002 to 0.004, 0.2 to 0.04 and 0.4 to 0.6 respectively). Rounded to one decimal place, the same scour depths were predicted in all cases.

TABLE B.6

RESULTS OF FENCO DYNAMIC ICE SCOUR MODEL RUNS: KO07 GROUNDING

	COMMENTS							
	BASE CASE	BERG LGTH AND WIDTH SWITCHED	ICE SOIL ADHESION IGNORED	MINIMUM BEDSLOPE	MAXIMUM BEDSLOPE	BERG DRIFT RATE AND CURRENT SPEED DBLD	1.BERG MASS INCREASED BY 4 2.BERG LGTH AND WIDTH SWITCHED	BERG MASS INCREASED BY 4
INPUT PARAMETERS								
Berg length- ft	755	590	755	755	755	755	1180	1510
Berg width - ft	590	755	590	590	590	590	1510	1180
Berg depth - ft	869	869	869	869	869	869	869	869
Bed slope -deg	0.32	0.32	0.32	0.05	0.75	0.32	0.32	0.32
Ice Pack thick-ft	0.0	0.0	0	0	0	0.0	0.0	0.0
Soil frict.angle-deg	0.0	0.0	0	0	0	0.0	0.0	0.0
Ice Soil frict-deg	0.0	0.0	0	0	0	0.0	0.0	0.0
Soil adhesion -psf	121	121	0	121	121	121	121	121
Soil cohesion -psf	121	121	121	121	121	121	121	121
Soil sub.wt-pcf	36	36	36	36	36	36	36	36
Soil elastic mod at bed surface-psf	14400	14400	14400	14400	14400	14400	14400	14400
Poisson's Ratio	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Mod change with depth -psf/ft	14400	14400	14400	14400	14400	14400	14400	14400
Air dens-slugs/ft3	0.00237	0.00237	0.00237	0.00237	0.00237	0.00237	0.00237	0.00237
Wind speed- ft/sec	36.6	36.6	36.6	36.6	36.6	36.6	36.6	36.6
Sail Surf Drag coeff	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Ridge intensity factor	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Sail form rough drag coeff	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sail Fbd Drag coeff	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Water density-pcf	64	64	64	64	64	64	64	64
Ice density -pcf	57	57	57	57	57	57	57	57
Current ft/sec	0.253	0.253	0.253	0.253	0.253	.506	0.253	0.253
Keel drag coeff	1.0	1.0	1	1	1	1.0	1.0	1.0
Wave ht - ft	3.28	3.28	3.28	3.28	3.28	3.28	3.28	3.28
Pack ice force kips/ft	0	0	0	0	0	0	0	0

TABLE B.6 CONTINUED.

	BASE CASE	BERG LGTH AND WIDTH SWITCHED	ICE SOIL ADHESION IGNORED	MINIMUM BEDSLOPE	MAXIMUM BEDSLOPE	BERG DRIFT RATE AND CURRENT SPEED DBLD	1. BERG MASS INCREASED BY 4 2. BERG LGTH AND WIDTH SWITCHED	BERG MASS INCREASED BY 4
INITIAL VALUES								
Init x-displ-ft	0.0	0.0	0	0	0	0.0	0.0	0.0
Init z-displ-ft	0.0	0.0	0	0	0	0.0	0.0	0.0
Init. pitch displ-deg	0.0	0.0	0	0	0	0.0	0.0	0.0
Init x-vel-fps	0.253	0.253	0.253	0.253	0.253	0.506	0.253	0.253
Init z-vel-ft/s	0.0	0.0	0	0	0	0.0	0.0	0.0
Init. pitchvel-deg/s	0.0	0.0	0	0	0	0.0	0.0	0.0
OUTPUT VALUES								
LEADING CORNER OF ICEBERG DISPLACEMENT:								
Scour length-ft	4.8	90.5	175.1	1.3	10.7	21.8	19.1	31.8
Berg lift -ft	-2.9	57	-0.2	-4.2	-1.4	-0.7	-0.2	-0.3
Scour depth-ft	2.9	-56.5 [2]	1.1	4.2	1.5	0.8	0.3	0.5

Notes: 1. Scour depth calculated as outlined in FENCO (1975) as:
(Scour length tangent bed slope angle) - Berg lift.

2. Numerical instability in program.

TABLE B.7

RESULTS OF FENCO DYNAMIC ICE SCOUR MODEL RUNS: CAROLINE BERG

	COMMENTS														
Soil Strength	low	low	low	high	high	low	low	low	low	low	high	high	high	high	high
Windspeed	max	min	max	max	min	max	min	min	max	min	max	max	min	max	min
Current	mean	mean	mean	max	max	max	max	max	max	mean	max	mean	mean	mean	max
Sig.wave ht	max	max	most prob	max	max	max	most prob	max	most prob	most prob	most prob	most prob	max	max	most prob
INPUT PARAMETERS															
Berg lgth-ft	590	590	590	590	590	590	590	590	590	590	590	590	590	590	590
Berg wdth-ft	590	590	590	590	590	590	590	590	590	590	590	590	590	590	590
Berg dpth-ft	761	761	761	761	761	761	761	761	761	761	761	761	761	761	761
Bedslope-deg	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Ice Pk Thk-ft	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Soil friction angle -deg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ice-soil frict deg.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Soil adh-psf	84	84	84	209	209	84	84	84	84	84	84	209	209	209	209
Soil coh-psf	84	84	84	209	209	84	84	84	84	84	84	209	209	209	209
Soil sub.Wt-pcf	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
Soil elastic mod at bed surface-psf	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400
Poisson's ratio	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Mod change with depth psf/ft	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400
Air Density slugs/ft	.00237	.00237	.00237	.00237	.00237	.00237	.00237	.00237	.00237	.00237	.00237	.00237	.00237	.00237	.00237
Wind Spd-ft/sec	138.0	0.0	138.0	138.0	0.0	138.0	0.0	0.0	138.0	0.0	138.0	138.0	0.0	138.0	0.0
Sail Surf drag coeff.	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Ridge Intensity factor	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Sail form rough drag coeff	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sail Fbd drag coeff	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Water den-pcf	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64
Ice den-pcf	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57
Current ft/sec	0.46	0.46	0.46	1.532	1.532	1.532	1.53	1.53	1.53	0.46	1.53	0.46	0.46	0.459	1.53

Table B.7 continued

Soil Strength	low	low	low	high	high	low	low	low	low	low	high	high	high	high	high
Windspeed	max	min	max	max	min	max	min	min	max	min	max	max	min	max	min
Current	mean	mean	mean	max	max	max	max	max	max	mean	max	mean	mean	mean	max
Sig.wave ht	max	max	most prob	max	max	max	most prob	max	most prob	most prob	most prob	most prob	max	max	most prob
Keel drag coef	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Wave ht-ft	15	15	4	15	15	15	4.0	15.0	4.0	4.0	4.0	4.0	15	15	4
Pack Ice force															
Initial Values															
Init x disp-ft	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Init z disp-ft	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
In pitch dsp-°	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Init x-vel-fps	0.46	0.46	0.46	1.532	1.532	1.532	1.53	1.53	1.53	0.46	1.53	0.46	0.46	0.459	1.53
Init z-vel ft/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Init pitch-vel -deg/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OUTPUT VALUES															
Displacement of Leading Corner of Iceberg:															
Scour lgth-ft	21.9	19.2	19.2	65.3	65.0	145.6	142.7	144.4	143.9	19.3	65.2	6.7	6.7	6.7	5.6
Berg Lift-ft	-1.5	-2.0	-2.0	-1.2	-1.1	-2.2	-1.5	-1.9	-1.8	-1.9	-1.1	-2.2	-2.2	-2.2	-2.9
Scour dpth-ft	1.6	2.1	2.1	1.6	1.5	3.1	2.4	2.8	2.7	2.0	1.5	2.2	2.2	2.2	2.9

NOTE: 1. See tables 5.2 and 5.4 for ranges of input parameters.
2. Scour depth calculated as outlined in FENCO (1975)
as: (Scour length tangent bed slope angle) - Berg lift.

TABLE B.8

RESULTS OF FENCO DYNAMIC ICE SCOUR MODEL RUNS: FRANCES BERG

	COMMENTS														
Soil Strength	high	low	high	high	high	high	low	low	low	high	low	low	high	low	low
Windspeed	max	min	min	max	min	min	max	max	max	min	min	min	max	max	min
Current	mean	mean	max	max	mean	max	max	max	mean	max	mean	max	mean	mean	max
Sig. wave ht	most prob	max	most prob	max	max	most prob	max	most prob	most prob	max	most prob	max	max	max	most prob
Input Parameters															
Berg length-ft	1181	1181	1181	1181	1181	1181	1181	1181	1181	1181	1181	1181	1181	1181	1181
Berg width-ft	1181	1181	1181	1181	1181	1181	1181	1181	1181	1181	1181	1181	1181	1181	1181
Berg depth-ft	522	522	522	522	522	522	522	522	522	522	522	522	522	522	522
Bed Slope-deg	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Ice Pk thk-ft	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Soil friction angle-deg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ice-soil friction-deg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Soil adh-psf	501	292	501	501	501	501	292	292	292	501	292	292	501	292	292
Soil coh-psf	501	292	501	501	501	501	292	292	292	501	292	292	501	292	292
Soil sub.wt-pcf	53	53	53	53	53	53	53	53	53	53	53	53	53	53	53
Soil Elast.Mod bed surfc-pcf	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400
Poisson's ratio	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Mod change with depth-psf/ft	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400	14400
Air density slugs/ft3	.00237	.00237	.00237	.00237	.00237	.00237	.00237	.00237	.00237	.00237	.00237	.00237	.00237	.00237	.00237
Wind spd-ft/sec	138	0.0	138	138	0.0	0.0	138	138	138	0.0	0.0	0.0	138	138	0.0
Sail Surf Drag coeff	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Ridge Intensity Factor	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.2	0.2	0.2
Sail Form Rough Drag coeff	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sail Frd Drag Coeff	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Water den-pcf	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64
Ice dens-pcf	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57
Current-ft/sec	0.35	0.35	1.128	1.128	0.35	1.128	1.128	1.128	0.35	1.128	.038	1.128	0.35	0.35	1.128
Keel drag coef	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

TABLE B.8 CONTINUED

Soil Strength	high	low	high	high	high	high	low	low	low	high	low	low	high	low	low
Windspeed	max	min	max	max	max	min	max	max	max	min	min	min	max	max	min
Current	mean	mean	max	max	mean	max	max	max	mean	max	mean	max	mean	mean	max
sig. wave ht	most prob	max	most prob	max	max	most prob	max	most prob	most prob	max	most prob	max	max	max	most prob
Wave ht-ft	4	15	4	15	15	4	15	4	4	15	4	15	14	15	4
Pack Ice Force kips/ft	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
INITIAL VALUES															
Init-x disp-ft	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Init-z disp-ft	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
In Pitch(0)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Init-x vel-fps	0.35	0.35	1.128	1.128	0.35	1.128	1.128	1.128	0.35	1.128	0.35	1.128	0.0	0.0	0.0
Init-z vel-ft/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.35	0.35	1.128
Init pitch vel - deg/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OUTPUT VALUES															
DISPLACEMENT OF LEADING CORNER OF ICEBERG:															
Length - ft	0.70	0.70	2.30	2.30	0.70	2.30	21.0	21.0	0.70	2.30	0.70	21.0	0.70	0.70	21.0
Berg lift -ft	+0.1	+0.10	+0.1	+0.1	+0.1	+0.1	-1.6	-1.6	+0.1	+0.1	+0.1	-1.6	+0.1	+0.10	-1.6
Pred scour depth - ft	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	1.6	1.6	-0.1	-0.1	-0.1	1.6	-0.1	-0.1	1.6

NOTE: 1. See tables 5.2 and 5.5 for ranges of input parameters
2. Scour depth calculated as outlined in FENCO (1975) as: (Scour length tangent bed slope angle) - Berg lift.

APPENDIX C

GROUND TRUTH DATA

ARCTEC CANADA LIMITED

KARLSEFNI K-007 BERG

SAGLEK EAST MOSAIC

THE K-007 BERG DISCUSSED BY SMITH AND BANKE (1983) (PAPER ENCLOSED) AND SMITH AND LEWIS (PAPER ENCLOSED) GROUNDED IN OCTOBER 1976. REPETITIVE SURVEYS IN 1978, 1979, 1981 AND 1982 INDICATE A FEATURE SIMILAR TO THE DRIFT TRACK RECORDED ON THE RADAR OF THE DRILL SHIP.

INITIALLY THIS FEATURE WAS LOCATED ON ALL THE AVAILABLE SIDE SCAN DATA BUT WHEN PLOTTED UP TO 650 M DISCREPANCY WAS NOTED.

MR C. LYNAS AND V. BARRIE OF C-CORE DOUBT THAT THIS FEATURE CAN BE DEFINITELY ATTRIBUTED TO THE K 007 BERG.

A GRID 58°53' - 58°54' N AND 61°44' - 61°46' W WAS ANALYSED RECORDING ALL AVAILABLE DATA FOR SCOURS WHICH COULD BE IDENTIFIED ON BOTH SIDE SCAN AND HUNTEC DTS (HUNTEC MEASUREMENTS ARE BASED ON 1500 M/SEC VELOCITY IN WATER)

THE SEAFLOOR IN THE STUDY AREA CONSISTS OF A GLACIO-MARINE SILT UNIT RANGING FROM WELL STRATIFIED IN WATER DEPTHS > 167 M, POORLY STRATIFIED FROM 167 – 157 M AND NON STRATIFIED IN WATER DEPTHS < 157 M. THE STRATIFICATION HAS BEEN DESTROYED BY ICEBERG SCOURING. THIS HAS ALSO RESULTED IN OVERCONSOLIDATION OF THIS MATERIAL

GEOTECH	STRATIFIED UNIT 4
WATER CONTENT	37 – 52 %
BULK DENSITY	1.5 – 1.7 g/cc
SHEAR STRENGTH	3.5 – 4 KPa
UNIFIED SOIL CLASS	CL.

Core 82.054.004 C

SABLE EAST 79-39 MOSAIC

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	[illegible]	21	22	23	24	25	26	27	
SCOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	[illegible]	21	22	23	24	25	26	27	SCOUR
LENGTH OF SCOUR	1500	2000	[illegible]	[illegible]	[illegible]	1000	1000	[illegible]	(800 - 1000)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	750	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	LENGTH OF SCOUR
WATER DEPTH RANGE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	WATER DEPTH RANGE
SCOUR AZIMUTH	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	SCOUR AZIMUTH
MINIMUM SCOUR WIDTH,	50	10	40	15	15	20	30	15	35	20	25	75	50	50	10	20	15	15	[illegible]	[illegible]	30	45	30	15	15	15	MINIMUM SCOUR WIDTH
WATER DEPTH (STARTS AT)	159	165	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	WATER DEPTH (STARTS AT)
MAX SCOUR WIDTH (STARTS AT)	75	55	60	30	40	[illegible]	[illegible]	30	55	[illegible]	35	[illegible]	[illegible]	60	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	65	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	30	MAXIMUM SCOUR WIDTH (STARTS AT)
WATER DEPTH	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	WATER DEPTH
MEAN SCOUR WIDTH	65	40	45	20	5	25	30	[illegible]	40	35	[illegible]	[illegible]	6	56	[illegible]	[illegible]	[illegible]	55	55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	MEAN SCOUR WIDTH
NUMBER OF CROSSINGS WITH HIGHEST GSC LINE	1	3	1	1	1	1	1	1	1	1	1	3	2	2	2	1	1	1	2	2	1	1	1	1	1	1	NUMBER OF CROSSINGS WITH HIGHEST GSC LINE
CROSSOVER NUMBER (1 BEING 2 ... 3 ...)	1	1 2 3	1	1	1	1	1	1	1 2 3	1	1	1 2 3	2 3	2 3	2 3	3	3	3	2 3	2 3	2	3	2	2	2	2	CROSSOVER NUMBER
ANGLE OF CROSSOVER (WITH GSC LINE)	45°	90° 90° 90°	38°	55°	65°	90°	90°	60°	90° 90° 85°	55°	40°	33° 27° 40°	70° 74°	70° 70°	[illegible]	35°	64°	60°	[illegible]	[illegible]	70°	80°	[illegible]	40°	45°	60°	ANGLE OF CROSSOVER
SCOUR WIDTH	65	40 56 34	40	15	40	20	35	30	30 55 45	20	35	50	[illegible]	60 55	[illegible]	[illegible]	15	50	55 45	[illegible] 45	20	20	20	45	35	20	SCOUR WIDTH
SCOUR DEPTH	6.0	1.0 1.5 1.1	2.5	1.0	2.2	1.9	1.9	0.5	1.0 2.5 1.5	0.5	1.2	1.2	[illegible]	[illegible]	[illegible]	2.0	0.5	1.9	2.5 1.5	[illegible]	2.5	2.2	1.3	0.8	[illegible]	4	SCOUR DEPTH
BERM HEIGHT	2.0	0.6 2.5 2.5	1.5	0.5	1.0	1.0	2.5	0.2	0.5 1.0 1.5	2.2	1.7	2.0	[illegible]	[illegible]	[illegible]	1.4	0.5	2.8	1.0 1.0	[illegible] 1.5	1.5	1.4	0.7	0.5	[illegible]	1.0	BERM HEIGHT
WATER DEPTH	159	160 162 164	160	157	157	155	162	155	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	165	165	166	[illegible]	[illegible]	167	165	155	[illegible]	[illegible]	165	WATER DEPTH
BOTTOM TYPE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4(1.1)	BOTTOM TYPE
Remarks	Long straight scour	Long straight scour, [illegible]	Long straight scour, [illegible]	Long [illegible] curved scour [illegible]	Straight scour	Straight scour	Straight scour	Curved scour, [illegible]	Straight scour, [illegible]	Straight scour	[illegible] scour	Long straight scour, [illegible]	[illegible]	Long straight scour	[illegible] scour	Curved scour	Curved scour	Curved scour	[illegible]	[illegible]	Curved scour	[illegible]	[illegible] scour	Curved scour	[illegible]	STRAIGHT SCOUR	

THIS INFORMATION TAKEN FROM CROSSOVER POINT.

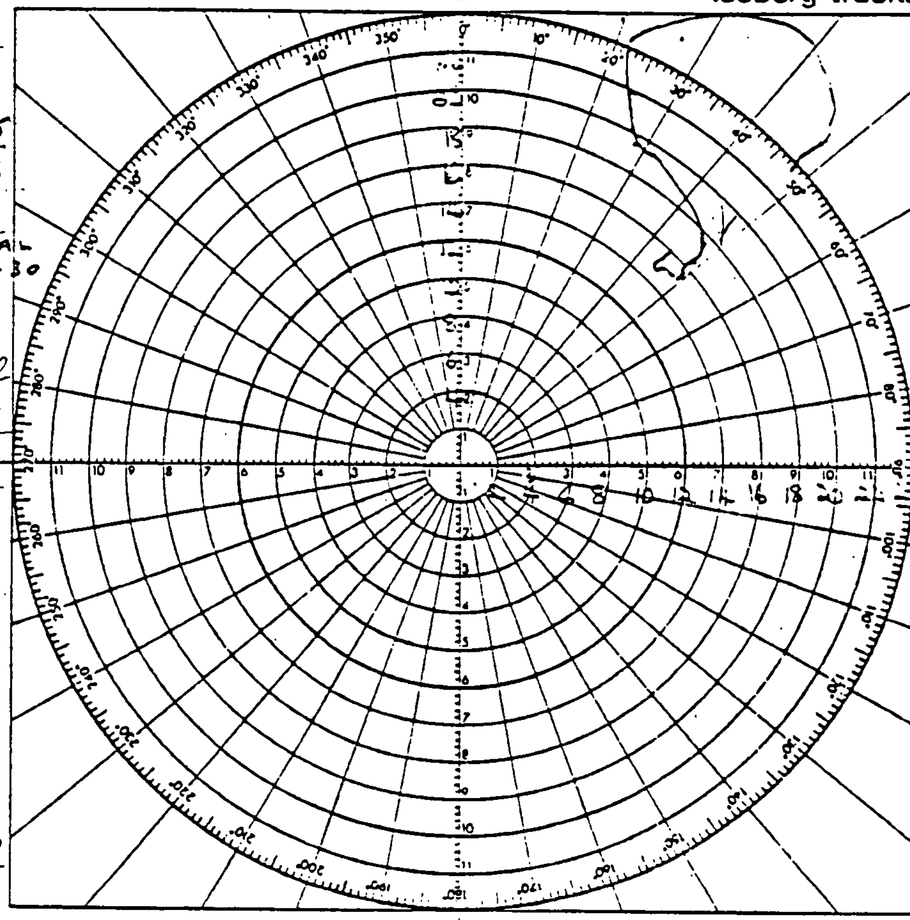
BOTTOM TYPE
UNIT 4 (1) STRATIFIED
(1.1) POORLY STRATIFIED
(2) NON STRATIFIED

ICEBERG LOG PELICAN   IDENTIFICATION No. K007

DATE/TIME	Range Nautical Miles	Bearing Relative True N.	Spd. (Kts)
15·9·76			
0100	24.0	043	
0200	24.0	043	0
0430	24.3	048.5	0.15
0600	25.2	048	1.68
0700	25.1	049	0.45
0800	NO TRACE		VISUAL AT 0730
1000	26.7	045	0.80
1300	25.2	046	0.52
1500	25.9	045	0.41
1630	26.4	047	0.67
GROUNDED	IN 80 FATHOMS)		
STARTED MOVING AGAIN.			
20-21/9/76			
22/9/76			
1830	27.3	015	
23/9/76			
1615	22.0	029	0.30
2200	19.5	029	0.52
2345	19.3	032	0.51
24/9/76			
0500	17.5	047	1.13
0730	16.4	049	0.50
0830	16.0	043	0.49
0920	15.9	050	0.65
1000	15.5	049	0.72
1100	15.5	046	0.81
1200	15.4	045	0.29
1545	14.9	044	0.15
1700	15.0	045	0.22
1900	15.3	046	[illegible]
— GROUNDED —			
2000	15.0	046	
25/9/76			
0600	15.0	044	
1300	15.2	044	
1800	15.2	044	
2300	15.00	044	

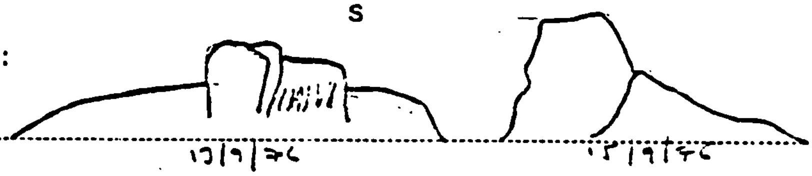
RADAR PLOT   iceberg tracks

N



S

NOTES:



First sighted visually 13/9/76 NE. Then did not come closer 15-20 miles & disappeared – prominent blocky features – very regular square tower main in identifying shape from Lande.

HEADING N.E. DISCONTINUED AT 1630

SIDESCAN	SONAR
HEIGHT	85m
WIDTH	180m
Length	230m
DRAFT	180m

EST MASS | 30+ million tons (W. TAB/BLOCKY) / 25 m tons avg.
(WEATHERED TAB) 15+ " " (PINNACLED)

MASS EST = 25 mill. tons

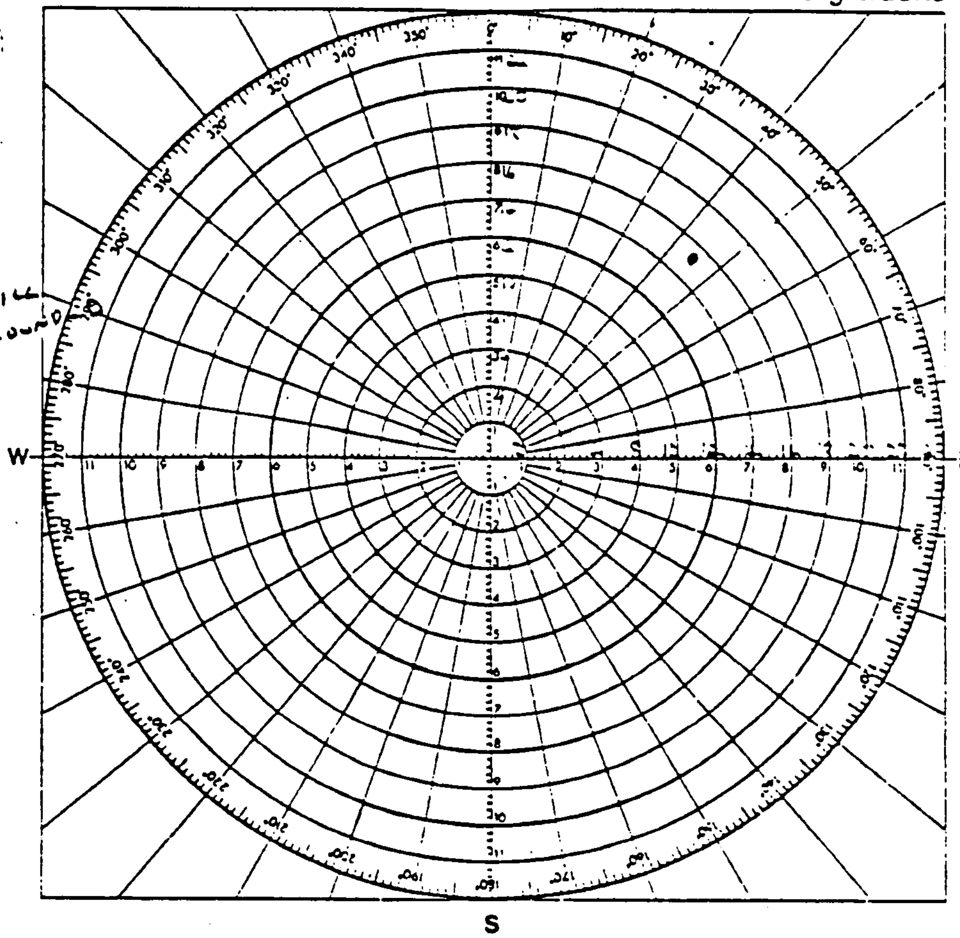
marex

ICEBERG LOG PELICAN IDENTIFICATION No. K007

DATE/TIME	Range Nautical Miles	Bearing Relative True N.
26/9/76		
0100	15.0	044
0300	15.0	044
0600	15.1	044
2400		
27/9/76	15.0	044
0600	15.0	044
1200	15.0	045
28/9/76		
0900	15.0	046
1200	15.0	046
1600	15.1	047
2400	15.0	046
29/9/76		
0600	15.0	045
30/9/76		
0800	15.0	046
1800	15.0	045
2400	15.1	045
1/10/76		
0300	15.2	045
0600	15.2	045
1800	15.1	045
2/10/76		
0100	15.1	045
0300	15.1	046
0600	15.1	046
1000	15.0	046
1500	15.0	046
1800	15.0	047
2200	15.0	047
3/10/76		
0200	14.9	047
0600	14.9	046
1100	15.0	046
1500	15.0	045
2400	15.0	049
4/10/76 0200	15.0	047
0600	15.0	047

STILL GROUNDED

RADAR PLOT — iceberg tracks



NOTES:

REVISED SIZE ESTIMATES 50m x (158m + 53m)

RANGE 0.125 ML:

SEXTANT ANGLES – 12° 17.5' HEIGHT (HIGHEST 20.m)

– 39° 00' LENGTH (MAIN 390m)

– 13° . 00' " (TONGUE)

2/10/76 same range & bearing but seems to have shifted position, showing some what different face toward Pelican.

marex

ICEBERG LOG

IDENTIFICATION No. K007

DATE/TIME	Range Nautical Miles	Bearing Relative True N.
4/10/76		
1200	11.9	042
1700	15.0	042
2400	15.0	046
05/10/76		
0300	15.0	047
0600	15.0	047
1130	15.0	042
2400	15.0	045
06/10/76		
BOTH RADARS U.S.		
O/S CHECKING ON K007		
FOR CALVING.		
1230	15.0	045
2000	15.0	045
7/10/76		
0900	15.0	045
1500	15.0	046
1715	15.0	043
1800	15.0	043
2300	15.0	045
8/10/76		
0200	15.0	046
2000	15.0	045
09/10/76		
0030	15.0	045
2400	15.0	045
10/10/76		
0300	15.0	045
1600	15.0	045
12/10/76		NB
2000	15.0	045
13/10/76		
1400	15.0	045
2400	15.0	045
14/10/76		
1630	13.7	049
1700	13.7	043
[illegible]	[illegible]	[illegible]

PORT RADAR U/S NOW

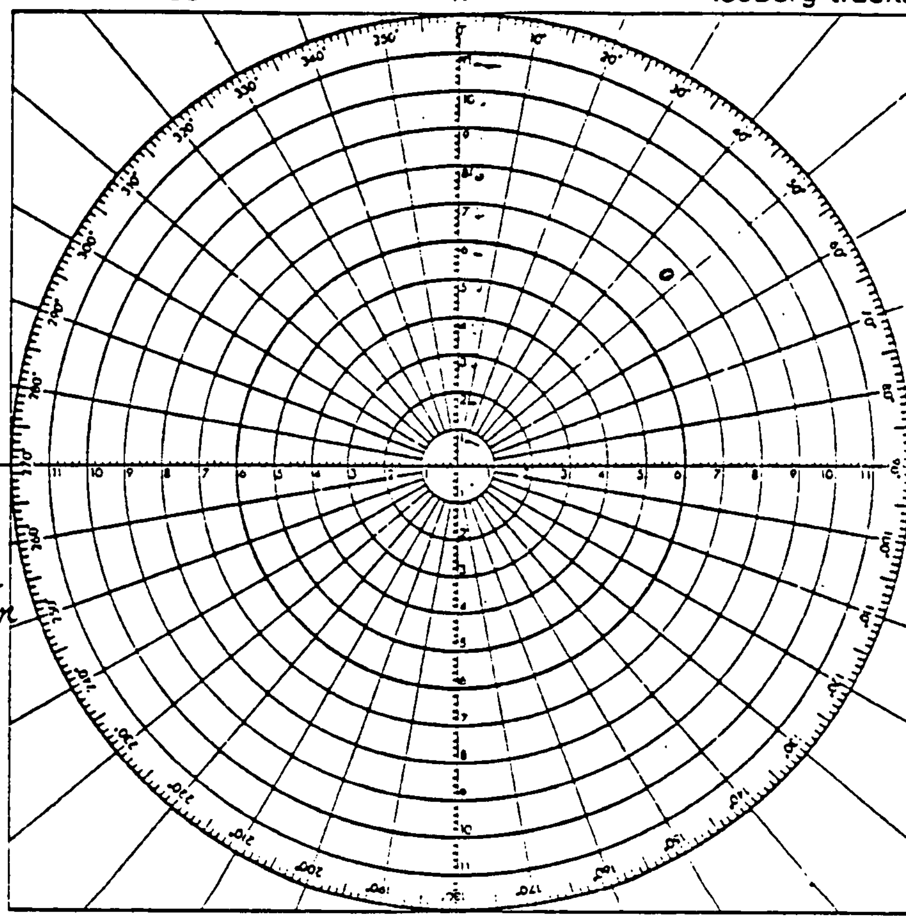
?

POOR info

!

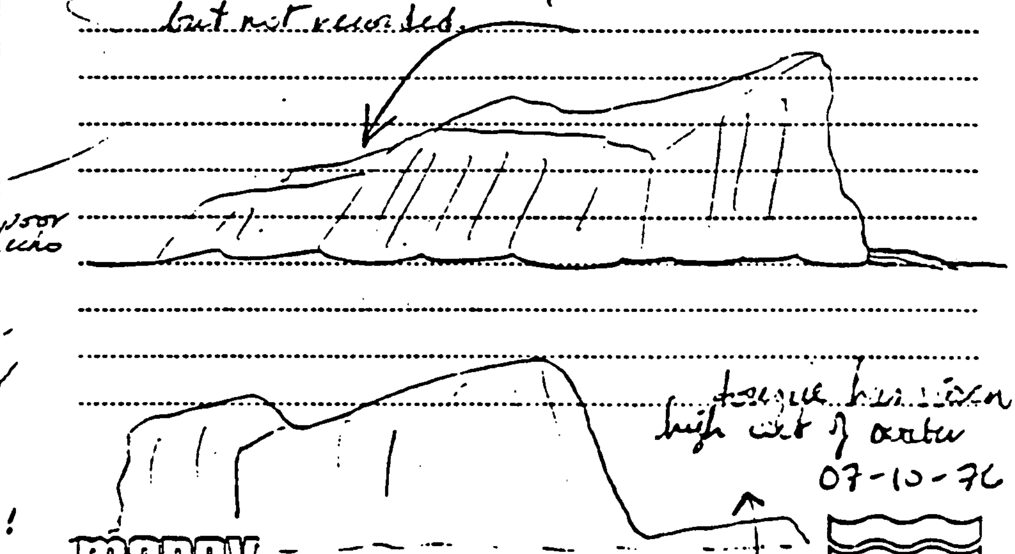
RADAR PLOT

iceberg tracks



NOTES:

1130 / 05-10-76
Sometime in past day #7 has rolled over; still grounded the NE corner has sunk.
Drawing sketched [illegible] at 1110 [illegible]
but not recorded.



marex

ICEBERG LOG

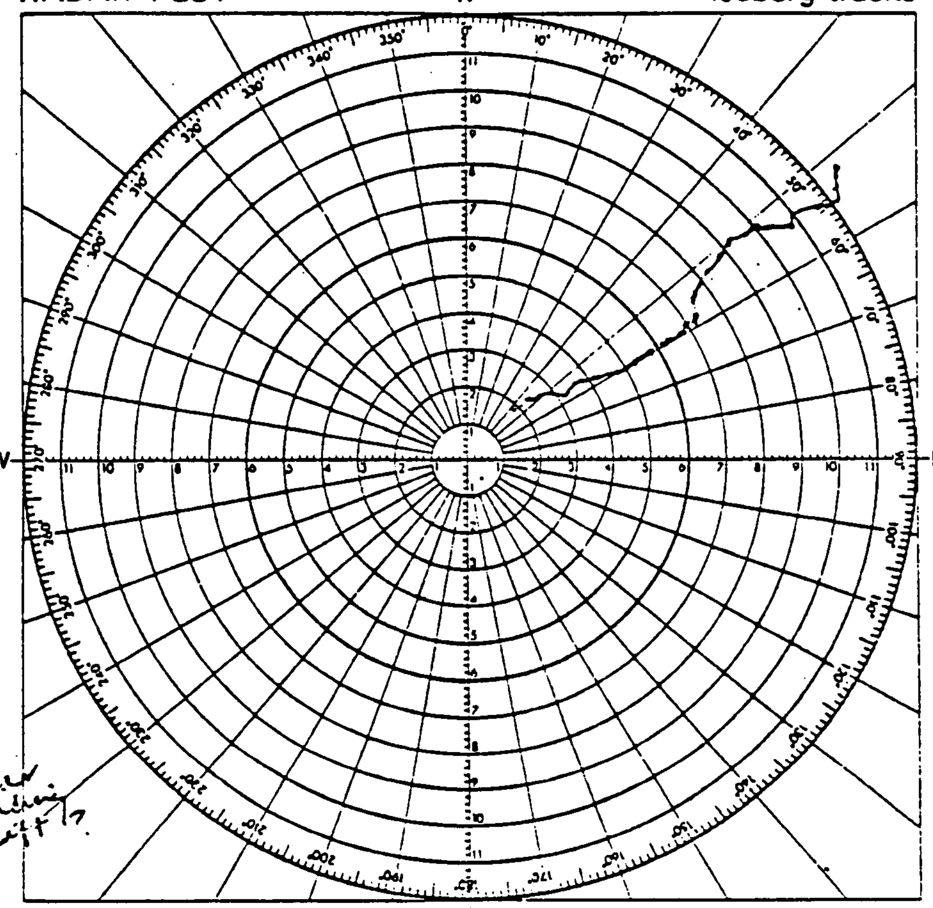
IDENTIFICATION No. /K 004

DATE/TIME	Range Nautical Miles	Bearing Relative True N.
14/10/76		
1900	13.2	052
2000	12.7	053
2100	12.2	054
2200	11.7	054
2300	11.1	053
2400	10.7	054
15/10/76		
0115	10.1	052
0200	10.0	051
0300	9.7	051
0400	9.4	050
0500	9.0	051
0600	8.8	052
0700	8.45	053
0800	7.6	054
0900	7.3	054
0930	7.0	055
1000	6.9	059
1030	6.3	059.5
1100	6.2	059
1200	5.7	059
1230	5.2	060
1300	4.76	060
1330	4.4	059
1400	4.1	059
1430	3.83	056
1500	3.50	055
1600	3.1	053
1700	2.69	049
1730	2.50	046
1800	2.25	046
1900	1.88	042
2000	1.88	042
2100	1.88	042
2200	1.88	042
2300	1.88	042
2400	1.88	042
16/10/76 0100	1.90	042

radar heading drift ?

RADAR PLOT

iceberg tracks



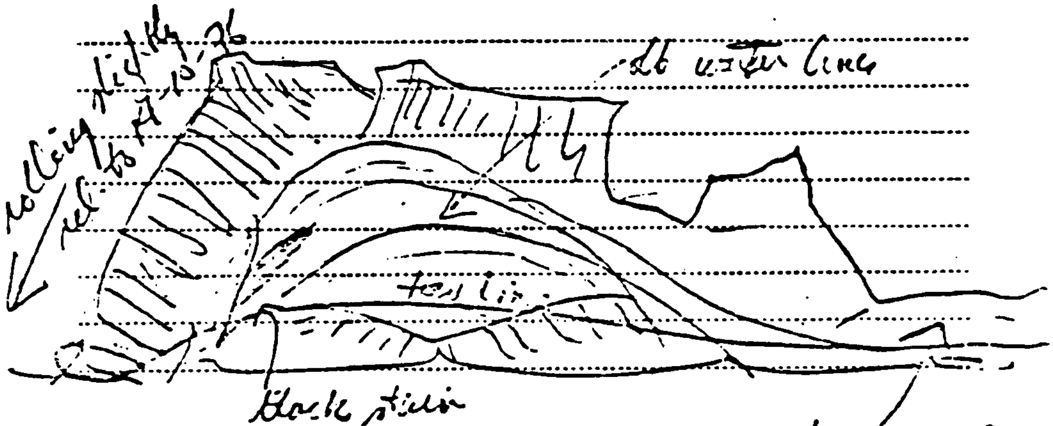
NOTES:

Sextant 15.5' x 57' or (60M x 328M)

Range 7.3 miles at 0900, 15-10-76

Sextant (21' x 64') at 6.2 miles => 57M x 2KM

1100 hrs.



MASS ≈ 22 mill. tons

tracks now raised ?

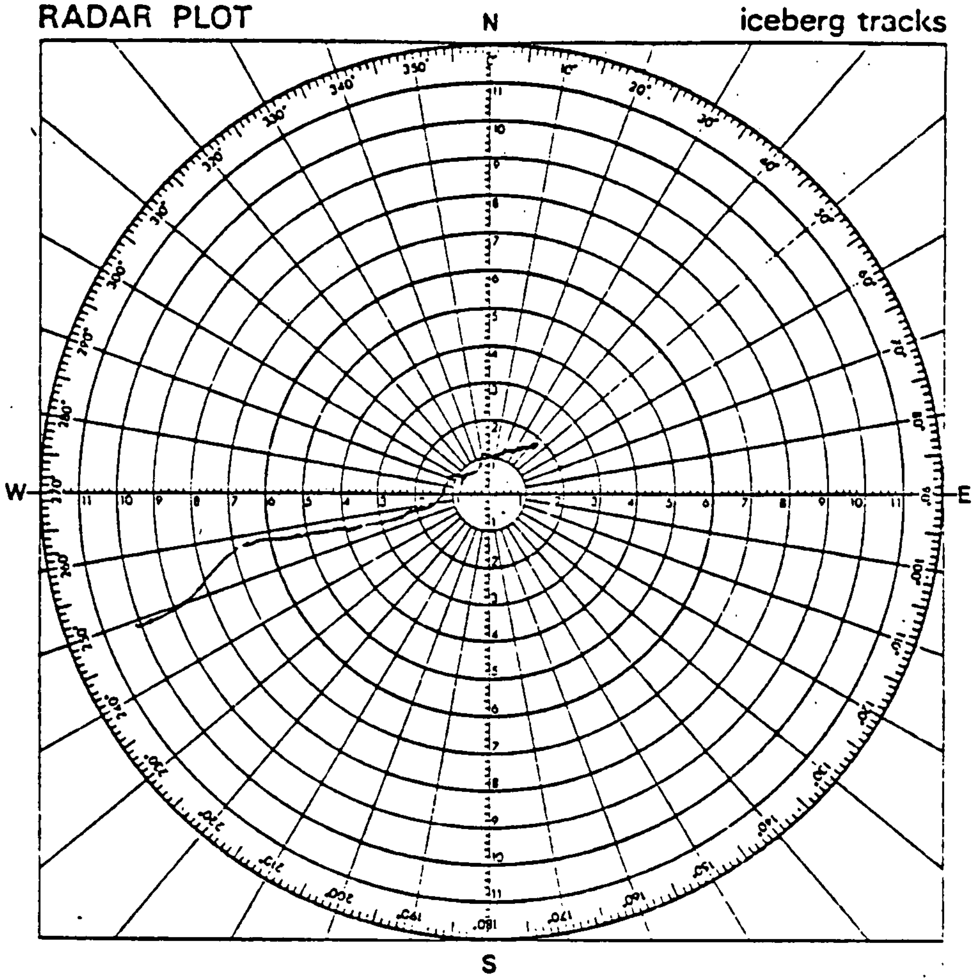
marex

ICEBERG LOG PELICAN

IDENTIFICATION No. K 007

DATE/TIME	Range Nautical Miles	Bearing Relative True N.
16/10/76		
0200	1.94	041
0300	1.92	041
0400	1.92	041
0500	1.92	041
0600	1.92	041
0700	1.92	041
0800	1.92	041
0900	1.92	041
1000	1.92	041
1100	1.92	041
1200	1.92	041
1300	1.92	041
1400	1.90	041
1500	1.60	036
1530	1.36	029
1600	1.20	020
1630	1.08	010
1700	1.04	358
1730	0.96	344
1800	0.95	330
1830	0.96	315
1900	1.00	303
1930	1.03	293
2000	1.08	284
2100	1.28	269
2200	1.65	260
2300	2.12	257
2400	2.67	255
17/10/76 0100	2.77	256
0200	4.07	255
0300	4.84	257
0400	5.5	258 +
0500	5.9	250
0600	6.3	254
0700	6.9	257 *
1100	8.2	252
1200	8.7	250
1400	9.8	249
1500	10.3	249

RADAR PLOT — iceberg tracks



NOTES:

Start towing 1430

* 12 HOUR INOP.

marex

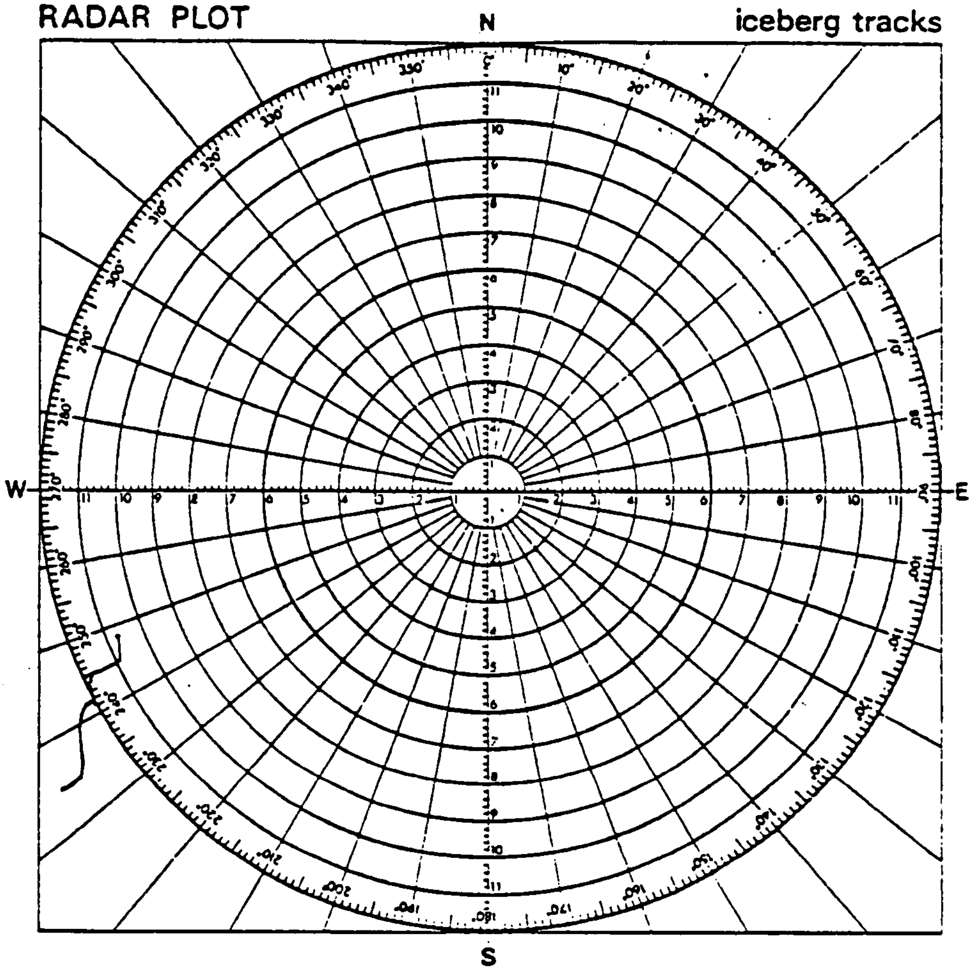
ICEBERG LOG

IDENTIFICATION No. H007

DATE/TIME	Range Nautical Miles	Bearing Relative True N.
17/10/76		
1600	10.7	243
1700	11.0	245
1800	11.3	245
1900	11.8	245
2100	12.2	242
18/10/76 0100	13.7	235
0200	14.2	234
0500	15.2	236
0600	15.5	236
0700	15.7	236
1500	16.9	233
1800	17.5	233

RADAR PLOT

iceberg tracks



NOTES:

marex

NAME OF VESSEL:	D.S. PELICAN		
POSITION	Latitude: 58° 52' N	Date:	15/9/76
	Longitude: 61° 47' W	Time Zone:	Z-3

DAILY OBSERVATIONS LOG

Time (Local)	WINDS: Mean Hourly Speed (kts)	WINDS: Speed from Calibration Instrument	WINDS: Mean Wind Direction	WAVES: Significant Wave Height	WAVES: Maximum Height (3 hours)	WAVES: Mean Zero Crossing Period	WAVES: Swell Height	WAVES: Swell Period	WAVES: Swell Direction	CURRENTS 15m.: Speed (kts)	CURRENTS 15m.: Direction (Towards)	CURRENTS 50m.: Speed (kts)	CURRENTS 50m.: Direction (Towards)
0100	14		220							0.20	350	0.61	280
0200	25		240							0.47	360	0.41	300
0300	22		240	1.1	2.1	7.0	1.0	7	220	0.32	360	0.32	290
0400	18		240							0.14	360	0.11	300
0500	14		225							0.4	120	0.10	250
0600	15		230	1.1	2.1	7.2	0.5	8	99	0.25	130	0.17	220
0700	18		220							0.34	130	0.15	230
0800	26		225							0.31	150	0.10	330
0900	23		225	1.1	2.1	6.0				0.26	140	0.12	280
1000	27		220							0.45	140	0.22	260
1100	23		215							0.50	330	0.12	270
1200	27	.	220	0.8	1.5	6.0				0.48	340	0.14	300
1300	25		220							0.40	360	0.10	290
1400	20		200							PROFILING			
1500	23		210	0.9	1.7	6.3							
1600	22		255							0.21	250	0.15	290
1700	20		355							0.08	180	0.05	310
1800	20		360	0.7	1.2	5.7				0.10	180	0.04	280
1900	28		325							0.13	180	0.06	180
2000	27		320							0.15	210	0.11	220
2100	21		335	1.6	2.6	5.9				0.17	230	0.07	260
2200	18		320							0.26	240	0.06	350
2300	16		320							0.27	260	0.05	030
2400	19	.	320	1.0	2.0	6.6				0.22	230	0.01	300

6 HOUR LOG

G.M.T.	Local Time	Visibility Code	Weather Code	Barometric Pressure (M.B)	Pressure Trend Code	Air Temp. Wet °C	Air Temp. Dry °C	Clouds 8ths	Clouds Types	Clouds Height of Lowest	Sea Temp. °C
0600	0300	98	02	1017.6	7	2.1	4.2	8	CM7	7	1.5
1200	0900	98	02	1015.2	7	2.4	4.3	7	CL5	4	1.4
1800	1500	98	15	1013.7	3	1.5	2.9	7	CL3 CM4	5	1.7
2400	2100	98	01	1014.5	7	0.6	2.2	5	CL8 CM7	5	1.7

NAME OF VESSEL:	D.S. PELICAN		
POSITION	Latitude: 58° 52' N	Date: 16/9/76	
	Longitude: 61° 47' W	Time Zone: Z - 3	

DAILY OBSERVATIONS LOG

Time (Local)	WINDS			WAVES						CURRENTS			
	Mean Hourly Speed (kts)	Speed from Calibration Instrument	Mean Wind Direction	Significant Wave Height	Maximum Height (3 hours)	Mean Zero Crossing Period	Swell Height	Swell Period	Swell Direction	15m.		50m.	
										Speed (kts)	Direction (Towards)	Speed (kts)	Direction (Towards)
0100	07		295							0.47	250	0·30	300
0200	12		310							0·34	240	0·16	300
0300	16		330	1-6	2-8	6·7				0·19	340	0·05	310
0400	23		325							0·10	250	0·03	320
0500	18		325							0·13	190	0·04	220
0600	21		330	1·9	3·6	7·7				0·17	180	0·15	200
0700	18		325							0·12	210	0·18	210
0800	17		320							0·20	180	0·16	210
0900	17		320	1·9	3·6	6·8	1·5	7	330	0·20	230	0·13	240
1000	22		315							0·25	230	0·24	280
1100	17		320							0·38	240	0·20	270
1200	18		310	1-5	2-9	6·5	1·0	6	330	0·37	260	0·27	310
1300	12		290							0·40	260	0·25	240
1400	14		320							0·41	220	0·26	260
1500	10		310	1-1	2-1	7-5	1·0	8	330	0·18	240	0·06	270
1600	05		260							0·10	100	0·04	110
1700	02		255							0·11	140	0·12	160
1800	02		255	0·9	1-7	6·9				0·06	190	0·05	200
1900	02		250							0·13	170	0·15	210
2000	03		180							0·22	150	0·26	200
2100	03		180	1-1	2·2	6·8	1·0	7	330	0·09	200	0·23	240
2200	07		160							0·22	170	0·12	290
2300	08		135							0·17	160	0·23	290
2400	12		125	0·9	1·7	7·4		7	330	0·39	150	0·31	300

6 HOUR LOG

G.M.T.	Local Time	Visibility Code	Weather Code	Barometric Pressure (M.B)	Pressure Trend Code	Air Temp.		Clouds			Sea Temp.
						Wet °C	Dry °C	8ths	Types	Height of Lowest	°C
0600	0300	98	02	1015-3	2	0·7	3·0	4	CL 4	5	1·6
1200	0900	98	02	1015-2	4	0·2	2·3	7	CL 5	4	1·7
1800	1500	98	02	1013·0	7	1·0	3·7	7	CL 5	5	1·8
2400	2100	98	02	1010·0	7	0·2	2·4	8	CL 5	5	1·7

NAME OF VESSEL:	O. S. PELICAN		
POSITION	Latitude: 53°52'	Date: 17-9-76	
	Longitude: 61° 47'	Time Zone: Z -3	

DAILY OBSERVATIONS LOG

Time (Local)	WINDS			WAVES						CURRENTS			
	Mean Hourly Speed (kts)	Speed from Calibration Instrument	Mean Wind Direction	Significant Wave Height	Maximum Height (3 hours)	Mean Zero Crossing Period	Swell Height	Swell Period	Swell Direction	15m.		50m.	
										Speed (kts)	Direction (Towards)	Speed (kts)	Direction (Towards)
0100	11		170							0·46	330	0·35	300
0200	15		180							0·37	020	0·29	320
0300	15		170	0·7	1·4	8·0	0·5	8·0	330	0·40	020	0·26	3·0
0400	17		170							0·44	020	0·18	330
0500	20		160							0·21	040	005	310
0600	22		150	1·1	2·1	6·1	0·5	8	330	0·17	050	0·03	330
0700	17		145							0·27	130	0·07	270
0800	15		135							0·29	090	0·12	180
0900	14		125	1·3	2·4	6·3				0·14	110	0·10	170
1000	14		120							0·10	150	0·23	240
1100	15		120							0·11	120	0·15	260
1200	13		130	0·9	1·7	6·3	8·3			0·13	360	0·23	270
1300	10		120							0·07	030	0·17	310
1400	10		115							0·22	030	0·22	310
1500	11		100	0·9	1·7	6·7	0·5	7	180	0·10	040	6·07	320
1600	10		100							0·10	060	0·07	300
1700	12		110							SHIP TURNING			
1800	15		110	1·1	2·1	7·5	1·0	8	180	0·12	060	0·13	120
1900	11		095							0·16	020	0·18	130
2000	12		100							0·27	110	0·15	170
2100	12		095	1·5	2·9	8·9	1·5	9	030	0·36	100	0·07	170
2200	15		085							0·34	090	0·11	180
2300	11		080							0·23	100	0·10	190
2400	11		065	1·4	2·8	8·3	1·4	8	030	0·25	090	0·18	200

6 HOUR LOG

G.M.T.	Local Time	Visibility Code	Weather Code	Barometric Pressure (M.B)	Pressure Trend Code	Air Temp.		Clouds			Sea Temp.
						Wet °C	Dry °C	8ths	Types	Height of Lowest	°C
0600	0300	97	81	1002·1	7	1·7	2·4	8	CL7, CM2	3	0·16
1200	0900	97	16	998·3	6	2·1	2·3	8	CL6	2	0·16
1800	1500	95	10	1000·0	2	2·0	2·3	8	CL6	2	2·0
2400	2100	94	10	1005·0	2	2·3	2·3	9			2·4

NAME OF VESSEL:	D.S. PELICAN.		
POSITION	Latitude: 58° 52' N	Date:	18/9/76
	Longitude: 61° 47' W	Time Zone:	Z-3.

DAILY OBSERVATIONS LOG

Time (Local)	WINDS: Mean Hourly Speed (kts)	WINDS: Speed from Calibration Instrument	WINDS: Mean Wind Direction	WAVES: Significant Wave Height	WAVES: Maximum Height (3 hours)	WAVES: Mean Zero Crossing Period	WAVES: Swell Height	WAVES: Swell Period	WAVES: Swell Direction	CURRENTS 15m.: Speed (kts)	CURRENTS 15m.: Direction (Towards)	CURRENTS 50m.: Speed (kts)	CURRENTS 50m.: Direction (Towards)
0100	12		065							0.27	090	0.07	210
0200	14		065							0.20	090	0.05	260
0300	12		060	1.3	2.5	8.9	1.0	8	030	0.21	050	0.12	220
0400	10		055							0.15	320	0.10	220
0500	9		055							0.15	350	0.07	280
0600	9		050	1.3	2.5	8.9	1.2	9	030	0.15	030	0.03	350
0700	2		020							0.25	090	0.12	070
0800	7		350							0.36	100	0.21	120
0900	8		345	1.3	2.4	8.6	1 / 1	8 / 8	150 / 070	0.36	100	0.27	130
1000	12		005							0.48	105	0.19	130
1100	12		360							0.46	100	0.20	110
1200	11		335	1.3	2.4	8.0	1.3	8	030	0.42	110	0.19	140
1300	15		355							0.27	100	0.23	130
1400	16		350							2.24	140	0.13	210
1500	16		360	1.1	2.1	8.9	1.0	8	030	0.21	140	0.10	200
1600	15		360							0.15	160	0.08	170
1700	16		350							0.20	150	0.14	150
1800	19		360	1.3	2.5	8.3	1.0	8	030	0.20	120	0.06	230
1900	15		350							0.21	150	0.11	180
2000	09		345							0.18	110	0.10	140
2100	05		340	1.4	2.8	7.7	1.0	8	030	0.23	080	0.12	170
2200	06		355							0.22	090	0.18	130
2300	05		270							0.25	090	0.18	130
2400	05		255	1.6	3.0	8.3	1.6	8	030	0.23	120	0.23	200

6 HOUR LOG

G.M.T.	Local Time	Visibility Code	Weather Code	Barometric Pressure (M.B)	Pressure Trend Code	Air Temp. Wet °C	Air Temp. Dry °C	Clouds 8ths	Clouds Types	Clouds Height of Lowest	Sea Temp. °C
0600	0300	96	60	1003.7	2	1.2	1.6	9	+	+	2.4
1200	0900	97	22	1012.6	1	1.7	2.3	8	CL6, CM7	4	2.7
1800	1500	98	01	1014.1	1	1.6	2.5	7	CL8	4	2.2
2400	2100	98	01	1016.5	1	0.9	-0.4	2	CM7	6	2.0

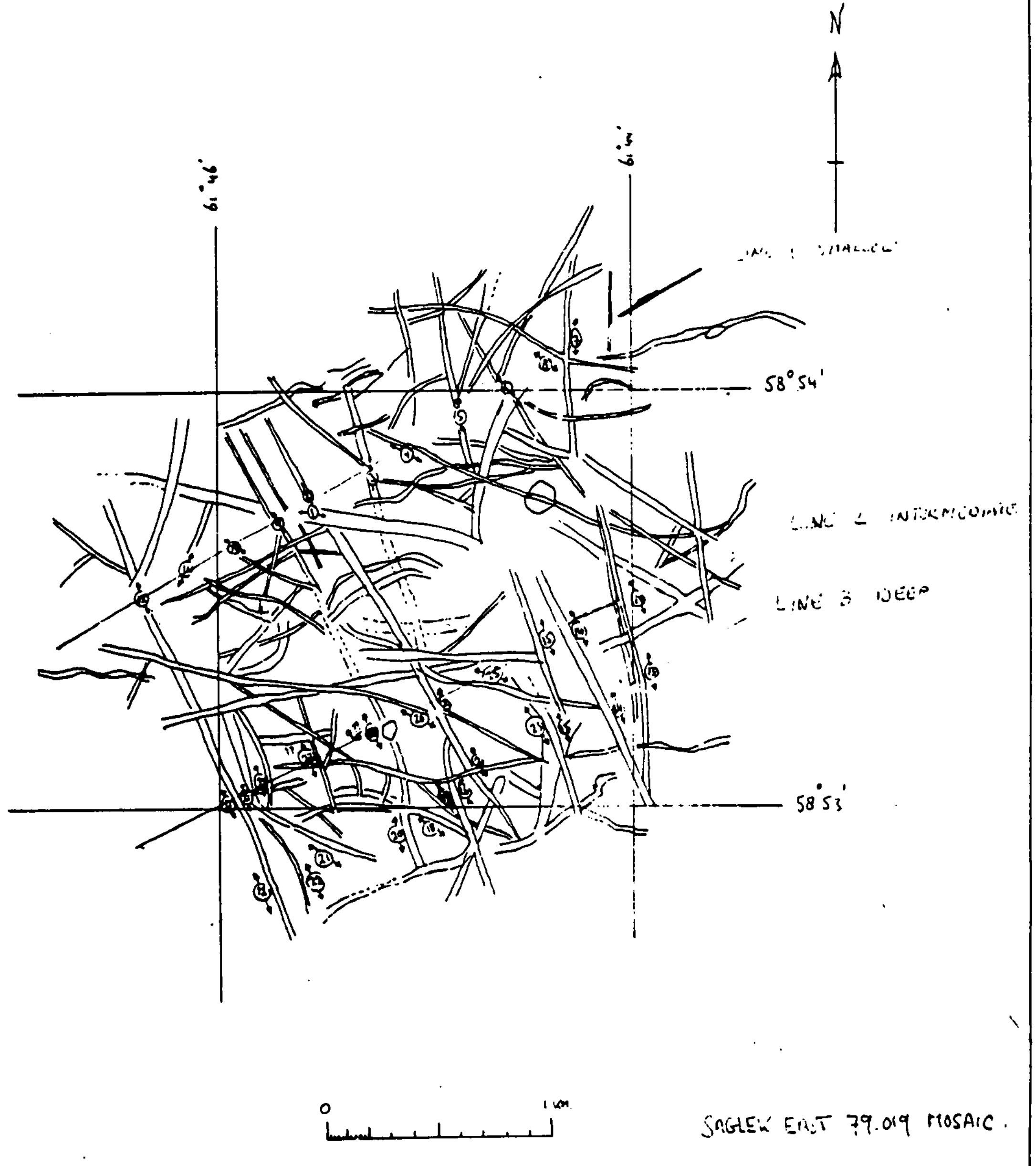
NAME OF VESSEL:	J.S. PELICAN		
POSITION	Latitude: 58° 52'N	Date: 19-9-76	
	Longitude: 61° 47'W	Time Zone: Z-3	

DAILY OBSERVATIONS LOG

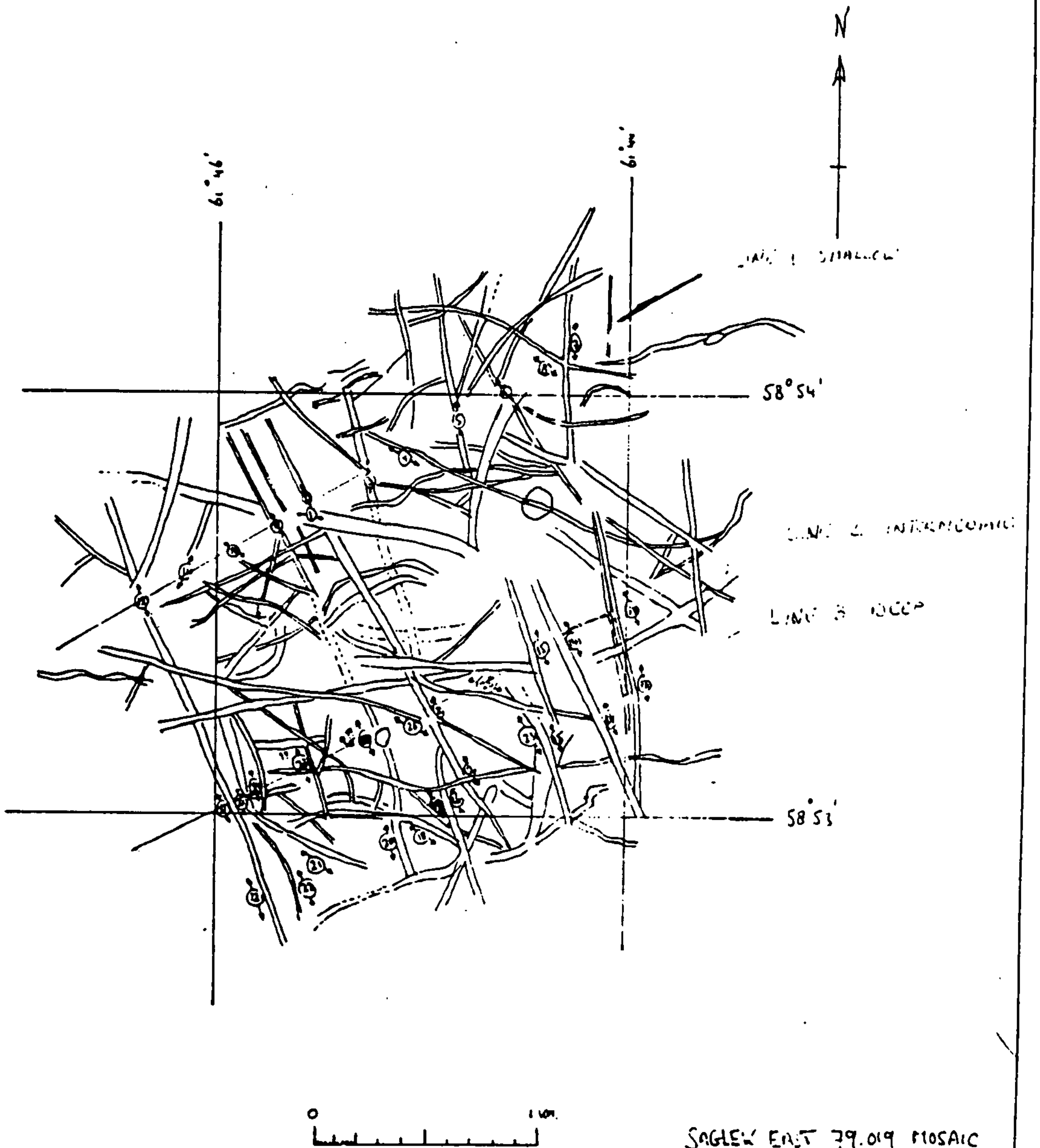
Time (Local)	WINDS: Mean Hourly Speed (kts)	WINDS: Speed from Calibration Instrument	WINDS: Mean Wind Direction	WAVES: Significant Wave Height	WAVES: Maximum Height (3 hours)	WAVES: Mean Zero Crossing Period	WAVES: Swell Height	WAVES: Swell Period	WAVES: Swell Direction	CURRENTS 15m.: Speed (kts)	CURRENTS 15m.: Direction (Towards)	CURRENTS 50m.: Speed (kts)	CURRENTS 50m.: Direction (Towards)
0100	08		260							0·39	120	0·16	230
0200	10		240							0·19	120	0·07	230
0300	10		240	1-1	2-1	8-6	1·0	9	030	0·25	130	0·14	230
0400	06		240							0·36	360	0·32	250
0500	06		240							0·31	350	0·27	260
0600	04		240	1-6	3-1	8·8	1·5	9	030	0·29	360	0·26	270
0700	05		200							0·09	050	0·23	320
0800	02		VAR C130 (sustn'ed)							0·12	080	0·08	270
0900	12		180	1-6	3·1	7·4	1·5	7·5	030	0·10	110	0·08	270
1000	12		180							0·14	100	0·07	070
1100	22		180							SHIP	CHANGING HG		POSITION
1200	24		170	1-9	3-7	8·3	1·5	8	030	0·11		0·11	
1300	30		165										
1400	32		165										
1500	30		160	2-0	3·8	6·7	0·5	7·5	030				
1600	32		160										
1700	32		160										
1800	33		160	2-4	4·6	7·7							
1900	33		160										
2000	37		170										
2100	34		165	2·8	5·4	6·5							
2200	33	GUSTS 48	160										
2300	40		160										
2400	35	30·3	155	3·4	6·5	6·8							

6 HOUR LOG

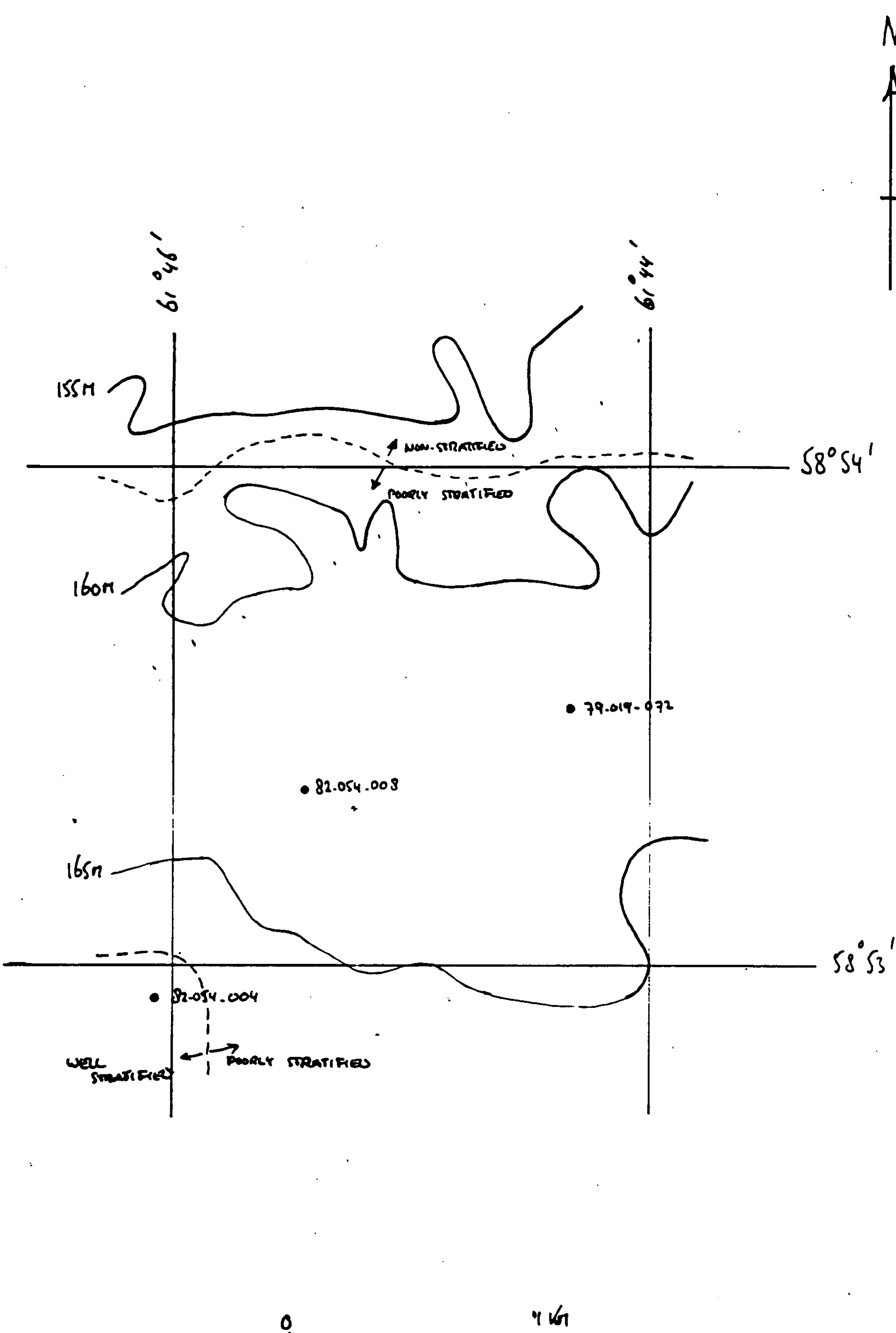
G.M.T.	Local Time	Visibility Code	Weather Code	Barometric Pressure (M.B)	Pressure Trend Code	Air Temp. Wet °C	Air Temp. Dry °C	Clouds 8ths	Clouds Types	Clouds Height of Lowest	Sea Temp. °C
0600	0300	93	02	1015-5	7	-0·4	1·8	5	CM7	6	1·8
1200	0900	93	14	1014·4	8	1·0	2-8	6	CL4 CM3 CH1	4	1·9
1800	1500	97	10	1008·0	6	1·8	3·0	8	CL6	3	1·7
2400	2100	97	62	1003·5	6	1·8	0·7	8	CL6	3	2·4



SAGLEK EAST 79.019 MOSAIC.

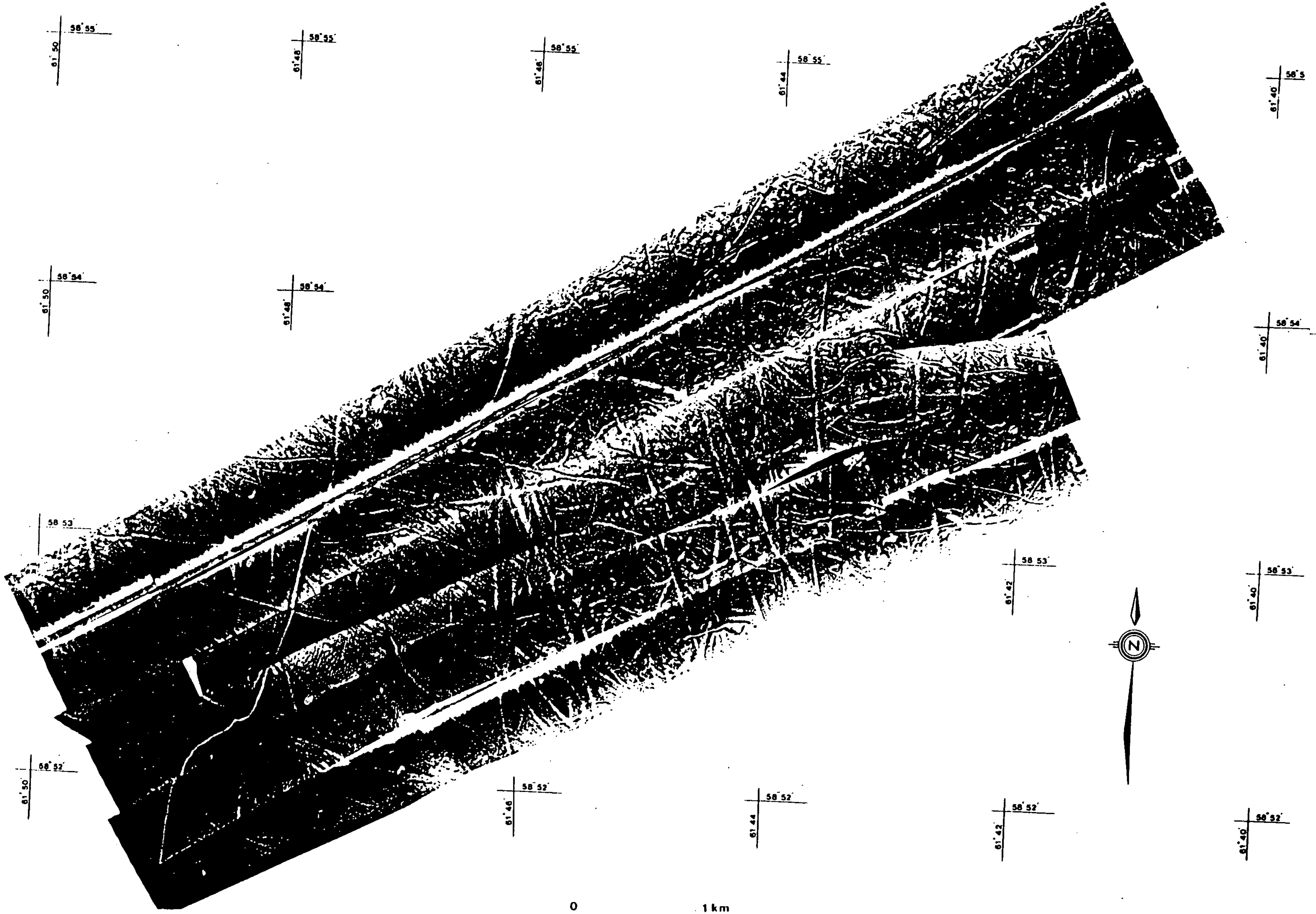


SAGLEK EAST 79.019 MOSAIC



SAGLEK EAST 79-019 MOSAIC

SIDE SCAN MOSAIC, SAGLEK BANK
CSS HUDSON 79-019



ARCTEC CANADA LIMITED

CAROLINE BERG

CAROLINE BERG

V. BARRIE OF C-CORE HAS THE DETAILED DATA. IN CALGARY

GROUNDED SUMMER 1979

OBSERVED HUDSON CRUISE 79-019

MOSAICS 1979 DATA AND 82-054 DATA.

LOCATION 59° 21' N / ~~63~~ 62° 34' W

DESCRIPTION
- ON THE 79-019 MOSAIC THE ACOUSTIC INTERFERENCE CAUSED BY THE BERG WHILE GROUNDED CAN BE SEEN
- ON THE 82-054 MOSAIC THE DOUBLE KEEL OF THE CAROLINE BERG SCOUR IS ALSO VISIBLE

CROSSOVERS

1.) 295/1401

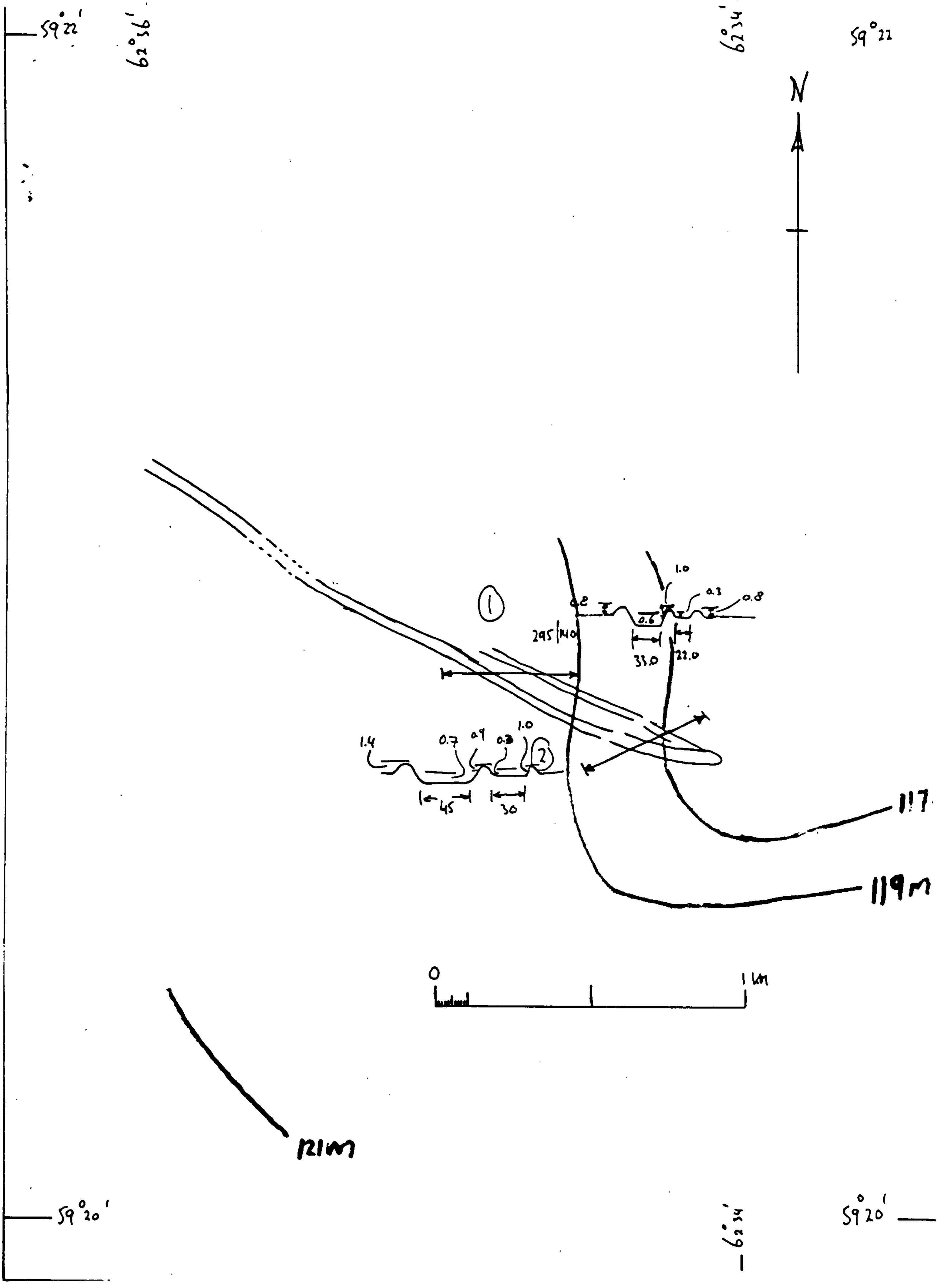
W. BERM HEIGHT	0.8	M
W. SCOUR WIDTH	33.0	
W. SCOUR DEPTH	0.6	
CENTER BERM HEIGHT	1.0	
E SCOUR WIDTH	22.0	
E SCOUR DEPTH	0.3	
E BERM HEIGHT	0.8	

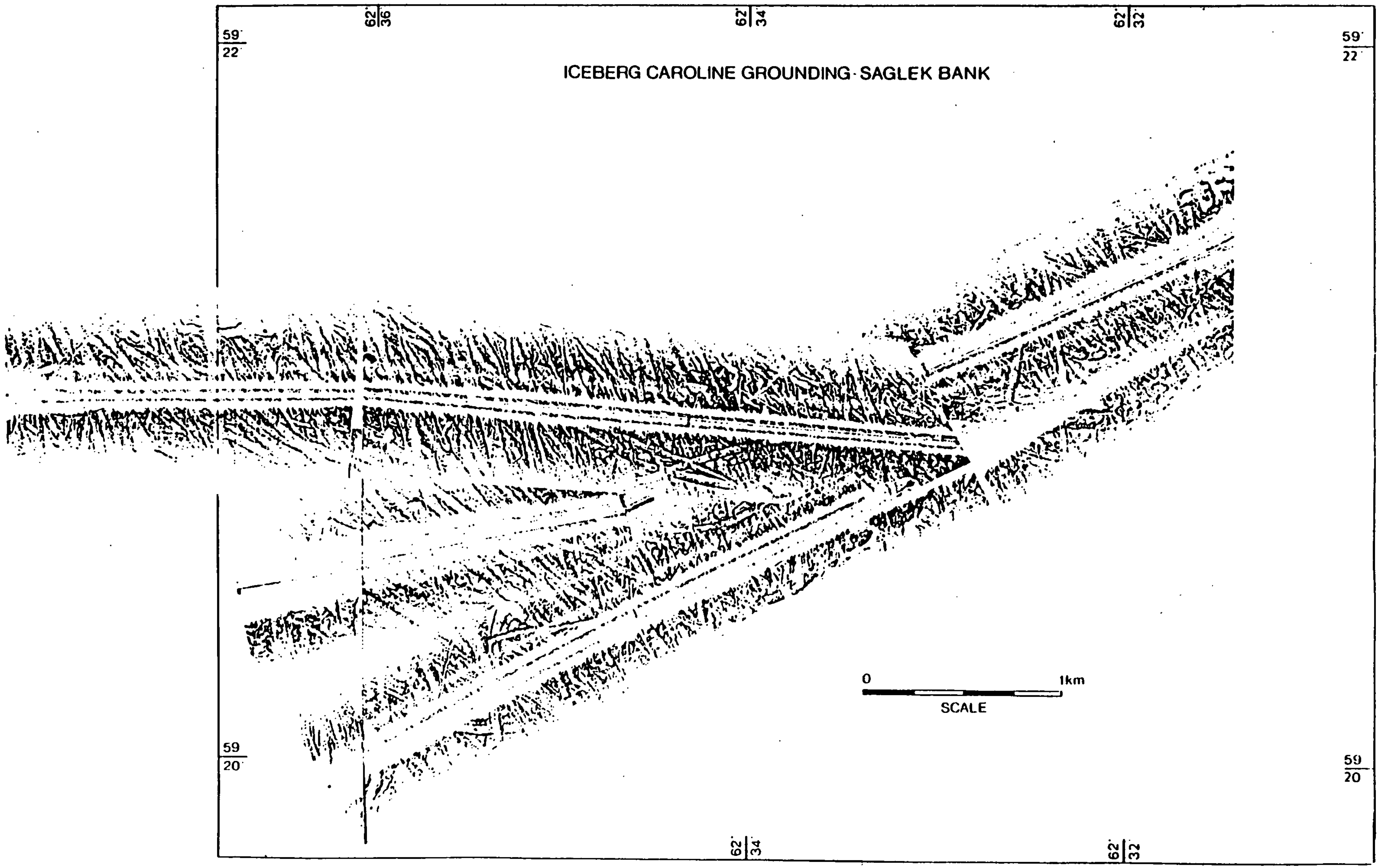
2.) 295

SW BERM HEIGHT	1.4
SW SCOUR WIDTH	45.c
SW SCOUR DEPTH	0.7
CENTER BERM HEIGHT	0.9
NE SCOUR WIDTH	
NE SCOUR DEPTH	0.3
NE BERM HEIGHT	1.0

SEAFLOOR OVERCONSOLIDATED GLACIAL TILL WITH WITH POCKETS OF SANDY MATERIAL UP TO 3 M. THICK (SEE HUNTEC RECORD 1.)

THERE IS NO GEOTECH AVAILABLE FOR THIS SURVEY AREA AND NO EQUIVALENT


59°22'
62°36'
62°34'
59°22
N
1
2
1.0
0.3
0.8
0.6
295
140
33.0
22.0
1.4
0.7
0.9
45
30
117
119m
0
1 km
RIM
59°20'
62°34


ICEBERG CAROLINE GROUNDING · SAGLEK BANK
62° 36
62° 34
62° 32
59° 22
59 20
0
1km
SCALE

SIDE·SCAN MOSAIC
ICEBERG CAROLINE, SAGLEK BANK