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Ice Scour and Seabed Engineering

Proceedings of a Workshop on Ice Scour Research

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Environmental Studies Revolving Funds
Report No. 049

December 1986

ICE SCOUR AND SEABED ENGINEERING
Proceedings of a Workshop on Ice Scour Research

Edited by

C.F.M. Lewis
D.R. Parrott
P.G. Simpkin
J.T. Buckley

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PREFACE AND ACKNOWLEDGEMENTS

The growth of research activity related to ice-seabed interaction within the past one and one-half decades has paralleled the needs of the offshore oil industry, and its regulators. Engineering concepts for the design of oil production and transportation systems require information to assess the risks of ice collisions with seabed structures and the difficulties posed by ice-disturbed sediment. A meeting organized in 1982 in Montebello, Quebec, by R. Pilkington, emphasized methods to estimate the recurrence rate of ice scouring events, in addition to the review of new knowledge of ice scour processes and ice scour distribution. While basic knowledge and understanding continued to advance after 1982, so did engineering concepts. We felt it timely to bring together design engineers and researchers in a workshop to disseminate the advancing knowledge of ice-seabed interaction and to learn more about the developing information requirements for design of seabed structures at risk of ice contact. We felt too that this meeting would also provide a forum for discussion of major field experiments to examine ice scour processes and scouring rates proposed by the Environmental Studies Revolving Funds Committee on Seabottom Ice Scouring.

The foregoing objectives were accomplished on February 5-6, 1985, in Calgary where 69 persons from Canada, United States, Norway and West Germany gathered to discuss the subject of ice-seabed interaction at this Ice Scour Workshop. The sessions were accommodated in conference facilities supplied by Gulf Canada Resources Inc. at Gulf Canada Square. Other expenses were borne jointly by the Environmental Studies Revolving Funds and the Offshore Geotechnics Program of the Federal Panel on Energy Research and Development. This volume documents those oral presentations and discussions. First, aspects of the engineering requirements were brought out through discussion of selected Beaufort pipeline and structure designs, a Lake Erie cable crossing design, and general considerations of risk assessment. With this sampling of design concepts in mind, attention turned to current research in ice scour processes, seabed response to ice forces, regional ice scour distributions and data bases, and ice scour frequency and risk. The main points of discussion are preserved with each paper and a general discussion of each session, managed by the session chairmen, has been printed. Finally, overviews of the meeting from the perspectives of several participants, are reproduced in the concluding session. We hope the volume provides an index to recent research and a point of departure for further work.

Many of the reports contained in this volume were transcribed and initially edited by P.G. Simpkin from recordings of the oral presentations made at the Workshop. Some authors supplied manuscripts. The transcripts were circulated to contributors for clarification and revision. All manuscripts were edited technically by J.T. Buckley. The contributions were then edited for scientific content, guided through a review process, and compiled into the final volume by C.F.M. Lewis and D.R. Parrott. Since the terminology used for ice-generated seabed features has not been standardized within the international research community, we have maintained the terminology used in the original oral presentations.

The abundance of information in this volume reflects the enthusiasm of the contributors. We are indebted to the session chairmen for their skill and efficiency in stimulating and managing the discussions. We appreciate the review comments and helpful suggestions of D. Allan, J.V. Barrie, W. Bobby, R.M.W. Frederking, D. James, W.R. Livingstone, J.A.N. Ransom and A.F. Stirbys. The compilation was assisted in many ways by P.W. Durling, D.C. Mosher and C.E. Anthony. We especially thank Sharon Hiltz of the Bedford Institute of Oceanography for her patience and perseverance in typing the manuscript, and Art Cosgrove of the BIO Drafting and Illustrations Group for adding clarity to many of the figures.

December 1986

The Organizing Committee

C.F.M. Lewis
W.R. Livingstone
D.R. Parrott
A.F. Stirbys

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INTRODUCTION

WELCOME AND INTRODUCTORY REMARKS

C.F.M. Lewis
Atlantic Geoscience Centre
Geological Survey of Canada
Bedford Institute of Oceanography
Box 1006, Dartmouth, Nova Scotia, B2Y 4A2

Welcome to the Ice Scour Workshop of 1985. The committee members who have shared in the labours of organizing this workshop are: Bill Livingstone and Tony Stirbys from Gulf Canada Resources, and Russell Parrott from the Geological Survey in Dartmouth, Nova Scotia. We thank Gulf Canada Resources for hosting the workshop and for providing the excellent facilities. It is a real benefit to have this support as will be realized over the next two days.

As a group of researchers, scientists, and engineers we work in one of the most demanding environments in nature; namely, the interface of ocean, ice, and seabed. To understand their interaction requires a truly multi-disciplinary approach. In return it provides a fertile field for scientific enquiry and is a challenging domain for engineering excellence.

It has been three years since the last major meeting on ice-scour research in Canada, which was held at Montebello, Quebec, and was organized by Roger Pilkington on behalf of the National Research Council of Canada. During those three years many developments have occurred, and many new perspectives have been gained. Today we gather to update our knowledge of current work and recent achievements and to look ahead to future projects. We see a great need now to focus our endeavours on the knowledge required to support the development of offshore resources in a safe, secure, and environmentally acceptable way. Consequently, this workshop has been organized with engineering applications in mind. We hope to learn at the outset the kind of problems recognized, and the kind of information needed for engineering design in the ice-infested frontier. Later as we hear sessions on ice and ice-scour processes, on seabed response, on regional ice-scour studies and data bases, and on ice-scour frequency and risk, we hope that you will reflect how research on the ice-scour processes can provide new guidance for offshore development. We anticipate that the basic requirements will be confident knowledge of ice-scour frequency and depth and the extent of seabed disturbance. We hope that new perspectives will emerge in the next two days. As the workshop progresses we ask that you direct your thoughts and comments to the ways and means by which ice-scour frequency and depth and these new perspectives can be better evaluated.

We could not have organized this workshop without support from the Environmental Studies Revolving Funds (ESRF) and the Panel on Energy Research and Development (PERD).

Dr. Olav Loken, Director of the Environmental Studies Revolving Funds will say a few words on behalf of the ESRF.

OPENING ADDRESS

Olav H. Loken
Director, Environmental Studies Revolving Funds
355 River Road
Ottawa, Ontario, K1A 0E4

Ladies and Gentlemen, we in the ESRF are very pleased to co-sponsor this workshop and to see it organized in such a short time. For those of you who have not been in touch with our offices, I would like to say a few words about the ESRF. The Environmental Studies Revolving Funds provide a rather unique mechanism to sponsor studies that will provide decision makers with information regarding oil and gas activities on Canada Lands. Canada Lands, in this context, cover the land mass north of latitude 60° and all the offshore, which includes the Grand Banks of Newfoundland, Labrador Banks, Baffin Bay, and the Beaufort Sea. All these areas are subject to ice scouring. The funds were established according to the Canada Oil and Gas Act and are divided into two areas of responsibility; one for activities north of latitude 60° and one for activities south of latitude 60°. Both funds are administered through one central office.

The funding for the ESRF is obtained from the oil industry but the administration is provided by the federal government at the cost of the industry. The actual operations of the funds reflect a very close co-operation between industry and government through the program study committees consisting of specialists from government and industry. Fundamental to the success of our work, these committees have been set up to address ten, separate, priority subject areas, such as oil spills and their countermeasures, waves, and icebergs, however, the one of prime importance to us here is on seabottom ice scour. Bill Livingstone is the extremely effective chairman of this committee.

The Committee on Seabottom Ice Scour has given a great deal of thought to what it has done so far, what it is doing now, and where it intends to go in the future. The main rationale for the ESRF in co-sponsoring this workshop is to provide a forum at which to present our studies, the results they have yielded to date and to have them examined critically by peers in the field. The feedback will then be used as a basis on which to plan future work.

Just a few words will describe the magnitude of our operation. The ESRF has been in operation for about 18 months, and already has more than 70 study agreements in effect. These range from tasks that might run for two months to major projects that might last up to three years. The dollar figures involved range from $15,000 for a rather small study to around $145,000 for the larger ones. The activities include field work, office studies, and laboratory studies. We also have a bibliographic project and, later on in the workshop, you will be introduced to our ice-scour bibliography which is now in draft form and which will be printed in the near future.[1]

The first ESRF report is now at the printers and several others will follow in the next few months. The publications will provide another opportunity to criticize our work and, hence, a means to improve our performances. As I mentioned, our clients are the decision makers in the

[1] Goodwin, C.R., J.C. Finley, and L.M. Howard. 1985. Ice scour bibliography. Environmental Studies Revolving Funds Report No. 010. Ottawa. 99 p.

oil and gas industry and in governments and unless we produce good and relevant work on a timely basis we shall not succeed. We see this workshop as an effort to improve on our performance and to make sure that we stay "on target" at all times. We are asking for your co-operation, for your frank comments on, and constructive criticisms of the work, that has been done to date; and for your suggestions about the direction we should go in the future. This information should lead to smoother and more-efficient decision making on matters concerning oil and gas activities in the frontier regions of Canada.

Thank you for your interest and good luck.

PANEL ON ENERGY RESEARCH AND DEVELOPMENT

S.M. Blasco
Atlantic Geoscience Centre
Geological Survey of Canada
Bedford Institute of Oceanography
Box 1006, Dartmouth, Nova Scotia, B2Y 4A2

The federal government, through the Panel on Energy Research and Development, funds seabed research in areas of potential hydrocarbon development. The seabed problem that we are concerned with here is ice scouring by sea ice and icebergs. The Panel on Energy Research and Development through its program on Offshore Geotechnics supports research in engineering geology that is complementary to the environmental studies referred to in the ESRF.

We hope that by co-sponsoring your efforts over the next two days, this workshop will achieve a perspective on providing solutions to the ice-scour question for the offshore industry, a perspective which will eventually lead to economic benefits from development.

ENGINEERING APPLICATIONS

Session Chairmen:

D. Allan
W. Roggensack

MARINE PIPELINE DESIGN IN ICE ENVIRONMENTS

D.S. McKeehan
INTEC Engineering, Inc.
16801 Greenspoint Park, Ste. 105
Houston, Texas, 77060, U.S.A.

INTRODUCTION

In presenting some aspects of the planning necessary for offshore pipelines, particularly with respect to ice scour, I have selected three interrelated topics; the ice-scouring mechanism, the requirements for trenching, and the repair of a damaged offshore pipeline. All three should be considered when estimating trench depth, or when deriving a requirement for protection.

ICE-SCOURING MECHANISM

The parameters that relate ice scour to pipeline design are summarized in Table 1. The scour depth distribution and the frequency of occurrence, when combined, form a statistical model of how deep the trench needs to be.

The variation of ice scour with water depth along a specific route is important because it determines the usefulness of different equipment that might be used to trench the pipeline, such as suction cutter and trailing suction dredging equipment, or post-trenching tools.

The likely period of critical exposure is useful in assessing when damage by ice keels can be expected. For example, could damage occur during break-up, or is it more likely to occur during the middle of winter? What is the likelihood that contractors would have to wait until break-up to effect a repair, and what would the cost be in terms of lost production? Thus, the period of critical exposure influences the repair response.

Keel width defines the potential for length of damage or how much pipe will have to be replaced. The questions remain: should 15-m or 120-m sections of pipe be held in inventory? What will be the practicality of working from two locations and of making repairs at each end of a lengthy break some distance apart?

The directionality of the ice scour is a very site-specific parameter. If it is generally orthogonal to the pipeline, there exists a higher risk for damage, but a shorter length of damage should it occur. If the directionality is parallel to the pipeline, the risk may be lower, but a longer section of pipe might have to be replaced.

TABLE 1

Summary of ice-scour parameters versus pipeline requirements

Ice-scour parameters	Effects on requirements in pipeline design
Scour depth distribution	Defines trench depth
Frequency of occurrence	Defines trench depth
Variation with water depth	Establishes practical use of dredging equipment
Critical exposure period	Influences repair response
Keel width	Defines length of damage and repair response
Directionality of scour	Influences risk and length of potential damage for specific routes
Keel residence time	Defines potential for accessibility to repair site
Mechanism of scour Keel-soil interaction Available forces Keel strength Keel shape	Defines feasible methods of protection
Correlation to surface ice conditions	Defines feasibility of operational monitoring
Influence of structures	Defines special requirements for trenching near structures

The next parameter is the residence time of the keel. If the scouring ice is likely to remain over the pipeline for any length of time, a repair method that addresses this contingency will have to be developed.

The mechanism of scour refers specifically to the interaction of keel and soil, the available gouging force, the shearing force, keel shape and the keel strength. These parameters are all useful in defining requirements for, and feasible alternative methods of, burying and covering pipelines. The mechanism of scour is important because compaction forces transmitted through the soil and soil deformation may require the pipeline to be buried deeper than the maximum expected keel depth. This mechanism needs further study.

The final two parameters are concerned more with operational aspects. For operational monitoring, it would be useful to have a correlation between ice keel features and surface ice conditions. If high ice ridges were known to be heading towards an installation, it might be possible to take pre-emptive measures against impending damage.

Finally, Arctic structures such as caisson-retained islands and gravel berms can affect the trenching requirements and protection of a pipeline from local rubble-pile ice gouging in the vicinity of the production structure.

REQUIREMENTS FOR TRENCHING

In terms of determining scour risk, consider areas, such as the Canadian or the U.S. Beaufort Sea, that are scoured during break-up or at some time during the winter. Figure 1 illustrates the possible depth of a trench for a 160-km length of marine pipeline with the expectation of one scour impact in 1500 years. The selection of a level of risk such as the 1500-year return period (see Fig. 1) relates to the frequency of repair and the cost of preparing trench depths.

Project costs are influenced significantly by a curve such as that shown in Figure 1, partly because several limiting factors emerge. First, existing dredging equipment is capable of achieving 5-6 m of trench depth, but is not suitable for working in water deeper than 15-20 m. Thus, such a trench design may not be suitable for dredging. Secondly, conventional pipeline trenching equipment can work in deep water, but is unsuitable for trench depths greater than 2.5 or 3 m. With these operational constraints, there remains a requirement for deep-water trenching that is beyond the present capability of the equipment. Thus, financial benefits would likely result from developing and upgrading trenching systems.

It is important to note that, although the cost for trenching depends on the volume of material removed from the trench, cost is also a function of the type of system and the trench cross-section. Generally, costs are proportional to the square of the trench depth.

Pipeline Protection

Three possible methods for the protection of pipelines are presented. The first method is a gravel causeway or berm (Fig. 2) which can be used in fairly shallow water, such as in the fast-ice zone. The second method is a partial burial of the pipeline with gravel back-fill which is suitable in areas where there is only light scouring. The third method is the preparation of a refrigerated frozen soil bulb that is resistant to ice scour. These methods allow some reduction in overall cost compared with the cost of deep trenches. However, to verify their effectiveness, the magnitude of loading forces and the frequency of contact along these structures must be known.

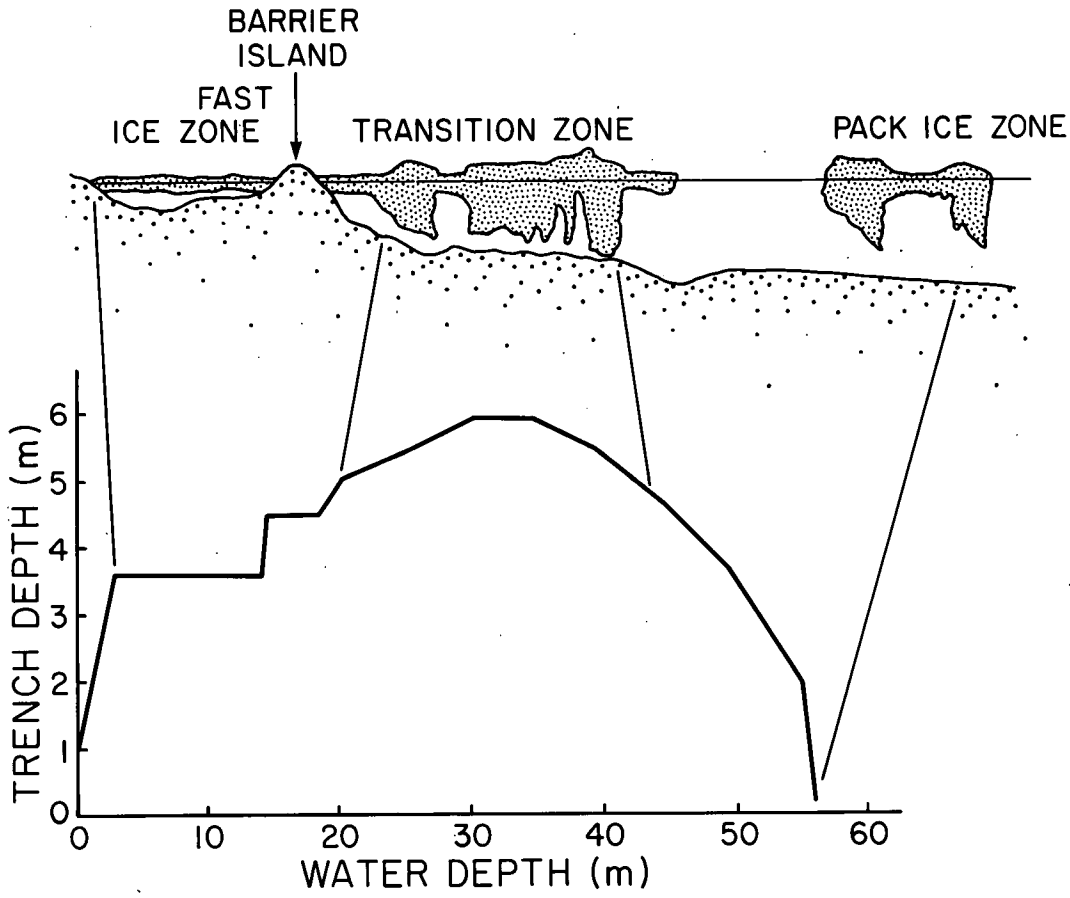

Figure 1. An example of possible trench depth requirements for ice scour protection in the Beaufort Sea under the conditions: return period = 1,500 years; length = 160 km (100 miles).

Trenching Methods

An alternative to schemes such as back-fill and gravel coverage is trenching. Figure 3 is an example of a large cutter-suction dredger. There are advantages and disadvantages of this type of conventional dredging. In operation, the cutter-suction dredger pivots on spuds at the stern and swings back and forth. There are lateral pull wires off to the side which must be continually redeployed as the dredger moves forward. This method, which is referred to as having a lateral type of cutting action, is not very attractive for preparing long pipeline trenches. A linear trenching mode, which would work along the pipeline and would remove the minimum amount of material, is preferred.

The forward rate of trenching is influenced by trench depth. Assuming existing cutter-suction equipment, if we have a 4-m deep trench, the forward rate of trenching is about 10 m/h. If the trench depth requirement is increased to 8 m, the forward rate drops to about 5 or 6 m/h, because of the time required to set the anchors and to move the spuds. These forward rates are significantly lower than those theoretically available on the basis of volume capacity.

In deep water (>25 m), where dredging is not feasible, alternative techniques, such as ploughing or other post-trenching techniques can be used after the pipeline is installed to achieve another 1, 2, and potentially 3 m of trench depth. For example, a single-pass plough, which is a large piece of equipment, weighing about 130 tonnes and measuring about 25 m in length, excavates a 2-m deep trench. However, in most of the Alaskan and Canadian sectors of the Beaufort Sea, 2 m is unlikely to be sufficient, except perhaps very nearshore. Nevertheless, this method could be used in conjunction with pre-dredging techniques.

Another post-trenching technique is the mechanical trencher with shield (Fig. 4). The pipeline is laid through the trencher, and, as the shield progresses, the walls collapse and cover the pipe. This example illustrates another method that dredging and trenching contractors might develop.

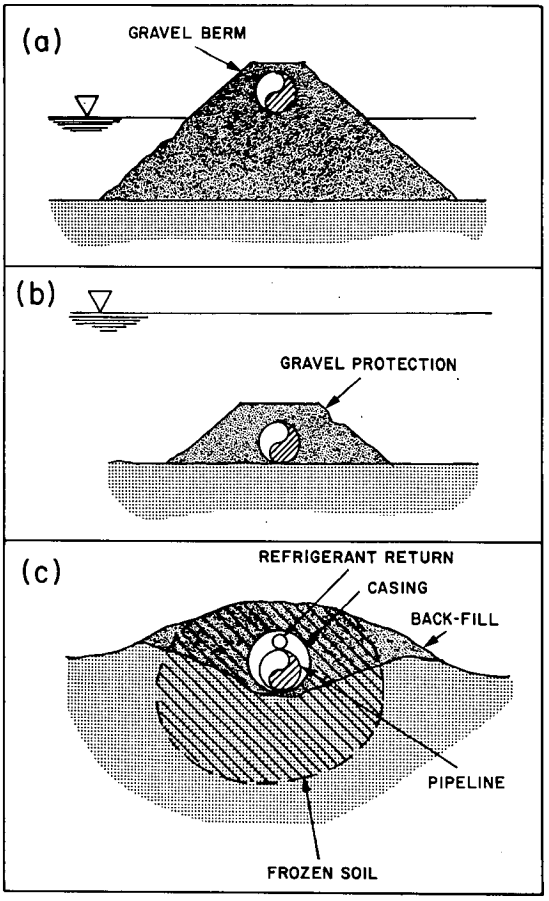

Figure 2. Alternative methods for ice scour protection: (a) gravel berm or causeway for shallow water; (b) partial berm for lightly scoured sub-Arctic areas; and (c) soil freezing for short line segments.

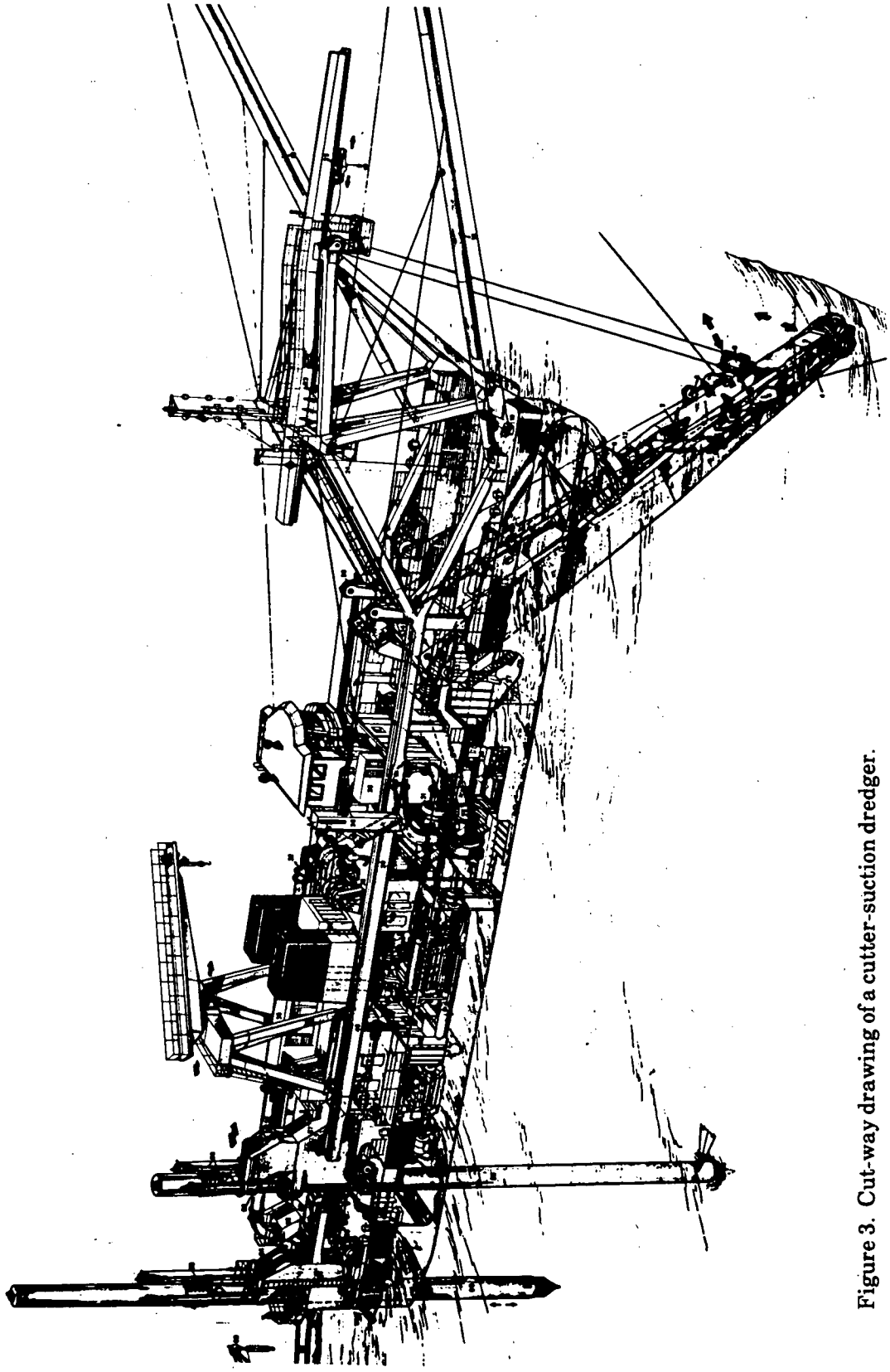

Figure 3. Cut-way drawing of a cutter-suction dredger.

There are other types of post-trenching systems; conventional jetting, purely mechanical systems, and combinations of jetting, mechanical, and ploughing. However, all these have similar limitations in terms of depth of trench -- 2- to 3-m capability.

The cost to develop this type of equipment for the Beaufort Sea is going to require further study, particularly in view of the possible range of water depth and the range of trench depth that would be required along a site-specific route.

As indicated earlier, trenching costs have to be traded off, not only against the possibility of damage that requires clean-up, access to the damage site, and pipeline repair, but also against minimizing the loss of production.

ARCTIC PIPELINE REPAIR

To minimize the loss of production, a number of repair procedures are applicable. Figure 5 illustrates one method that would be considered for a short section of damaged pipe where the exact location of the damage is known. The pipe may or may not be leaking but, in either case, a jumper pipe can be installed across the damaged section. This method would be used in a localized area involving, perhaps, 12 or 15 m of damage.

It is possible that the ice keel which caused the damage may still be located over the section requiring repair. It is also possible that because of the direction of the scour, the length of the damage could be 120 m instead of 12 m. In such a case, a long section of pipe would be required. Towed steel pipelines 120 m in length are compatible with this type of repair technique. "Tie-ins" can be made at some distance on either side of the damaged site, which allows the repair procedure to be conducted independently and simultaneously at both ends of the damaged section, perhaps 1 km apart. The repair teams operate either from the ice or from floating equipment. The difficulty with this method is that the new section of pipe would also have to be trenched. Even with a temporary repair, it would be necessary to bury the pipeline below the keel depth of the ice feature responsible for the original damage.

CONCLUSIONS

The major considerations in planning offshore Arctic pipelines are:

- development of the trench depth criteria;
- selection of the trenching and protection methods; and
- evaluation of the technique for damage repair.

Additional considerations, such as the cost of clean-up, have been omitted, because to some extent these are felt to be outside the focus of this workshop.

As engineers, we do not need to answer all of these questions. We find, however, that the better the answers are in each of these categories, the more reliable the estimates will be in terms of developing the overall costs of construction and installation, and in establishing a reliable repair response plan for Arctic pipelines.

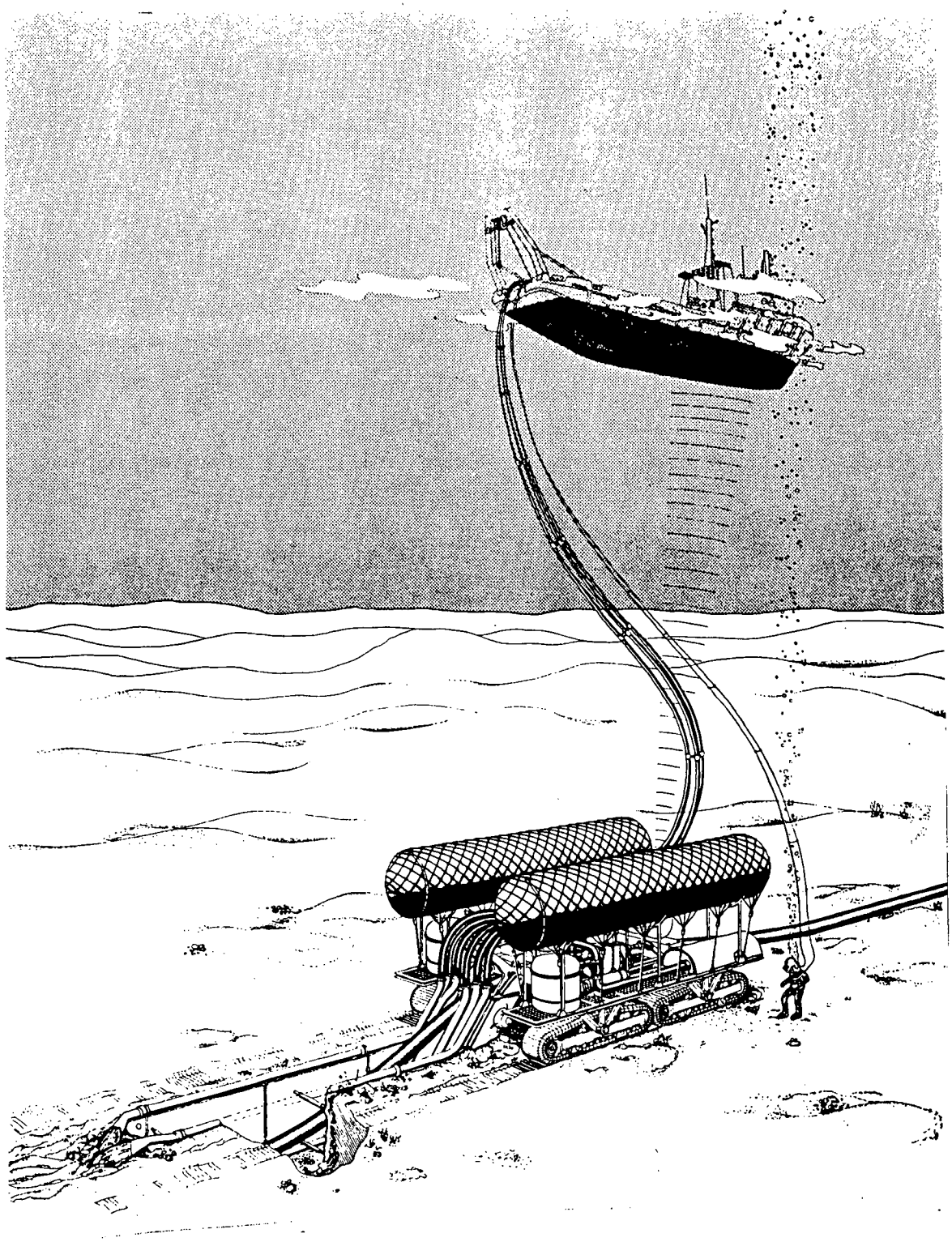

Figure 4. Mechanical trencher with shield and back-fill capability.

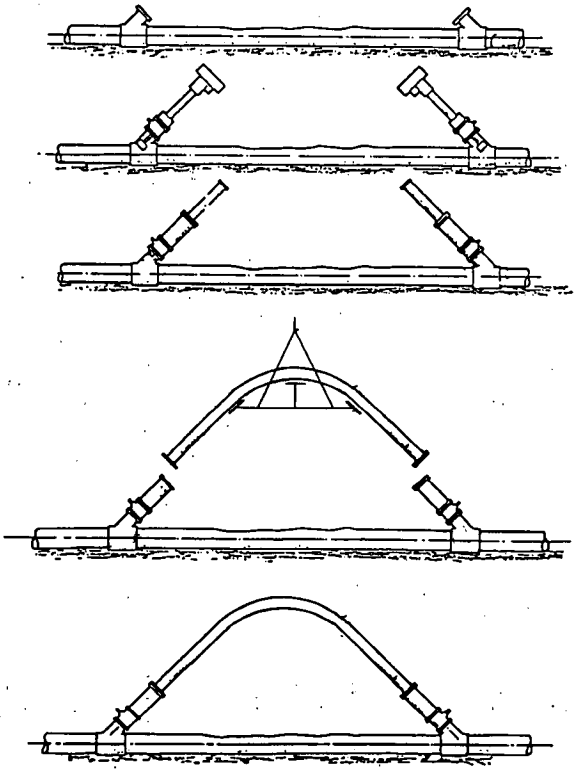

Figure 5. Five stages in the installation of a cold tap with jumper.

DISCUSSION

Mahar Nessim, Det norske Veritas: Do you envisage any periods of the year in the Beaufort Sea when you will not be able to reach the pipeline for repairs? You mentioned open water where you have access by vessel and also over the ice in the wintertime, but do you envisage a period during break-up or freeze-up when it becomes inaccessible?

David McKeehan: That is an excellent question. The answer is that there probably will be times of the year when you cannot reach the pipeline. Access will depend on the water depth and, of course, on the ice conditions. I must admit that other people at this workshop have better expertise than I on that aspect. Research is being done in that area right now, and it appears that there will be times of the year when pipeline access, particularly in the outer edges of the fast ice, will not be possible.

ENGINEERING ASPECTS OF ICE GOUGING

R.G. Bea[1]
PMB Systems Engineering Inc.
400-500 Sansome Street
San Francisco, California 94111

INTRODUCTION

This presentation describes several engineering aspects of ice gouging, on which the Bantrel Group has worked for several years, principally in the U.S. Beaufort Sea, involving four interdisciplinary areas of interest (Fig. 1):

- the influence of ice gouging on the engineering characteristics and properties of Arctic sediments;
- the effects of ice gouging on base mat contact pressures and capacity efficiencies of Arctic gravity structures;
- the effects of ice gouging on buried and armoured pipelines; and
- the role of ice gouging in reducing the global ice forces on Arctic structures.

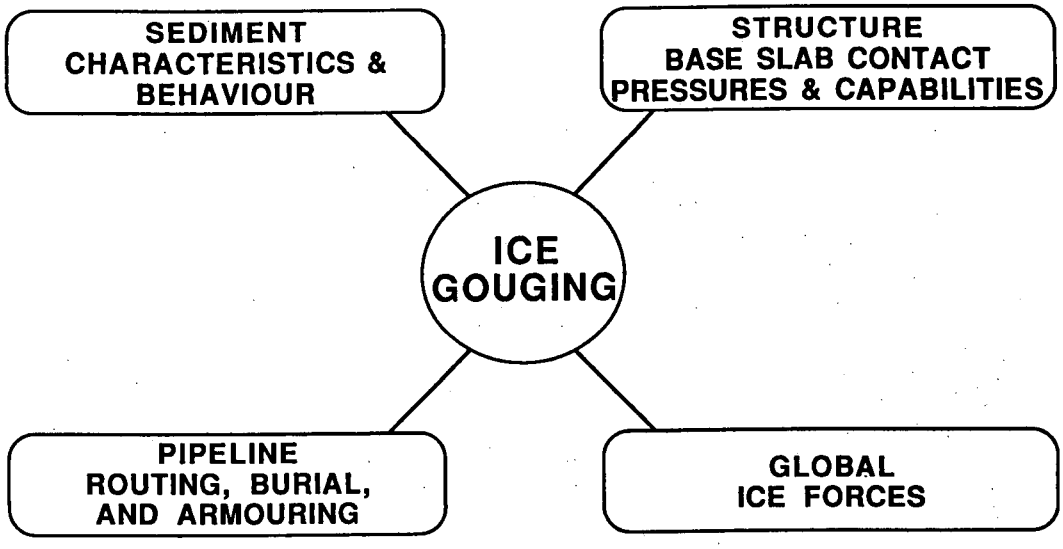

Figure 1. Four, interdisciplinary, engineering aspects of ice gouging.

[1] Representing the Bantrel Group of Calgary.

SEDIMENT CHARACTERISTICS AND BEHAVIOUR

Ice gouging has been found to exert important influences on the distribution of near-seafloor sediments and on their engineering properties. The understanding of the geologic aspects of ice gouging is a pre-requisite to realistic assessment of the engineering behaviour of these materials. The reworking of sediments by ice gouging has exerted important influences on the strength and stiffness properties of Holocene sediments, which are of critical importance to foundations of structures and pipelines.

Examples of the variability in the sediment section are shown in Figure 2, in which drained shear strength is shown against depth. High-strength materials, which we think represent the Holocene sediments, result from a combination of environmental factors and sediment type with ice gouging playing an important role in their development.

BASE SLAB CONTACT PRESSURES

We are now landing large, gravity-based structures on an irregular seafloor. The design of these structures has important economic and risk implications. In the U.S. Beaufort Sea, one of our objectives is to design these structures and land them on an unprepared, but surveyed, seafloor. It is necessary to design a system that will withstand the contact pressures, such as are shown in Figure 3, in terms of contact stress against the base slab versus seafloor ridge width. These base slabs are a very important part of the volume of that structure and, hence, in the cost of that structure. Penetrating pressures must be controlled by instrumentation, and, after landing, the remaining irregularities beneath the base slab have to be infilled. All the cost implications are related to the problem of ice gouging.

When a slab system lands on an unprepared gouged seafloor, there is a contact efficiency related to sliding (Fig. 4) versus the seafloor shear strength. If the seafloor shear strength is low and the contact pressure of the system is high, the irregularities will flatten out and contact efficiencies will increase. However, if the seafloor shear strength is high, as in the U.S. and western Canadian Beaufort Sea, then the structure's vertical pressure is usually not sufficient to flatten the depressions significantly. The limited contact area reduces the contact efficiency, which brings about the need to design base slabs with skirts and artificial roughness to comply with the ice-gouged seafloor relief. Berm construction is another approach that has to be considered as a means of increasing this efficiency.

PIPELINE BURIAL AND ROUTING

Pipeline burial is essentially a cost-risk problem (Fig. 5) in which, after a certain point, the initial construction cost increases exponentially with increasing burial depth. The repair costs fall with increasing burial depth. An economic optimization model is developed to search for a cost-effective burial depth equivalent to the low point of the total cost curve; the minimum value in the combination of curves for shut-down and repair plus initial construction costs.

As an alternative to burial, structural solutions have been investigated. David McKeehan (this volume) outlined several possible methods that are effectively geotechnical solutions; for example, frozen soils and berms on top of the pipeline. Another technique is to use

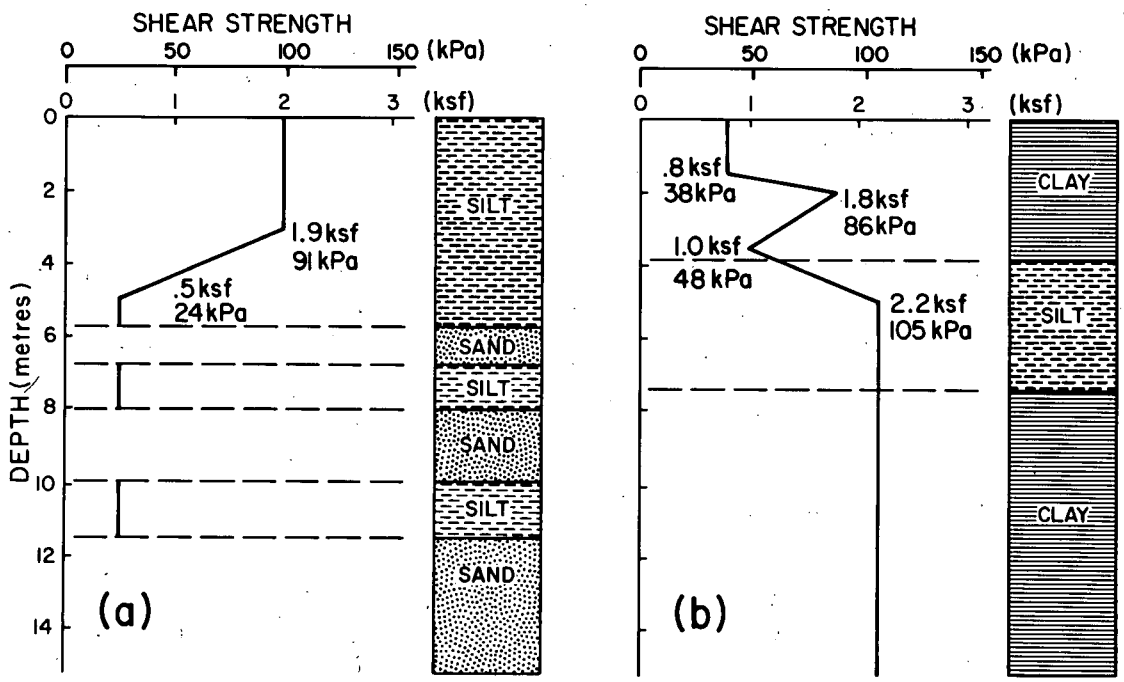

Figure 2. Drained shear strength versus depth in sediment sections of (a) silty sand, and (b) clayey silt.

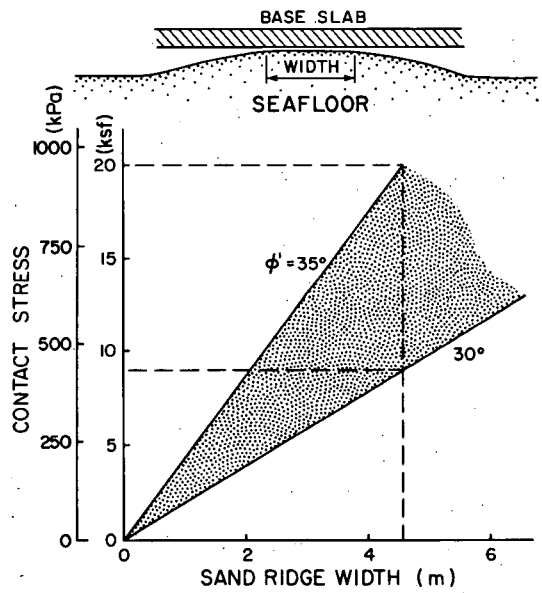

Figure 3. Seafloor ridge width versus contact stress against the base slab for sediments with friction angles between 30° and 35°.

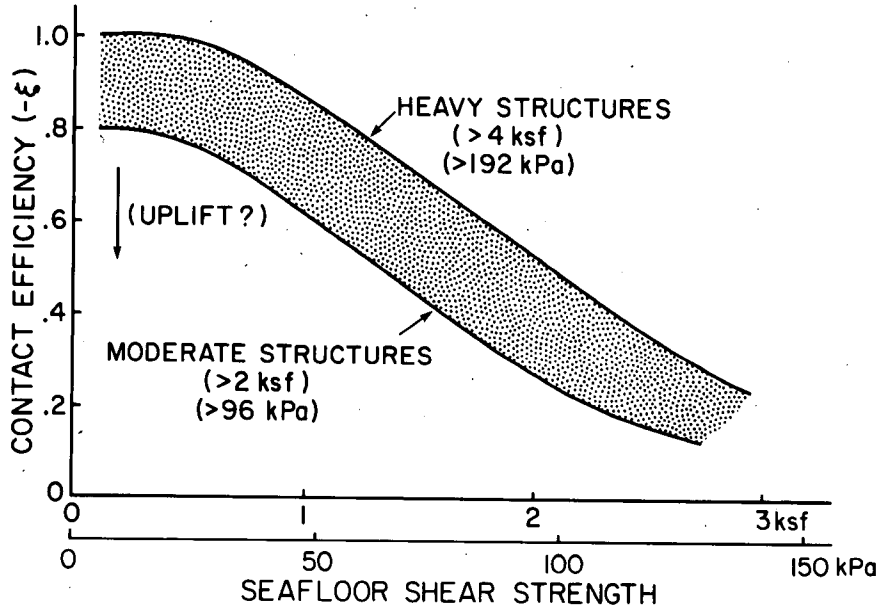

Figure 4. Contact efficiency related to sliding versus the seafloor shear strength.

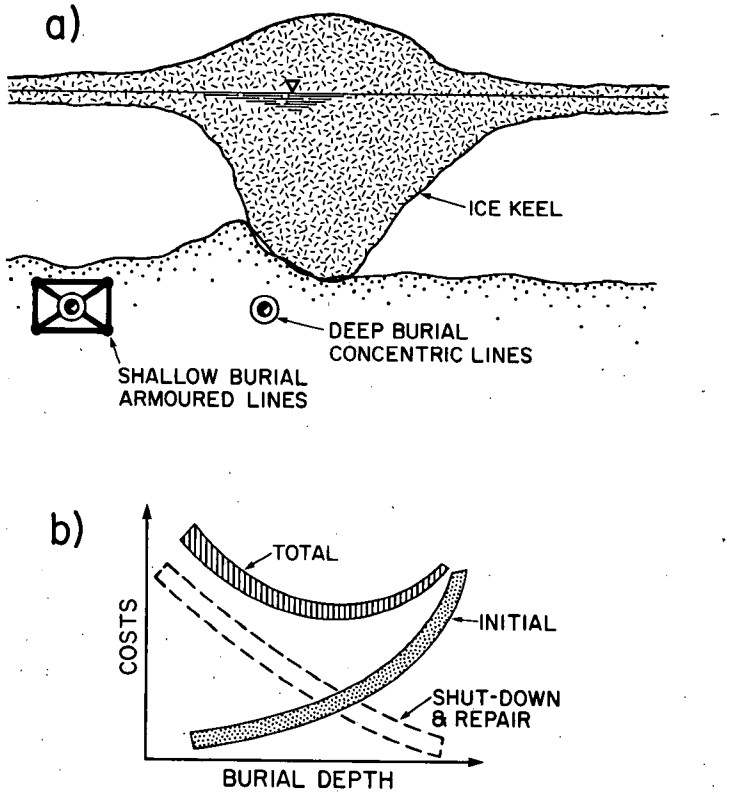

Figure 5. (a) Methods of pipeline protection by burial; and (b) pipeline costs as a function of burial depth.

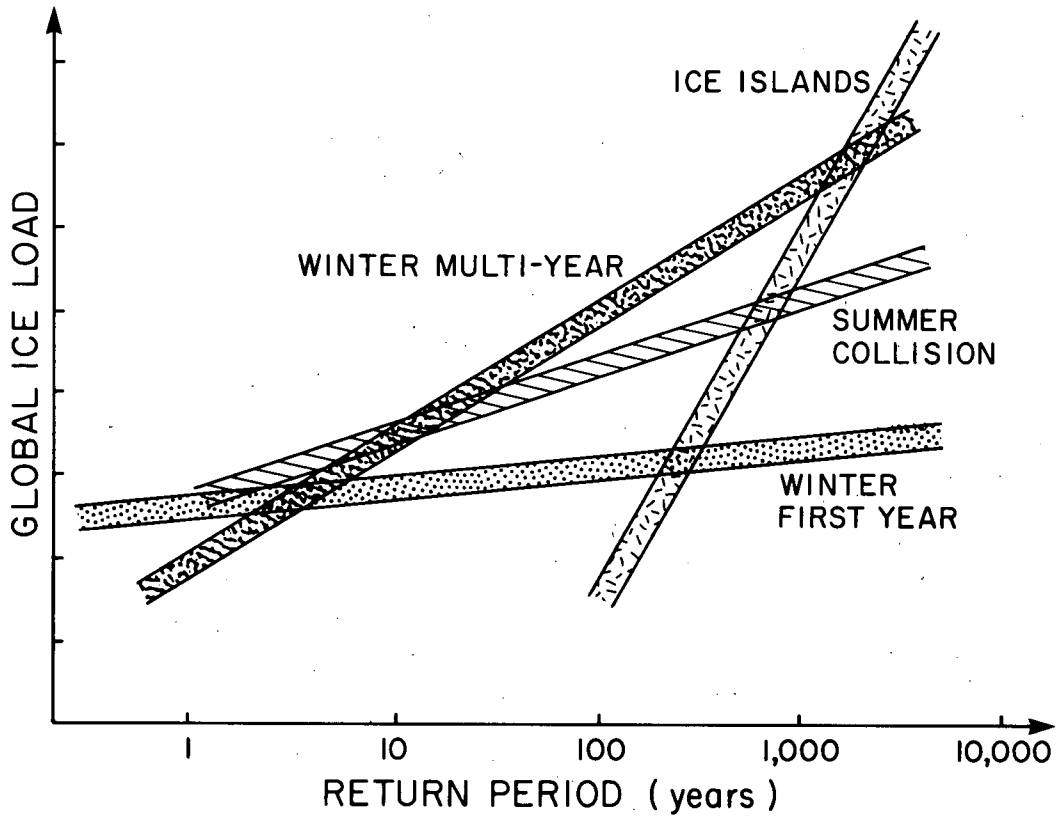

Figure 6. Diagram of global ice load versus return period.

combinations of structural solutions in which the structure interacts with the soil in an attempt to give the system strength. This technology is borrowed from our experience developed in mudslide areas where structural solutions, alternative routing, and break-away couplings are used as a means of improving our ability to route and to reconfigure pipelines.

GLOBAL ICE FORCES

Evidence suggests that a beneficial effect may be derived from ice gouging. One of the many critical loading hazards for fixed structures in the Beaufort Sea is the force exerted by ice. Figure 6 shows diagrammatically the late winter and early spring transition zone between the pack ice and fast ice conditions. The global forces acting against a structure are shown on the vertical scale of Figure 7. The shear drag effect that is believed to exist between the pack ice in its floating condition and the fast ice is identified by the question mark which implies a reduction in the magntiude and effect of the shear drag resulting from seafloor resistance to gouging forces.

The model studied is one with a continuous or almost-continuous ice cover in which a large multi-year ice feature becomes lodged against a structure during a late winter or early spring storm (Fig. 8). A variety of forces act upon the ice cover; wind, current, and interacting ice. Grounding or shear drag effects exist when keels of ice features contact the bottom. In the U.S. Beaufort Sea, gouging is thought to be extremely intense because of the close proximity of the polar pack to the shelf edge. Ice gouging statistics (Fig. 9) show that the maximum gouge density, based on more than 2,000 observations occurs in water depths between 20 and 30 m. If the frictional drag effect resulting from the ice field were understood, it might then be possible to

estimate the force that is being subtracted from the ice canopy by the shear drag effect on the bottom.

This drag effect includes the side and bottom resistances of the keel acting on the seafloor, and is outlined in Figure 10. We have taken a conventional geotechnical model and made estimates of gouge resistance developed. Values of gouge resistance against shear strength for different sizes of keel features in contact with the seafloor are summarized in Figures 11a and 11b based on a geotechnical model set up for material and an internal friction angle of 30°. In both figures, the passive resistance , R_P, and the shear resistance, R_S, are shown together with the total gouging resistance, R_G. The model indicates that the principal contribution to the gouging resistance is from shear contact of the feature with the seafloor, and not from the passive resistance against the frontal faces of the feature.

Of all parameters, the most important characteristic necessary in the estimation of the shear drag effect is the contact factor, ε, that is the area of the ice in contact with the seafloor referenced to the total area of the ice at a given time and place. Figure 12 shows the contact factor versus water depth, based on annual gouge survey results and on keel statistics published by Wadhams (1983). Typical distances offshore for the U.S. Beaufort Sea are shown versus the water depth along the horizontal scale. The resulting graph mirrors the cross-shelf gouge statistics for the U.S. Beaufort Sea (Fig. 9). Thus, the contact factor is crucial in estimating the frictional resistance as we now understand it.

A typical result for a design scenario from (Bea et al. 1985) is summarized in Figure 13. This model has been set up for a winter storm scenario that has an average wind speed of 64 kts. The contact factor for this particular scenario was taken as 2×10^{-4}, a relatively weak shear strength of 24 kPa (0.5 KSF) was used. The force F_W plus F_I is in essence the total force that is developed by the wind (F_W) and the ice/ice interaction forces (F_I) acting on various floe sizes. For example, a relatively large floe of 9,000 m^2 (30,000 ft^2) produces a lateral loading in the order of 1.1×10^6 kN (2.5×10^5 kip). The lower force limit is given by

$$F_W + F_I - F_G$$

where: F_G = the gouging or frictional force.

A reduction in the order of 50% is implied for the force against a structure for the large ice floes using a realistic combination of contact factor and the shear strength of the seafloor in contact with the particular ice floe.

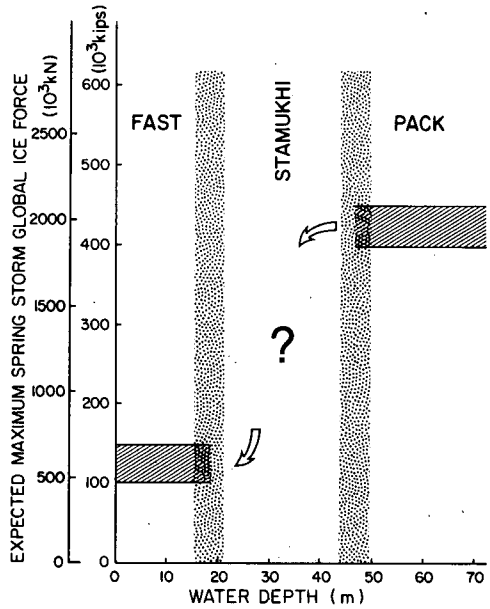

Figure 7. Expected global force during maximum spring storm in water of different depths.

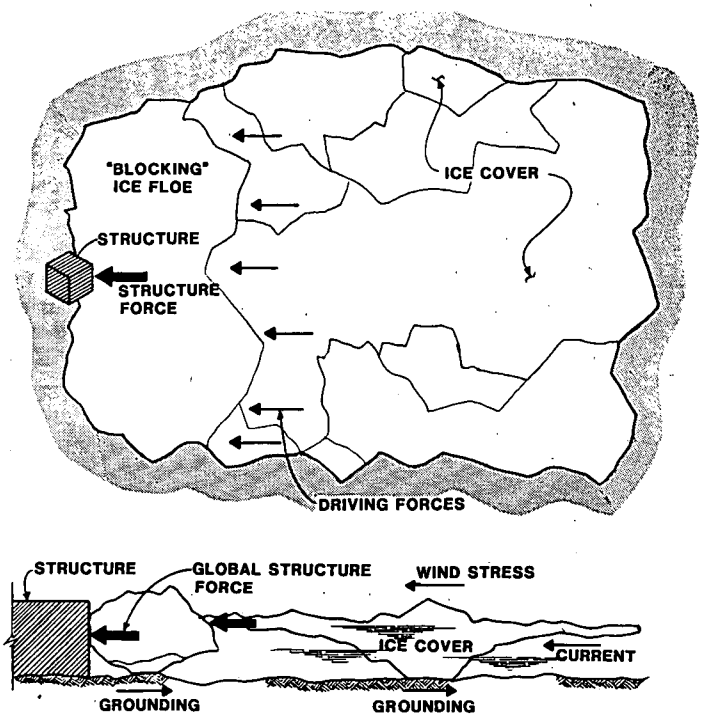

Figure 8. Interaction of forces when ice feature lodges against a structure (a) in plan, and (b) in cross-section.

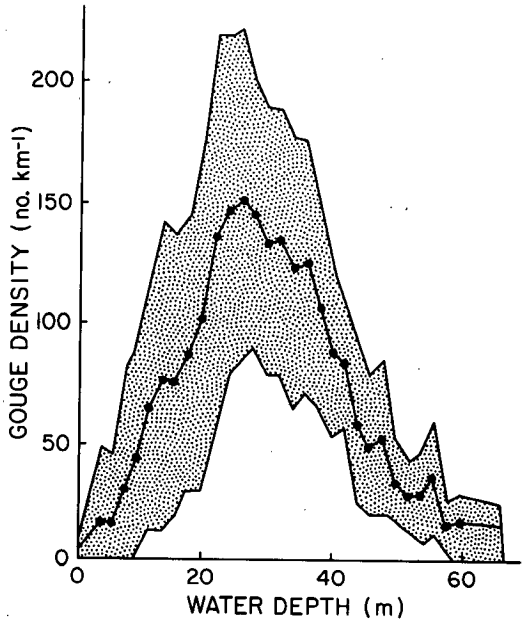

Figure 9. Ice-gouging statistics (derived by Barnes and Reimnitz 1986).

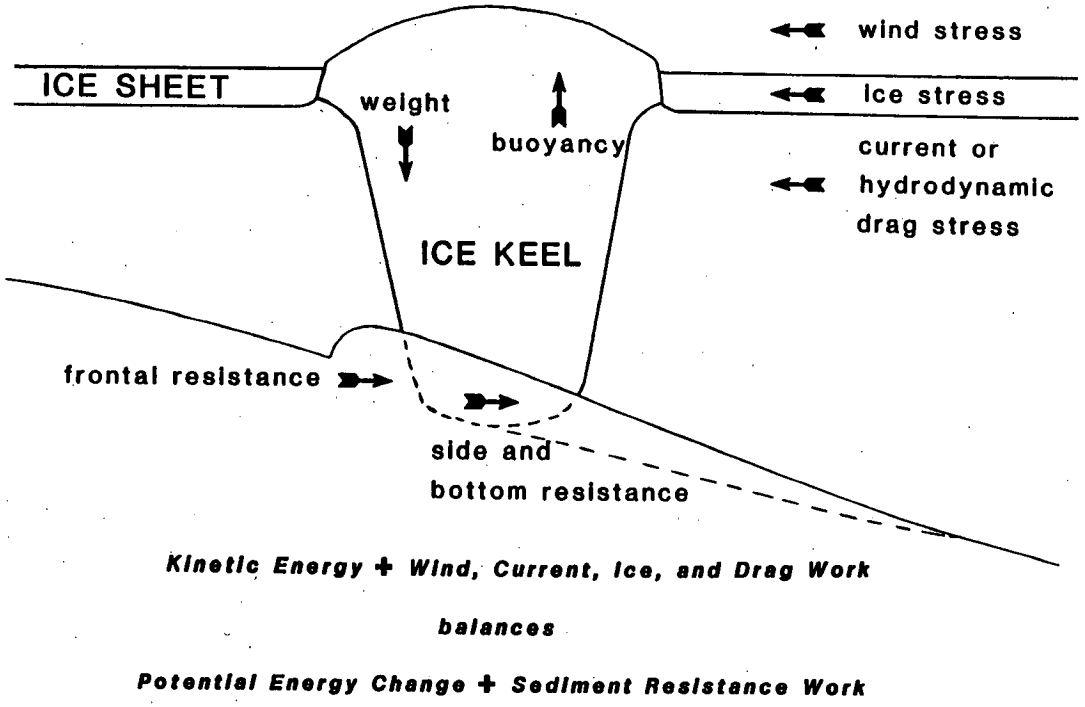

Figure 10. Diagrammatic representation of the drag forces acting during ice gouging.

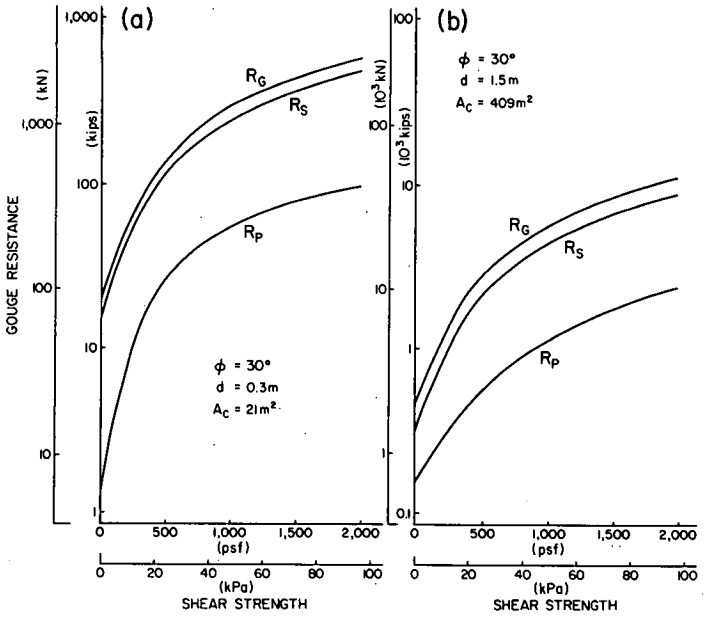

Figure 11. Gouge resistance versus shear strength for two ice features gouging to different depths, d, and with different areas is in contact with the seafloor, A_c.

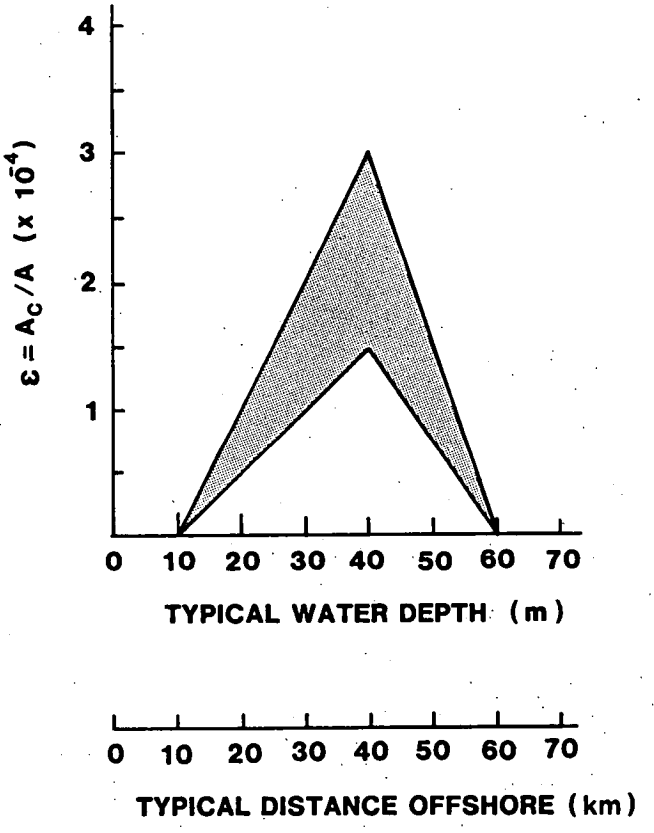

Figure 12. Contact factor, ε, versus water depth.

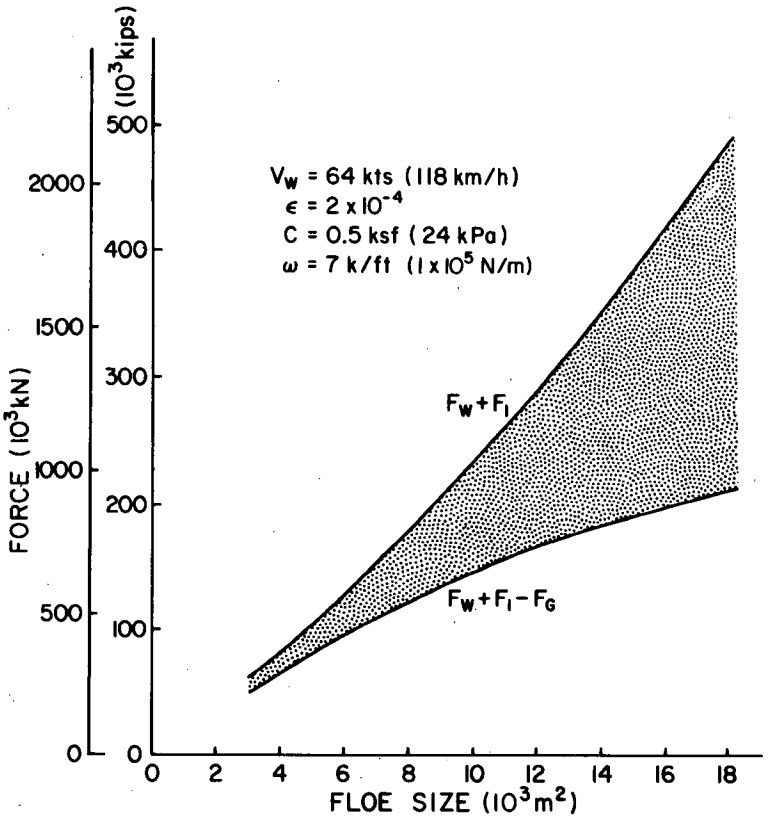

Figure 13. Force acting against a fixed structure versus floe size.

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DISCUSSION

T.R. Chari, Memorial University: You showed the bottom resistance as greater than the passive resistance. Would it not be a function of the uplift of the ice keel?

Bob Bea: In essence, if you were able to build a significant amount of ice above sea level, then high vertical forces would develop. At that point, the passive forces would become much more important. The displayed data sets are for normal scenarios of ridge height, keel depth, and water depth.

Bill Roggensack, EBA Engineering Consultants: Perhaps it would be appropriate to note that the analogy is really applicable to ice ridging, and the same kind of consideration may take on a different format if you were looking at icebergs.

Bob Bea: Indeed they would, if you were looking at perimeter/man-made ice rings for defensive structures, such as accumulations of ice on sub-seabottoms. There would be a significant amount of vertical pressure which in essence begins to change this picture of what dominates what.

[Editors' Note: A more complete and technical version of this presentation which includes an extended reference list, was presented (Bea et al. 1985) at the Arctic '85 conference held at San Francisco, California, under the auspices of the American Society of Civil Engineers.]

ICE-SCOUR AND ICE-RIDGING STUDIES IN LAKE ERIE

J. Grass
Ontario Hydro
700 University Avenue
Toronto, Ontario, M5G 1X6

INTRODUCTION

In 1980, Ontario Hydro proposed the construction of a high-voltage transmission cable system across the eastern basin of Lake Erie from the Nanticoke Generating Station to a site near Girard, Pennsylvania. Unfortunately, the project was cancelled in June 1982 for economic reasons before the cable could be laid. However, a tremendous volume of bottom and subbottom data was collected during the geotechnical investigations which included barge drilling, sediment sampling, and marine geophysics. The geophysical surveys provided a clear picture of the lake bottom and subbottom characteristics, particularly the occurrence of long, wide, and shallow ice scours in the soft sediments on the Canadian and American sides of the cable corridor.

ICE SCOURING AND RIDGING

Ice scours up to 6 km long, up to 100-m wide, and up to 2-m deep were found in water depths ranging from 13 to 25 m.

Ice scouring is an ongoing process in Lake Erie. Ice damage has occurred to gas pipelines during the winter on the Canadian side, and new scours were found on the American side when geophysical records from resurveyed areas were compared.

Ice was considered a major hazard to the cable security and operation. Hence, knowledge of the ice conditions on the lake and specifically ice ridges was important to a better understanding of the ice-scour process. During a helicopter reconnaissance flight, the ice-ridging process was observed in action at the edge of an ice island in Lake Erie. The action of the ice ridging was filmed from the ice surface and from the air.

A 10-m-high ice island was grounded in about 18 m of water in the mid Lake Erie area. A detailed geophysical survey of the area in the following spring showed a fresh scour 2.5 km-long, up to 1.5-m deep, and up to 30-m wide.

Based on the ice scour studies, it was recommended that the cables be laid in trenches excavated into the lake bottom to a depth of 1-3 m. In areas of soft sediment and high susceptibility to ice scouring, 3-m-deep trenches were proposed. In areas of rock, only 1-m-deep trenches were proposed.

RESULTS

A more detailed description of the investigation results and interpretatioans of data can be found in the Proceedings of the 7th International Symposium on Ice, International Association for Hydraulic Research (IAHR), Hamburg, August-September, 1984.

DISCUSSION

Bob Bea, PMB Systems Engineering Inc.: I would like to ask a question regarding the gas development in Lake Erie. You indicated that the well-head assembly to which the gas lines are connected uses conventional trees. Have you heard of any reports of damage to those trees caused by ice gouging or scour?

Jim Grass: As far as I know, damage happens almost every winter.

Bob Bea, PMB Systems Engineering Inc.: Do you mean damage to the trees themselves or to the lines that connect the trees with the shore? I am unaware of any damage to the trees themselves.

Jim Grass: I know for a fact that, on occasion, up to 600 m of pipe line has just gone. As to the trees, I don't really know the answer.

Bob Bea, PMB Systems Engineering Inc.: That might be an interesting case of, we could call it, "structural calibration" between the line and those trees, because those trees are obviously intersecting with keels and appear to be able to withstand that force.

Jim Grass: I haven't looked at that really. That's a good point.

Chris Woodworth-Lynas, C-CORE: You showed a sidescan sonar record of a scour where the keel just touched down and becomes slightly wider and then finally stops at the large soil pile. Was that keel moving up slope or was the "under plating" process (eds. note: movement of surface ice under the keel) actually causing the keel to become deep and more entrenched? Or was it a combination of both?

Jim Grass: It is a combination of both. In this example the ice was going upslope. Generally speaking we found that the scours got deeper with shallower water. In other words, in 25-m water depth the scour would be very shallow, and when it arrived in 13 m of water it would be 1.5 m-deep.

Chris Woodworth-Lynas, C-CORE: What were your criteria in deciding that 2 or 3 m was a safe burial depth for your cables? The work that Dr. Chari from Memorial has been involved with over the last few years, on the forces imposed on the soil by scouring, shows that if a pipeline were buried below the maximum scour depth it could be destroyed by downward varying pressure in the soil itself (Chari, T.R. 1979. Geotechnical aspects of iceberg socurs on ocean floors. Canadian Geotechnical Journal 16(2):379-390).

Jim Grass: We attacked this question from the other end. I was told that the trenching equipment had a maximum depth capability of 3 m.

ENGINEERING APPLICATIONS AND RISK ASSESSMENT: SUMMARY AND DISCUSSION

Chaired by
Drew Allan[1]
Petro-Canada
P.O. Box 2844
Calgary, Alberta, T2P 3E3

and

Bill Roggensack
EBA Engineering Consultants Ltd.
14535-118th Avenue
Edmonton, Alberta, T5L 2H7

SUMMARY

Table 1 summarizes what we have heard in the presentations so far concerning the important aspects in ice-scour applications to engineering design. Essentially the question is "What impact does ice scour have on design of pipelines and subsea installations?"

TABLE 1

Discussion of ice-scour applications in engineering design

Applications	Area of Discussion
Pipelines and subsea installations	Mitigation of risk Protection Repair Route conditions
Offshore structures	Foundation conditions Global forces/grounding
Scouring (or Gouging) process	Impact Models

[1]Presenter.

I would like to emphasize the use of subsea installations, although so far they have not yet been mentioned. Offshore oil and gas development may involve use of subsea well heads, templates, manifolds, and many other point-type as well as linear installations such as pipelines and flowlines. These point facilities are just as important as pipelines and require different protective measures such as glory holes, caissons, and silos, as opposed to the trenching and protective berms and covers that are being considered for pipelines.

We have heard about the potential for damage to installations by scouring ice. We want to know not only what the risk is and then what can be done to mitigate that risk; but also how we can protect installations, and how they can be repaired. Then there are the route conditions, or in the case of structures, foundation conditions that have to contend with the physical aspects of many years of scouring.

We heard Bea (this volume) mention that ice scour is important because of the impact it has on reducing the global ice forces on structures caused by grounded ice ridges. There is also a need to understand the gouging process so that we can determine the effect of changes made to the environment. In other words, if we build a berm, we have to understand the gouging process so that we can predict the ice forces on the installation.

Figure 1 is a flow diagram that may help in understanding ice-scour risk assessment from an engineering perspective. The environmental data are used to derive environmental statistics which are then used in the different scour models. Various scour models will be reviewed later in the workshop.

To determine the interaction between scour and installation, the results from the scour models are entered into a procedure that attempts to determine what happens when the scouring keel passes over a pipeline. We know that there are going to be soil pressures generated and that there is going to be movement of the soil. The question is: "How deep does a pipe have to be buried below the keel to be protected from ice damage?" Alternatively: "Can the pipe be thickened to reduce the amount of cover necessary?"

Caissons for well heads are designed with shear joints. However, we have to understand how ice keels can interact with the caissons and, how those caissons would fail. In case of failure we have to provide the caisson with a means of re-entry so that it can be secured later. If a frozen-bulb technique is to be used to protect the pipeline, the interaction of the keel with the frozen bulb must be well understood. Finally, in areas where rock outcrops occur, protective covers anchored to the rock may be a possible solution.

When the interaction between scouring process and installation is understood, a probability of damage has to be calculated and the results used in risk assessment. The consequence of damage is just as important as the probability of damage. To determine the consequence of damage, we must address the preliminary design and the socio-economic and environmental conditions. Not only must the impact and the consequences of damage to the environment be assessed, but also the risk of injury and possible loss of life. For example, a disruption in the supply of hydrocarbons to the market place could lead to loss of life if alternate fuels were not available. Other consequences are cost of repairs and lost or deferred production.

Once the consequence and the probability of damage are fed into the risk assessment, we have to decide whether the risk is acceptable or unacceptable. If it is acceptable, we can finalize the design and layout of facilities and can proceed with construction. If it is unacceptable, it is necessary to investigate possible mitigative measures, before returning to the preliminary design and to another cycle through the risk assessment until an acceptable design is found.

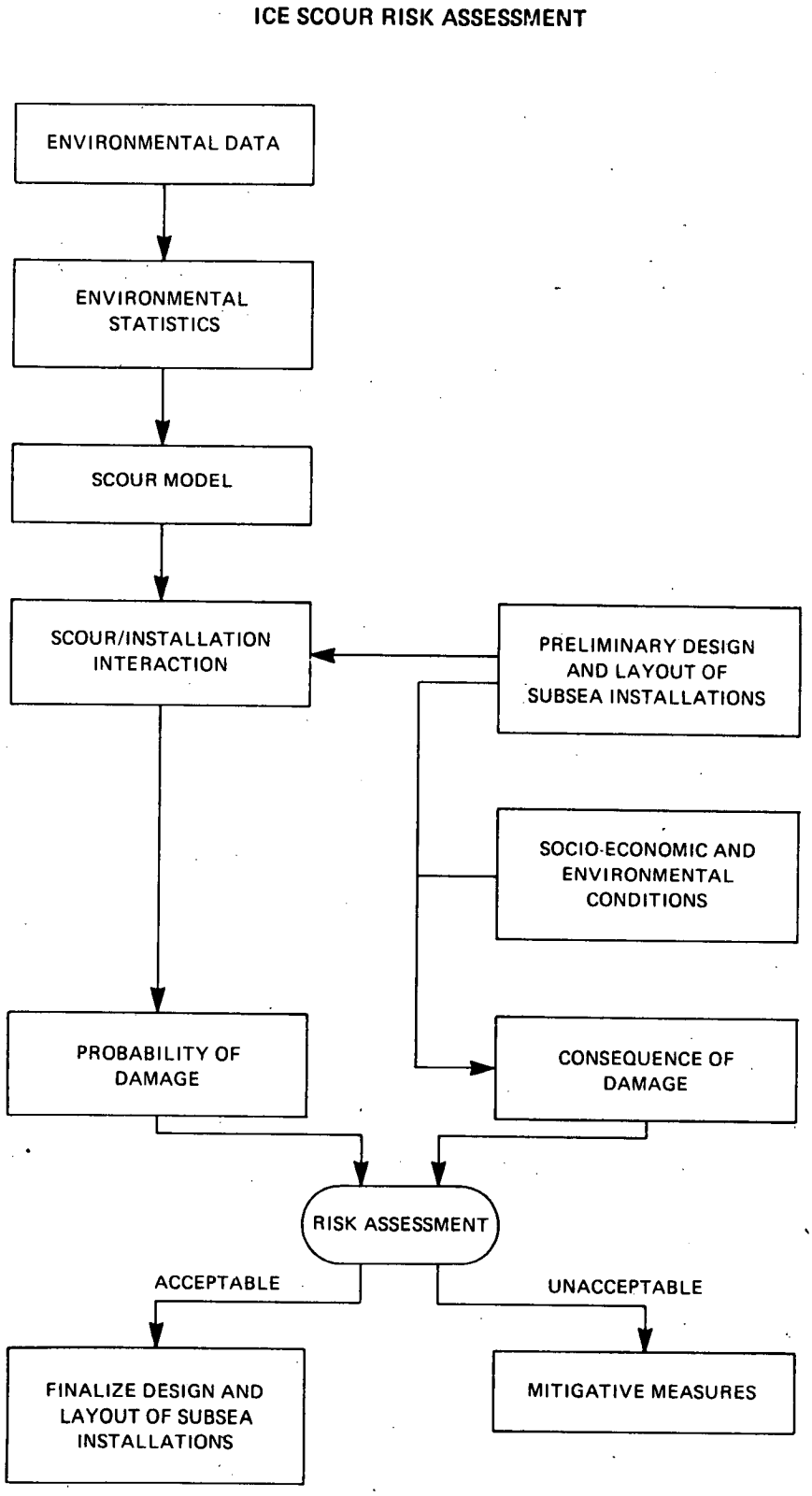

Figure 1. Ice-scour risk assessment.

One of the problems in risk assessment is determining the level of acceptable risk. Considerations in determining the acceptable level of risk are as follows:

(a) Is acceptable risk to be defined on a component, system, or regional basis?

(b) Should acceptable risk be assigned on a per unit, per unit length, or per unit produced basis?

(c) Should risk to life, environment, and economic return be considered separately?

(d) How can the treatment of the risk of ice-scour damage be made consistent with the treatment of other damage risks currently accounted for in the design of offshore developments?

(e) Should the uncertainty in our ability to predict the risk of ice-scour damage be taken into account when determining the acceptable level of risk?

This presentation was designed to help delegates focus on the total engineering approach to the problem. At these workshops we get very excited about data that we are collecting, the statistics we are generating, and the models we are using. However, we often forget that these elements have ultimately to feed the design process, as our end objective.

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DISCUSSION

Peter Barnes, U.S. Geological Survey: The last comment about getting excited with data collection, statistics, and models is very valid. We need more information from people concerned with aspects of design and mitigative measures. From an engineering perspective, it is essential to know what inputs are needed here so that the relevant data can be collected, analysed, and presented in a useful manner.

Drew Allan: The most important aspect is the scour model and then how we infer damage to facilities from that model. I've attempted to summarize how we look at the data requirements as follows:

(a) Is the data set representative of the population?
- Is the sampling method random, or is there a bias?
  - ·regional bias?
  - ·seasonal bias?
  - ·selection bias?
- Are the data points independent?
- Are there enough data points to provide statistical confidence?

(b) Are the data sets sufficient to identify variations that occur: seasonally, yearly, and regionally?

(c) Is the value being measured dependent upon water depth, soil conditions, or other parameters?

(d) Have the data points been measured directly, calculated based on measured values, or inferred from other data using correlations?

(e) What is the accuracy of the measured, calculated, or inferred data points?

Basically you have to ask the question: Is the data set representative of the population? For that to be accurate, you have to look at the sampling method and determine whether it is random or whether a bias exists. A bias can be introduced on a regional basis. Thus, statistics resulting from regional data may not apply to a broader region. Similarly, the statistics may only be relevant on a seasonal basis. A bias may also be introduced on a selection basis. For instance, by selecting only large icebergs as part of a study, a bias may be introduced into the data set. There is a real need to ascertain the independence of data, for example, one iceberg may scour over a large area during one scouring episode and may produce a discontinuous scour consisting of many small individual scours, which are not independent events. Another question concerns the statistical validity of a sample relative to the total population. All too often, we have insufficient data points and we must use what we have, although, the statistical confidence levels, may be quite large.

We need sufficient data if we are to identify variation that occurs seasonally, annually, and regionally. We might want to know whether most of the damage will occur in the winter when it could be more difficult to deal with. Also what happens if, after five years with very little ice-keel activity, the sixth year presents very intense ice-keel formation, intense scouring, and, as a result, many repairs are required? From an operational point of view these problems are difficult to assess. Another important consideration is the dependence of various parameters on other parameters. If we can establish this dependence, it helps in data collection and design. For example, in the Beaufort Sea there is a dependence between the depth of scours and the water depth.

The final data consideration concerns the data points themselves. How are they collected? Are they measured directly or are they the result of calculations based on many separate measurements? Are parameters inferred from other measurements, as in the case of estimating iceberg draught from length measurements? Quality of data is equally important. Every data point should have an estimate of accuracy associated with it. These are some questions that should be addressed in trying out a risk model. One question that arises, concerns the accuracy and inherent assumptions of a scour model. For many of these scour models, we need to understand not only the density, frequency, depth, width, length, and orientation of the scours, but also iceberg or ice-ridge flux, iceberg or ice-ridge draught, and scour infill rates. What confidence do we have in these parameters and how sensitive are the end results to their variance? For one of the models, an important problem concerns the determination of the time taken to produce the features that can be seen in seafloor records. Another problem on the east coast is the distance that an iceberg can scour upslope. This measure is important because, in looking at a draught distribution, we do not want to consider all icebergs deeper than the water depth. Physically, an iceberg with a draught of 180 m will not be found in 80 m of water. At some point the draught distribution will have to be truncated. If we are to aspire to understanding the entire process and to develop a comprehensive simulation model of scour, we are going to have to understand the morphometry of icebergs and ice ridges, their driving forces, the soil conditions, and all other relevant inputs.

This short presentation is an attempt to familiarize participants to this workshop with the overall aspects of data collection. Any comments on the above considerations will be most welcome.

Alan Ruffman, Geomarine Associates Ltd.: The list is really quite complete. In 1975, off Labrador, Geomarine towed a sidescan sonar close to the seafloor in a survey for the EastCan Group. The intention was to measure the depth of scours as well as their orientation. In that particular study, berm heights were of no interest whatsoever. I would like to know if berm heights are still of no significance. I believe little work has been done on the subject.

At one site we also looked at the depths of all the scours. At the request of the client, scours less than 1 m in depth were edited out of the data set because only larger scours were considered important. Such editing certainly affects the ultimate statistical information.

Another problem is client bias. Scour lengths were not of interest, so scouring upslope and downslope was not addressed. We had an example of scouring into a topographic low, which was not accepted at the time. Only now are such phenomena of interest.

I also would like to comment on Bob Bea's question about whether the pipeline trees in Lake Erie were being affected by ice (Grass, J. 1986. Ice-scour and ice-ridging studies in Lake Erie, this volume.). Consumers Gas, which operates these facilities, must have collected statistics on damage with respect to ice action and are a possible source of information. My recollection is that the trees are out in deeper water and, in a number of cases, are beyond the shear zone. Therefore, they are not as vulnerable to ice-scour damage. Consumers Gas certainly has had a lot of experience in repairing pipes or turning off gas in the winter time. Re-routing gas using alternative pipeline sections is often used to maintain supply, which allows them to repair damage in summer under more favourable conditions.

Bob Bea, PMB Systems Engineering Inc.: There is another aspect to this business, and that is uncertainty. Earthquakes and mudslides are examples and there is a wealth of literature that addresses major elements in this problem. I feel that another category should be added to Drew Allan's ice-scour risk assessment diagram after the scour/installation interaction box (see Fig. 1). This box would be titled the "Evaluation and Assessment of Uncertainty" and is felt to be crucial for several reasons. It asks questions such as, and forces answers to, the considerations posed in determining the acceptable level of risk (Allan, this paper). Secondly, there are two types of uncertainty, one of which we'll call unavoidable uncertainty that is primarily because of Mother Nature. It is very variable and our knowledge of it is limited. The other type of uncertainty is associated with the techniques of modelling. This category is critical because it identifies those topics that can be developed to improve our management of uncertainty. These factors relate to the collection of environmental data at the start of the risk assessment program.

Drew Allan: I had envisioned uncertainty being taken into account in the probability-of-damage category.

Bob Bea, PMB Systems Engineering Inc.: I think it has to be considered before you get to the probability of damage. By that time we are "convolving" demand and capacity elements. Another comment concerns earthquakes, waves, mud slides, and other catastrophic events. We have yet to determine if we can address these problems confidently using a purely statistical approach. If we are worried about extreme events then probability assessments may indicate for how long we should gather data. If the periods are not realistic then we may be forced to combine models to gain a basic understanding. A statistical base would be used in the calibration of these models and then we could project into the future using a combined approach. I suggest you expand the "Environmental Statistics" category and include these other elements. There are many dangers associated with a purely statistical approach.

Drew Allan: I wasn't inferring that it was a purely statistical approach. There is a lot of inference required for some inputs into the scour model and in the interaction between scour and installation. Perhaps "Environmental Statistics" should be changed to "Environmental Inputs."

I believe this is the point that you originally made. In other words, should the uncertainty in our ability to predict the risk of ice-scour damage be taken into account when determining acceptable levels of risk?

So far we have concentrated on how to determine the risk of scour damage and discussed considerations in determining acceptable levels of risk. I would like now to shift to a brief discussion of ways of mitigating the probability of damage and reducing the consequences of damage events. The following list outlines various mitigative measures that can be used in the design and operation of subsea facilities:

(a) Measures for mitigating pipeline damage

- ·minimize number and length of pipelines
- ·appropriate route selection
- ·ice management (detection, towing, rolling)
- ·backfilled trench
- ·open trench
- ·protective berm
- ·protective covers
- ·tunnel
- ·causeway/bridge
- ·thicker wall pipe
- ·other.

(b) Measures for mitigating damage to subsea equipment installations

- ·minimize number and size of subsea installations
- ·appropriate site selection
- ·ice management (detection, towing, rolling)
- ·minimize height of installation
- ·caisson
- ·silo
- ·glory hole
- ·protective berms
- ·protective bunkers
- ·other.

(c) Consequence of damage to pipelines and subsea equipment

- ·emergency procedures and contingency plans
- ·provision for alternate energy sources to service market
- ·effective spill containment and clean-up methods
- ·leak/damage detection systems
- ·purging of subsea lines and installations when damage imminent
- ·isolation valves
- ·shear joints
- ·provision for quickly locating and repairing damage
- ·redundancy of facilities and capacity
- ·other.

I suggest that these measures should be kept in mind when designing facilities in ice-scoured regions.

ICE AND ICE-SCOUR PROCESSES

Session Chairmen

J.V. Barrie
P.W. Barnes

ICE-GOUGE STUDIES, ALASKAN BEAUFORT SEA

Peter W. Barnes[1] and Erk Reimnitz
United States Geological Survey
355 Middle Field Road, MS999
Menlo Park, CA 94025

INTRODUCTION

Recently, ice-gouge studies by the U.S. Geological Survey have advanced in three areas. First, we have statistically characterized the total gouge population in the Alaskan Beaufort Sea. Secondly, we have characterized the datable gouge population to determine the rate of seabed reworking and have reached conclusions on the seaward limit of present-day gouging on the Alaskan Beaufort shelf. Finally, we are beginning to understand the effect of gouging on the overall shelf morphology and sedimentology.

Figure 1 is a bathymetric and trackline map of the shelf and coast of north Alaska. Most of our data are concentrated in the inshore region (mean water depth less than 20 m) and thus form a bias to the data set; however, limited data have been collected over the outer part of the shelf.

TERMINOLOGY

The term "ice gouge" is used here for the characteristic seafloor furrow and associated morphology of the seabed caused by ice keels as they drag across the seafloor. Each furrow is considered a separate gouge even when many gouges result from the same ice-gouging event. Gouges created simultaneously by a multi-keeled ice ridge are described as a gouge "multiplet".

The terminology used for the quantitative enumeration of an ice-gouged seafloor is outlined in Figure 2. Two aspects need more detailed explanation.

Gouge "intensity" is a quantitative estimate of sediment disruption calculated as the product of gouge density, maximum gouge depth, and maximum gouge width.

Gouge "density" is the density of all ice-produced sublinear features preserved on the seafloor. The measurement expresses the number of preserved gouges per square kilometre of seafloor by the normalizing of trackline data. Gouge density, or alternatively gouge frequency, identifies and enumerates all linear features and does not equate to the number of gouging events, each of which may have resulted in one or more gouges. Other characteristics of gouges shown in Figure 2 are discussed in detail in Barnes et al. (1984).

Figure 3 is an example of sidescan sonography of gouges produced by an ice ridge with many keels. The reason that the density of gouges cited in American literature is greater than

[1]Presenter

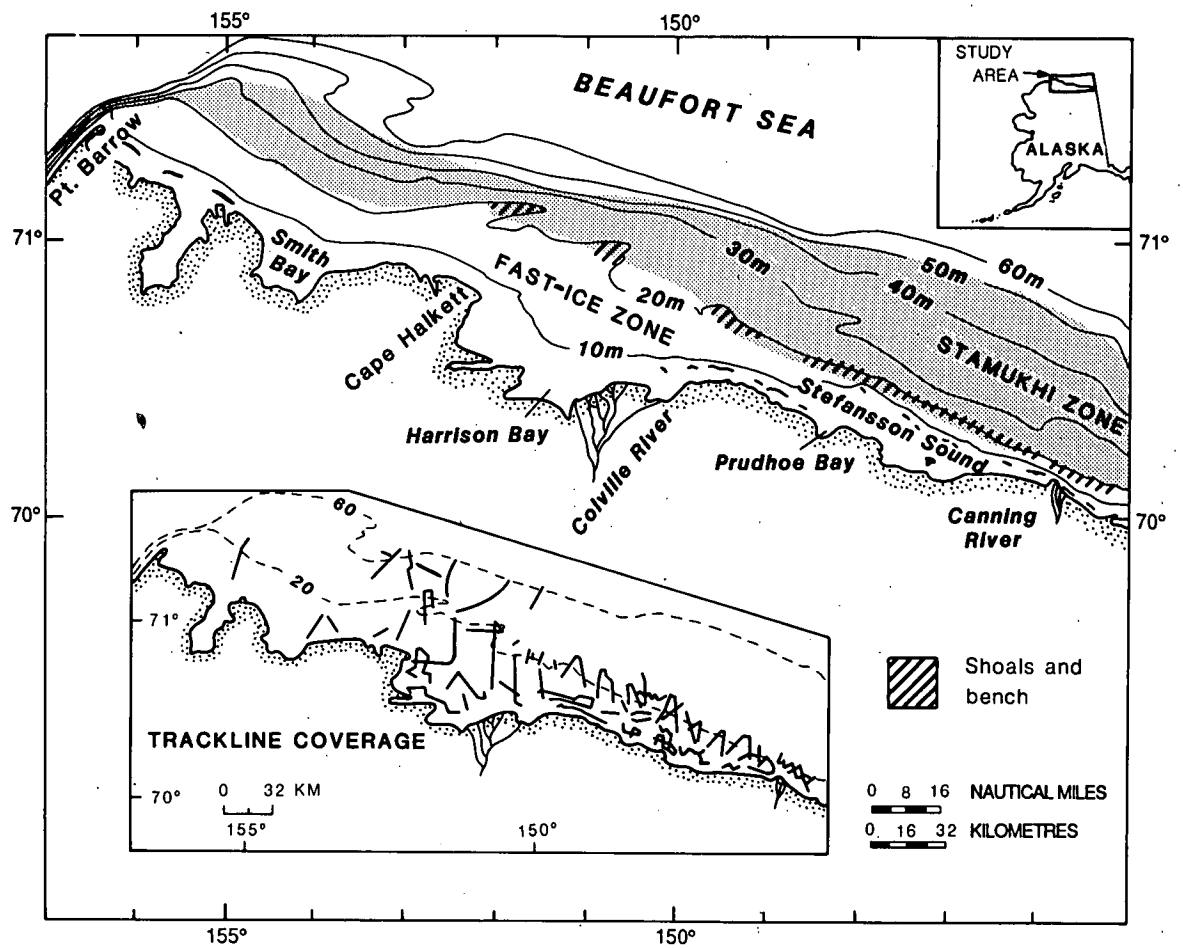
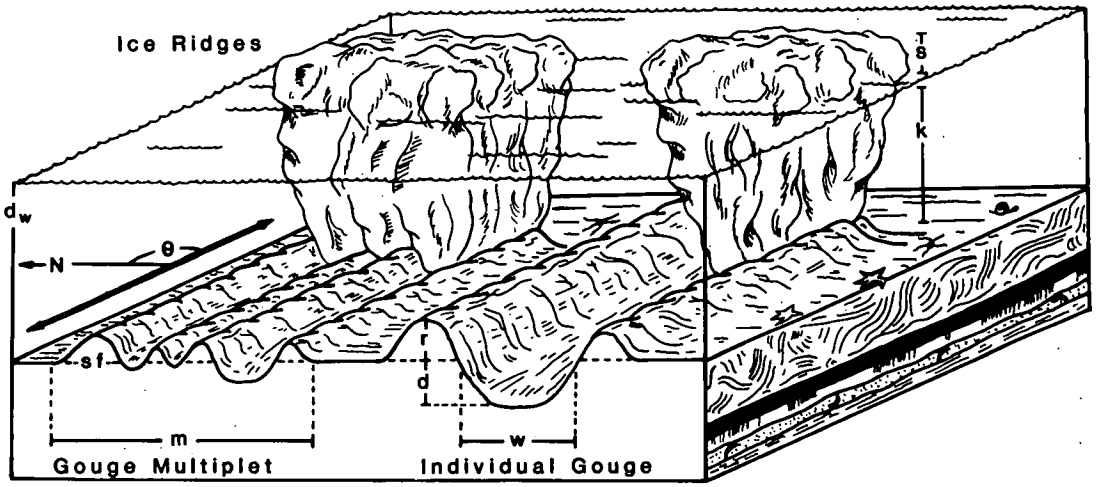


Figure 1. Study area, bathymetry, and ice zonation in the western Beaufort Sea off Alaska.



N - True North	θ - gouge orientation
d_w - water depth	d - gouge depth
sf - sea floor	w - gouge width
k - keel depth	r - ridge height
s - sail height	m - multiplet disruption width

Figure 2. Idealized sketch illustrating the relationship of an ice gouge and gouge multiplet to ice keels and the associated terminology (after Barnes et al. 1984).

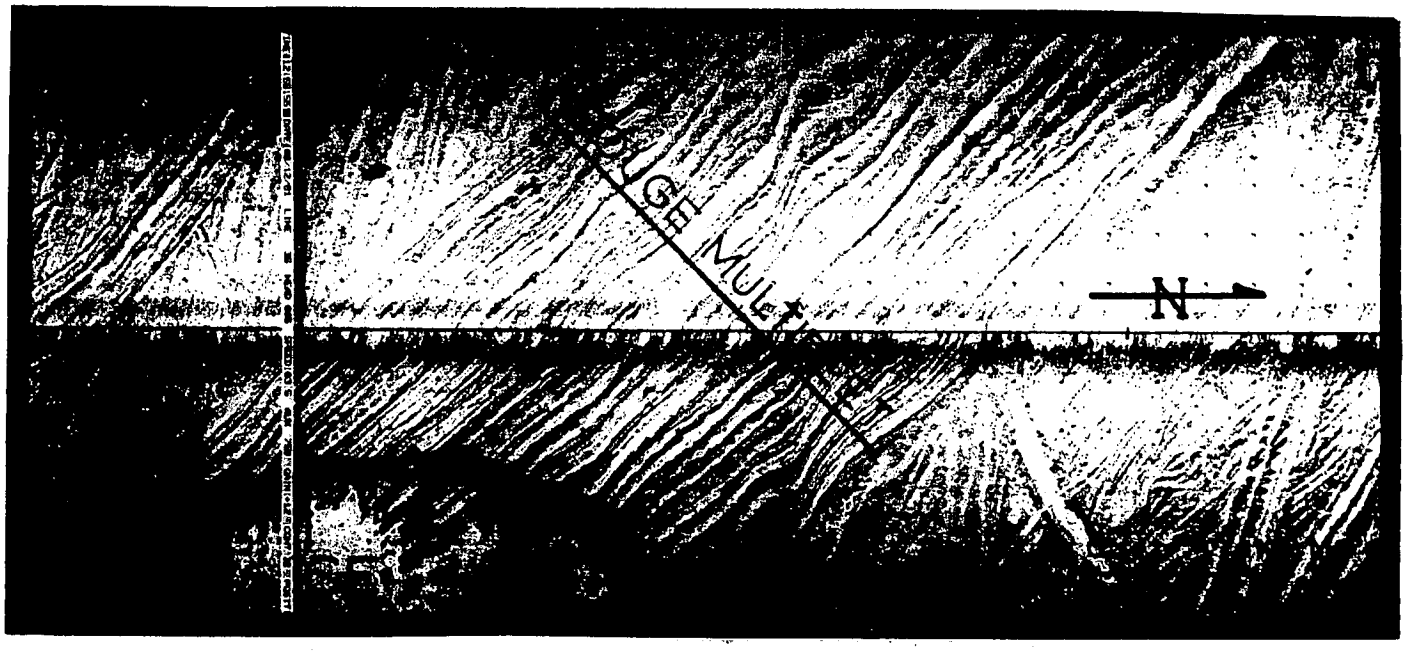


Figure 3. Sonograph of a gouge multiplet from 25-m water depth east of Barter Island. Note the ice mass along the margin of the record. This ice mass is grounded over about the same width of bottom as is covered by the multiplet, and may have scoured the multiplet gouge (after Barnes et al. 1984).

that found in Canadian studies is perhaps that we count every single furrow indenting the seafloor as an individual gouge.

Ice Regime

The area of the Alaskan shelf from which the bulk of our gouge data has been collected, emphasizes the shelf inshore of the stamukhi or shear ice zone. The stamukhi zone marks the boundary between the moving polar pack and the stable fast ice and is the loci of numerous linear grounded ridges (Reimnitz et al. 1978). This zone commonly occurs in water depths of 15-40 m with its inner edge in depths of 15-20 m (see Fig. 1).

TOTAL GOUGE POPULATION

Distribution of Data with Water Depth

The six distributions in Figure 4 show the mean and standard deviations of six gouge parameters with water depth based on 1-km line segments. Five of the distributions -- density (or frequency), maximum gouge depth, width, intensity, and ridge or berm height -- show a typical bell-shaped characteristic similar to that seen in Canadian waters. There are, however, a few interesting features to be seen. Around 20-m water depth, each curve shows a persistent "nick" that corresponds to the water depth at the inner edge of the stamukhi zone. None of the remaining "nick points" has correlatable features. The nick is very pronounced in the intensity diagram where the intensity level increases markedly seaward of the nick point. From these data, a rule of thumb relating maximum gouge depth with water depth has been derived. For water depths up to 40 m, the maximum gouge depth is about 10% of the water depth. Ridge heights and gouge

depths are about equal for shallow gouges, but ridges are only about one-third as high as large gouges are deep.

The areal distribution of ice-gouge intensity (Fig. 5) shows that highest values correspond with the stamukhi zone. The high-intensity regions should indicate an intense area of reworking.

Multiplet gouges characterized by a broad footprint with many shallow, parallel incisions commonly less than 20 cm in depth (see Fig. 3) are believed to have been formed by first-year pressure ridges that had grown in contact with the seabed. We cannot see another logical reason why multiple keels would occur within so few centimetres of one another. The lack of block-to-block freezing in first-year keels leads to weak scouring tools that could explain the shallow incisions.

Gouge orientation in the Alaskan Beaufort Sea is subparallel to the coastline, suggesting that ice impacted the bottom from the east. However, the orientations in the Canadian Beaufort Sea suggest that ice impacted the bottom from the northwest. In 1972, surface drifters were released on the Alaskan Beaufort shelf about 100 km west of the Canadian/U.S. border. Most of the drifters travelled west as expected, but some of the most easterly drifters travelled east into Canada. In 1983, surface and bottom drifters were released in the Barter Island area between longitudes 142° and 145° W, and both surface and bottom drifters travelled east, contrary to the postulated circulation patterns in the area. In fact, the drifters crossed the Mackenzie

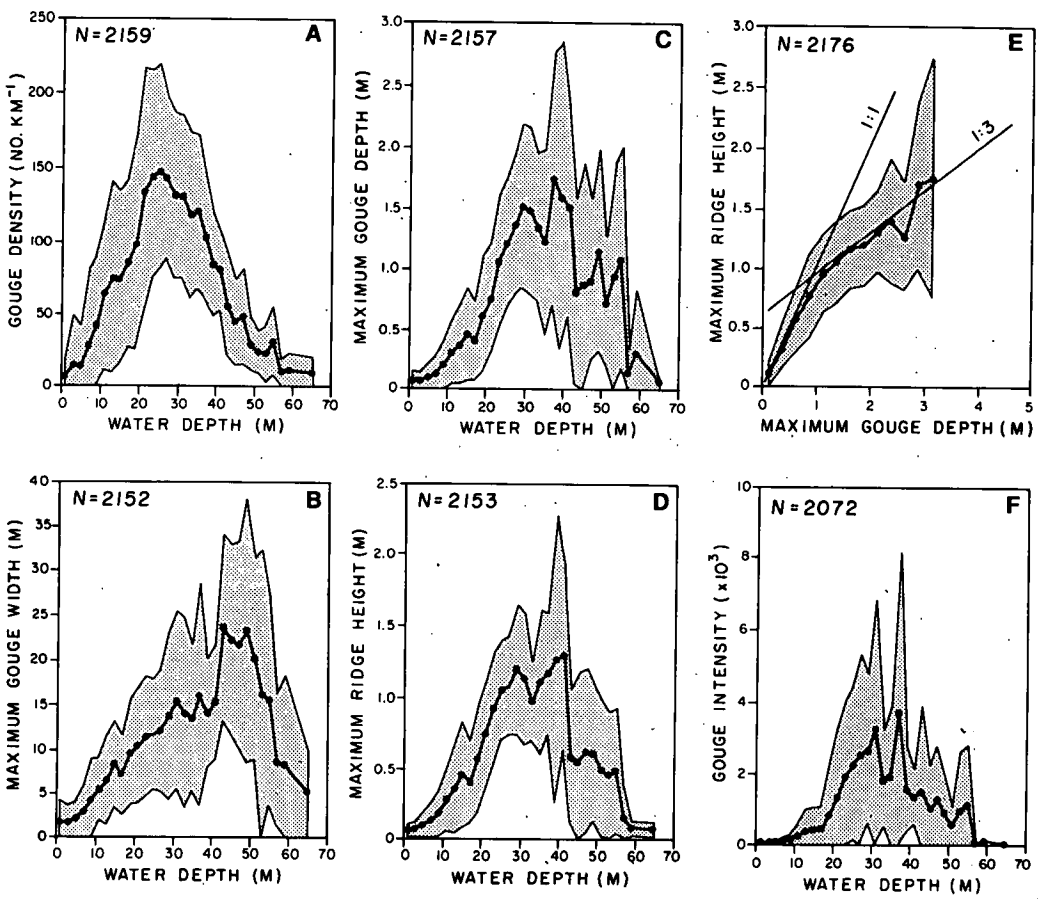


Figure 4. Mean (connected dots) and standard deviation (shaded areas) of ice gouge parameters measured in 1-km segments in 2-m depth increments. N refers to the number of observations in the distribution (after Barnes et al. 1984).

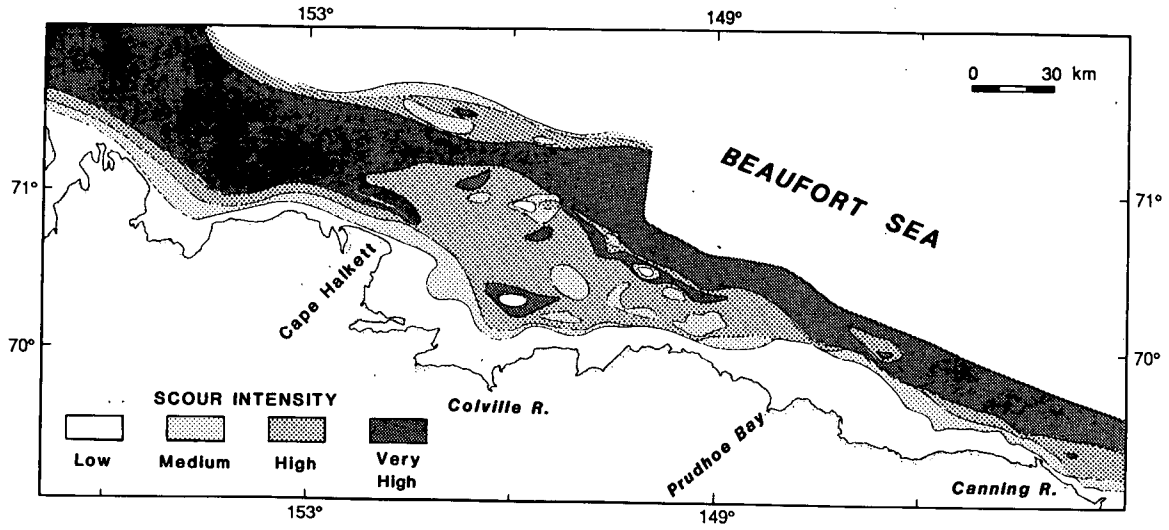


Figure 5. Regional distribution of ice-gouge intensity (product of maximum gouge depth, maximum gouge width, and gouge density) in 1-km trackline segments (after Barnes et al. 1984).

Delta area into the Amundsen Gulf, where several were recovered. An examination of the wind regime at Barter Island indicated that the drifters were influenced by local winds. The long-term regime of local winds at Barter would support the results we observed. Thus, a divergence in ice-gouge orientations and surface currents should be expected in the vicinity of Barter Island.

GOUGE DATING

Nine survey corridors form the data base used in dating gouges (Barnes et al. 1984). The data are concentrated inshore of the inner boundary of the stamukhi zone. Navigation is by line of sight ranges with errors of less than 20 m at 20 km, and by range/range radio navigation systems with range errors of less than 10 m. The gouge population is dated by two methods. An absolute date for some scours is obtained by comparing side-scan sonographs from two consecutive years, for example, 1977 and 1978. Thus we have the population formed between the 1977 and 1978 surveys. These data go into the population of gouges that are less than 1 year old. Some resurveys did not occur until 4 years after the initial observations, and these dated gouges can be observed only to be "less than 1 year old." A dated gouge can be remeasured in subsequent years, and estimates of infill rate can be determined; however, this analysis still has to be undertaken.

The average dated gouge is less than 1 year old and has a depth of 20 cm. The area of the reworked seafloor varies from less than 1% up to 6%, and on average is about 4%. Furthermore, dated gouges make up more than 10% of the total population of gouges in our study area, suggesting that the gouge population is renewed about every 10 years or less. Although gouges were ubiquitous along the survey corridors, they were concentrated on the seaward flanks of shoals and in the stamukhi zone. More than half of these features are multiplet gouges, which suggests that first-year ice ridges are the dominant cause of seafloor disruption.

Gouge density on the survey corridor northwest of the Colville River increases locally between water depths in the range of 15-20 m (Fig. 6), with a corresponding increase in maximum disruption width. Where the survey corridors cross into the stamukhi zone at 22 m water depth,

gouge density and disruption width increase dramatically to more than 20% of the seabed per year (see Fig. 6).

The year-to-year variability of gouging is shown in Figures 7 and 8, with data from two survey corridors northeast of the Colville River. There are no obvious correlations, which suggests that the ice regime that interacts with the seafloor can vary over short distances and is highly variable.

DEEP WATER GOUGES

Ice gouge patterns on the Alaskan Beaufort Sea shelf extend from the coast seaward to water depths of at least 64 m (Fig. 9). The maximum measured draught of sea ice in the Arctic Ocean, however, is only 47 m. Thus the numerous gouges seaward of the 47 m isobath might be relict, cut during times of lower sea-level many thousands of years ago. Sedimentation rates along the shelf break are very low, and a rain of particles settling vertically in a quiet environment on these bedforms would not soon obliterate them.

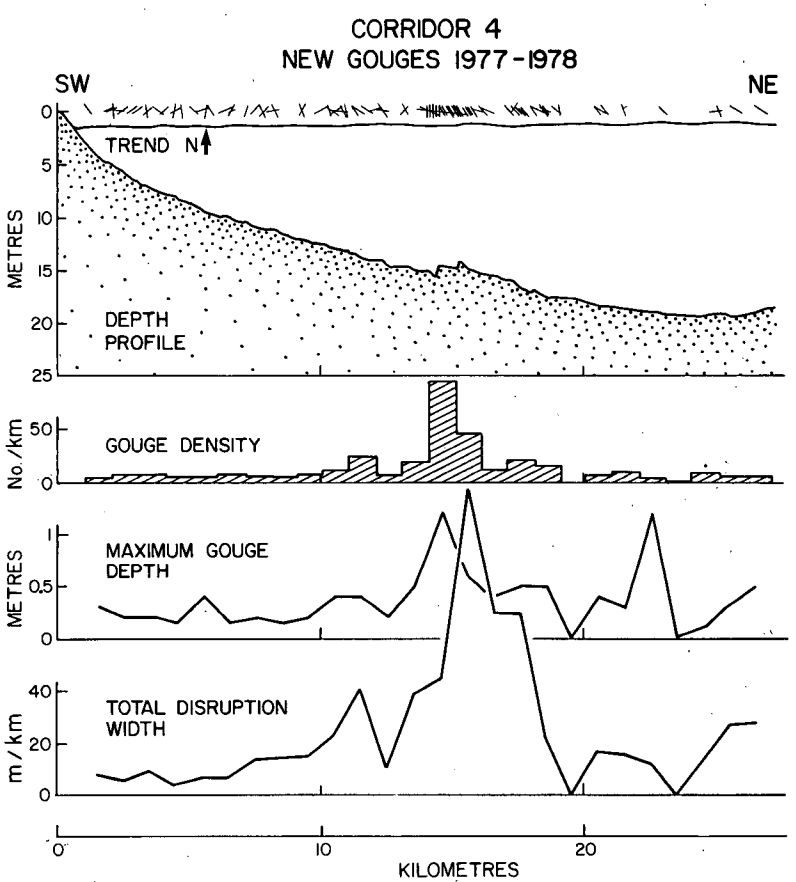


Figure 6. Distribution of dated (new) gouges from repetitive surveys in 1977 and 1978 off Cape Halkett. Note the concentration of gouging associated with the topographic anomaly in about 15-m water depth.

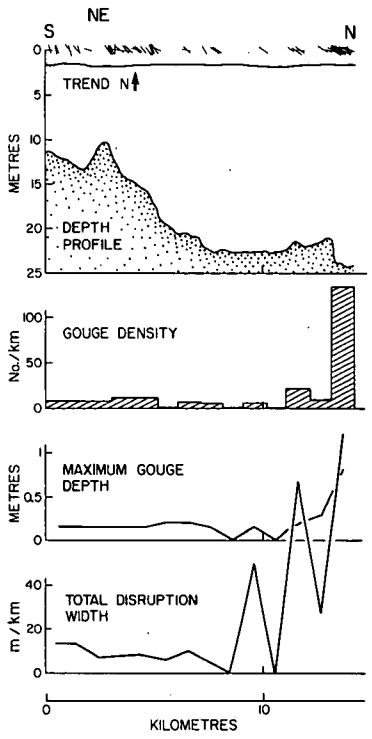


Figure 7. Distribution of dated (new) gouges from repetitive surveys in 1979 and again in 1982 north of Prudhoe Bay. Note the increase in disruption width and maximum gouge depth at the seaward end of the line where the inner edge of the stamukhi zone is marked by the seafloor step.

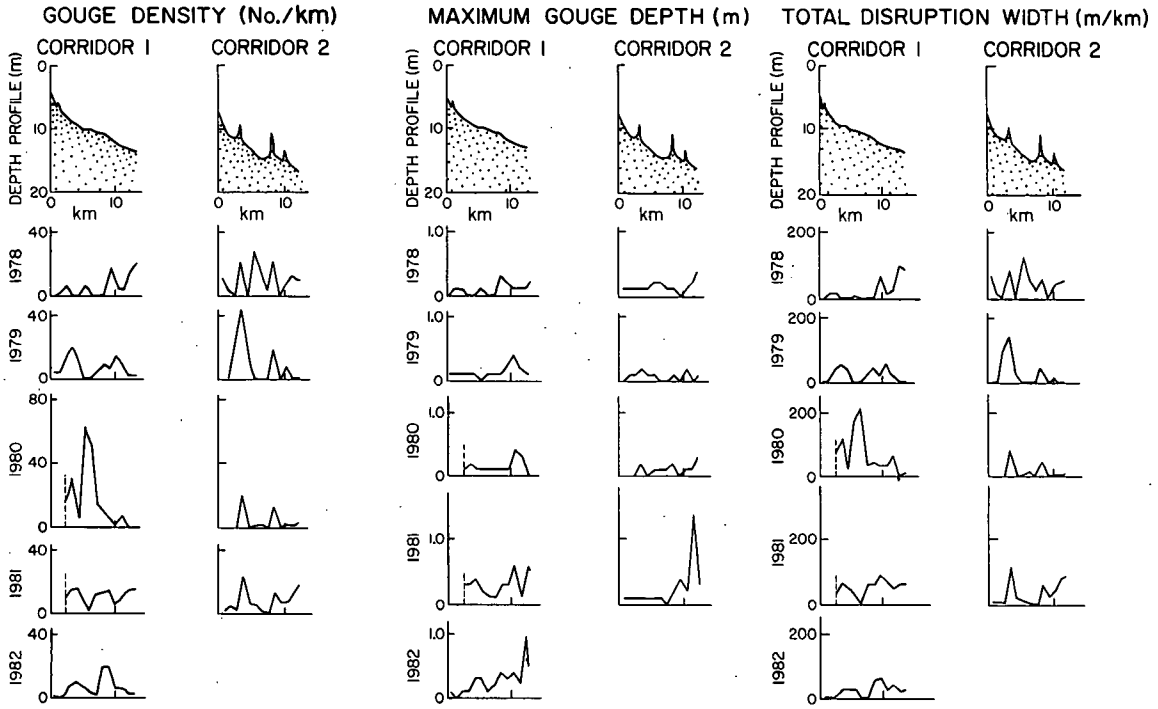


Figure 8. Year-to-year variability of dated gouge parameters as observed in two corridors northeast of the Colville River. Note the lack of year-to-year correlation between corridors.

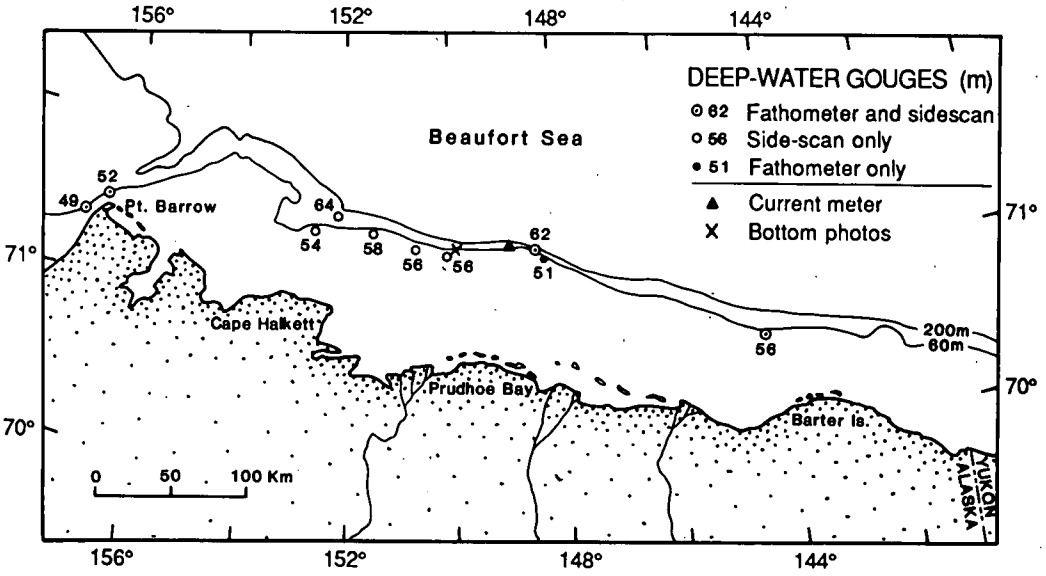


Figure 9. Observed depths of the seaward limit of ice gouging in the Beaufort Sea and the location of corroborating observations (after Reimnitz et al. 1984).

Several lines of evidence suggest, however, that these deep-water gouges are modern features (Reimnitz et al. 1984). Continuous, 380-day, current records at 60-m depth near the shelf edge show that the environment is dynamic, with long-period current pulses up to 70 cm/s capable of transporting medium-to-coarse sand as bedload and fine sand in intermittent suspension. A rich benthic fauna also reworks the upper 20 cm of sediment and provides sedimentary particles for current transport. The water depth along the seaward limit of the ice-gouged shelf surface, if of relict origin, should shoal eastward in the region where isostatic rebound after deglaciation occurred. The deep limit of gouges instead varies irregularly between 49- and 64-m water depth along the shelf edge, as one would expect from an interaction of sporadic ice reworking to 64 m depth during the last 200 years and continuous reworking by currents and organisms. For offshore petroleum development, this interpretation has the important implication that bottom-founded structures at more than 47-m water depth may not be safe from ice impact.

SHELF MORPHOLOGY

Linear accumulations of grounded ice ridges (stamukhi) form a zone separating the stable land-fast ice inshore from the moving pack ice offshore. During the winter a major portion of the oceanic and atmospheric energy imparted to the Arctic Ocean ice cover is expended in this zone. The zone's inner boundary occurs in about the same location year after year. Coincident with the inner boundary of the stamukhi zone is a linear, coast-parallel, 2- to 4-m high step in the seafloor topography. A 1- to 2-m shoal may occur on the lip of the step (Fig. 10). A detailed bathymetric, seismic, and sidescan sonar survey of the inner stamukhi boundary north of Alaska determined that a consolidated gravelly mud of pre-Holocene age is being gouged and eroded by

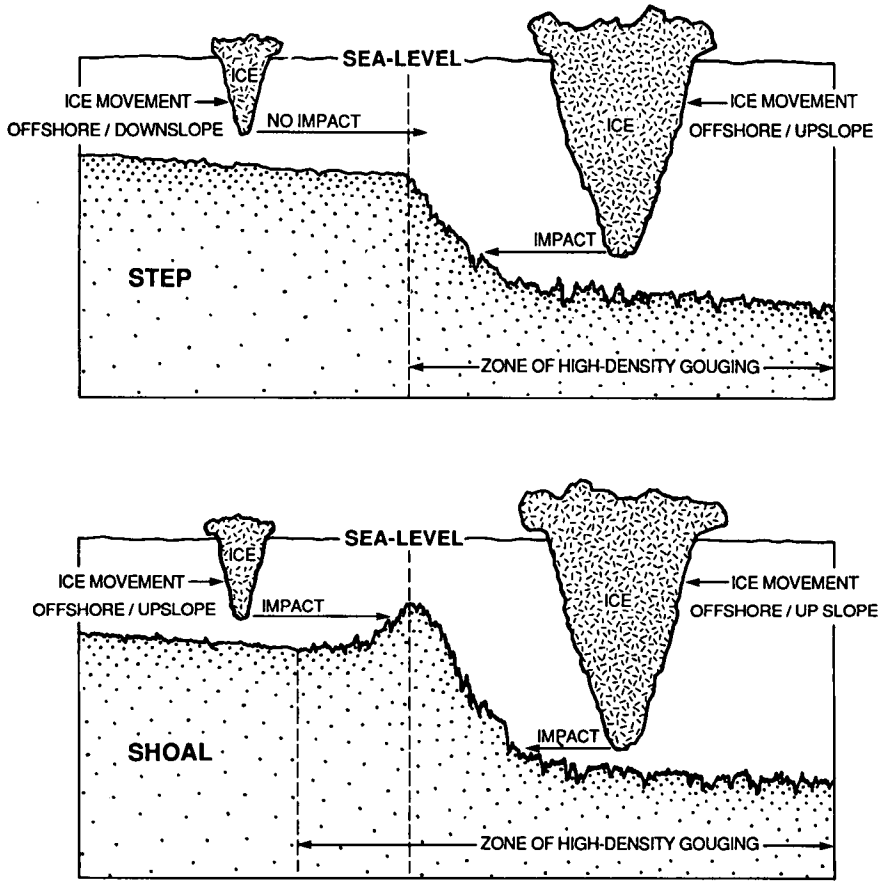


Figure 10. Erosional step at the inner edge of the stamukhi zone.

ice to form the step. This finding may be quite different from the Canadian Beaufort Sea shelf which is mostly depositional. Ice gouging seaward of this boundary is markedly more intense than inshore. It is characterized by deep incisions and by multiplet gouging reflecting the local formation of grounded ridges (Barnes et al. 1984). The upper metre or so has been reworked into a "rototilled" surficial unit. Inshore of the boundary, the seafloor is characteristically smooth, albeit still an erosional, surface. Thus, the step appears to mark the inshore boundary of intense ice-seafloor interaction and a zone of major energy expenditure (Bea et al. 1985) similar to the surf zone of lower latitudes. We postulate that the polar pack streamlines along the coastal and shelf promontories to form the inner edge of the stamukhi zone at the same location each year. The ice keels of the stamukhi thus also occur at roughly the same location year after year and act to erode the seafloor step. Interplay of current winnowing and ice replowing results in lag gravels that may be bulldozed into discontinuous piles to form the shoals atop the step.

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INCURSION OF ALASKAN MULTIYEAR ICE FEATURES AND THEIR ASSOCIATED SCOURS IN THE CANADIAN BEAUFORT SEA

David McGonigal[1], A.F. Stirbys, and J.L. Lussenberg
Gulf Canada Resources, Inc.
401 9th Avenue SW
Calgary, Alberta, T2P 2H7

INTRODUCTION

This presentation describes a study of grounded ice features undertaken by Gulf Canada Resources in April 1984. It was a short project investigating some unusual ice features which had invaded the Beaufort Sea during the previous summer, and which had grounded in the 15- to 25-m water depth range.

THE ICE SITUATION -- SEPTEMBER 1983

A side-looking airborne radar (SLAR) image of the Canadian Beaufort Sea in September 1983 is shown in Figure 1. The feature of interest is a plume of ice south of the Pitsuilak drillsite. It appears white in the SLAR image, indicating that it had a very rough ice surface. At that time it was drifting southeastward past Herschel Island; later it was to drift into Mackenzie Bay and then north. A few days later the SLAR indicated that the plume of very dense ice had reached some of the drill sites and had begun to drift to the east (Fig. 2). The artificial island Kadluk was close to some pieces of this ice plume, and the drilling platform Kulluk at Pitsiulak was experiencing some difficulty.

The situation a month later is shown in the SLAR image for October 10 (Fig. 3). During September the mass of pack ice had progressed all the way across the Beaufort Sea to the northernmost tip of the Tuktoyaktuk Peninsula. At some point it had been driven towards shore and had grounded in places, producing the scours that are discussed later. The grounded ice would become the nucleus for the fast ice that year. The edge of this grounded ice more or less followed the 25-m contour, and this is clearly seen as the distinct border between white (ice) and black (open water) in the middle of the image. Meanwhile, the rest of the ice pack drifted off to the north in the form of gigantic floes up to 40 km (25 miles) across.

The ice consisted of hummock fields of dense highly consolidated shear ridges. These shear-ridged hummock fields were interspersed with normal first-year ice. At the time of our surveys, we referred to those hummock fields as second-year ice, because they had obviously survived the previous summer. We believe it came from the "stamukhi" zone of Alaska, which is a zone of intense shear ridging at the outer edge of the fast ice in the Alaskan Beaufort Sea (see Barnes and Reimnitz, this volume).

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[1] Presenter.

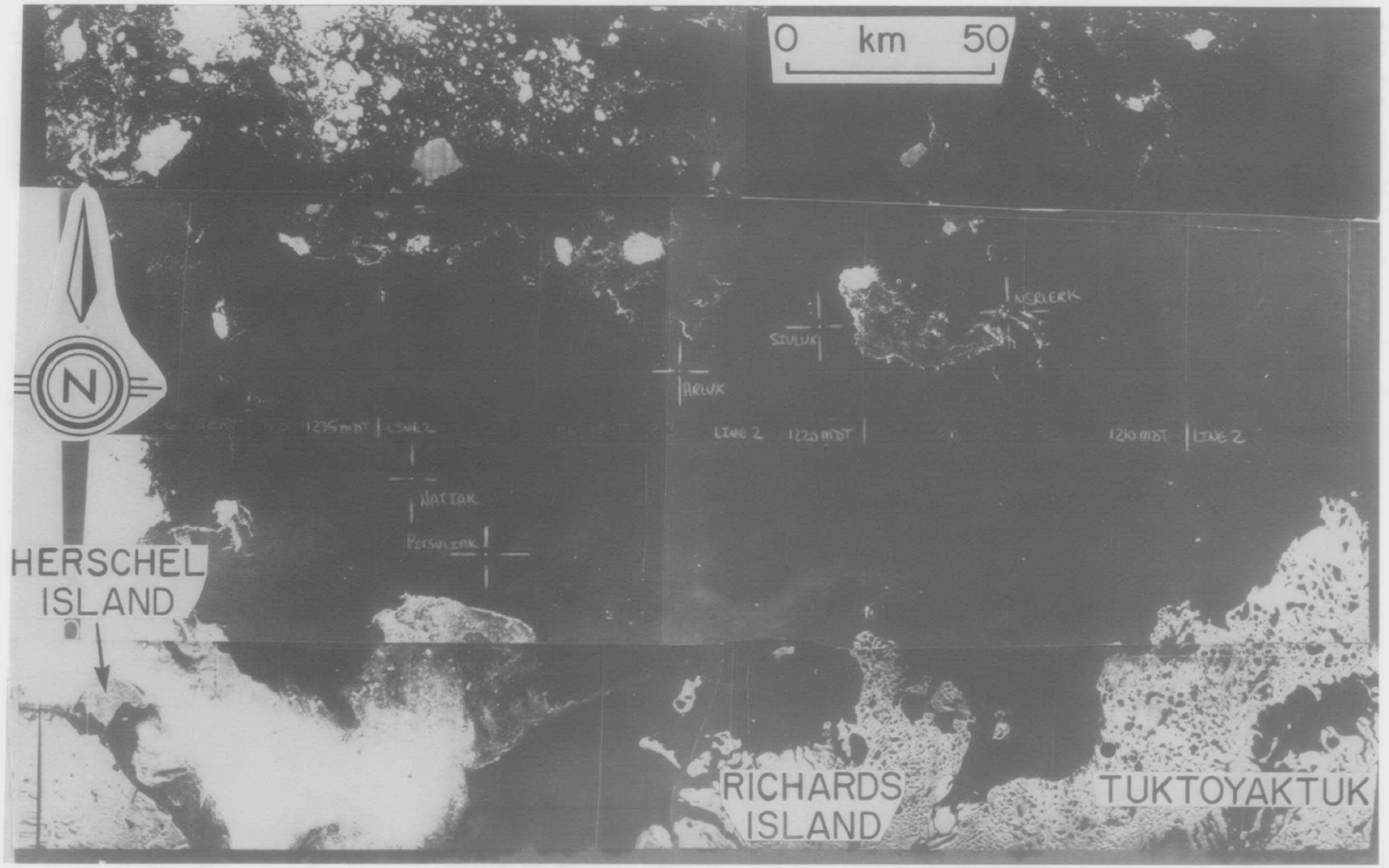

Figure 1. A SLAR image of the Canadian Beaufort Sea on 6 September 1983.

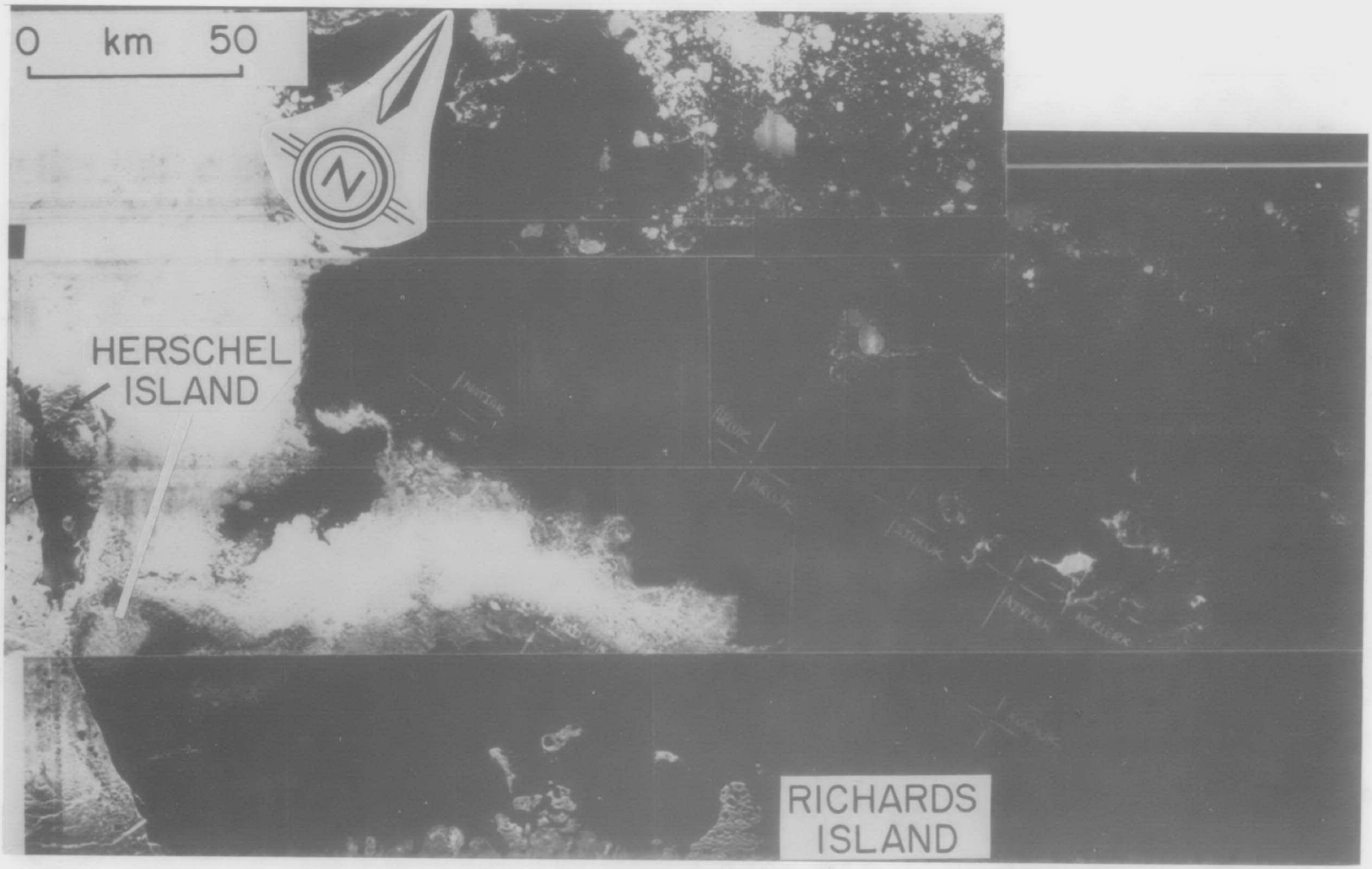

Figure 2. A SLAR image of the Canadian Beaufort Sea on 9 September 1983.

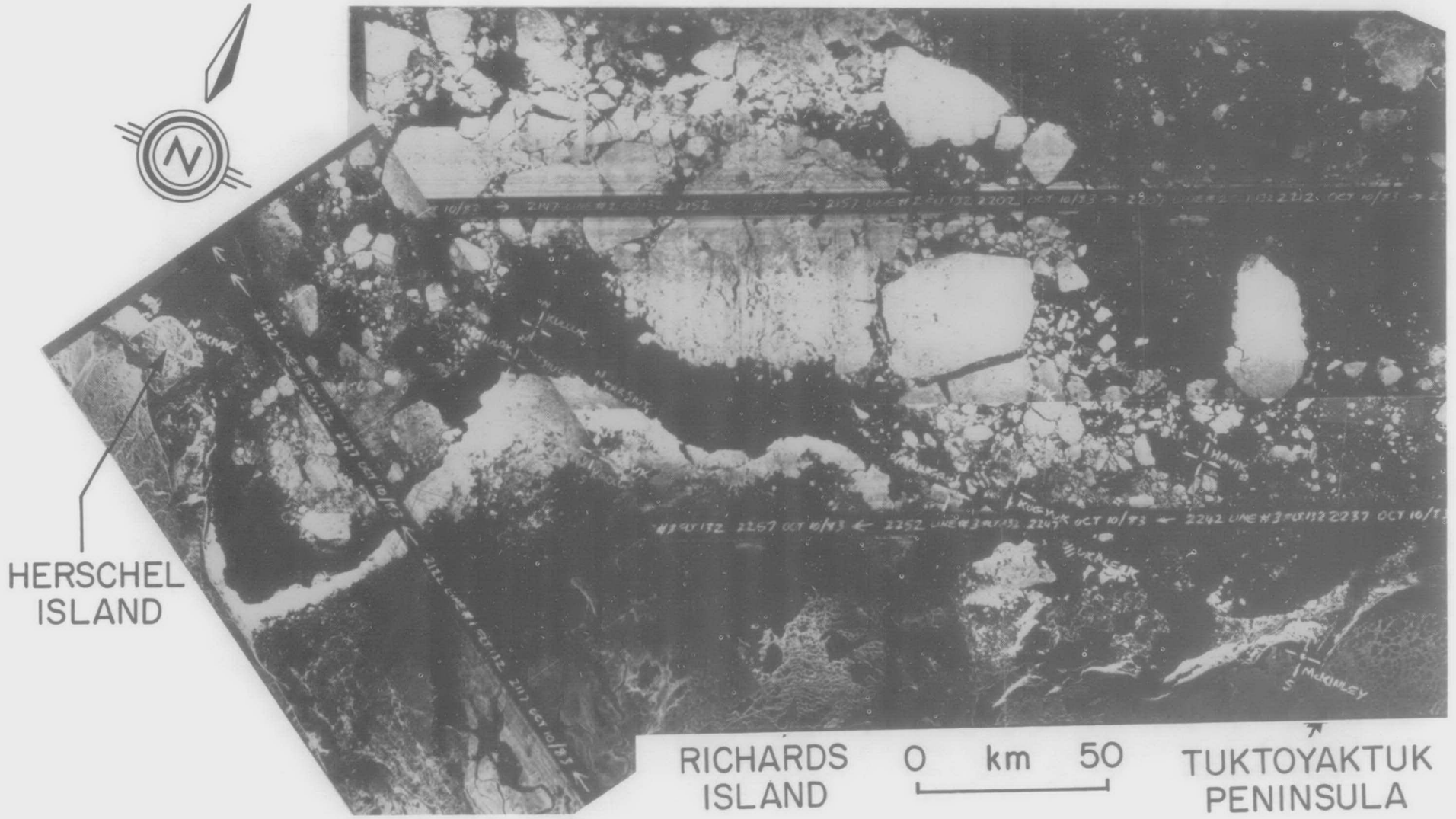

Figure 3. A SLAR image of the Canadian Beaufort Sea on 10 October 1983.

Some very large pieces of ice were noted aground during an ice survey in October 1983. For example one piece about 70 m square, with a maximum sail height of 11 m was grounded in 24 m of water. This ice feature with a total maximum ice thickness of 35 m, was thought to be causing a large scour suitable for study. We also thought the adjacent thin ice would be an ideal working platform from which to document the scour using sonar instrumentation to be deployed from an hole drilled through this ice. This type of study had been done previously, but this piece of ice was of special interest because it was located at the very edge of the fast ice and it was old ice.

WINTER SCOUR PROJECT OBJECTIVES

Later that winter (in April 1984), it was resolved to investigate the scours caused by this severe ice incursion at several potential drilling and production sites. The aim of the two-week field program was to find the scours associated with certain grounded features. More specifically, nine grounded ice features were to be investigated in water depths of 15-25 m in three areas: Kugmallit Bay, the Issungnak-Tarsiut region, and, north of Richards Island in the western Canadian Beaufort Sea including Mackenzie Canyon.

In each area we planned to document three different types of ice feature, namely singular features, hummock fields, and large floes. The ice feature mentioned earlier was a singular feature about 70 m across. There were also many hummock fields about 0.5-1.0 km across, with an average thickness of 6 m. These were much more massive. Of special interest were large floes, more than two km across with big internal ridges. These last features were expected to produce extreme scours. At each feature, we intended to measure scour depth and width, scour length, if possible, and spoil pile height ahead of the ice feature and on either side of the scour. The ice keel and the ice topside profiles were to be measured also so that the mass of ice in each feature could be calculated. In addition, general observations on the grounding process, evidence of uplift, and soil type would be noted. Documentation of these parameters was thought to be sufficient to verify the currently available deterministic scour-depth prediction models. Finally, an accurate position (± 1 m) using a Satnav receiver was to be obtained at each location to position future site investigation. Additional data was collected on scour lengths the following summer (Shearer and Stirbys, this volume).

FIELD DATA COLLECTION PROGRAM

The main underwater measuring tool was the Mesotech 971 sonar which could be operated either in a sidescan or in a profiling mode. Mounted in a bracket, as shown in Figure 4, it was deployed through a hole in the ice. The sonar was first operated in the sidescan mode to detect suitable target scours (see Fig. 4a). The head was then tilted and the system used in the profiling mode to obtain successive profiles of the seabed and of the ice keel (see Fig. 4b). The sonar head could rotate a full 360 degrees, and thus continuous data could be obtained. The maximum range obtained with the Mesotech 971 was 50 m.

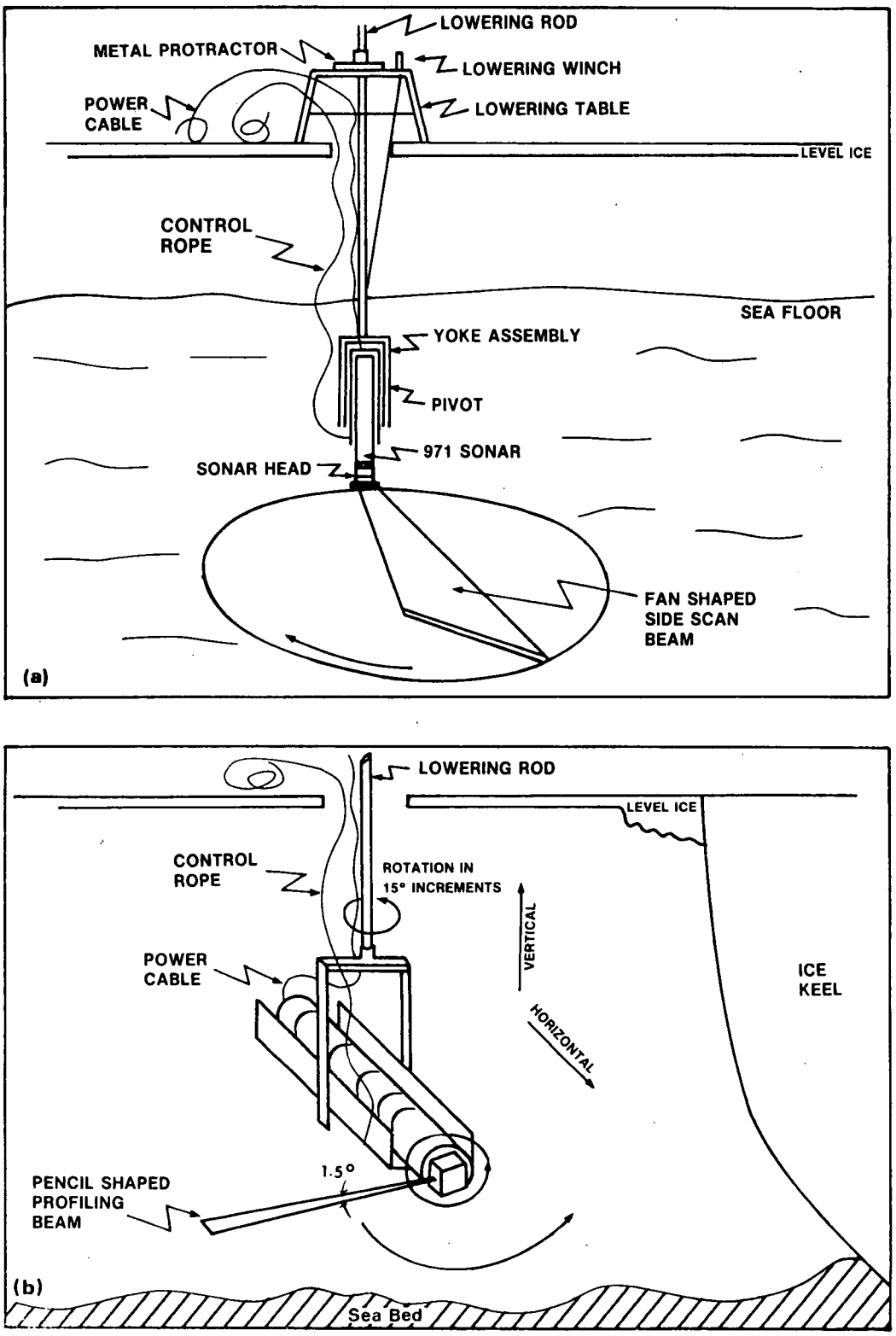

Figure 4. Set-up of the Mesotech 971 sonar in (a) sidescan sonar mode, and (b) profile mode.

RESULTS

In the 10-day field project, data from eight features were collected. Of these, six were profiled in detail, four with a complete sonar survey and two with a partial survey. The data of six of the features were augmented by stereo aerial photography gathered earlier in the winter.

Results are shown for one example feature identified on an aerial photograph taken in the fall. This feature, an ice ridge about 80 m across with a sail height of 8 m, was found grounded in a 21-m water depth. Figure 5 is an actual sonar profile showing the underwater ice surface and the keel in contact with the seabed. Figure 6 is another profile from the same site, showing the ice surface and scour that is associated with the ice feature.

From multiple profiles based on a circular array a three-dimensional view of the scour was constructed which showed the central trench and spoil piles on either side. A great variability in the geometry at the bottom of the scour was observed. We did notice a lot of uplifting at the leading edge of the ice. In one instance an old waterline had been raised some 2 m above sea level.

SUMMARY

In April 1984, measurements were successfully completed on six, grounded, ice features using a small team of personnel, light equipment, and small helicopters. It is concluded that the grounding process is complex, involving vast areas of pack ice interacting with itself and with the seabed. Floe uplifting and splitting is a common occurrence. Our observations show that a deep keel on a floe will ground and be uplifted. Large sections of the floe then break away and continue drifting, perhaps to ground in shallower water; a process that makes estimation of the size and mass involved in the original grounding event very difficult.

Also observed were crater-like scours that suggest either a bouncing type of mechanism or rolling and yawing of the feature during grounding.

Measurements were made on an unique ice incursion. It was highly consolidated second-year ice and that had invaded the Beaufort Sea in September 1983. This type of event occurs about once every 10 years. The resulting scours may therefore be different in form and severity from scours produced by first-year ridges in winter.

ACKNOWLEDGEMENTS

We feel that the contractors involved in the program deserve special mention. Offshore Survey and Positioning Services Ltd. mobilized and operated most of the equipment under severe constraints. Their hard work and dedication was greatly appreciated. Offshore Systems Ltd. reduced the profile data and produced the plots. We are indebted to helicopter pilots Jim Hodges and John Currie, whose knowledge of the Arctic saved us much time and money.

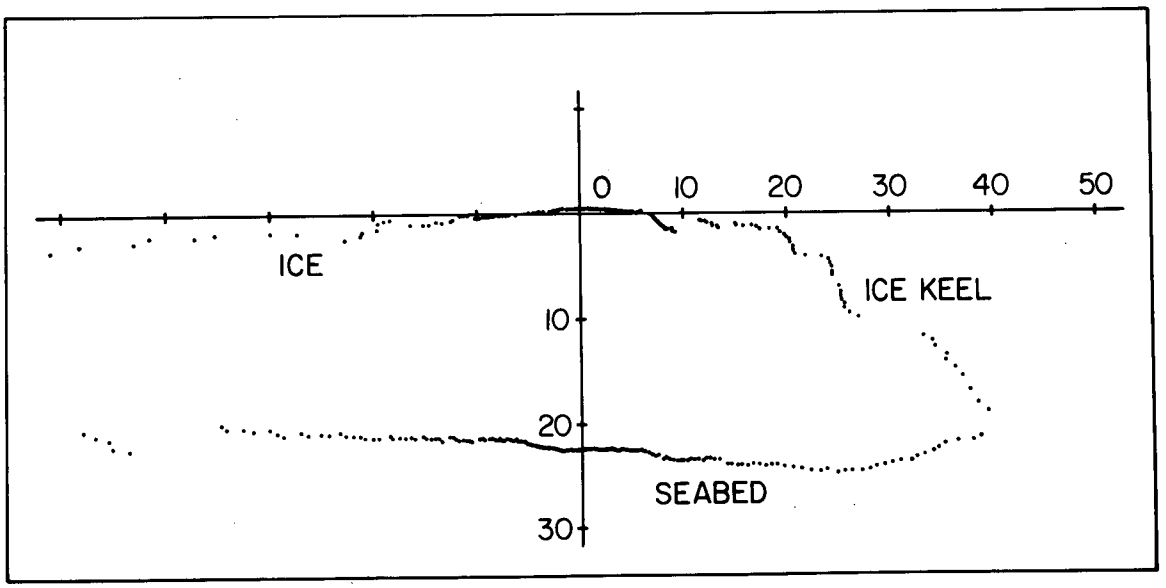

Figure 5. Sonar profile, Hole # M2:S3, showing underwater ice surface and keel in contact with seabed.

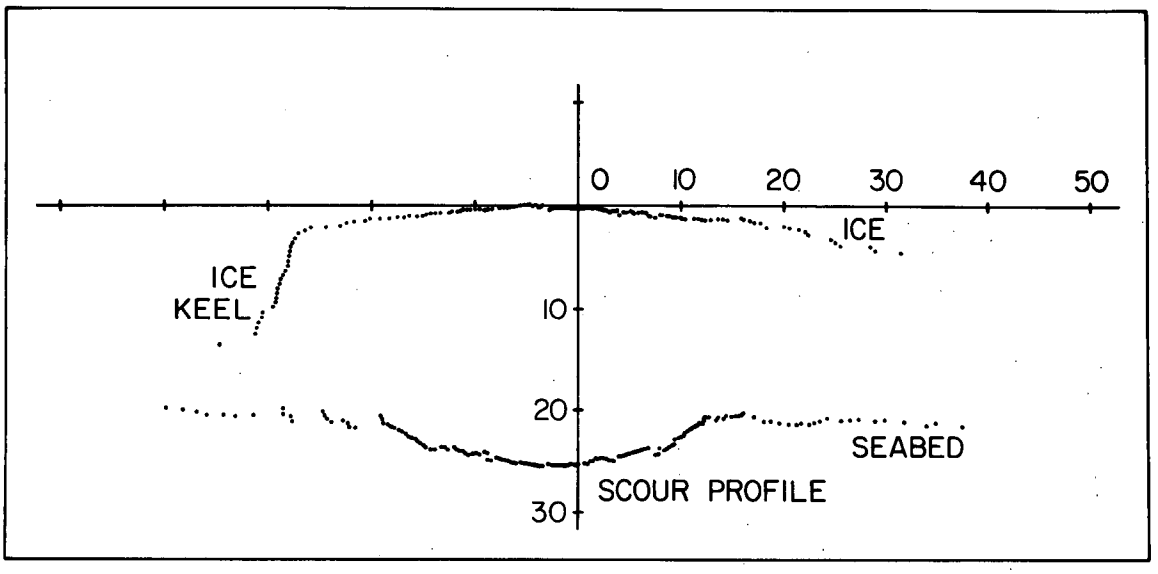

Figure 6. Sonar profile, Hole # M2:S4, from same site as in Figure 5.

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Gilbert, G.R., and S.M. Blasco. 1986. Ocean-bottom sea-ice scour: a computer-based data management system. In Lewis, C.F.M., D.R. Parrott, P.G. Simpkin, and J.T. Buckley (eds). 1986. Ice Scour and Seabed Engineering: Environmental Studies Revolving Funds Report No. 049. Ottawa. 322 p.

Shearer, J. and A.F. Stirbys. 1986. Towards repetitive mapping of ice scours in the Beaufort Sea. In Lewis, C.F.M., D.R. Parrott, P.G. Simpkin, and J.T. Buckley (eds). 1986. Ice Scour and Seabed Engineering: Environmental Studies Revolving Funds Report No. 049. Ottawa. 322 p.

DISCUSSION

Alan Ruffman, Geomarine Associates Ltd.: One SLAR image taken early in the season showed quite a large fragment of ice. What observations were made of that?

David McGonigal: That would have been a good site for investigations, and it was targeted for measurement later in winter. Unfortunately, it was inaccessible because of very rough ice. I suspect that it would have given quite a deep scour. The only observations were made above water: it was 11-m high at its peak, and the water depth was about 23 m. Therefore, it must have been grounded. It was about 70-m long by 50-m wide, and it was obviously a fragment of a larger mass of ice.

From the floor: Do you have a location for that first piece of ice?

David McGonigal: No, not accurate enough for comparison. It was about 1.5 km northeast of the feature discussed in detail today.

HYDRODYNAMIC FORCES AND ICEBERG STABILITY

D.W. Bass and G.R. Peters[1]
Faculty of Engineering and Applied Science
Memorial University of Newfoundland
St. John's, Newfoundland, A1B 3X5

SUMMARY

The project in which the authors are involved is a computer simulation of a basic iceberg shape representing a stable iceberg. Portions of this basic shape are sliced off and the new stable position is computed.

In the course of their work, the authors have obtained some interesting results which indicate that the draught of an iceberg could be increased by as much as 50% through instability, rolling, and rotation. The first set of results of this work was reported in Bass and Peters (1984).

The authors continue to work on the same problem with more input parameters and their results are presented at the 1985 POAC (Port and Ocean Engineering under Arctic Conditions) Conference in Greenland (Bass and Peters 1985). Some of their salient findings are given in Table 1, and the shapes assumed for the iceberg are shown in Figure 1.

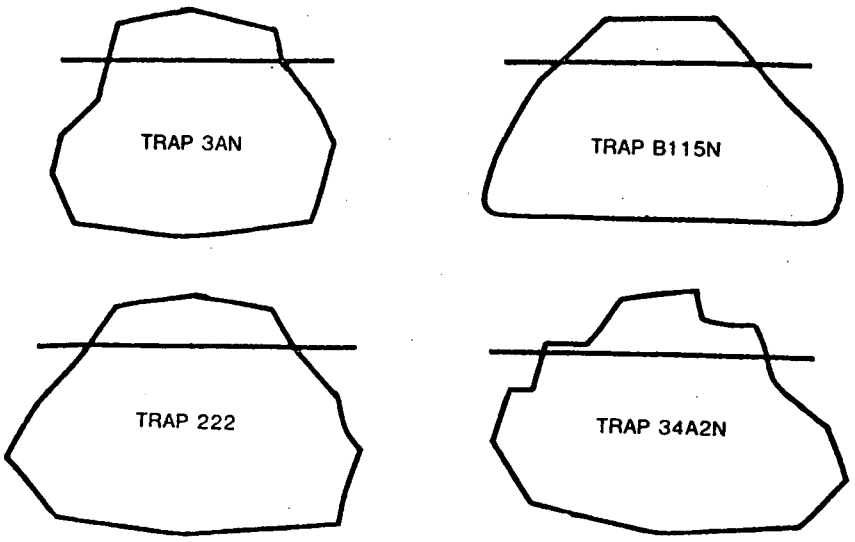

Figure 1. Iceberg profiles.

[1]Presentation summarized by T.R. Chari.

TABLE 1

Maximum increase in draught for different iceberg shapes

Iceberg Type	Calving above waterline		Calving below waterline	
	% Ice loss k	Maximum draught increase %	% Ice loss k	Maximum draught increase %
Trap 3AN	0.1	26	0.5	26
	0.5	27	2.0	23
	1.0	27	4.0	21
Trap B11 5N	0.1	46	0.5	44
	0.5	51	2.0	48
	1.0	55	4.0	52
Trap 222	0.1	20	0.5	-
	0.5	24	2.0	28
	1.0	27	4.0	30
Trap 34A2N	0.1	-	0.5	-
	0.5	27	2.0	28
	1.0	28	4.0	30

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DISCUSSION

John Miller, Petro-Canada: Is that a two- or three- dimensional stability analysis?

T.R. Chari: It is a three-dimensional stability analysis. They are looking at the net upward and downward forces, and then locating the centre of buoyancy. It has to be a three-dimensional shape if you are to look at the buoyancy. In terms of calving, I think it is a two-dimensional problem. The third dimension, I believe, is assumed to be constant, which has to be taken into account for the buoyancy.

Roger Pilkington, Gulf Canada Resources: You say the draught will be increased by 50%?

T.R. Chari: The conclusion was that this increase appeared to be possible, starting from what was an iceberg of reasonable shape, undergoing normal decay processes.

From the floor: That is in conflict with at least one other published paper which suggested very minimal increase.

T.R. Chari: Not necessarily. The paper that is coming out for the POAC Conference supports the possibility of a 50% increase, and an attempt is made in that paper to examine this important question in some detail.

Lorne Schoenthaler, Mobil Oil Canada Ltd.: Is this work based on icebergs in the North Atlantic? Also, how do they decide which pieces of ice they wanted to break off when conducting their stability analysis?

T.R. Chari: They started with a basic shape which was very stable and then assumed that certain portions of the iceberg would be calved. Calving, of course, depends sometimes on how the ice has been formed; therefore, several alternatives are possible.

SEDIMENT TRANSPORT AND ICEBERG- SCOUR PRESERVATION AND DEGRADATION, EASTERN CANADIAN SHELF

J.V. Barrie
C-CORE, Memorial University of Newfoundland
St. John's, Newfoundland, A1B 3X5

SUMMARY

The degree of preservation or degradation of iceberg scours on the eastern Canadian continental shelf (which can be used to determine relative scour age) depends on the type of sediments, their physical and geotechnical properties, and the hydrodynamic regime to which the sediments are exposed (Barrie 1983). Evidence drawn from sediment textures, mineralogical analyses, observations from submersibles, acoustic geophysical surveys, and various hydrodynamic environments demonstrate that the rate of scour degradation is determined primarily by wave-induced oscillatory motion and, to a lesser extent, by bioturbation, by unidirectional currents at the seabed, and by the sediment available for deposition. Soil types and their ability to maintain scour side-slopes over time and the size and quantity of large cobbles and boulders in scour berms also dictate the longevity of a scour feature. Assuming that the hydrodynamic processes can be quantified and soil types can be defined, then scour frequencies and rates of scour degradation (scour equilibrium) can be determined more accurately.

REFERENCE

Barrie, J.V. 1983. Sedimentary processes and the preservation of ice-scours on the eastern Canadian continental shelf. Seventh International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Helsinki, Finland, Vol. 4, pp. 635-653.

RELICT ICE SCOURS ON KING WILLIAM ISLAND, N.W.T.

Chris Woodworth-Lynas, D. Christian
C-CORE, Memorial University of Newfoundland
St. John's, Newfoundland, A1B 3X5

M. Seidal
Petro Canada Resources
Box 2844, Calgary, Alberta, T2P 3E3

and

T. Day
Day and Associates
Box 368, Station M
Halifax, Nova Scotia, B3J 2Z1

INTRODUCTION

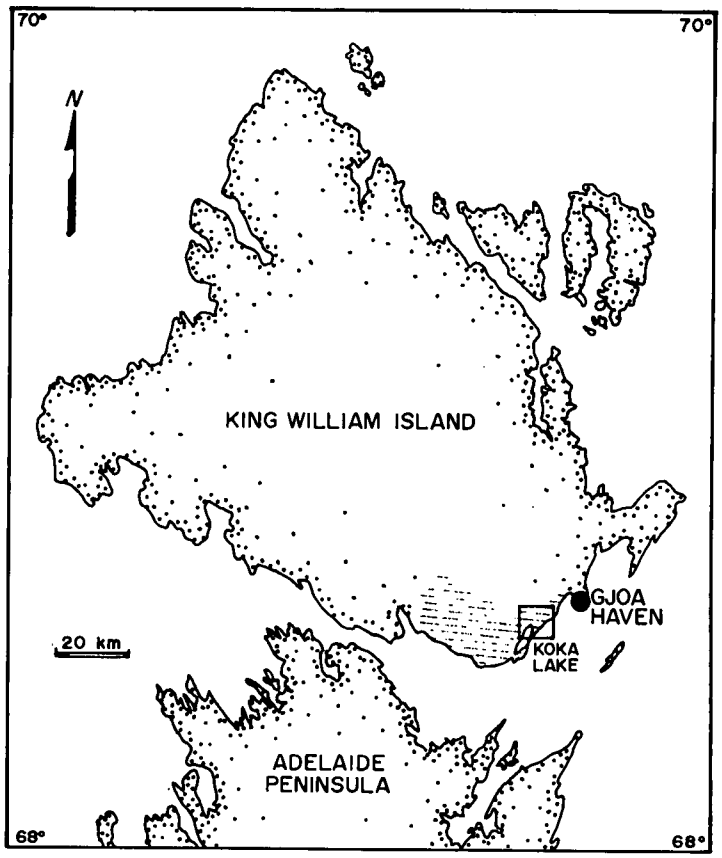
Mapping the microphysiography of scours on the seabed is virtually an impossible task, even with a submersible. If you wish to examine the seabed soils, to measure the geotechnical properties, or to look at the regional geology in detail, a possible alternative method is to find relict scours on land that were developed in a geological and oceanographic situation analogous to the kind of environments that are to be found offshore today.

In 1983, Bob Helie of the Geological Survey of Canada discovered a group of relict scours on the southern end of King William Island in the eastern Arctic. Figure 1 is an aerial photograph of this area that shows several linear and curvilinear scours on the ancient seafloor now 10-15 m above sea level.

DESCRIPTION OF SCOUR

The King William Island scours have been subjected to Arctic conditions, and permafrost now exists in the soils at about 1 m below the surface. The soils consist of silty sands with boulders similar to the types of seafloor sediment that form parts of the Labrador Shelf and large areas of the Grand Banks of Newfoundland. The scours in this area were formed around 8,800 to 8,600 years ago when the McClintock ice dome collapsed, retreating southwards over King William Island and calving icebergs into the sea. At that time the water depth was about 120 m, which compares favourably with present-day water depths over much of the eastern Canadian continental shelf.

The scour we chose to investigate in detail is about 1.8 km long. It has a right-angled turn where the iceberg presumably came to a stop before moving off in another direction. In one area the scour traverses a rise in bathymetry of 5 m upslope and downslope. In total, 23 stations over a 660-m stretch of the scour were surveyed, and the resulting profiles were used to generate



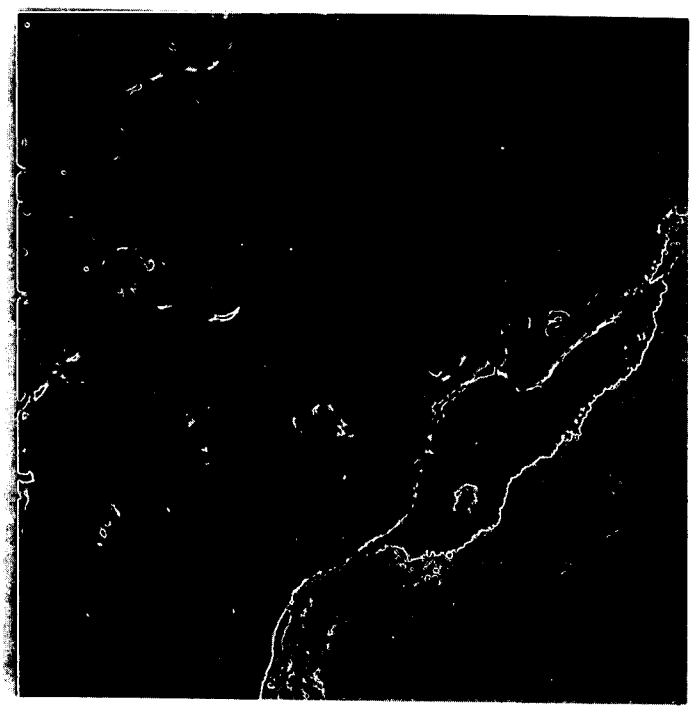


Figure 1. Location map of study area (region of grey tone west of Gjoa Haven represents area where relict scours are found) and air photo of Koka Lake region showing some of the scours (arrows) and the studied scour presented in this paper (labelled 'a').

the profile shown in Figure 2. Cross-sections enabled the microphysiography of the trough to be studied; a consistent asymmetry was detected along length of the scour that may reflect, to some degree, the shape of the original scouring keel.

Figure 3 shows the bouldery berm on one side of the trough; the difference in surface texture between the berm and ancient seabed can be clearly seen. On the left the seabed appears as a rough-surfaced bouldery area, whereas the scour trough is reasonably smooth. The scour trough is occupied by a present-day oblong lake (seen in the distance) before it turns to the right. The ancient seabed, although undulate, generally has little relief.

Figure 4 is a view looking across the scour, showing the two berms. Transverse cracks that occur only in the scour trough can be seen. It is not believed that these features were formed during the scouring process, but a reasonable explanation is still wanting. Fine silts and clays were expected in the area; unfortunately, however, the presence of large numbers of boulders and sand, meant that the drilling program met with little success. Sampling was carried out mainly from trenches dug down to the permafrost.

A view of the ancient seabed when excavated is shown in Figure 5. It is composed of poorly sorted silt, clay, and sand with gravel and boulders. It is water-saturated and slumps back into the pits very quickly. In remarkable contrast is the sand immediately inside the scour trough and between the two scour berms, which consists of clean-washed, medium-grained sand, without boulders or gravel, and no silt or clay (Fig. 6).

The triangular grain-size diagram of Figure 7 shows the contrast between the sediments inside the scour and outside. An attempt made to determine the deformation within the soils using remanent magnetism of the heavy minerals is summarized elsewhere by Day (this volume).

PROPOSED SCOURING MODEL

Figure 8 shows a model for the scouring processes that possibly took place to produce the features described above. The iceberg keel scours the bouldery seabed charged with gravel. The front part of the keel bulldozes the seabed sediment and, at the same time, brings into suspension all the fines, including the sand. This process generates a gravel- and boulder-rich deposit, in front of the iceberg keel, that is ploughed into two berms as the keel progresses. Once the sediment is in suspension, all the fines are winnowed away by the currents, and the sand falls back into the trough (possibly within 1 or 2 hours) and immediately masks the incision depth. The lack of any bedding structures in the sand, except for one pit which showed cross-bedding, is the prime reason for suggesting the instantaneous fallback of sand. Although excavations could be made only as far as the permafrost table at 1-m depth, there was still sand to be found below. Therefore, there is at least 1 m of massive sand within the scour trough. The sand was not deposited over an extended period because it is expected that some sort of layering or grading possibly resulting from storm events and other changes in the local current regime would be observed. Because the iceberg keel is riding over a saturated seabed, there is the possibility that it could be causing an increase in pore pressure within the sediment. The resulting decrease in the effective weight of sediment could contribute to the winnowing of fine sediments. This winnowing, coupled with the fallback and jetting of sediment, could contribute to an effective sorting process.

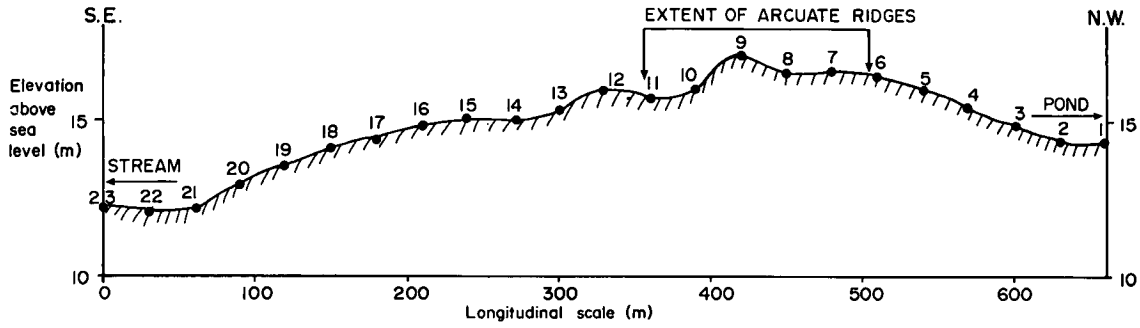


Figure 2. Longitudinal profile of the scour showing change in relief of over 5 m and also the area of arcuate ridges found within the scour trough.

Figure 3. View looking northwest along the scour berm showing the relatively bouldery seabed and the smooth, sandy scour trough.

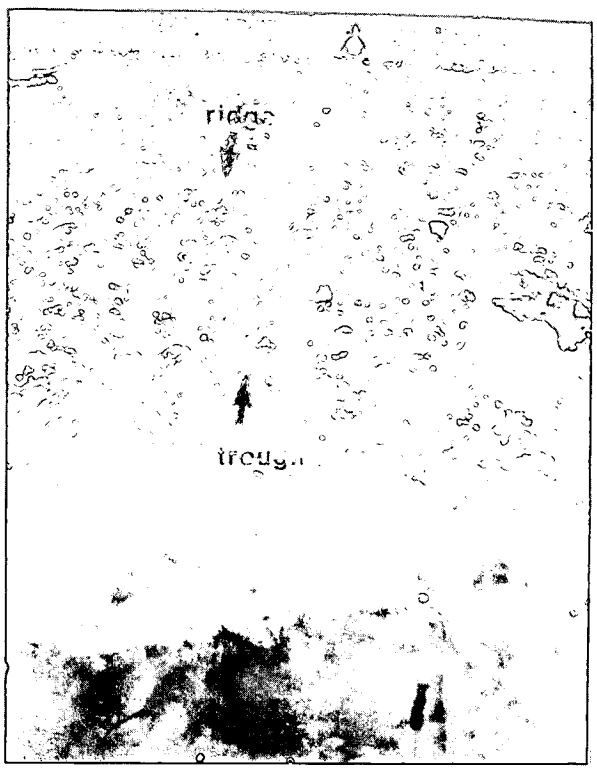


Figure 4. View looking across the scour from one of the excavated pits in one berm. Person is sitting on the other berm. Note the transverse troughs and ridges normal to the berms.

Figure 5. An excavation in the seabed material which consists of poorly sorted silt, clay, sand, gravel and boulders.

Figure 6. A view of a section within the scour trough to show the massive nature of the clean-washed medium-grained sand which characterizes the scour infill. Layering at top is organic in origin.

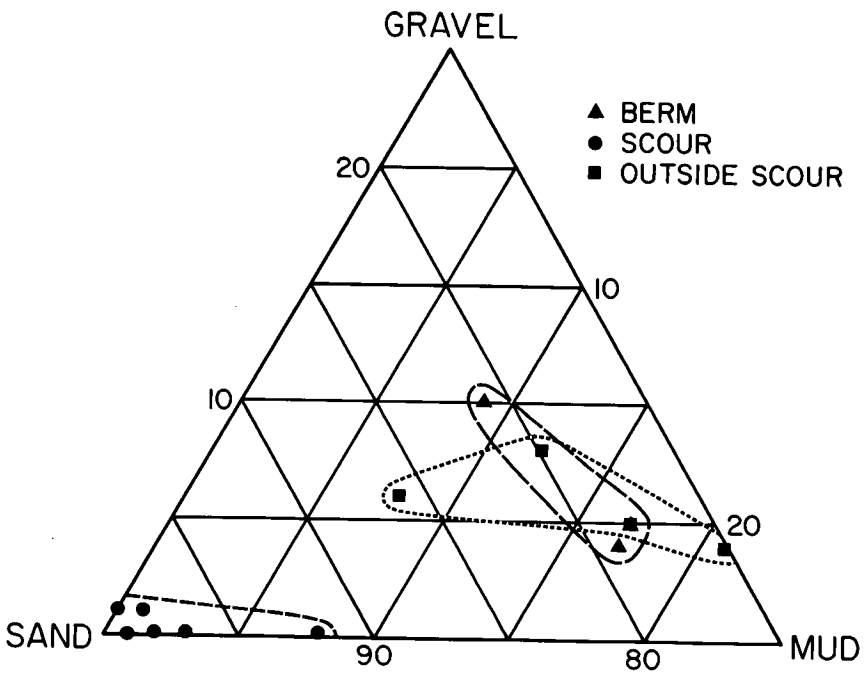


Figure 7. Triangular diagram to illustrate the textural difference between the scour trough sand and the seabed and berm material.

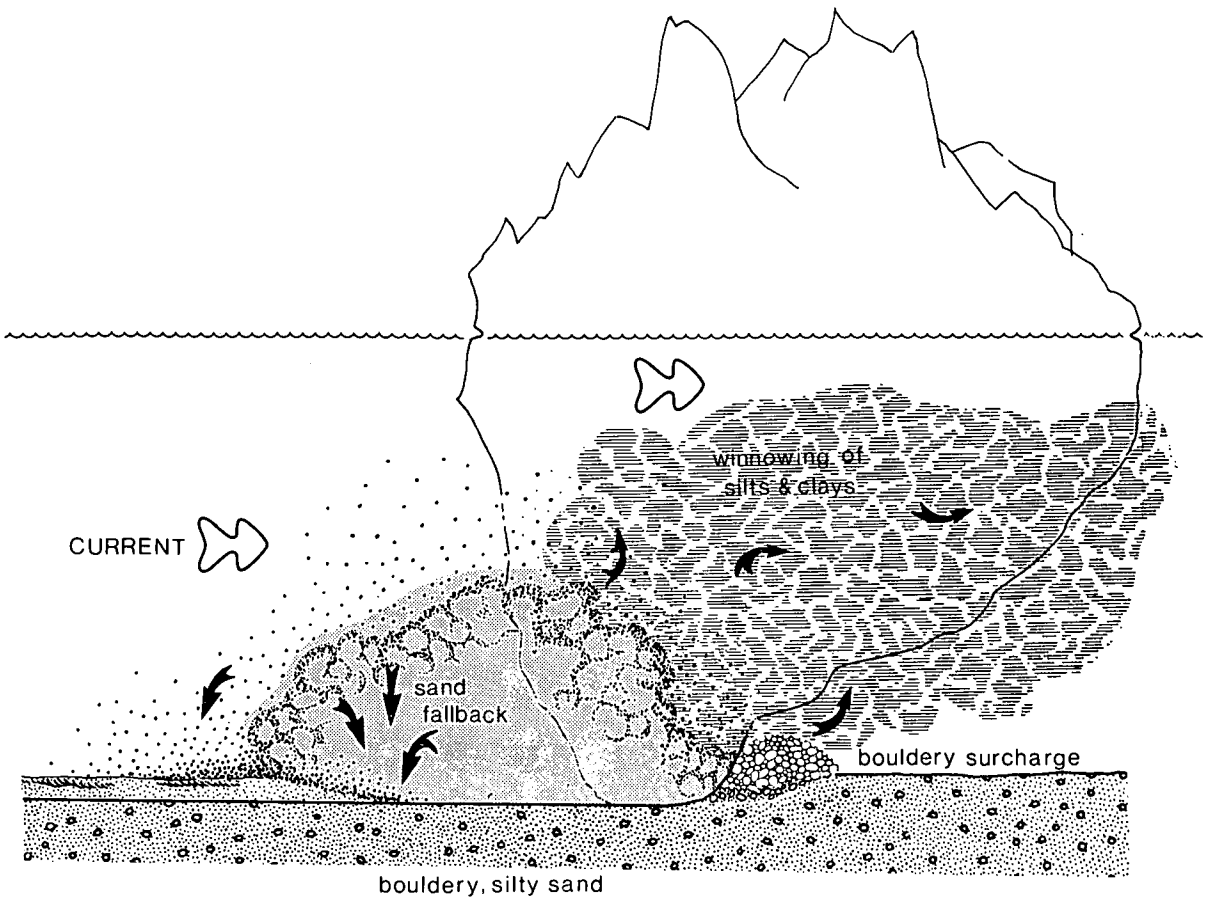


Figure 8. Scour model showing a bottom-dragging keel. The keel puts the fine sediments, including the sand, into suspension by mechanical action and possibly by enhanced current flow at the keel. This helps generate a coarse lag which is bulldozed and concentrated in front and to the sides of the keel to form the bouldery berms. Silts and clays are winnowed away by currents but the coarse sands fall back into the scour trough, masking the original scour incision depth.

SUMMARY

This model may explain the scouring processes operating where the seabed consists of poorly sorted glacial material like that seen on King William Island. The model may not be applicable for areas where clean sands exist, because of the absence of fines for winnowing and boulders to produce bouldery berms. However, it does represent a starting point in determining what to look for when observing a scouring event. We hope to be able to record the scouring process later this year during the Dynamics of Iceberg Grounding and Scouring (DIGS) experiment described by C.F.M. Lewis (this volume).

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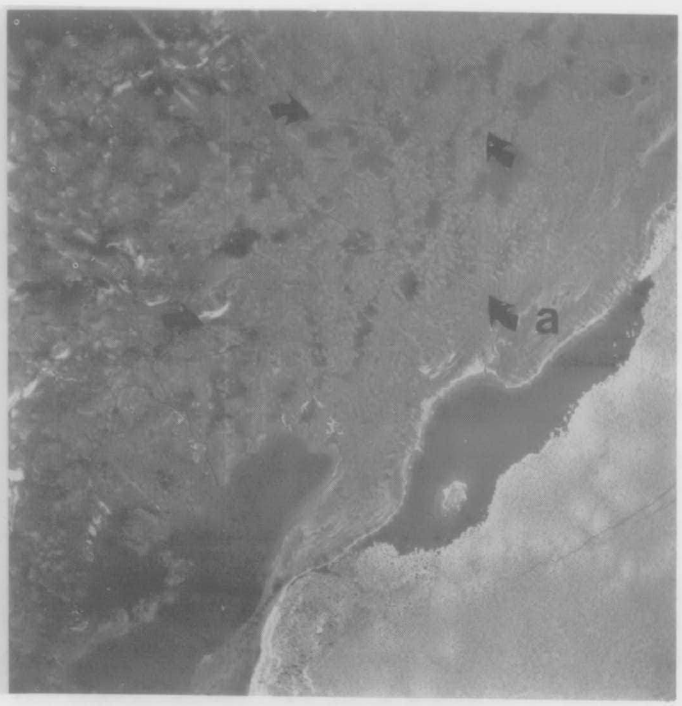

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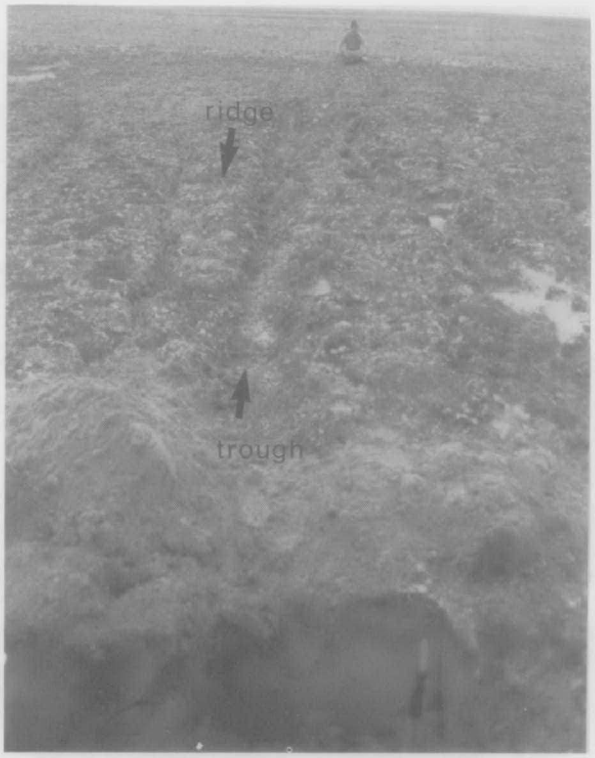

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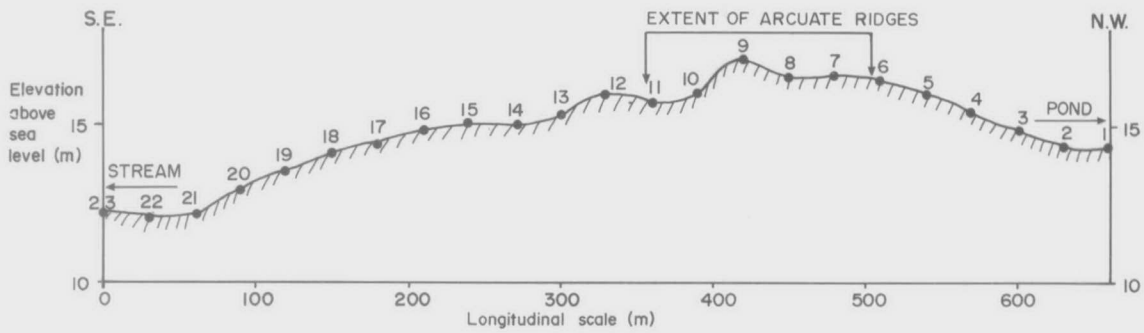

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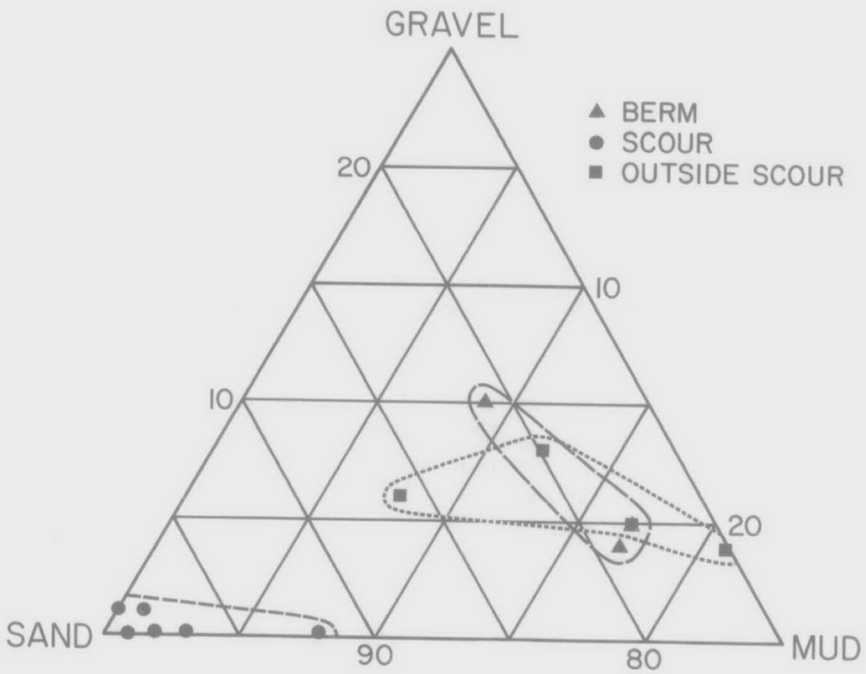

Figure 7. Triangular diagram to illustrate the textural difference between the scour trough sand and the seabed and berm material.

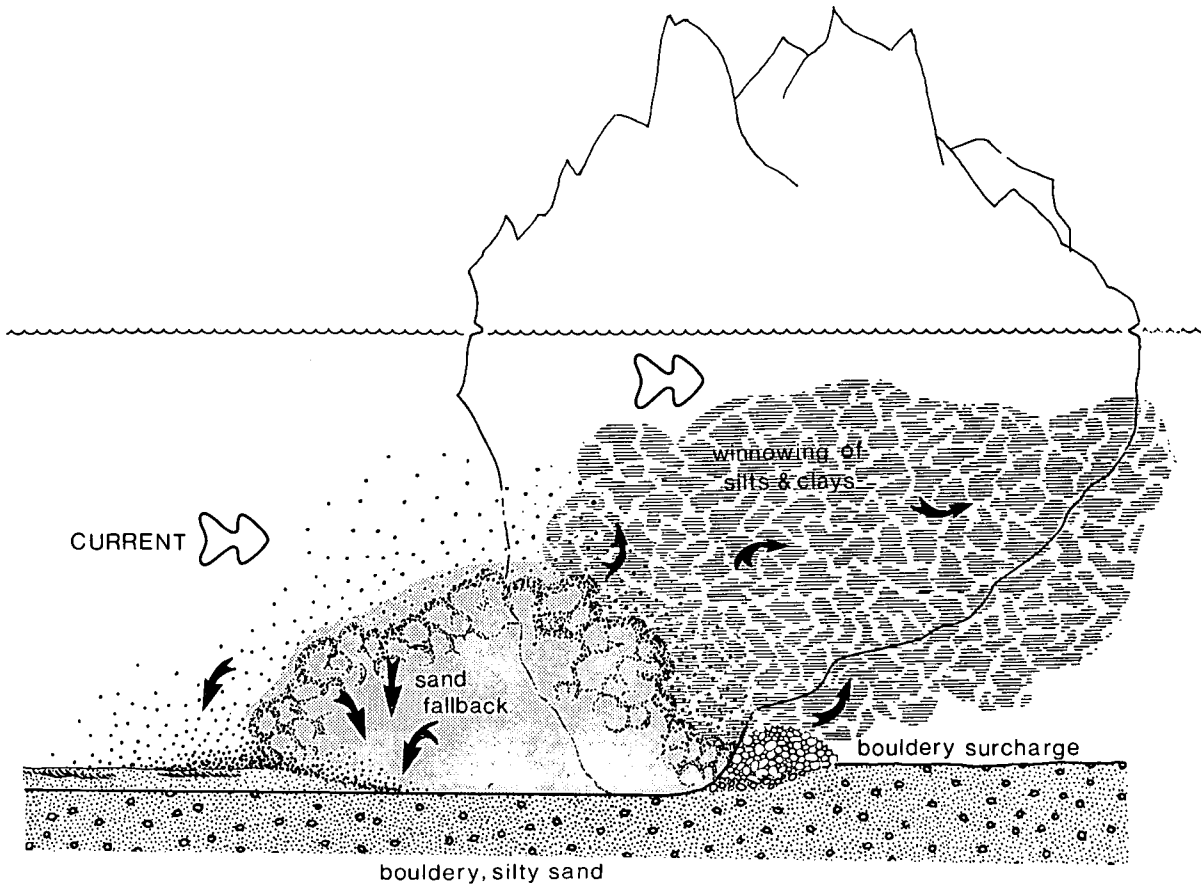

Figure 8. Scour model showing a bottom-dragging keel. The keel puts the fine sediments, including the sand, into suspension by mechanical action and possibly by enhanced current flow at the keel. This helps generate a coarse lag which is bulldozed and concentrated in front and to the sides of the keel to form the bouldery berms. Silts and clays are winnowed away by currents but the coarse sands fall back into the scour trough, masking the original scour incision depth.

SUMMARY

This model may explain the scouring processes operating where the seabed consists of poorly sorted glacial material like that seen on King William Island. The model may not be applicable for areas where clean sands exist, because of the absence of fines for winnowing and boulders to produce bouldery berms. However, it does represent a starting point in determining what to look for when observing a scouring event. We hope to be able to record the scouring process later this year during the Dynamics of Iceberg Grounding and Scouring (DIGS) experiment described by C.F.M. Lewis (this volume).

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Lewis, C.F.M. 1986. Dynamics of iceberg grounding and scouring (DIGS) experiment. In Lewis, C.F.M., D.R. Parrott, P.G. Simpkin, and J.T. Buckley (eds). 1986. Ice Scour and Seabed Engineering: Environmental Studies Revolving Funds Report No. 049. Ottawa. 322 p.

DISCUSSION

Peter Barnes, U.S. Geological Survey: I have a comment concerning the boundary of the stamukhi zone in the Beaufort Sea. We get that boulder ridge but we don't see the sands like you have indicated.

Chris Woodworth-Lynas: Could your observations result from enhanced current winnowing when the keel is very close to the seabed?

Peter Barnes, U.S. Geological Survey: We do see some winnowing.

Chris Woodworth-Lynas: I like the idea of enhanced currents around the iceberg's keel generating sufficient current to strip away the fines leaving the sand behind to fall back.

Heiner Josenhans, Atlantic Geoscience Centre: I very much like your model. I wonder whether you would expect to find all the sand falling back into the trough as your real-world example seems to demonstrate. Considering the currents pushing the iceberg along, I would expect that quite a bit of the sand spillover would also be found on either side of the trough. Did you find any decrease in the amount of the sand as you move away from your scour ridge?

Chris Woodworth-Lynas: That is a difficult question to answer. We dug only five trenches into the scour and two trenches on either side of the scour outside the berms. The trenches were 1.2 x 1.2 m, and we didn't notice anything in the top layer or any enrichment in the sand content immediately adjacent to the scour itself. Many people do not like the concept of sediment being dumped back into the trough during a single event, but the conclusion that the action was instantaneous was made because the massive sand contains almost no sedimentary structures.

Bill Roggensack, EBA Engineering Consultants Ltd.: With the possibility of vertical motion of the iceberg during the scouring process, and if you had a wave state that was, say, 3, 4, or 5 m at the time the iceberg was moving along, it is also possible that you could have had iceberg heave that may have exaggerated the current or water velocities in the vicinity of the seabed. This added current may have aided the winnowing process with the removal and dispersion of the fine-grained material to leave the bouldery clay. If the iceberg moves up and down you are going to have very high velocities, particularly on the periphery of the iceberg within a few tens of centimetres of the seabed, not necessarily in the area of intimate contact, but as you move out toward the edges of the scour feature.

Chris Woodworth-Lynas: This "jetting" process is very relevant in the paper by Barrie et al. (see Barrie, J.V., W.T. Collins, and D.R. Parrott, Grand Banks Pits: Description and Postulated Origin, this volume).

Alan Ruffman, Geomarine Associates Ltd.: Were the cuspate features inside the scour pointed, and do you know in which direction the iceberg was scouring?

Chris Woodworth-Lynas: It is estimated that the iceberg was heading to the northwest, because the one example of cross-bedding seen was normal to the scour trough with foresets dipping

towards the northwest which is probably the same direction as the current which drove the iceberg.

Alan Ruffman, Geomarine Associates Ltd.: The features that you showed inside the scour were somewhat cuspate. They may have been enhanced by subsequent frost action.

Chris Woodworth-Lynas: If the model is correct, the sand was dumped back in the trough soon after scouring. These cuspate features must be post-scour features. They are concave downslope on both sides of the topographic rise scoured by the iceberg.

Alan Ruffman, Geomarine Associates Ltd.: I just wondered if they were perhaps related to some of the features that have been observed in the Beaufort Sea and, I think, the Weddell Sea. There were other scours displayed earlier with "tire track" types of features. These are also observed in modern scours, so in this case are they relict from the scouring process and perhaps obscured by the frost action?

Chris Woodworth-Lynas: Yes, that could be.

Glenn Lanin, R.J. Brown and Associates: Regarding the infill of that remnant ice scour found on King William Island, wave- and current-induced infill was effectively eliminated because of the lack of bedding. Has wind-induced infill been considered?

Chris Woodworth-Lynas: No, this has not been seriously considered because of the types of sediment on the surface (sand mixed with silt and clay). There was no evidence of aeolian bedforms in the scour.

Glenn Lanin, R.J. Brown and Associates: Wind will provide a mechanism for very good sorting of sands and for the formation of clean sand beds.

Chris Woodworth-Lynas: We have not eliminated all forms of bedding. An organic peat in the top 30 cm is very recent.

Terry Day, Day and Associates: If aeolian activity was involved, it would have affected both inside and outside the scour. There was no evidence of this.

Walter Bobby, Newfoundland Petroleum Directorate: In the scour model you indicated that the sand redeposits immediately when the iceberg scours gravelly material. Does the sand fall back into the bottom area or outside the scour?

Chris Woodworth-Lynas: The sand must fall both inside and outside the scour, because the scour has depth.

Walter Bobby, Newfoundland Petroleum Directorate: When we take the scour depth statistics, do we need to consider infilling when scouring is in gravelly material, where the actual depth of the original scour is greater than that measured?

Chris Woodworth-Lynas: Yes. This appears to be the case in this type of material. What is measured is meaningless unless the incision depth below the infilling sediments can be seen. In many cases this is not possible, because of limitations in the measuring techniques. An example of this phenomenon is the profile of the iceberg pit presented by Barrie et al. (see Barrie, J.V., W.T. Collins, and D.R. Parrott, Grand Banks Pits: Description and Postulated Origin, this volume). The masking of the true scour shape by side reflections is to some degree inevitable with all sonar systems.

GRAND BANK PITS: DESCRIPTION AND POSTULATED ORIGIN

J.V. Barrie and W.T. Collins
C-CORE, Memorial University of Newfoundland
St. John's, Newfoundland, A1B 3X5

and

D.R. Parrott
Atlantic Geoscience Centre
Geological Survey of Canada
Bedford Institute of Oceanography
Box 1006, Dartmouth, Nova Scotia, B2Y 4A2

INTRODUCTION

Circular depressions or pits in the seabed have appeared in numerous site-specific and regional survey lines on Grand Bank (part of the Grand Banks Newfoundland) below 80-m water depth. These features have been identified in facies Units A, B, C, and D of Barrie et al. (1984). The subbottom profiles show a depression measuring up to 8 m in depth with widths averaging about 100 m. In some cases, a low-amplitude berm can be detected beside the pit. In places downturned reflectors dip into the pit. These features can be three times deeper than the iceberg scours commonly found within the water depths of this region (Lewis and Barrie 1981).

In June 1980, a circular depression measuring 5.4 m deep and 100 m wide was discovered 11 km east-southeast of the Hibernia P-15 discovery well in 87-m water depth. In an effort to describe this feature, to explain its origin, and to assess its potential hazard to bottom-sitting facilities, two submersible dives were completed (Barrie and Collins 1985) using the SDL-1 submersible off the tender vessel HMCS Cormorant.

DESCRIPTION OF PIT

In preparation for diving operations, the pit was surveyed using 100-kHz sidescan sonar with a 3.5-kHz subbottom profiler. The sidescan sonogram showed an area of low acoustic reflectivity with an irregular outline and two smaller features, 60 m and 30 m wide, which were interpreted to be related features, lay 50 m to the southwest (Fig. 1). The subbottom profile showed a V-shaped depression with a raised berm.

Based on subsea observations from the submersible and on the previous acoustic geophysical surveys of the feature, a composite illustration was produced (Fig. 2). The feature has the planimetric shape of a square, with indentations on the east and west sides. The depression occurs in the southern section of the feature. From observations, the maximum width was 100 m. The maximum depth of the feature, measured by the depth gauge of the submersible, was about 10 m; the depth measured by the original geophysical survey was 5.4 m. The discrepancy in the recorded depth of the feature clearly accentuates the problems of obtaining accurate depth

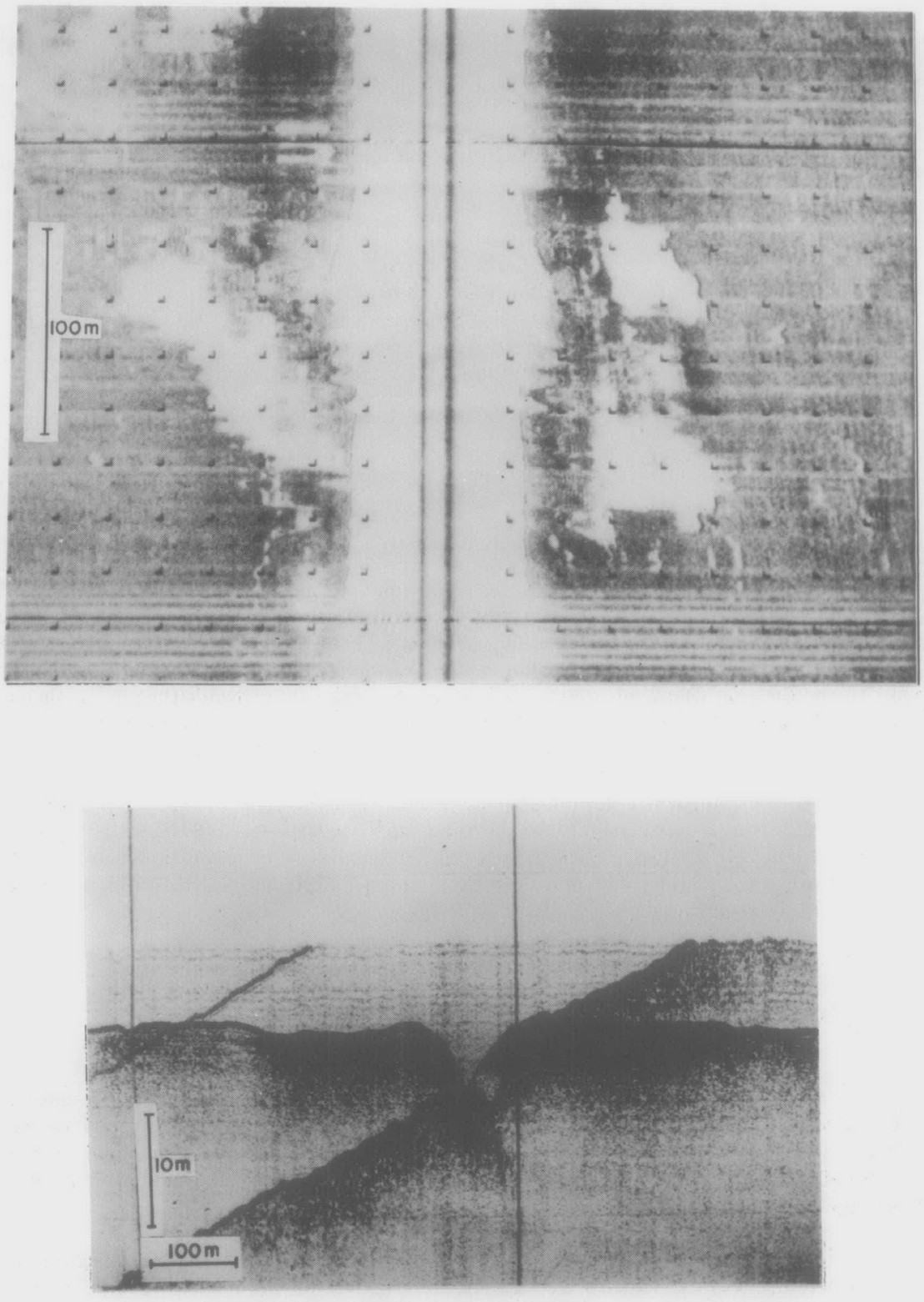

Figure 1. Klein sidescan sonar with Huntec DTS profile of an iceberg pit located in Unit D. (Interference from an airgun can be seen traversing the DTS profile from lower left to upper right and should be ignored.)

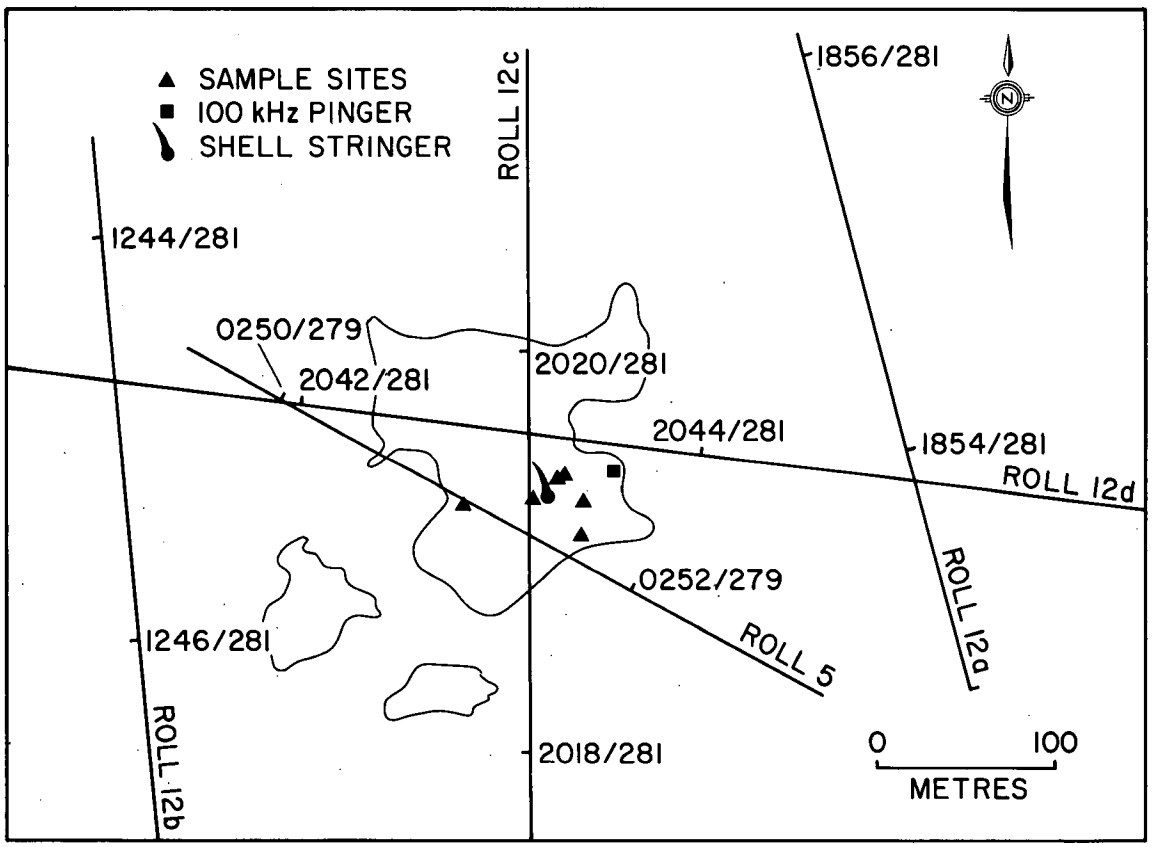

Figure 2. Composite drawing of the iceberg pit shown in Figure 1 showing sample locations and sidescan sonar lines.

measurements of steep-sided features with high-resolution profiling systems. Furthermore, the discrepancy suggests that other depth calculations made from profiling systems may be underestimated by 30-50%. A berm of boulders and large cobbles (Fig. 3) surrounds the depression, except to the north. In places the berm rises more than 2 m above the seabed, with clast sizes ranging up to 2 m in diameter. The depression has side walls to the east, south, and west, with slope angles up to 30 degrees. From the pit floor a shallow slope (10 degrees) rises northward. There is a series of troughs or runnels running down the slope. It is unclear whether these are related to the formation of the pit or to the prevailing hydrodynamic conditions within the pit. Numerous boulders that may have rolled from the berm were found at the interface between floor and slope. The floor of the feature was relatively flat, with fine- to medium-grained sand and a "comma-shaped" shell (scallop) stringer near the centre. Wave-induced ripples were observed on the pit floor.

The feature is located within an area of the Grand Banks Gravel (Unit D) (Barrie et al. 1984) with a thickness of 0.2-0.5 m, overlying hard clays likely to be Late Tertiary to early Pleistocene in age. Within the feature the exposed clays on the steep slopes dip 10-15 degrees inwards towards the centre. Bioturbation was apparent in the grey clay beds.

Figure 3. The berm of the iceberg pit as seen from the SDL-1 looking from the outside towards the centre of the feature.

PIT ORIGIN

A series of events is postulated to explain the formation of this feature. Morphologically, its overall "amphitheatre" shape, with steep back (south) and side walls surrounded by a berm and a less steep-sloped northern wall, suggests that the depression was formed by a grounding iceberg. To account for the depth of the depression, which was 8 m greater than average scour depth on the Grand Bank, and the dip of the clay beds towards the centre of the feature, it is postulated that the grounding event could have been followed by a bearing capacity failure of the clays.

Editor's Note: A more complete description and account of this pit is given by Barrie et al. (1986) and Clarke et al. (1986).

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DEFORMATION BY ICE OF SEDIMENT REMANENT MAGNETISM

Terry Day
T. Day and Associates
Box 368, Station M
Halifax, Nova Scotia, B3J 2Z1

INTRODUCTION

Paleomagnetism is conventionally used in the dating of sediments or in correlating the sediment sequences. The normal method used on core samples is to measure the remanent magnetic inclination or declination of subsamples along the core. Figure 1 is an example of results from a 5-m core taken off Labrador, and shows small-scale variations in the direction of the earth's magnetic field at the time when the sediments were originally deposited. The sediments are acting as a tape recording of geomagnetic change.

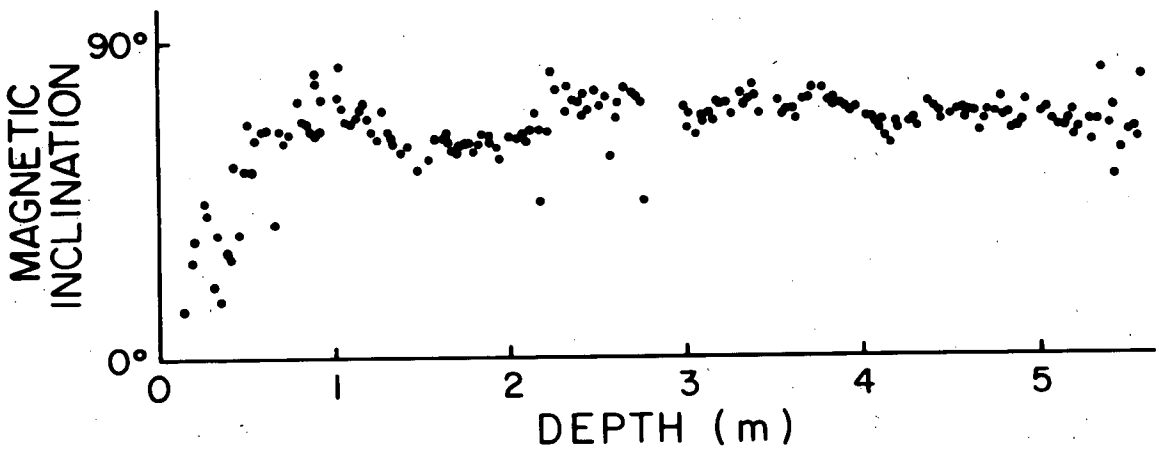

Figure 1. Remanent magnetism of material from a core collected on the Labrador Shelf.

REMANENT MAGNETISM

The remanent magnetism is acquired by the rotation of magnetic particles into the direction of the earth's magnetic field as they settle through the water column, and that orientation is retained when the particles hit the bottom and are buried. I have tried to extend this principle and to use remanent magnetism as a strain marker. Figure 2 shows several equal area plots of some glacio-lacustrine sediments from the Scarborough Bluffs just outside Toronto. The directions of several samples from a small block of the material are clearly well clustered. If mud is deposited in the laboratory, then the resulting directions are similarly well clustered. The reason for this is that the principal control on the direction of the remanent magnetism is the direction of the earth's magnetic field, and there are no non-geomagnetic forces realigning it. This

situation can be contrasted with a basal till. An example (Fig. 3) from England shows a reduction in the clustering of the remanent magnetism, which has been spread out, transverse to the direction of glacial flow. In some cases, the spreading is parallel to the direction of the glacial flow, and in other cases a cruxiform pattern is produced, indicating that both processes occurred. It appears that the remanent magnetism in this sample is an extremely sensitive strain marker. If the remanent magnetism of tills from present-day glaciers is measured, the mean direction from a group of samples gives the direction of the field with the spread around the original direction.

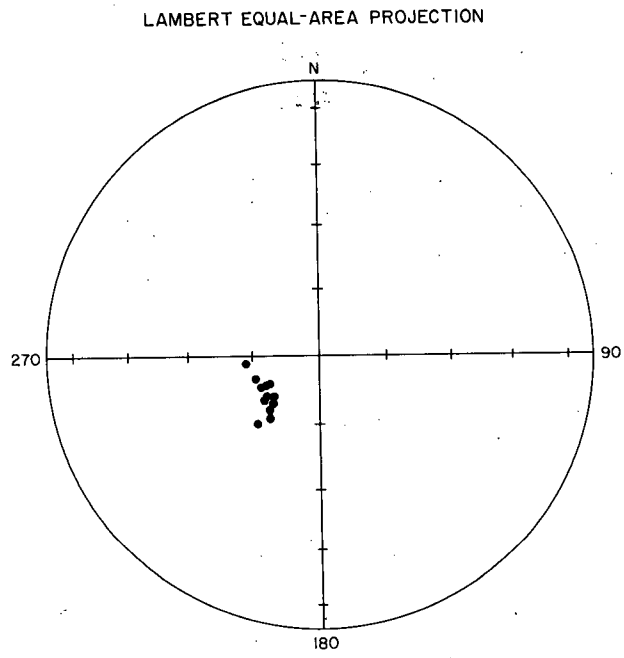

Figure 2. Remanent magnetism of glaciolacustrine sediments from the Scarborough Bluffs, Toronto.

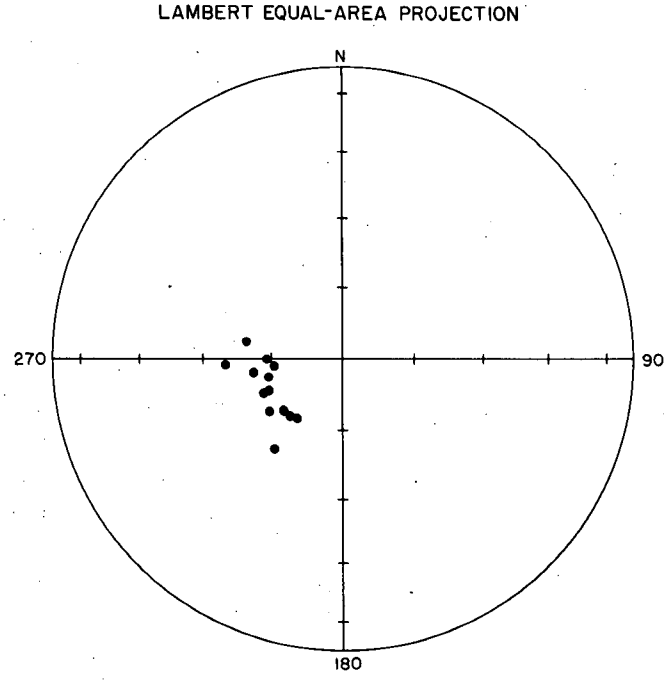

Figure 3. Remanent magnetism of a basal till from England.

DEFORMATION BENEATH ICEBERG SCOURS

At present, I am involved in several projects where remanent magnetism is used to determine the depth beneath the bottom of an ice scour to which the deformation extends. As yet, few data are available. However, as an example, Figure 4 shows the remanent magnetism of a striated block which was removed from a section adjacent to Lake Ontario. The block has a striated surface, probably as a result of scouring by lake ice. The upper-most centimetre of the block was subsampled and showed a slightly strained remanent magnetism. Evidence of the strain was not present 3 cm lower. In this case, sediment disturbance appears to have extended only about 1 cm into the block.

Using similar techniques, it should be possible to determine the depth of deformation beneath a scour. A large number of samples was collected during the expedition to King William Island described earlier by Chris Woodworth-Lynas (Woodworth-Lynas et al.,this volume). Preliminary results indicate that freezing of the soil has partly affected the remanent magnetism. However, differences in patterns of remanent magnetization are emerging between the scoured and unscoured sediments.

Deformation of the remanent magnetism may assist in understanding the deformation of sediments by ice.

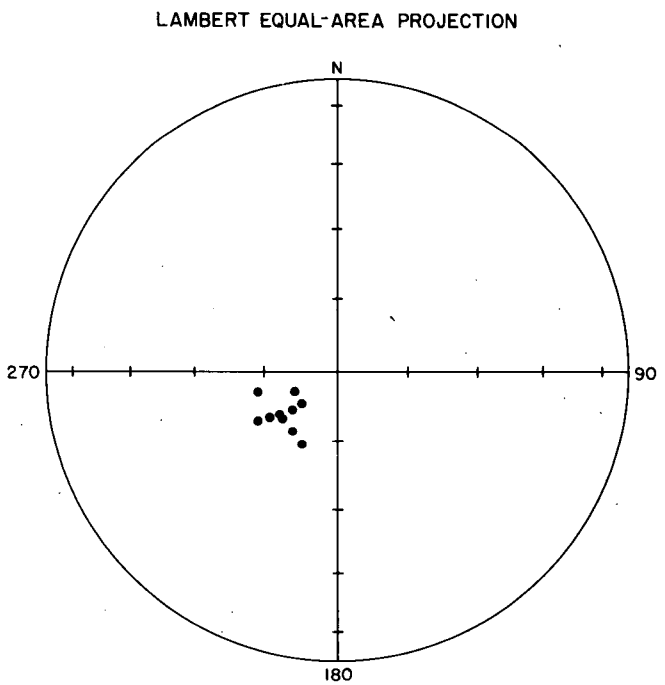

Figure 4. Remanent magnetism from a straited block of sediment from adjacent to Lake Ontario.

REFERENCE

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ICE AND ICE-SCOUR PROCESSES: SUMMARY AND DISCUSSION

Chaired by
J.V. Barrie
C-CORE, Memorial University of Newfoundland
St. John's, Newfoundland, A1B 3X5

and

P.W. Barnes
United States Geological Survey
355 Middle Field Road
MS 999 Meno Park, CA 94025

SUMMARY

Peter Barnes: Infill is an important process in modifying the scours, or gouges on the seafloor that we have detected during our surveys. These gouges are modified from their original form by erosion and infilling. In considering our observations in the Alaskan Beaufort Sea and off eastern Canada, we find an apparent enigma. In the Alaskan Beaufort Sea, we have indications that all of the gouges we observe are young (less than a few hundred years), as a result of infilling and current scour. The Beaufort Sea is not known as an especially dynamic environment for waves and currents. In contrast, the seas off the east coast of Labrador are known for their energetic waves and currents. Yet, the gouges observed on the east coast are apparently not subject to rapid infilling and, thus, are very old. We wonder what the differences in environment might be, as both shelves are apparently erosional surfaces. The water depths off the east coast are somewhat deeper; but, are the sediments coarser and is the availability of particulate matter less off the east coast, thus accounting for the apparent difference - high rates of infilling off a low-energy coast and low rates off a high-energy coast?

Vaughn Barrie: From an engineerng point of view the actual scouring forces and all the parameters driving the icebergs into the seabed are very important. Any discussion on these topics is very important considering that we are getting closer to actually observing and monitoring an iceberg scouring event on the seabed. All the papers so far have focussed on the processes during scouring and particularly on the effects after the iceberg has moved out of the area.

DISCUSSION

Peter Barnes: Scour infill is a topic in which I am interested. The data from the Alaskan Beaufort Sea, where there is little wave and current activity, show that there is very rapid infill because of biological and wave-induced action, whereas on the east coast, which is a dynamic environment, the infill rates are very slow. Why is there this difference? Are the sediments

different? I think we realize that we are trying to infill long, narrow features and that sediments do not have to move very far.

Vaughn Barrie: The scour degradation model for Hibernia was based on a bed-load transport equation which did not take into account the slope at the feature that could infill or suspend sediment transport. In ice-scoured areas on the east coast we find a very thin, mobile, surficial material underlain by a very dense material which is strong enough to hold the form of a scour. We have seen evidence that sand can fill such scour features and later can be re-excavated. Until you can re-densify that sand it is fully mobile. Also most of these scours have very shallow slopes, 2-3 degrees in many cases and I have difficulty in believing that these are actually catchment basins. On a high-resolution seismic profile they appear as nice "V shaped" features because of vertical exaggeration, but in reality they are extremely shallow troughs.

Heiner Josenhans, Atlantic Geoscience Centre: I would like to suggest that the term pockmarks not be used in the context of iceberg pits. Pockmarks have been well demonstrated to be formed by subsurface mechanisms, either gas or water, whereas Vaughn Barrie has demonstrated convincingly that in this case the mechanism is from above. It would be a pity to confuse the two and I suggest that an alternative term be used.

Vaughn Barrie: I certainly agree, there is a problem in the geological literature but what do we call them? Another problem: is do we use the genetic formation of these features as the term or do we use the morphological term for the feature? This problem will become more acute as they attract more attention.

T.R. Chari, Memorial University of Newfoundland: Did you find any "tire track" marks at the beginning or at the end of these pits?

Vaughn Barrie: No, not to my knowledge.

T.R. Chari, Memorial University of Newfoundland: The bearing-capacity failure hypothesis that Dr. Barrie mentioned concerns me (see this volume Barrie, J.V., W.T. Collins, and D.R. Parrott, Grand Banks Pits: Description and Postulated Origin). You would be concerned about the stability of a concrete platform where you have more of a punching and pulling type of action with the iceberg pushing aside the soil.

Vaughn Barrie: I cannot comment from a geotechnical point of view other than to say that these pits are an order of magnitude different in penetration depth from all the scours in the area, both pit and linear. That is why we are looking for a second mechanism.

Alan Ruffman, Geomarine Associate Ltd.: As more of these pits are documented, is the general slope of the pits randomly oriented or are they all facing to the north for example? If a large piece of ice calves from an iceberg and drives down to the ocean floor, is that a distinctive mechanism for a feature of this size? Can icebergs calve underwater as well as above water? Could that be another mechanism?

Jim Grass, Ontario Hydro: You mention that you had quite a few of these pits on the Grand Banks. Were there any subbottom records taken that might indicate any structural features in the bedrock, such as faults or fractures, that might have been activated by earthquakes and have released gas. We have noticed gas in formations at depth which could open up a section of sediment.

Vaughn Barrie: That was a distinct possibility which we considered. We ran deeper seismics over and near these features a year ago, but found no indication of subsurface controlling factors that might cause these features. We hope to do this again using the new external hydrophone on the Huntec Deep Towed Seismic (DTS) system.

Peter Barnes to Roger Pilkington: You questioned me about some of the problems involved in collecting input data for your statistical analyses. You suggested we might have some thoughts on relating single- and multiple scour events to help the engineers in interpreting their statistics. Can you elucidate?

Roger Pilkington, Gulf Canada Resources: I stand to be corrected. In Canada, we generally treat a rake scour (eds. - scour made by a multiple-keel sea-ice pressure ridge) as one scour. That is the information that we are putting into our data base. If you have a rake scour, you have 100% covariance between each individual scour in the data and therefore you are really not increasing your amount of data. If you have 25 individual scours all following each other you cannot say "There are 25 plus or minus 5 scours," you can only say "There is one plus or minus one scour." Am I correct?

Peter Barnes: No. These features will vary because they are long. They will vary in depth and in number.

Roger Pilkington, Gulf Canada Resources: If we are looking at the number of scours occurring in a year or an average number of scours occurring per year, what is the more important number: the 25 individual scours of a rake scour all following each other or the one event that has occurred?

From the floor: Neither one, the destruction width is the important number.

Roger Pilkington, Gulf Canada Resources: I tend to think that one scour rather than 25 has occurred from a pipeline burial point of view. However, because you are looking at the bottom end of your distribution, I do not think the classification is significant. What we have to do is to separate out the rake scours from the single scours which are most probably multiyear features. I think we will probably find that the scour depth distribution for first-year scours is very steep compared to the distribution for multiyear features. It is this bottom tail of the distribution curve that we require.

Steve Blasco, Atlantic Geoscience Centre: I think we can do that because we have both numbers in our data set, which is of course limited. We can separate out the two.

Roger Pilkington, Gulf Canada Resources: How do we enter rake and single scour data into the Canadian data bank?

Steve Blasco, Atlantic Geoscience Centre: We enter it as one event but we also flag it in the data base as a multi-keeled event so that it can be dealt with separately. There is another side to the question. If you treat it as one event, it has quite a large finite width. This morning someone was discussing the effect of width on the length of pipe disturbed. The width could have a major impact. But then if the scour is multi-keeled, you want to know that anyway.

SEABED RESPONSE TO ICE FORCES

Session Chairmen

W. Roggensack
T.R. Chari

ICEBERG SCOURING AND ITS INFLUENCE ON SEABED CONDITIONS: INVESTIGATION AND PROPOSED MODEL FOR THE NORWEGIAN SHELF

Reidar Lien
Reidar Lien A/S
Oevre Flataas Vei 10
N-7079 Flataasen
Trondheim, Norway

INTRODUCTION

North of latitude 61°N about 55% of the continental shelf of Norway is ice scoured (Fig. 1). Most scours are found north of latitude 62°N in water depths of 100-500 m. Iceberg scours are relict south of latitude 72°N. At latitudes higher than 74° or 75°N, active scouring is now occurring in water depths to about 100 m.

We have found very large scours up to about 25 m in relief and 250-300 m wide. The current direction and the general bathymetry are crucial for scour distribution. Some local areas have no scour marks as a result of bathymetric filtering (sheltering by updrift shoal areas that ground or deflect icebergs thereby protecting downdrift areas of deeper water from ice scoured.). The largest scours are found on the southwestern slopes of the banks, whereas there are often no scours on the opposite (eastern) side of the banks. When the sea-floor is flat, the orientation of the scours is more consistent in deeper water than in the shallow regions. The scours often parallel the contours. The size of scours usually increases with water depth, but their frequency (or seafloor density of scours) decreases with water depth.

On the Norwegian shelf south of latitude 72°N, the scours are all between 10,000 and 13,000 years old; however, even though they are relict they are of interest to oil companies. Figure 2 illustrates some of the problems we might have, especially when installing gravity structures and pipelines. Several features are sufficiently large that ordinary pipelines 1 m in diameter would not be able to span the open areas. It is estimated that a pipeline can withstand a 30- to 50-m free span, but in this area scour features may be much wider. In some areas, such as Haltenbanken offshore mid-Norway, about 100 such large scours have to be crossed before reaching the shoreline.

To collect more information about iceberg scouring, the ploughing process, and its influence on the seabed, the Continental Shelf Institute in Norway (IKU) undertook a comprehensive survey on behalf of the Norwegian companies Statoil and Norske Hydro.

Figure 1. Study area on the Norwegian continental shelf. Numbers represent depth contours in 100-m intervals.

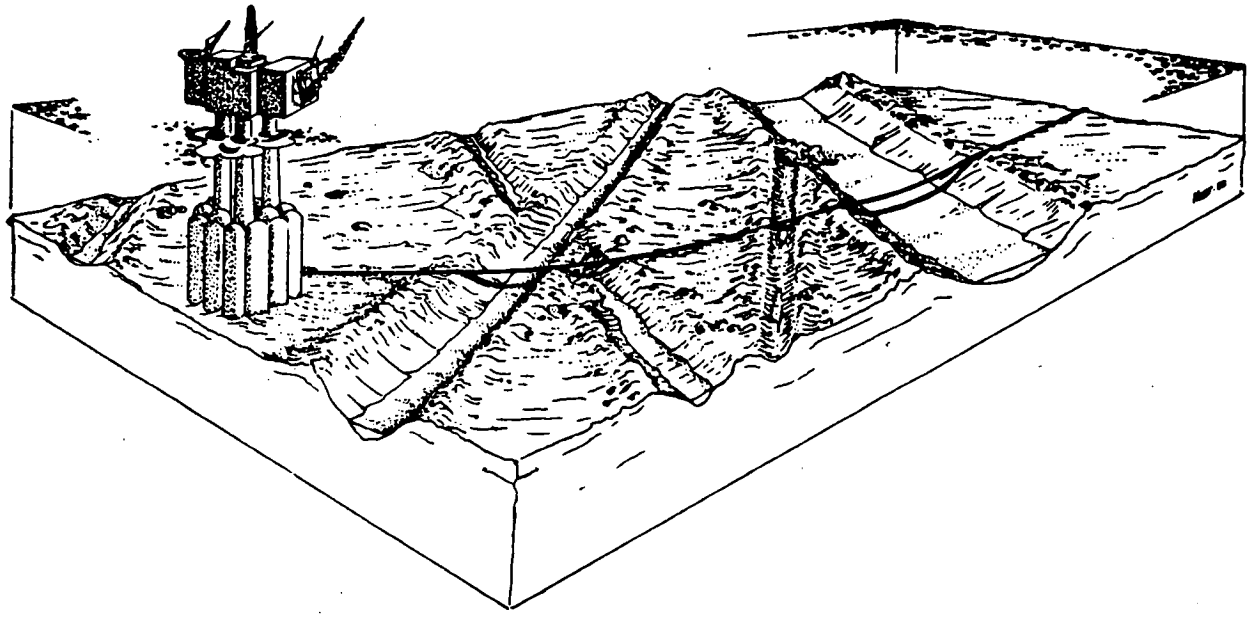

Figure 2. The installation of gravity structures and pipelines in an area of relict ice scours suggests problems.

SCOUR SURVEY PROGRAM

The area selected for survey was outside the TROMS-1 area off northern Norway (Fig. 3). The survey was planned in two stages. The first stage involved a conventional, shallow, seismic-profiling survey of a 5- by 6-km area using positioned, deep towed systems such as side-scan sonar and deep-towed boomer subbottom profiler, and echo-sounder with motion compensation. As a result of this study, a smaller area of 600 by 1,200 m was selected for detailed coverage. This second stage included a Remotely Operated Vehicle (ROV) study with video coverage, side-scan sonar, pinger, a precision bathymetry-recording device and also bottom sampling, in order to map and profile the seabottom. We grouped the sediments in three different classes, recorded all boulders larger than 0.5 m, and mapped all the minor grooves. Further, sampling and penetrometer testing were undertaken from a drillship at various locations.

Details of Survey

In Figure 4 the thick lines indicate the area covered by the shallow seismic systems at a 200-m line spacing. The thinner lines indicate the ROV lines run in the area. Because we had to manoeuvre the ROV at different heights above the seafloor as we collected video information and information with the other equipment, only alternate lines were covered. Sidescan sonar and bottom profiles were obtained for the lines in between. Precision bathymetric data were collected on all lines. Thus, bathymetric line spacing is about 15 m, whereas the line spacing for the video coverage is 30 m. Eleven bottom samples were collected using positioned samplers, and data were obtained from the drillship at three locations.

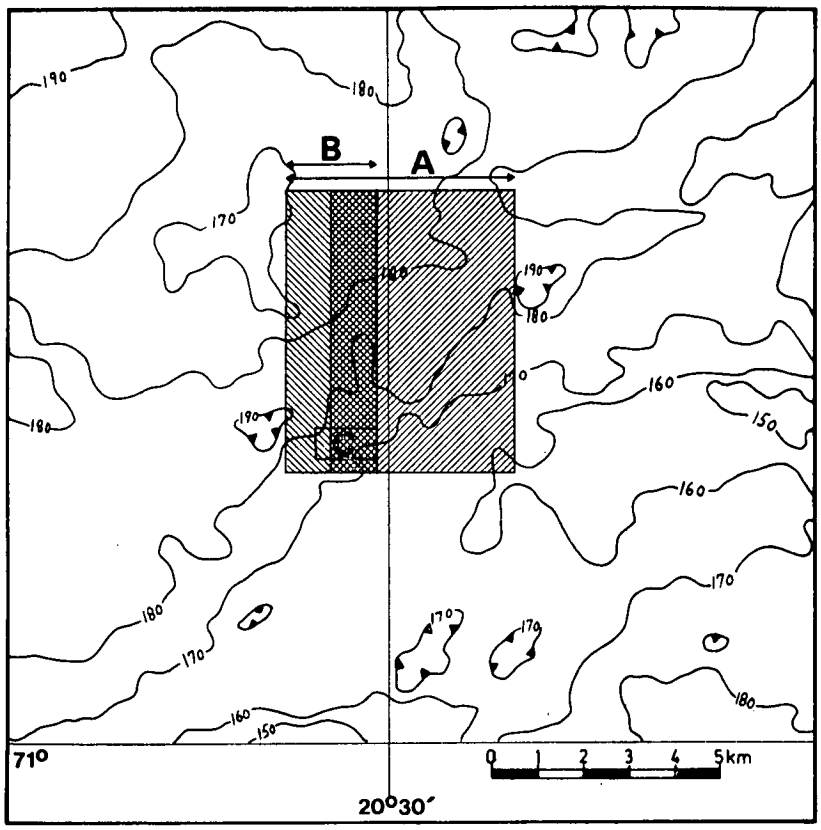

Figure 3. TROMS-1 field area for scour survey program.

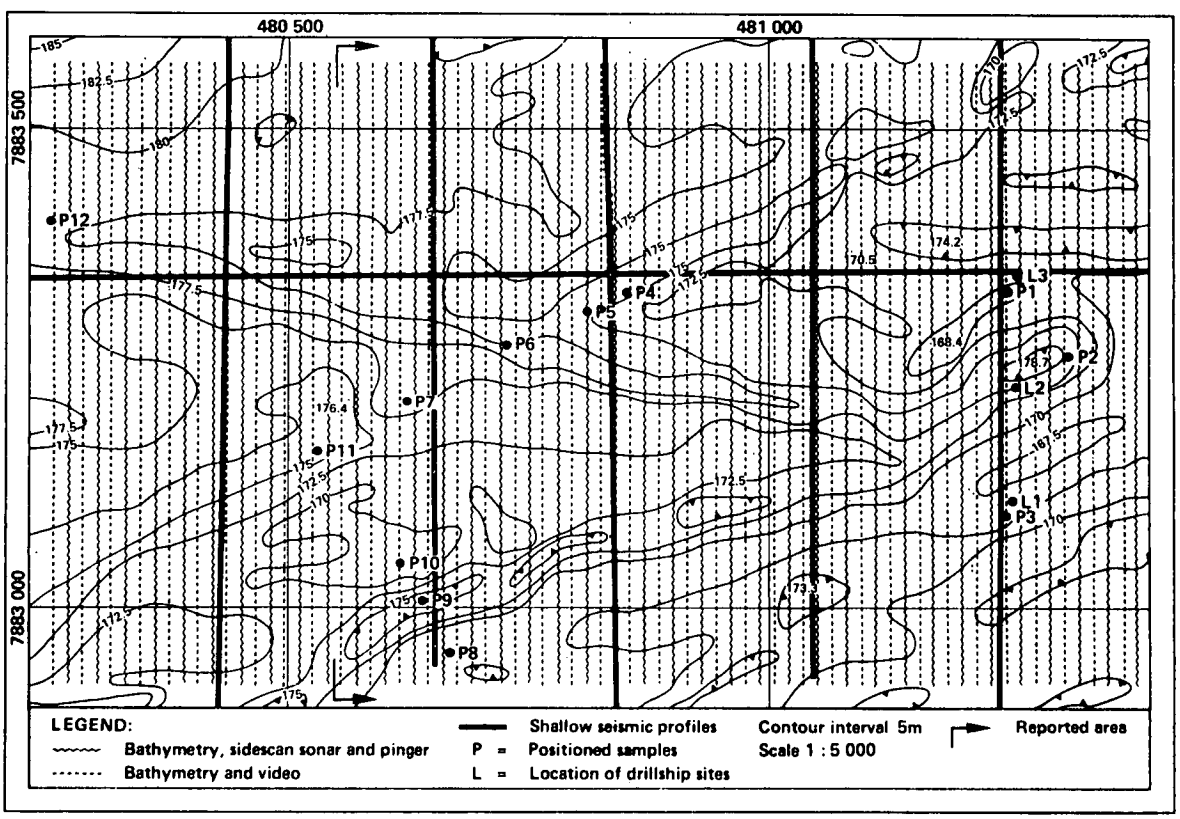

Figure 4. Bathymetry map showing detail of sampling coverage in the test area.

RESULTS

A sidescan mosaic of the test area was compiled from the sidescan sonograms. The main target features found in the mosaic were four iceberg scour marks. The relative chronology of the scours was determined from a close inspection of the scour crossings. Many other features were also evident in the sonograms, such as small scours, troughs, and mounds, that are remnants of old scours. The largest relief observed was about 14 m on the bathymetry map (Fig. 4).

This program was initiated to study the scouring process and to determine how this process influenced the seabed conditions. The sidescan songram (Fig. 5) shows the ploughed up mound paralleling the scour. The process involved here is a combination of ploughing and extruding the sediments. Deep-towed boomer records over the feature (Fig. 6) show reflectors in the sediments which might be the original seafloor surface. This feature has a rim or berm 1.5-2 m thick ploughed up, with some recognizable disturbance underneath.

A summary of the results from the drillship investigations is shown in Figure 7. All the sediments, except the sand on the top of locations 1 and 2, consisted mainly of clay with sand, gravel, and some boulders, which is a typical composition of till from the Norwegian continental shelf. The shear strengths vary. Usually the initial shear strengths are very high because of compaction by the ice sheet, but here we have layering. The upper clay layer at locations L1 and L3 had a shear strength of less than 20 kPa. In the bottom of the scour, we found a layer that had about the same shear strength values as the next layer on each side, i.e., between 60 and 150 kPa. Beneath this was another clay layer with a shear strength greater than the 450 kPa design limitation of the measuring instrument. All these boreholes showed very high shear strengths at the bottom, and lower shear strengths at the top. Other measurements based on the penetrometer testing showed a very steep or abrupt increase in shear strength at the transition between some of the layers.

Seafloor Conditions

In the scours, the general sediment distribution consists mostly of soft featureless sediments: sand, silt, and occasionally boulders and pebbles. On the rims and berms and other protruding areas, the seafloor is rough, and often there are coarse sediments mostly sand, gravel, and boulders. Most of these sediments lie on the top of the till. In the flat areas, there are various thin layers of soft sediments, often with exposed coarse sediments from the underlying layers.

Distribution of Larger Boulders

In the lower part of the scour, there are very few boulders. From the top of the rim or the shoulder and down towards the bottom of the scour, there is a concentration of boulders. In areas not directly affected by scouring, there is a more random distribution of the boulders and coarser sediments. Nearly all the boulders larger than 0.5 m lie on the top of the surface and are very seldom embedded; these large boulders are rare, even in soft sediments.

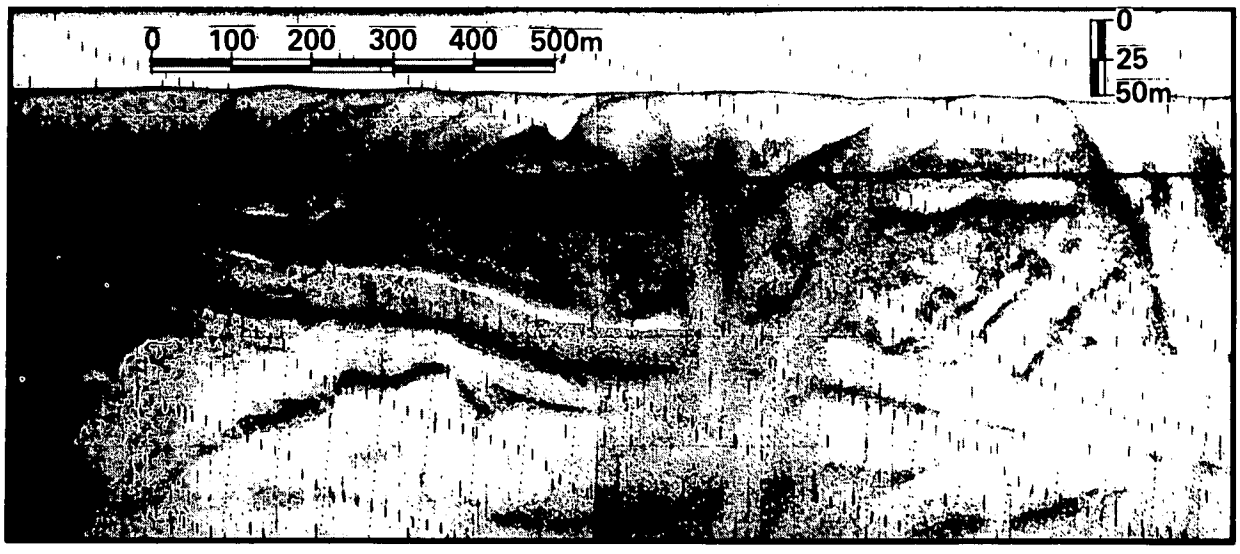

Figure 5. Sidescan sonogram showing plowed up mound paralleling the scour.

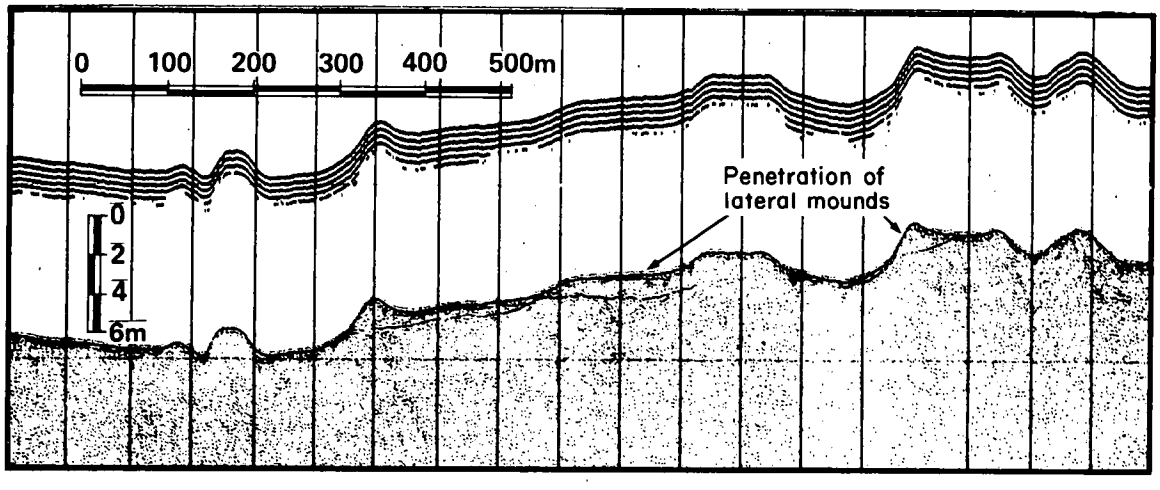

Figure 6. Deep-towed boomer record along a scour.

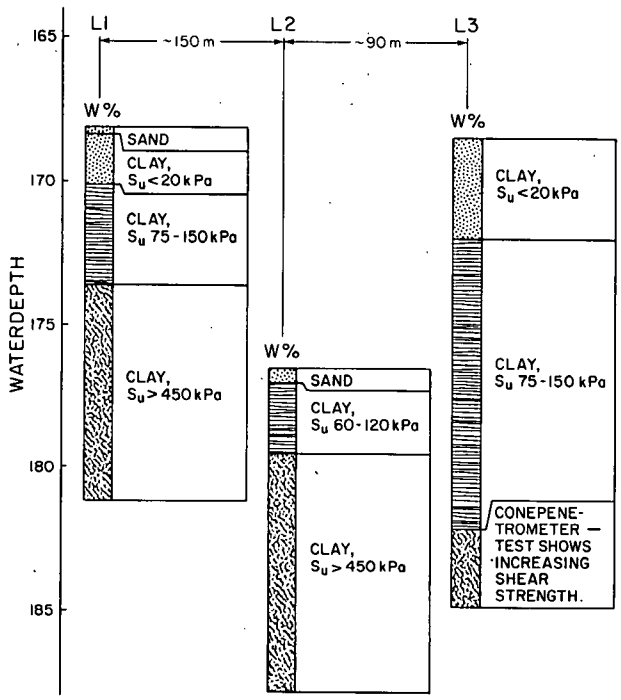

Figure 7. Summary of results from drillship investigations.

INTERPRETATION

If we look at the scouring from a geotechnical point of view we can think of it as a foundation problem. For an iceberg as shown in Figure 8, a failure diagram similar to that resulting from normal foundation calculations can be drawn. This failure diagram can be drawn more or less along the whole leading edge of the iceberg keel. Because the sediments fail as the iceberg moves with time, disturbed sediments result. We believe that, after repeated scouring, a zone of disturbed sediments is left to a certain depth beneath and beside the scour. The squeezed-up rims on either side are not shown in this diagram.

If we use this model as a base, a cross-section of a scour may appear as shown in Figure 9, with the ploughed-up mounds on each side and remoulded or disturbed sediments around and underneath the scour. Beneath these disturbed zones are the undisturbed sediments that maintain their original compaction.

If we compare this model with the results from the drill ship testing (see Fig. 7) we see similarities. There is a ploughed-up mound on each side with low shear strength; further, we have the squeezed or disturbed and remoulded sediments, and underneath are sediments that are unaffected. From this testing, we estimate that the disturbed layer underneath the scour is between 2 and 3 m thick, but it is thicker at L1 than at L3, perhaps because of the presence of an older scour close to L3 that has collected the unconsolidated material.

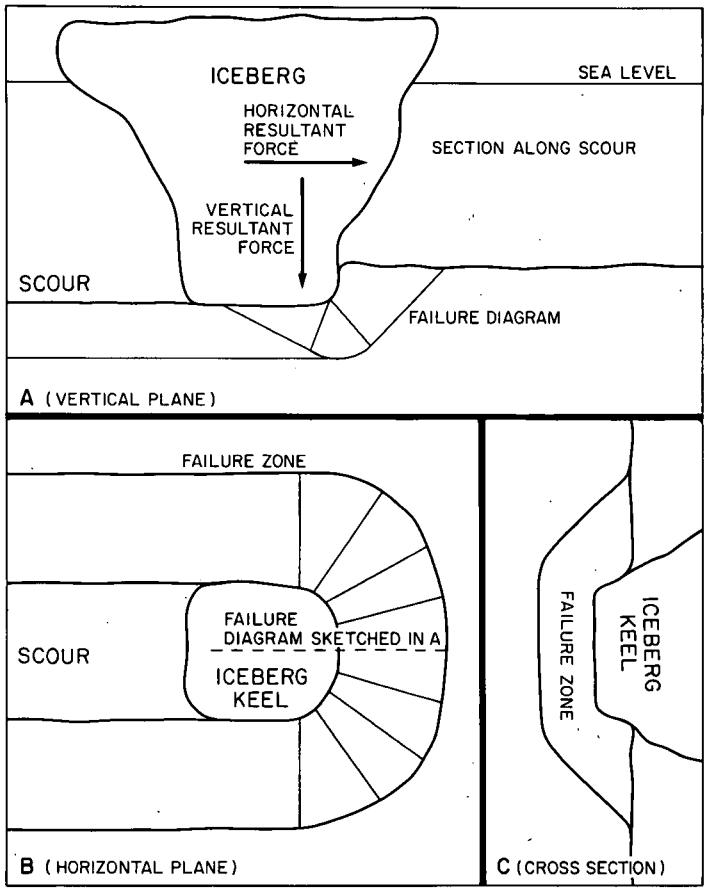

Figure 8. Geotechnical failure diagram of iceberg scouring.

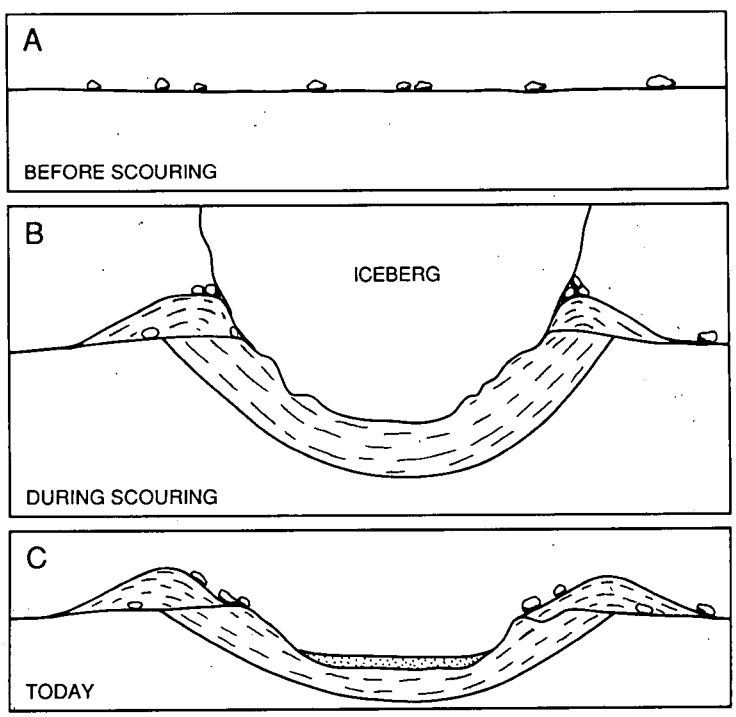

Figure 9. Cross-section of an ice scour based on the proposed model.

PROPOSED MODEL OF THE SCOURING PROCESS

From this survey, a model of how ice scouring affects the seabed, is proposed (Fig. 10). Before scouring started, many icebergs drifted into the area, carrying, we think, englacial sediments that eventually melted out. The larger boulders and coarser sediments, such as gravel and sand, fell directly on to the seabed, being distributed randomly into a thin layer of sand and gravel with boulders. When later icebergs arrived, they ploughed into this sediment layer, and all the large boulders and the sand were pushed to the side of the iceberg keel to form, mounds (rims or berms). There was also disturbance and extrusion in the layer underneath the iceberg, where unevenness of the keel produced the small grooves that can be seen on the video recording.

This scouring and deposition process lasted for at least 3,000 years, and usually the later scours are best preserved. Often accompanying these scours is a concentration of boulders on each side. Some of these scours have soft sediments in the bottom, the layers of which vary significantly from area to area and change with water depth. In some areas, the whole scour is infilled with only the top of the rim, or berm, protruding through the soft sediments, most likely as a result of different current conditions.

In a future program, we hope to test this pressure model on some of the relict iceberg scours that exist off Norway. We hope to do a practical test of the model, and we also hope to try out a mathemetical model.

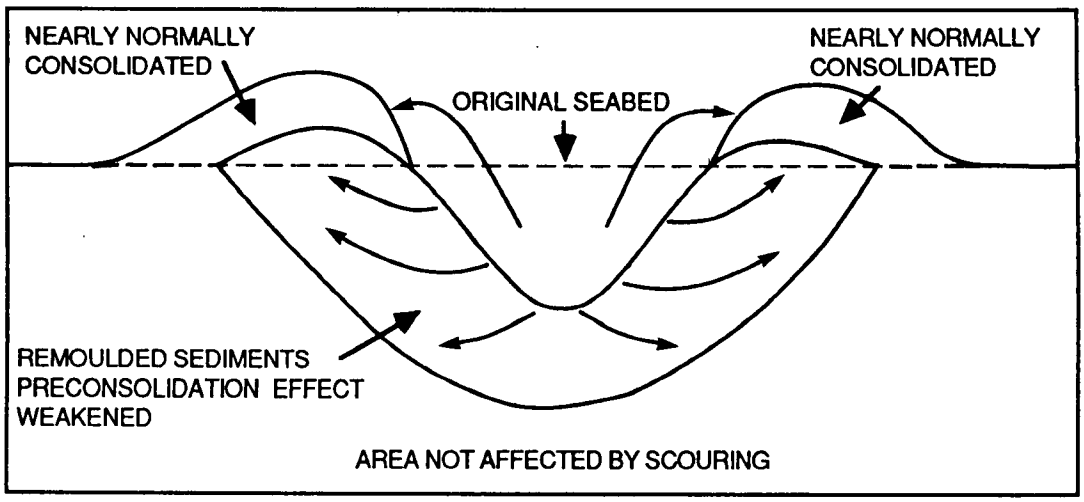

Figure 10. Pressure model to explain iceberg scouring.

DISCUSSION

Chris Woodworth-Lynas, C-CORE: The infilling process appears to differ from that which we observed on King William Island, in the way your boulders are pushed to the side and in your infilling of sand. We postulated almost instantaneous infilling. Do you have any idea about the stratigraphy in that layer of infilled sand? Is it a mass of sand or is it bedded?

Reidar Lien: It is mostly not bedded. We have dated it, and there appears to have been very little deposition in the last 7,000 yr.

Chris Woodworth-Lynas, C-CORE: So it looks as though it might be instantaneous?

Reidar Lien: I think it depends on when the scour is formed, but from our model most of the infilling most likely occurred within the scouring period (13,000-10,000 yr B.P.).

Alan Ruffman, Geomarine Associates Ltd.: How much up- and downhill scouring have you recorded in your work?

Reidar Lien: The most we have seen is between 10 and 15 m.

REVIEW OF DETERMINISTIC ICE-SCOUR MODELS

George Comfort[1] and Bruce Graham
Arctec Ltd.
#16 6325-11th Avenue SE
Calgary, Alberta, T2H 2L6

INTRODUCTION

In a recently completed ESRF study (Comfort and Graham 1986), we evaluated several deterministic ice-scour models. The scope of this project included a review of all the available models to establish parameters, the compilation of available validation data, and a calibration-type study in which we exercised the models by introducing validation data. From the review of the available models, we produced a list of significant parameters that needed to be quantified (Table 1).

PARAMETERS REQUIRED FOR MODELS

First, it is important to know something about the ice feature creating the scour, such as its mass and general dimensions; length, width, depth, freeboard. The shape of the keel is also important, as it helps to define the width of the scour and the number of scours, i.e., single or multiple tracks.

Secondly, it is important to include the seabed properties. Most models require information on the local bathymetry and the seabed slope. They also require data on the mechanical properties of the soil, such as cohesion, friction angle, and density. The variation of these properties is also important.

Thirdly, the environmental driving forces are important and need to be understood. These include the speed and direction of wind and currents; the size of waves; and the amount of pack ice, if it is present.

Finally, it is necessary to have information on the scour track itself, such as its general dimensions, including length, width, depth, and slope of the berm or side embankment, and whether it is single or multiple tracked.

[1]Presenter.

TABLE 1

Field observations required for ice-scour model evaluation

Parameter	Observation
Ice mass	Classification of shape General dimensions - length, width, depth, freeboard Mass estimate, if above not available Shape of keel, if sidescan data available Velocity prior to grounding
Seabed	Bathymetry along scour track Classification of surficial soils along track Strength of soils along track - cohesion, friction angle or both - density
Environment	Wind - average speed and direction during grounding Current - as for wind Pack ice, if present - ice type/floe size distribution, average thickness, speed, temperature, and direction of movement Waves - average height and period
Scour track	General dimensions along track - length, width, depth, embankment height, embankment slope Surficial soils - variation in strength across track

DATA COMPILATION

With these parameters identified, we set out optimistically to try to produce a quantitative data base for at least one event that would allow us to calibrate the models to some extent.

Unfortunately, this task proved to be impossible, mainly because, with the requirement for such a complete data set, the data available from the many different sources could not be ordered into a reasonable manner suitable for an in-depth analysis. Therefore, we had to include some data from environmental assessment studies, some "typical" soil properties, and some other unknowns.

We approached such institutions as the Bedford Institute of Oceanography (BIO) and the Centre for Cold Ocean Resources Engineering (C-CORE), as well as several other agencies, for information on icebergs. From the collected data, we identified five groundings that potentially would provide the kind of information that we required. These were the Karlsefni K007 iceberg grounding on Saglek Bank in 1976, and the Caroline grounding on Saglek Bank in 1979, and the Frances iceberg grounding on Nain Bank, in 1979. In addition, there were two groundings in 1983, Bergs 95 and 104, on northeastern Grand Bank that have been documented by Mobil Oil Canada Ltd..

Because of time limitations related to the study schedule, we were able to review the data only for the first three events. Table 2 summarizes the data, for iceberg groundings on the Labrador Shelf, that we were able to obtain.

Karlsefni Grounding

For the Karlsefni iceberg grounding, sidescan sonar data were available, and its position and movements were noted in a well-site log. Core samples had been collected in the area, and soil-strength information was available. In addition, the iceberg's velocity prior to grounding was known from the radar records collected by a drill-site ice observer. The wind and current velocities, and wave heights were also recorded in the well-site log.

In the case of the Karlsefni grounding, the exact scour track corresponding to the observed grounding event could not be distinguished from other scour tracks on the sidescan sonogram (J.V. Barrie, C-CORE, personal communication, 1984). Thus, we were forced to measure a range of scour depths within an area where the iceberg was known to have scoured.

Caroline and Frances Groundings

For the Caroline and Frances icebergs, values of the overall above-water dimensions were estimated from photographs. Seabed morphology was derived from sidescan sonograms and bathymetric data collected during local well-site surveys. Soil classification was derived from an interpretation of Huntec subbottom profiles from the area. For grounding information, we relied on environmental data at the time of the grounding provided by Petro-Canada Resources for the Labrador Shelf region. Finally, information on the scour track was obtained from general sidescan surveys and from Huntec subbottom profiles.

For these two icebergs, there is a good correlation between the scour marks and the estimated positions of the grounded icebergs. Thus, we are sure that scours observed were created by these particular icebergs.

TABLE 2

Available validation data by source for each grounding event

Parameter	K-007	Caroline	Frances
ICE FEATURE			
Berg shape or classification	1976 Karlsefni well-site log	Photos of grounded berg	Photos of grounded berg
Berg dimensions	Sidescan sonar survey recorded in Karlsefni well-site log	Estimated by scaling from available photos using helicopter as a basis Berg depth calculated from 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
SEABED 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 classifications	Lab tests of core samples	Huntec subbottom profiler interpretation	Huntec subbottom profiler interpretation
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

TABLE 2 - CONT'D.

Parameter	K-007	Caroline	Frances
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 windspeeds measured at Gilbert well site for August	Range of windspeeds measured at Gilbert well site for August
Current velocity	Karlsefni well site log (for 50-m depth)	Max. and mean current speeds measured at 62-m depth at 58°53'N; 62°10'W over July-October, 1980 (after Petro-Canada 1982)	Max and mean current speeds measured at 58°53'N; 62°10'W over July-October, 1980 (after Petro-Canada 1982)
Wave height	Karlsefni well site log	Max. and most probable significant wave heights measured at Gilbert well site	Max. and most probable significant wave heights measured at Gilbert well site
Pack-ice conditions	Karlsefni well-site log	Inferred from knowledge of typical ice conditions	Inferred from knowledge of typical ice conditions
SCOUR TRACK			
Scour cross-sectional geometry ·depth ·breadth ·single or multiple track	1. 1979 Sidescan sonar survey 2. 1982 Sidescan sonar survey 3. 1979 Huntec subbottom survey	1. 1979 Sidescan sonar survey 2. 1982 Sidescan sonar survey 3. 1982 Huntec subbottom survey	1. 1982 Sidescan sonar survey 2. 1982 Huntec subbottom survey

REVIEW OF MODELS

There are two main types of models that can be applied to the situation of a hard ice feature such as an iceberg or an ice ridge scouring the seabed (Fig. 1). One is the work-energy approach, and the other is the force-balance approach.

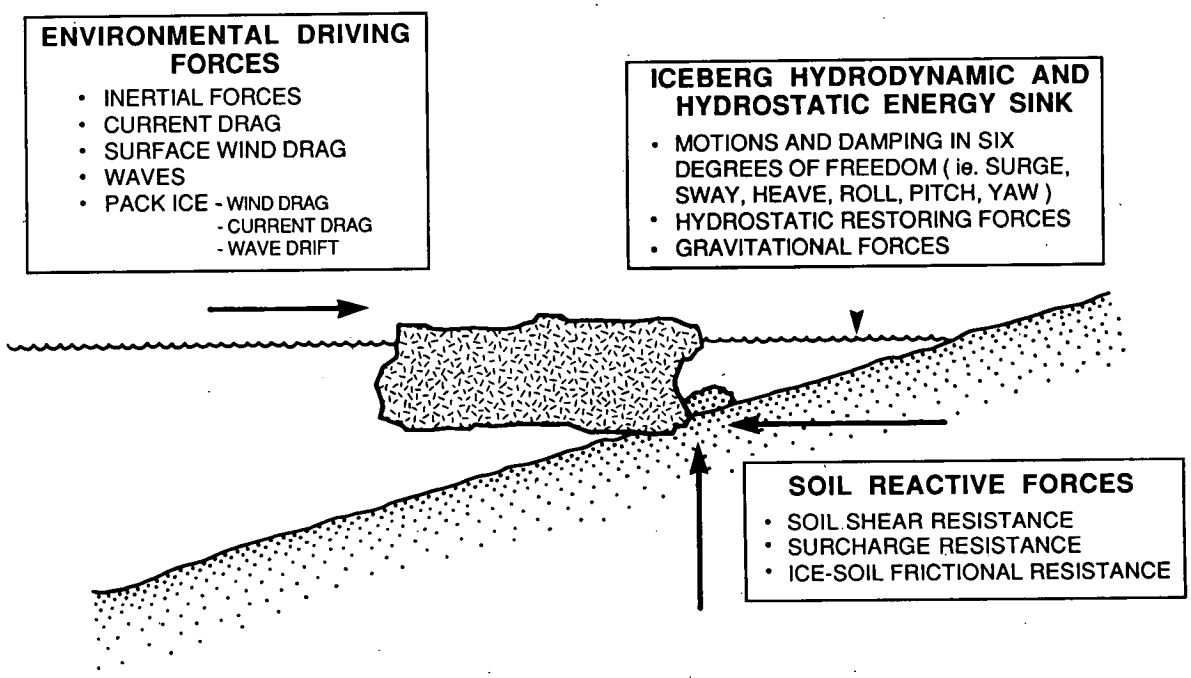

Figure 1. Diagram of force-balance approach applied to scouring by a hard ice feature.

Work-Energy Model

The work-energy model states that the initial kinetic energy of the body plus the work done by the current drag during scouring plus the work done by the wind drag are equal to the work done in deforming the soil. This type of model was proposed by FENCO (1975) and also by Dr. Chari from Memorial University (Chari 1979). These models have a single degree of freedom, which assumes that the iceberg moves only horizontally and that there is no rotation or vertical motion. Because they assume that the iceberg is floating, they ignore friction between the iceberg base and seabed and assume a constant seabed slope.

Force-Balance Model

The other type of model that we thought was applicable was the force-balance approach, which was proposed by FENCO (1975). Essentially, this type of model solves the differential equation of motion in a time-increment manner for the applied external forces: namely winds, waves, currents, and also pack ice, if it is present. The time step is an input parameter to the program, and can be changed as desired. This particular model has three degrees of freedom. It allows the iceberg to rotate, to move vertically, and to move horizontally. The effects of iceberg shape are not included, i.e.,if an iceberg is 150 m wide then this model predicts that its scour would also be 150 m wide. Soil resistance is calculated using Coulomb's theory. It uses a constant seabed and seabottom slope, and ignores friction on the side of the iceberg.

Model Prediction

Table 3 compares the ranges of measured scour depths with the output of the work-energy model. The ranges shown in Table 4 represent the range in input values, for parameters such as wind and currents, soil strength, and, for the Karlsefni case, bed slope, that were entered into the energy models. The difference between the FENCO force-balance model and the FENCO work-energy model is that, in the force-balance case, the work done by the current drag and that done by the wind drag forces during the scouring event are added together. In the FENCO work-energy report, they are not included. This explanation applies to the Chari model as well. The reason for the large spread in measurements of the Karlsefni scour depth is the uncertainty of knowing which scour is the one that was created by the iceberg.

In summarizing the results of the simulations, it appears that both models overpredict the ranges of measured scour depths, although the estimates are in the right order of magnitude. Also, it appears that the Chari model predicts higher values of scour depth than does the FENCO model.

We also exercised the FENCO dynamic model for the ranges of input values. Table 5 lists the values input to the dynamic model whereas Table 6 compares the ranges of measured and predicted scour depths. A negative scour depth is predicted in some cases indicating that the leading corner of the iceberg was lifting off the seabed. These predictions are considered unreliable. The reasons for this predicted anomaly are unclear. It was not possible to investigate this anomaly in detail within the study scope, and we can only speculate on possible explanations. It is suspected that this anomaly may stem from numerical instabilities resulting from the use of a relatively large time step of 2 s used in the program.

The ranges of predicted and measured scour depths compare well. However, it should be noted that the scour breadth is taken as being equal to the iceberg width by the dynamic model. Therefore the assumed scour breadth is too large. Since the scour depth increases significantly as the scour breadth is decreased it might be concluded that the dynamic model, overpredicts the scour depth. However, because anomalies in the form of negative scour depths were predicted by the dynamic model, the calibration work done with this model must be considered inconclusive.

TABLE 3

Comparison of work-energy model scour depth with measured values

Iceberg grounding event	Range of work-energy model scour depth predictions (m)				Range of measured scour depth (m)
	FENCO model (1975)	Modified FENCO model [a]	Chari model (1979)	Modified Chari model[a]	
K-007	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

[a] Work-energy models of FENCO (1975) and Chari (1979) modified to include work done by wind drag and current drag forces during scouring.

RESULTS OF SENSITIVITY ANALYSIS

To establish which factors produced the largest changes in the predicted depth, a sensitivity analysis was performed. For the work-energy model, the results showed that varying the iceberg mass by a factor of 4 increases the predicted depth by a factor of 2. An increase in the bed slope by a factor of 2 gives about a 1.5-fold increase in predicted scour depth. Wind speed has little effect. Current speed increases become quite significant as a parameter; doubling the speed increases the predicted scour depth 1.6 fold. A four-fold increase in soil strength decreases scour depths by one-third to one-fifth.

A similar analysis was carried out on the FENCO dynamic model. We varied soil properties, bed slope, wave height, wind speed, and so on. Basically, the results showed that both wind speed and wave height are fairly insignificant parameters. Two-fold increases in bed slope, current speed, wave height and berg mass yielded increases in scour depths of approximately 50, 50, 25 and 10% respectively. Again, we obtained a negative scour depth; a disturbing result.

CONCLUSIONS

Two important conclusions were drawn from this study. First, the need for a better set of validation data with which to calibrate ice-scour models is reflected in the wide range of the uncertainties in the present data. Secondly, scour processes can only be crudely modelled at present. For improved modelling our understanding of the physical processes involved must be improved. We recommend that future work should concentrate in that area.

TABLE 4

Work-energy model input values

Parameter	Input values for grounding event		
	K-007	CAROLINE	FRANCES
Iceberg dimensions:			
length (m)	230-460	180	360
width (m)	180-360	180	360
depth (m)	265	232	159
Scour breadth (m)	30	30	35
Windspeed (m/s)	11.1	0 - 42	0 - 42
Current speed (m/s)	0.08 - 0.17	0.14 - 0.46	0.11 - 0.34
Berg drift rate (m/s)	0.08 - 0.17	0.14 - 0.47	0.11 - 0.34
Ice density (N/m^3)	9,000	9,000	9,000
Water density (N/m^3)	10,000	10,000	10,000
Submerged soil density (N/m^3)	5,635	6,300	8,325
Soil cohesion (Pa)	5,800	4,000-10,000	14,000-24,000
Bedslope (deg)	0.05 - 0.75	0.37	0.1

Note, for all runs:

·the added mass coefficient was taken as 0.5

·drag coefficients was taken as:

	FORM	SKIN
Wind	1.0	0.005
Current	1.0	0.05

· for Chari's model (1979), H/D was taken as 1.4

· for all models, the ice-soil friction angle was taken as 0

TABLE 5

FENCO dynamic model input values

Parameter	Grounding Event		
	K-007	Caroline	Frances
Iceberg dimensions:			
length (ft)	590 - 1,510	590	1,180
width (ft)	590 - 1,510	590	1,180
depth (ft)	870	760	520
Bed slope (deg)	0.05 - 0.75	0.37	0.10
Pack-ice force (kips/ft)	0	0	0
Soil frict. angle (deg)	0	0	0
Ice-soil frict angle (deg)	0	0	0
Soil adhesion (psf)	0 - 121	84 - 209	290 - 500
Soil cohesion (psf)	121	84 - 209	290 - 500
Soil sub. wt. (pcf)	36	40	53
Soil elastic modulus at bed surface (psf)	14,400	14,400	14,400
Soil Poisson's ratio	0.33	0.33	0.33
Elastic modulus change with depth (psf/ft)	14,400	14,400	14,400
Wind speed (ft/s)	37	0 - 138	0 - 138
Sail surf. drag coeff.	0.003	0.003	0.003
Ridge intensity factor	0.02	0.02	0.02
Sail form roughness drag coefficient	0.0	0.0	0.0
Sail freeboard drag coeff.	1.0	1.0	1.0
Current (ft/s)	0.25 - 0.51	0.46 - 1.5	0.35 - 1.13
Initial berg drift rate (ft/s)	0.25 - 0.51	0.46 - 1.5	0.35 - 1.13
Keel drag coeff.	1	1	1
Wave height (ft)	3.3	4 - 15	4 - 15

TABLE 6

Comparison of FENCO dynamic model scour depth predictions with measured values

Iceberg grounding event	Range of predicted values		Range of measured values	
	Scour depth[a] (m)	Scour breadth (m)	Scour depth[a] (m)	Scour breadth (m)
K-007	-17[b] - 1.3	180 - 230	0.5 - 6.0	15 - 65
Caroline	0.5 - 0.9	180	0.3 - 0.7	22 - 45
Frances	0.0 - 0.5	360	1.0	30 - 42

[a] Scour depth calculated as outlined in FENCO (1975) using: (Scour length ·tangent bed slope angle) - berg lift.

[b] This predicted value is considered unreliable.

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DISCUSSION

John Miller, Petro-Canada: My question concerns the difficulty experienced in matching the Karlsefni iceberg to the scour. Was the problem in the iceberg position or in the location of the sidescan itself?

George Comfort: I'm not sure. Can I refer that question to Vaughn Barrie?

Vaughn Barrie, C-CORE: We knew the position of the iceberg from the well site observations of the grounding. We had collected sidescan mosaics in the area prior to, and after, that event, but there was definite uncertainty as to whether the scour that was identified as K007 was in fact K007.

Mike Lewis, Atlantic Geoscience Centre: That is basically correct. There have been a number of surveys through the K007 area since the 1976 grounding event. In 1981 a new scour mark was mapped which appeared to correlate with the observed trajectory of the iceberg. For a while we thought we had a nice correlation. The problem was that we had too much data. As Vaughn Barrie pointed out, if this correlation were to stand up, we should also be able to find evidence of it in sidescan records obtained in later years. We haven't yet reached a satisfactory explanation as to why we can't distinguish the scour mark in post-1981 surveys, yet we seem to be able to recognize it in pre-1981 surveys. I think George Comfort is quite correct in saying that at present, the data and their interpretation are too uncertain to permit a definitive correlation.

T.R. Chari, Memorial University: If the wind drag doesn't have a significant effect, what exactly is the modification that you made that shows the difference?

George Comfort: The only modification we made was the addition of one particular term: wind drag multiplied by the length of scour.

Roger Pilkington, Gulf Canada Resources: Wouldn't we expect the Chari model and the FENCO model to overestimate the scour depth because they assume the iceberg goes straight in? The second question is, do you have any evidence of any lifting in any of these actual observations that you obtained?

George Comfort: Your first point is correct. They do overestimate the scour depth. In the second case, the only information I have is a few photographs which aren't sufficient to allow me to say anything about that topic.

ICEBERG-SCOUR MODELLING AT MEMORIAL UNIVERSITY OF NEWFOUNDLAND

T.R. Chari
Faculty of Engineering and Applied Science
Memorial University of Newfoundland
St. John's, Newfoundland, A1B 3X5

INTRODUCTION

Research on iceberg-scour modelling has gone on for several years, and continues, in the Faculty of Engineering and Applied Science at Memorial University. This presentation reviews that research and focuses on the rolling of icebergs and the subsequent forms that are left on the seabed.

Review of Research

In the simple model that was developed several years ago (Chari 1979) (Fig. 1), the various possible mechanisms of iceberg scouring were examined. Different seafloor types were considered: from a hard bottom, up the slope on which the iceberg slides and rides, to a soft seabed into which the iceberg ploughs horizontally for some distance before coming to a halt when the energy balance is attained. In the first case, there are no visible scour features formed on the seafloor, whereas in the second case long scour tracks are produced to maximum scour depths. Between these two extremes is a possible situation in which an iceberg may plough and also ride up.

When the modelling program was initiated, the objective was to predict the maximum possible scour depth that an iceberg could cause under the worst conditions.

Figure 2 shows the basic model for a sloping seabed of soft sediments. The iceberg scours by ploughing horizontally, throwing out soil on both sides and in front of the berg, before finally coming to a stop. This situation can be modelled simply using the principle of energy balance and passive pressure theory for soils, by assuming that a series of rupture planes is successively developed. This results in an equation in which the energy resulting from the propelling forces is equal to the energy dissipated during the seabed scouring process.

$$\frac{MV_o^2}{2} + \frac{C_d \rho A L V_o^2}{6} = \frac{\gamma'(H+D)^2 BL}{6} + \tau DLB + \frac{\sqrt{2}}{3}\tau D^2 L \qquad (1)$$

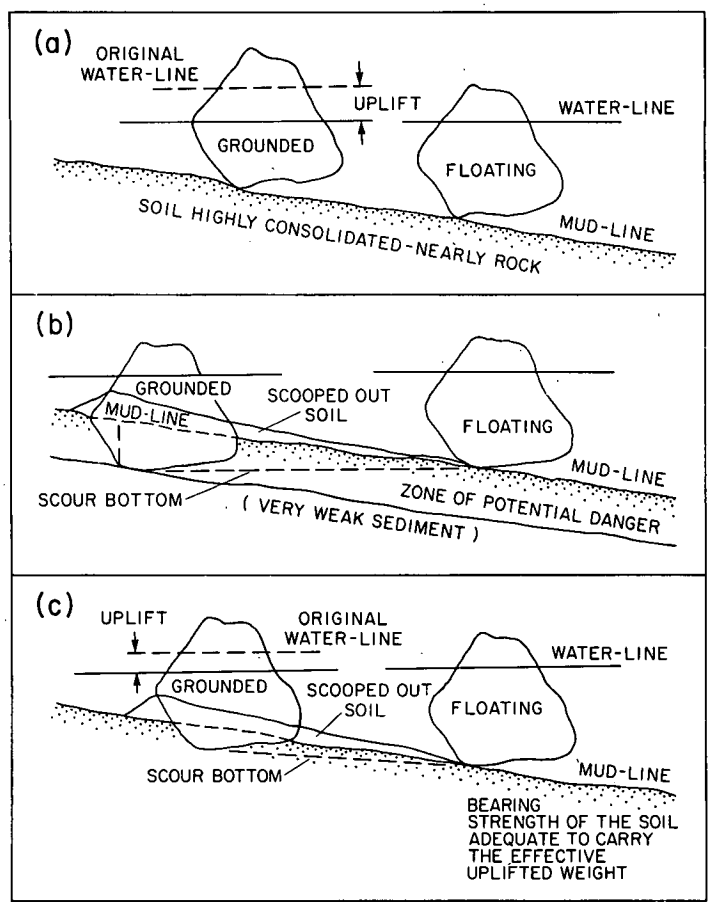

Figure 1. Typical modes of iceberg scouring: (a) full uplift and grounding; (b) horizontal ploughing; and (c) partial uplift and ploughing (after Chari 1979).

where: A = projected area of the submerged iceberg normal to the propelling currents

B = width of the idealized iceberg, also width of scour

C_d = drag coefficient

D = maximum depth of scour = $L \tan \beta$

H = final height of surcharged soil in front of the berg

L = maximum length of scour

M = mass of the iceberg

V_o = initial steady-state velocity of iceberg (also averaged current velocity)

β = seafloor slope

ρ = density of seawater

γ' = submerged unit weight of the ocean soil

τ = shear strength (undrained) of the ocean soil.

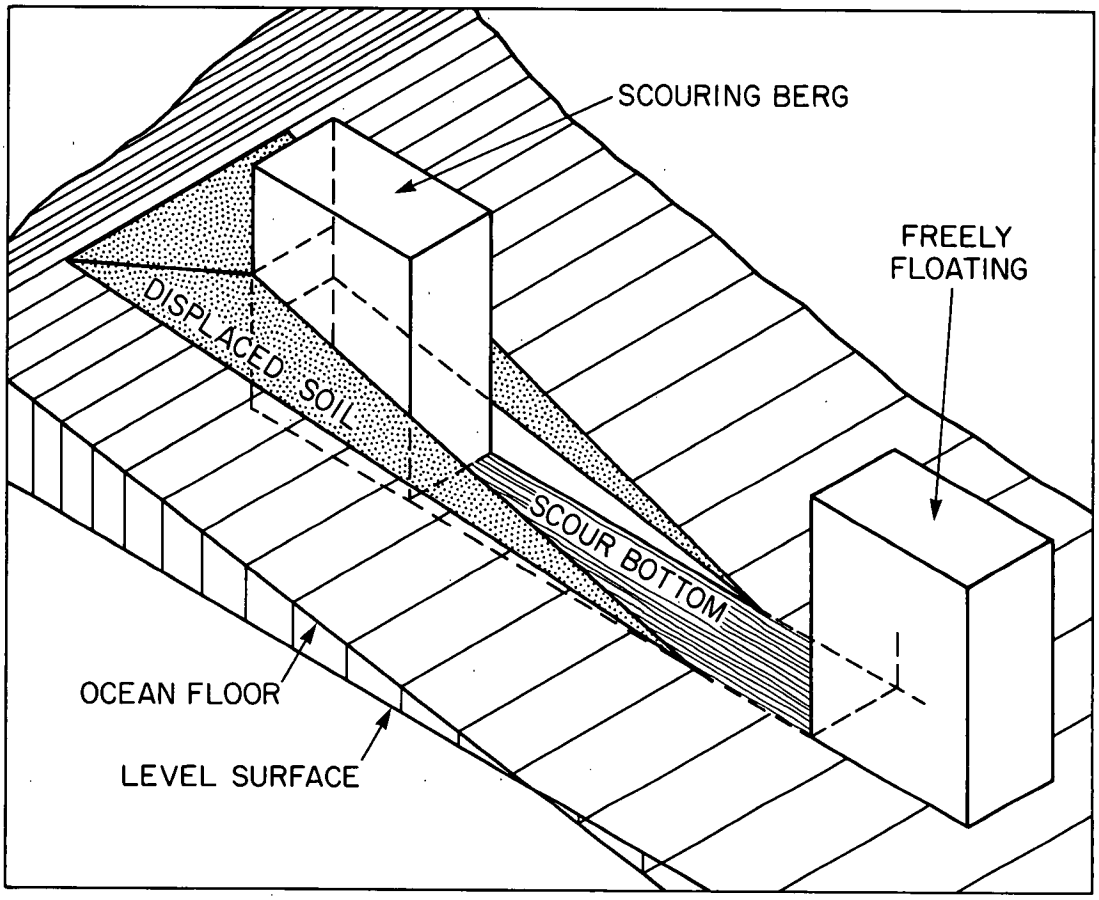

Figure 2. Iceberg scour model.

Equation 1 includes the kinetic energy, the drag energy, and the soil resistance, all of which can be computed. This simple model is well documented in the literature (Chari 1979).

Figure 3 shows a typical solution of equation 1. Initially the iceberg has some kinetic energy, which is a function of its mass and velocity. The initial energy compared with the energy resulting from the current drag, due to differential current and iceberg velocity, is relatively small. The resistance from the soil is initially zero; however, as the keel ploughs deeper, the energy resulting from soil resistance and the energy resulting from the driving forces become balanced, and the point is reached at which the iceberg finally comes to rest. This point represents maximum distance that the iceberg travels.

The scour depth for different sediment properties can be estimated using the model. Figure 4 is an example showing the scour depth for different iceberg sizes. However, unless the results can be correlated with measurements of actual scours on the seabed, models such as the one discussed here have little value. Verification of the results in the field is thus an important aspect of any model if it is to be of practical utility.

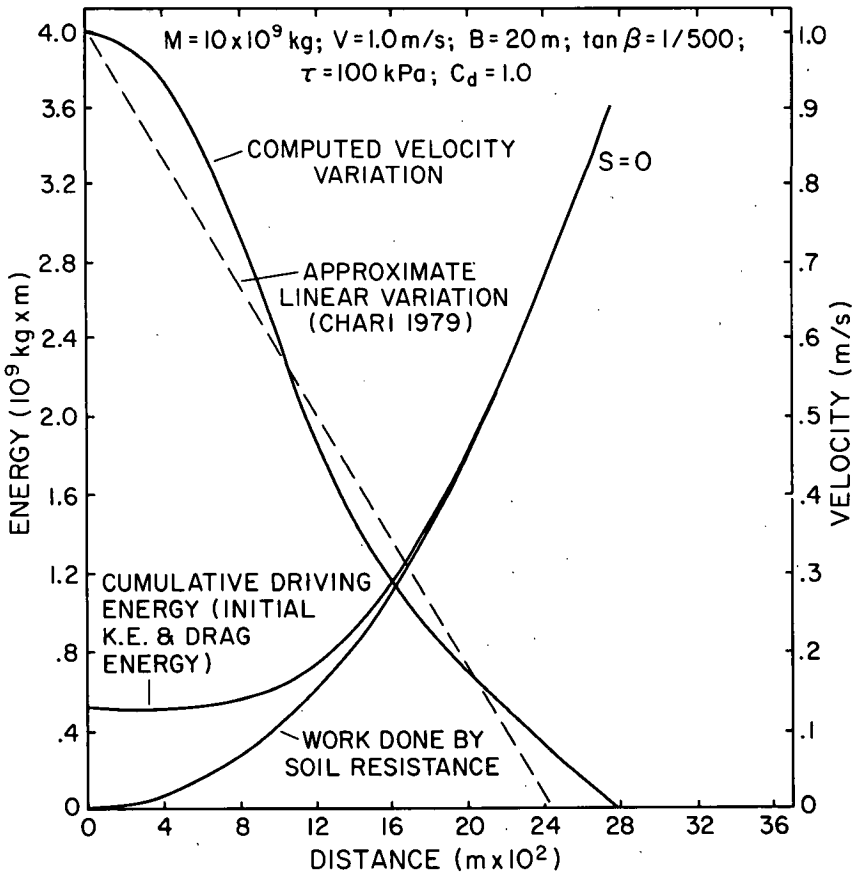

Figure 3. Work done and energy expended during scouring.

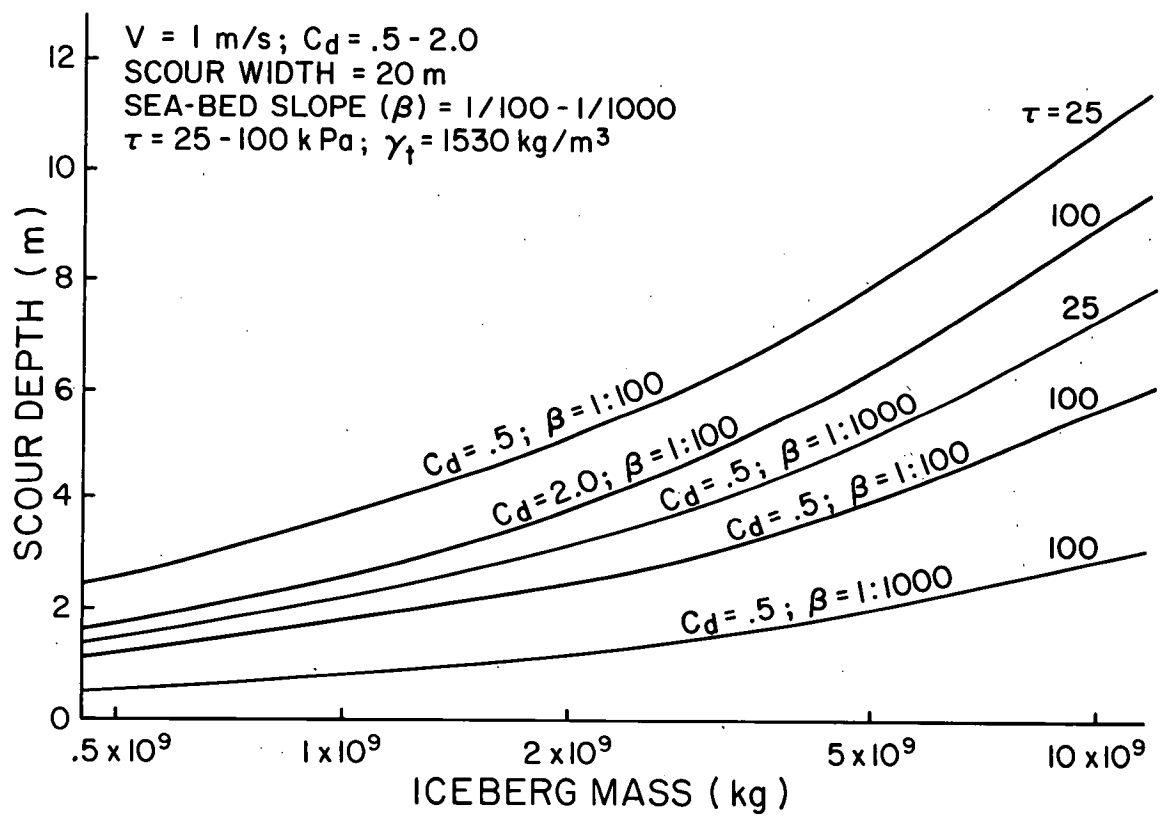

Figure 4. Theoretical estimates of scour depth.

FACTORS INFLUENCING THE SCOUR FORM

Several factors influence iceberg scour depth, including iceberg mass, drift velocity, hydrodynamic drag, underwater shape, draught, seabed shear strength, sediment density, keel shape and scour width, bathymetry, and seabed slope. The sensitivity of the iceberg scour to all these factors has been analysed, and the results are published in the literature (Chari and Peters 1981). An important factor influencing scour depth is the drag coefficient resulting from the underwater shape of the iceberg. Even a small change in the drag coefficient can result in significant changes in the scour form.

After an initial assessment of the sensitivity of the iceberg to some of the above parameters has been made, the next step is to consider the possibility of an iceberg actually rolling over, and then evaluate the seabed response if the iceberg penetrates the seafloor as a result of a change in the draught. Even when an iceberg rolls over, it still has the initial kinetic energy in its original direction of travel, and it is still being propelled by the currents. Figure 5 illustrates the concept of seabed scouring by icebergs as a result of rolling (Prasad and Chari 1985). In our model, it was assumed that the iceberg keel penetrates the seabed immediately after it rolls over, continues to move, and eventually comes to a halt. In terms of modelling, the depth of initial penetration, S, influences the energy balance equation described earlier.

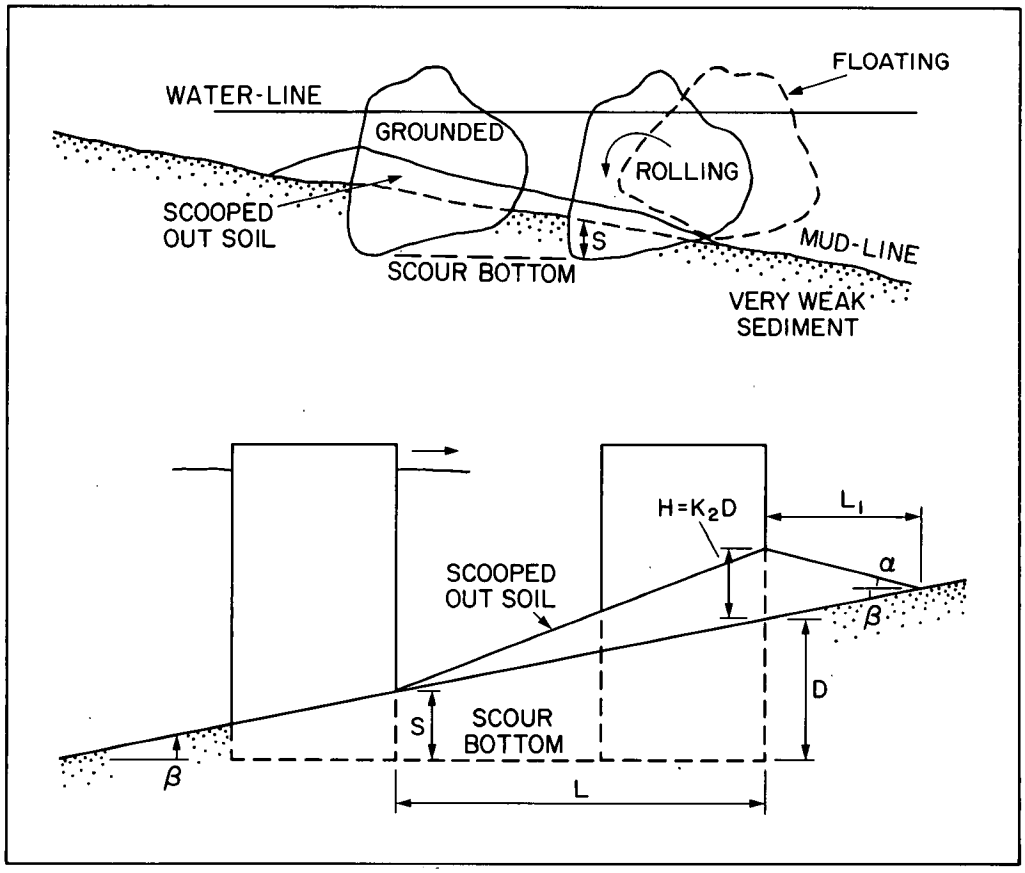

Figure 5. Iceberg rolling and consequent scouring. The direction of motion in the definition sketch (lower) is opposite to that in the event sketch (above).

Figure 6 shows the scour depth for different initial penetrations of icebergs of various sizes. An examination of the results showed that there are upper and lower bounds for the initial penetration that result in scours of certain forms. For an iceberg of mass M with an initial penetration corresponding to a lower bound value S_ℓ (about 5 m in Figure 6), scouring will take place as if the initial penetration were of no consequence. On the other hand, for the same iceberg, if the penetration were an upper bound value S_u of about 9 m, then the iceberg would stop soon after initial penetration. This effect may explain the process that was described by Barrie in his presentation on iceberg pits (Barrie et al.this volume). Simply stated, if an iceberg rolls over and penetrates the seabed, and if the initial penetration is equal to, or greater than, the upper bound value, then a pit will be formed. On the other hand, if the iceberg's penetration is less than the lower bound value, then the initial penetration will have little effect.

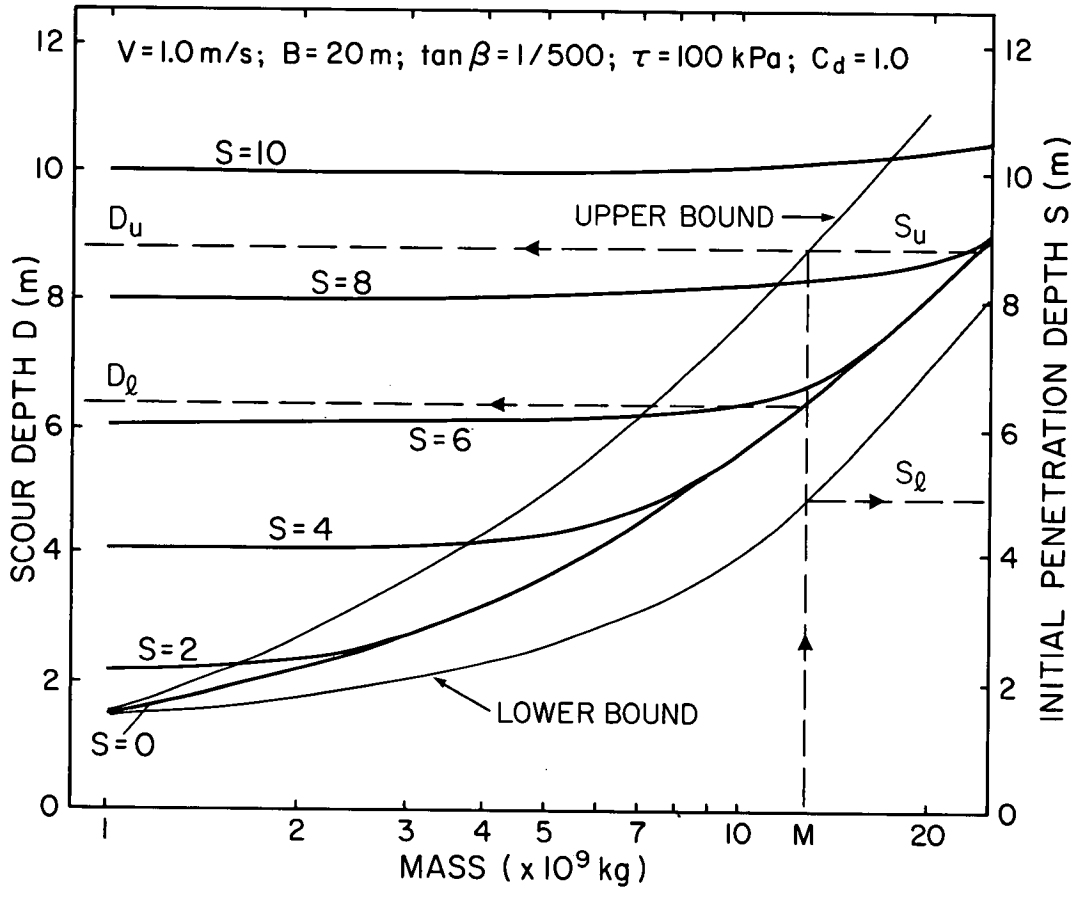

Figure 6. Effect of iceberg penetration of seabed on scour depth.

PHYSICAL MODELLING

Physical modelling and experimentation in the laboratory (Fig. 7) continue to be carried out. A variety of iceberg shapes has been used for the model. The failure planes, the form of the scour, and the berms have been studied. The degree of disturbance beneath a scour has also been measured with a model pipeline to assess the pressures and forces below a scouring iceberg.

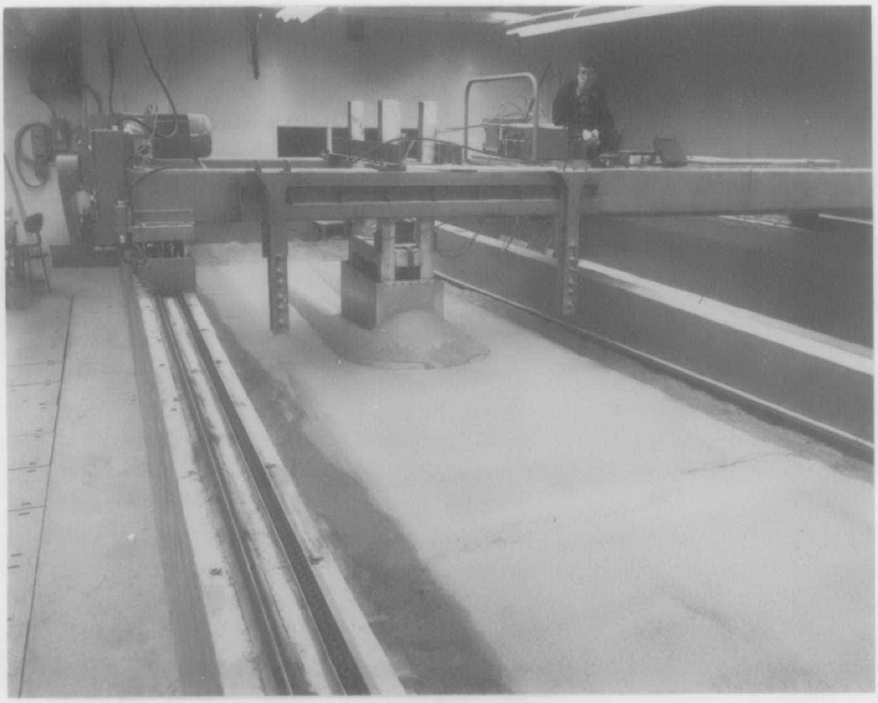

Figure 7. Physical modelling and laboratory tests.

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DISCUSSION

Dave McKeehan, INTEC Engineering: Can you elaborate on the pipeline model?

T.R. Chari: Yes I can, but I am not sure if I can present any definite answers at this stage. When we first looked at iceberg scouring several years ago, we were doing the physical modelling in a layer of clay material in a glass-sided tank using a Plexiglass model. We attempted to delineate the failure planes and discovered that the failure plane extended below the iceberg model. The reason for this is that the failure plane has a certain curvature associated with it. The other observation was that when the model moves forward into the sediment, the grains move in an inclined as well as in a horizontal direction, which means that there is a volume of sediment in front of and below the iceberg that is constantly in motion.

After observing this type of movement in a small tank, the next step was to see how the pressures and forces dissipate within the soil. We found that the dissipation is fairly rapid up to a depth of 1.5 times the scour depth. At this stage, I doubt if the results from the model can be extrapolated to real pipelines. We feel there are processes other than just the sediment displacement that create the trench during the scouring process.

Terry Day, Day and Associates: Would it be difficult to incorporate the effects of pore pressures in the sediments into your model? When you refer to the shear strength, do you mean the shear strength of the material prior to the experiment or after it?

T.R. Chari: When we refer to the shear strength, we are referring to the undrained shear strength. If it is a clay material, it is undrained shear strength that has to be taken into account, because the soil doesn't have time to drain. Shear strength can be determined in the laboratory by doing undrained shear tests or in the field by some sort of test in situ. With cohesionless material such as sand, pore pressure does not really matter because drainage will be fairly rapid. However, it will still be the undrained shear strength.

Terry Day, Day and Associates: Would it be possible to incorporate the effects of pore pressure in your model?

T.R. Chari: This doesn't really come into the picture, but you can measure the pore water pressure if it is required. I don't know how one incorporates it as a separate factor, because you are taking that into account when calculating the undrained shear strength.

Alan Ruffman, Geomarine Associates Ltd.: I think Figure 5 is quite interesting and presumably it describes a mechanism for scours that start in the middle of nowhere and continue on into deeper water. However, I am not sure how many scours do just start in the middle of nowhere, and I am not sure how well that phenomenon has been documented. Even in your rotating model, there appears to be a requirement for all icebergs that start scouring with a small scour to produce a scour that gets wider and wider. I believe this suggests that all icebergs are going to stop if they are going uphill. I don't think that happens. I think many icebergs continue scouring uphill. I believe that there is quite a bit of evidence to show that icebergs do drag their tails across the bottom for quite considerable distances. I think that the next stage in this research would be to look at mechanisms that allow icebergs to scour over considerable changes in vertical elevation.

T.R. Chari: If an iceberg rolls and travels downslope after initial penetration, it will scour the seabed and stop scouring when the water depth exceeds the draught, at which point it will float freely. If the seafloor is flat, theoretically the berg could form a scour several kilometres long. If it is moving upslope, it will come to a stop after a relatively shorter travel.

HIBERNIA ICE-SCOUR MODEL STUDIES

L. Schoenthaler
Mobil Oil Canada Ltd.
Box 62, Atlantic Place
St. John's, Newfoundland, A1C 6C9

INTRODUCTION

This presentation describes some of the work that Mobil Oil and Hibernia joint-venture participants have been doing over the last few years with regard to iceberg-scour modelling. The Hibernia participants are Chevron Canada Resources Ltd., Gulf Canada Resources Inc., Petro-Canada, Columbia Gas Development of Canada, and Mobil Oil Canada Ltd., (operator).

Historical Note

In 1981, the Hibernia participants conducted a review of existing ice-scour models. We concluded that no existing model adequately described the iceberg-scouring process. As a result, the Hibernia participants decided to undertake an engineering study to develop a scour model that would describe iceberg scouring more realistically.

Study Objectives

The aim in developing the iceberg-scour model is to have a means by which to estimate scour depth, given data on the iceberg, environmental conditions, and soil conditions. The objective of the study effort is to develop, verify, and refine an analytical model of iceberg scour capable of fully describing iceberg motion and scouring. We decided to develop a new model, rather than attempt to improve an existing model. Key features of our model, inspired by the limitations of earlier models are:

(a) The model should not be limited to oversimplified iceberg shapes. The user should have the choice of specifying a simple or a complex iceberg geometry.

(b) The model should be capable of modelling iceberg motion in the free-floating mode as well as in the scouring mode.

(c) Environmental conditions and soil properties should be defined by the user.

SCOUR MODEL

A fundamental assumption made in developing the scour model is that an iceberg has a rigid underwater keel. Ice strength characteristics are not included in the model for reasons of

simplicity. We felt this is a reasonable assumption in that, if the ice were to fail and break apart, the resulting estimate of scour depth calculated by the model would be conservative.

Iceberg motion in six degrees of freedom (rather than the three degrees of freedom used in earlier models) is incorporated into the model. By doing this, iceberg stability can be modelled while free-floating, scouring uphill, scouring downhill, or entering into a subsea excavation.

An important factor in developing a model is the need for flexibility in allowing the user to specify the input parameters, rather than having the model make decisions.

A simple analysis scheme for a scour model is shown in Figure 1. The inputs to the model include:

·iceberg geometry

·bathymetry (seabed slope)

·soil strength characteristics

·environmental conditions.

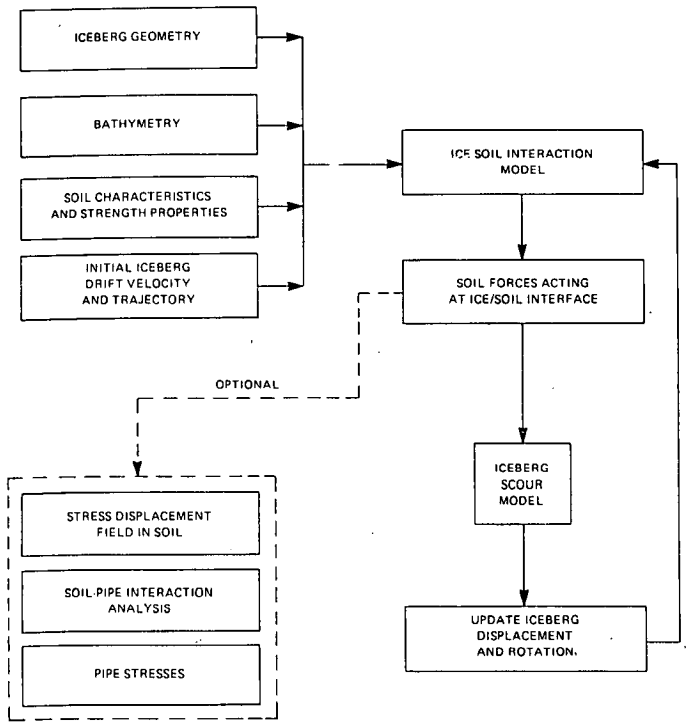

Figure 1. Analysis scheme for the scour model.

Usually, iceberg shape can be described using relatively simple geometries. The model has the capability to accept complex geometric shapes with up to 1,500 facets. Soil-resistance functions for typical soils are determined by the user in an offline calculation, and are input as a family of pressure-versus-penetration curves. Users can generate these curves using whatever soil model they wish, such as limit equilibrium or finite element analysis methods. Selection of environmental conditions by the user, (such as wind, waves, and current) establishes the iceberg's trajectory and velocity.

The two main components incorporated into the model are the hydrodynamic and ice-soil interaction components. The hydrodynamic component allows us to monitor continuously iceberg stability as we step through time. Both environmental forces and soil forces at the ice-soil interface (determined by the ice-soil interaction component) are calculated for all iceberg facets. At each time step, these forces are used to determine soil displacement and iceberg movement. Iceberg stability is checked, and a new iceberg position is determined. This procedure is used repetitively to follow an iceberg through a scouring event.

CONCLUSIONS

Our modelling efforts should provide us with a tool which can be used to determine scour depth, and which will allow us to determine the factors that have greatest influence on the scouring process. When the model development is complete, we plan to run parametric analyses. Factors such as iceberg shape, mass, and draught, wave height, wave period, current, wind, seabed slope, and soil-strength properties are to be considered. Optional refinements (see Fig. 1) could be made to the model to include, for example, soil-pipe interaction. This work has not been undertaken at this time.

DISCUSSION

Walter Bobby, Newfoundland Petroleum Directorate: You indicated that you had a hydrodynamic model for free-floating icebergs. Does this mean that during this scouring process you are varying your hydrodynamic parameters?

Lorne Schoenthaler: No. The hydrodynamic parameters are entered as input and are assumed to remain constant throughout the scouring process. The model has a stop-start capability which enables us to stop the program and to enter new hydrodynamic parameters, and then to continue if we were to observe a major change in berg stability. In general, the hydrodynamic parameters would not be varied during a scour.

Peter Barnes, U.S. Geological Survey: You didn't mention anything about ice forces from a surrounding ice field acting on the iceberg. Is this part of your model or is it an addition?

Lorne Schoenthaler: Generally, sea ice does not occur in conjunction with scouring icebergs in the Hibernia area. It is relatively simple to include additional forces on a berg from surrounding ice, if we wanted to.

Roger Pilkington, Gulf Canada Resources Inc.: How sophisticated is your soil-ice interaction? Are you assuming a blunt face on your iceberg, or are you assuming slanted faces?

Lorne Schoenthaler: We consider various seabed slopes and various berg face inclinations. The inclinations of the berg faces are input by the user when inputting berg geometry. The soil resistance functions take care of the angle of ice-soil interaction.

Mike Lewis, Atlantic Geoscience Centre: Can you say anything about the time increments that you chose from the viewpoint of those who might be proposing to monitor some icebergs? What sort of time step information would be of interest to you in looking at your model?

Lorne Schoenthaler: The time steps that we have been using in some of our initial runs are 1 s. We plan to use slightly larger time steps in the future to reduce computing time. The length of time step selected must be compatible with the wave period.

ICEBERG CRATER CHAINS AND SCOUR UP- AND DOWNSLOPE

Don Bass
Faculty of Engineering and Applied Science
Memorial University of Newfoundland
St. John's, Newfoundland, A1B 3X5

and

Chris Woodworth-Lynas[1]
C-CORE, Memorial University of Newfoundland
St. John's, Newfoundland, A1B 3X5

INTRODUCTION

An iceberg crater chain is the term given to a repeated scour feature which occurs randomly on the seafloor in areas affected by iceberg scouring. It has been observed on several side-scan mosaics that have been produced for the Labrador Shelf, but, as yet, has not been observed on the Grand Banks of Newfoundland. Crater chains occur in linear or curvilinear groups with crater diameter decreasing along the length (Fig. 1). Each chain consists usually of no more than six craters that are either linked together or spaced apart. Outlines of the crater on the seafloor indicate that the keel shape of the scouring berg may play an important part in determining crater morphology. Both linked and unlinked crater chains may be associated with one or both ends of a normal scour. We were interested in seeking an explanation for these features in terms of scouring icebergs, because they are found in areas where normal iceberg scours occur.

Don Bass at the Faculty of Engineering and Applied Science at Memorial University attempted an analysis of the features by extending Dr. Chari's model (described by Chari in this volume) to include impact of rolling icebergs with the seabed. The model is reduced to two dimensions by taking a normalized cross-section, which results in it having three degrees of freedom: vertical motion, rotation about a horizontal axis, and horizontal translation.

TWO-DIMENSIONAL MODEL

The results that follow were obtained using a model representing a 6-million-tonne iceberg with a shape that is fairly characteristic of large icebergs on the Labrador Shelf. The model has a trapezoidal-shaped keel. We perturbed this inherently unstable iceberg so that it rolled sufficiently for the keel to touch the seabed. Figure 2 shows the details of the keel's shape used in the model.

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[1]Presenter.

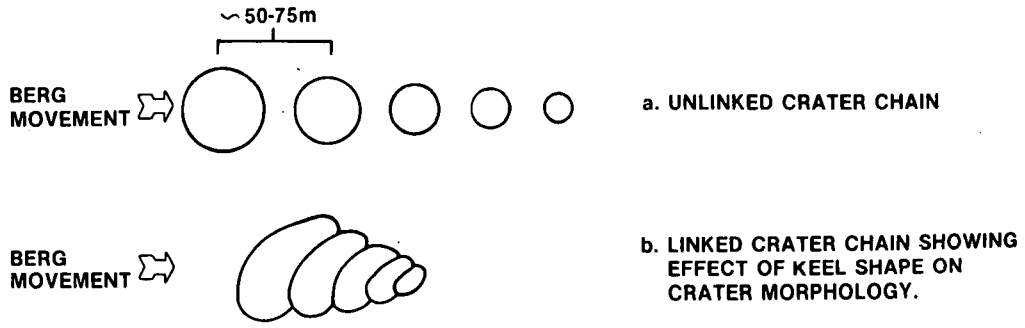

Figure 1. Iceberg crater chains: (a) unlinked crater chain; (b) linked crater chain showing effect of keel shape on crater morphology.

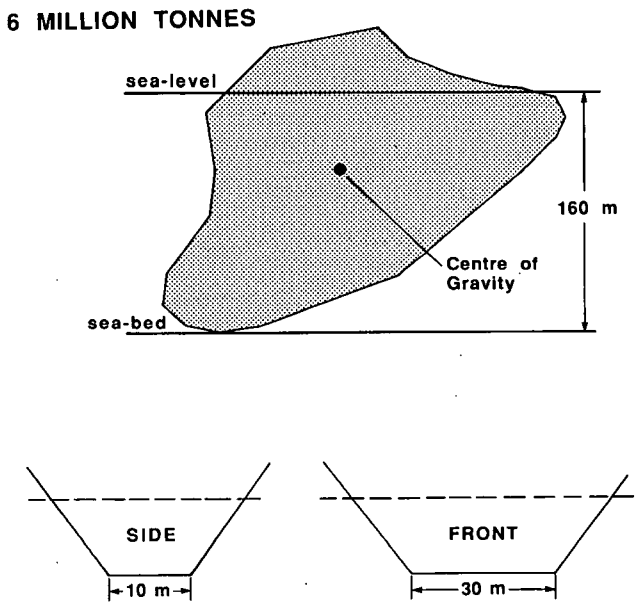

Figure 2. Characteristics of the iceberg keel.

In developing this model, emphasis was placed on iceberg dynamics rather than on the actual scouring mechanism on the seafloor. We have taken Dr. Chari's model for the horizontal impeding forces, and the vertical impeding forces are based on simple bearing-capacity formulae. Both these forces are dependent on the cohesive shear strength and the submerged unit mass of the soil. In the example discussed here shear strengths are taken in the range of 20-30 kPa. The submerged unit mass is taken as 1.5 tonnes per cubic metre.

It is felt that added mass is considerably underestimated because of the underkeel effects when an iceberg is so close to the seabed. The underkeel effect may increase the added mass by up to 1.5 times the actual mass of the iceberg. Thus, a 6-million-tonne iceberg may be driven into the seabed with the force equivalent to that produced by a 15-million-tonne iceberg. The model iceberg was induced to roll by "calving" a piece off, so that it started to oscillate backwards and forwards as the forward motion continued. Figure 3 indicates model results for the cratering sequence for a 6-million-tonne iceberg with a 160-m draft resulting in an unlinked crater chain developed in 25-kPa strength soil. A critical dynamic factor is the distance between the centre of gravity and the metacentre, GM, which in this case is 1.7 m. A drift velocity of 0.5 m/s has been used, which is a typical value for icebergs in the Labrador Sea.

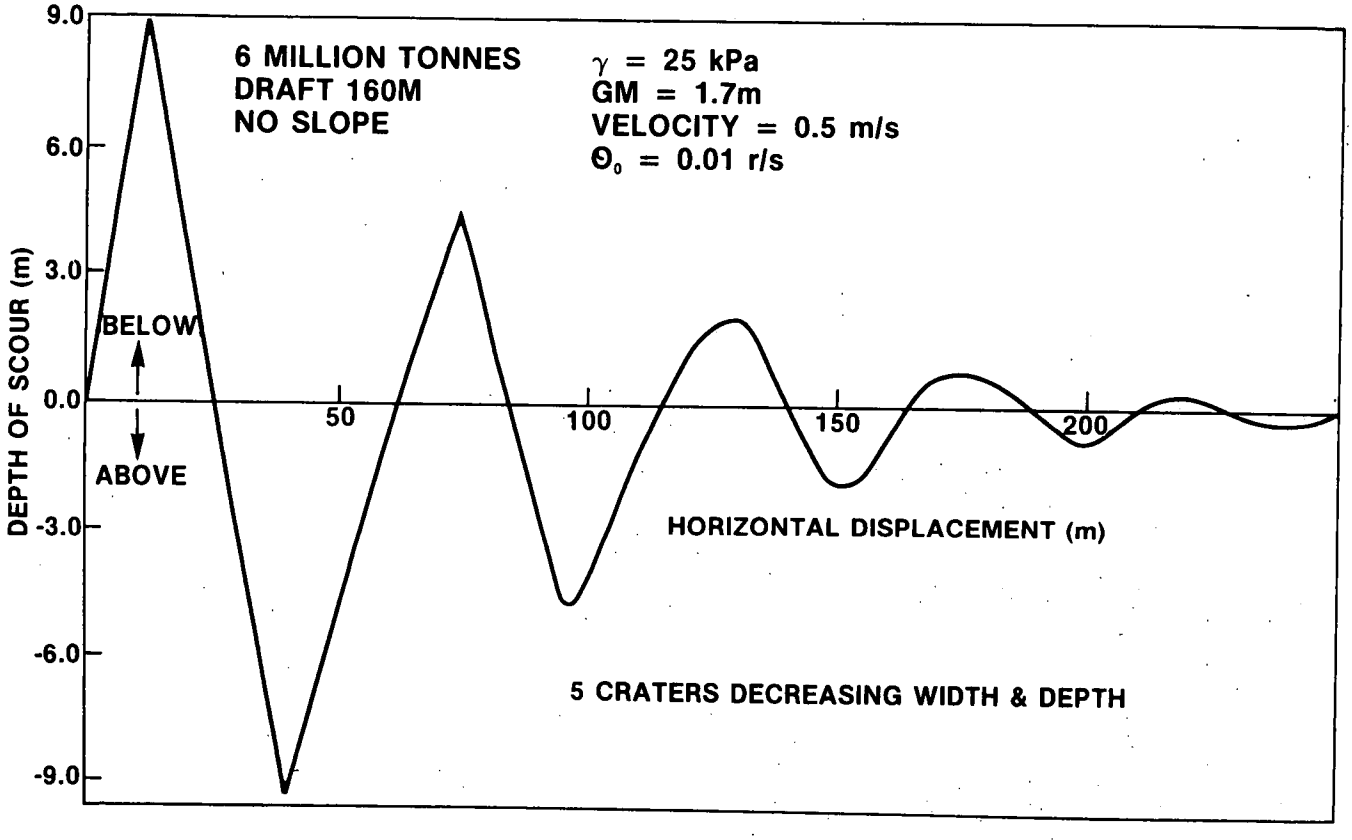

Figure 3. The cratering sequence for a 6-million-tonne iceberg.

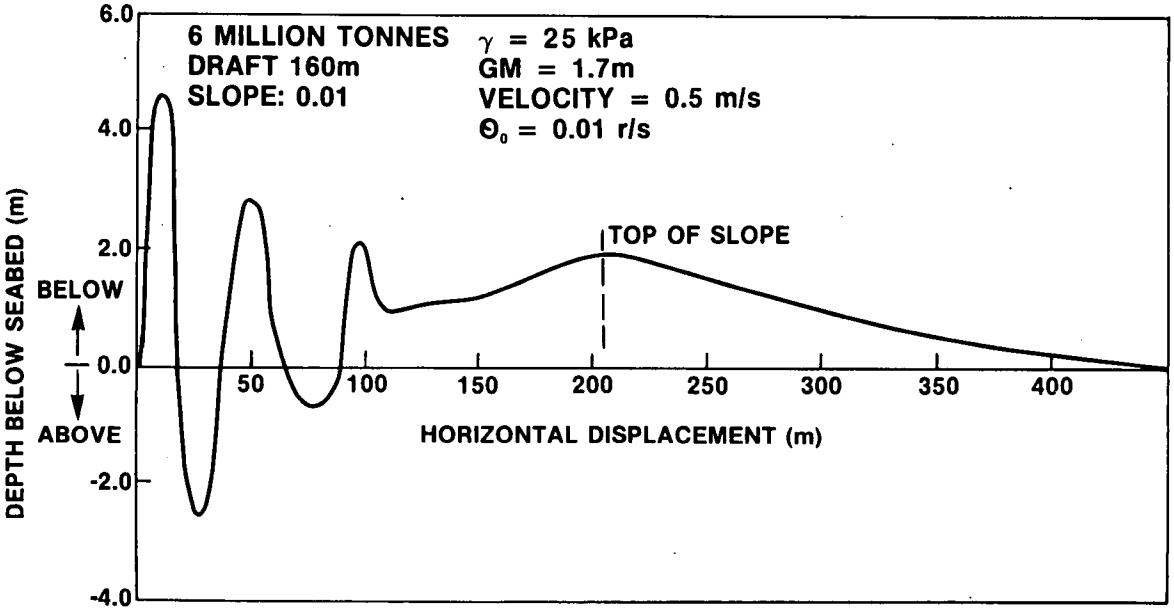

Figure 4. The sequence of events that occur as the modelled iceberg penetrates the seafloor.

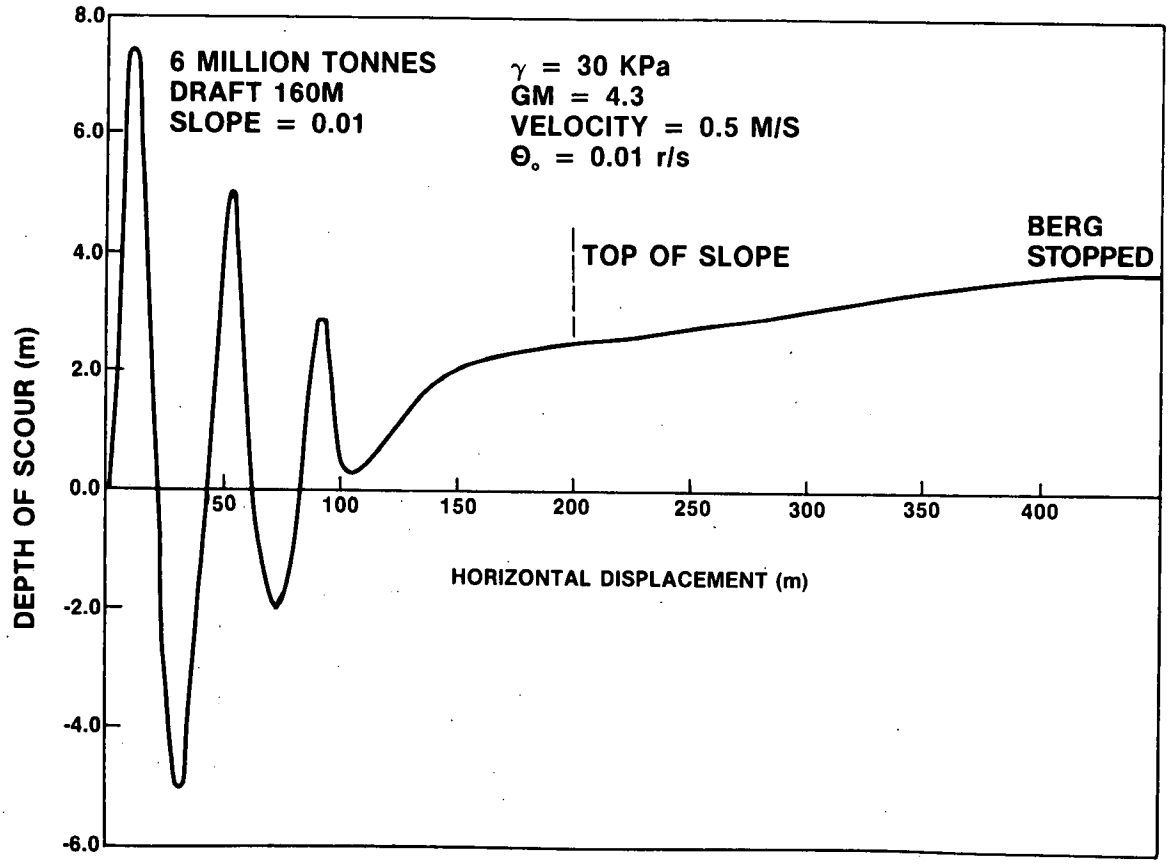

Figure 5. A cratering sequence with a seabed soil shear strength of 30 kPa.

RESULTS AND OBSERVATIONS

The sequence of events as the same modelled iceberg penetrates the sea floor is shown in Figure 3. The keel contacts the seabed and punches a hole 9 m deep. Restoring forces then cause the iceberg to lift, followed by another bottom contact with penetration of 4.5 m. This oscillation continues until the damping effects of the soil and hydrodynamic forces cause a state of equilibrium to be reached. With the input condition as above, the outcome of this process is a chain of five or six craters with a spacing of about 50 or 60 m. Side-scan records of actual events indicate similarly consistent spacing of unlinked crater chains.

PRESENT DEVELOPMENTS

An ESRF study of upslope and downslope iceberg scouring is currently underway at C-CORE. The same model can be extended to include upslope and downslope translation. We introduced a seabed slope of 1 in 100 to the model.

Figure 4 shows the same iceberg model as it oscillates and scours up- and downslope. After forming three craters at 15, 50, and 100 m the oscillations are damped and the keel becomes progressively more entrenched until it reaches the crest of the slope at 200 m. As it scours downslope, the keel gradually lifts out until the iceberg becomes free-floating 500 m from its starting point.

Figure 5 shows another cratering sequence with a seabed soil shear strength of 30 kPa. Under these conditions, the iceberg keel becomes entrenched after forming three craters, incises itself into the top of the crest, and continues to scour. The scour actually becomes deeper on the downslope side, in this case. A sequence in which the iceberg hits the slope without any initial rotation has also been generated but figures are not available. In this case, the iceberg scours into the seabed and into the crest of the ridge as before. As it comes over the top of the ridge, it starts to rotate backwards. However, the righting moment is apparently insufficient to cause the iceberg to scour as deeply into the downslope side as in to the upslope side. The scour depth on the downslope side is significantly less, and the iceberg actually lifts clear in a much shorter distance than previously. If this model is realistic, then, in geological terms, if a scour on one side of a ridge is longer than on the other side, the scouring direction can be extrapolated.

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DISCUSSION

Peter Barnes, U.S. Geological Survey: You didn't say anything about the connected craters?

Chris Woodworth-Lynas: That is a function of the current velocity. For connecting craters the forward velocity of the berg would be lower.

Peter Barnes, U.S. Geological Survey: Is there a description of these craters anywhere?

Chris Woodworth-Lynas: No, there is nothing in the literature. Our modelling work will address this.

Peter Barnes, U.S. Geological Survey: Can somebody say what size or what shape the craters are?

Chris Woodworth-Lynas: Craters are no more than 50 m in diameter and usually are spaced at intervals of 50-75 m between crater centres. We don't know how deep they are because they have never been traversed with an echo sounder. We don't know if the 9-m depths predicted by the model are realistic or not.

Randy Gillespie, Geonautics Ltd.: The models as usual are very elegant and beautiful in simplicity. Something concerned me in your description of the unlinked crater chains. It appeared that the time the keel would have been in contact with the seabed tended to increase as the oscillations dissipated. It means that the craters should smear out. Do you find that that happens?

Chris Woodworth-Lynas: This smudging effect has not been addressed in detail. It may be that the craters get slightly more elongated as the keel moves forward, but this is not significant. We have neither completed all the measurements on the observed crater chains nor compared them with model predictions.

Bill Roggensack, EBA Engineering Ltd.: Do you start the iceberg in an unstable orientation?

Chris Woodworth-Lynas: Yes, almost.

Bill Roggensack, EBA Engineering Ltd.: Do you apply a perturbation to the iceberg to take it out of static equilibrium and then start it against the seabed at some point? Are the observations the result of this damping process?

Chris Woodworth-Lynas: It is damping itself, but the seabed certainly has an effect on that too.

Bill Roggensack, EBA Engineering Ltd.: So at the end of this particular simulation, presumably the keel of the iceberg is in contact with the seabed?

Chris Woodworth-Lynas: It is just in contact with the seabed. The keel lifts out and re-enters. There are many variations you could put to this.

Bill Roggensack, EBA Engineering Ltd.: So it is the hydrodynamic aspect here that is very important in determining the type of prediction you make, with respect to both the size and frequency of the craters and also to the end scour depth and length of scour. It is quite interesting.

Brian Lee, Dobrocky Seatech: Anybody who has had the privilege of spending a couple of weeks on a supply boat on standby has probably seen icebergs roll, certainly when they are under tow. Looking at the periods of oscillation involved, I would say that your model's time scales are

realistic. The only way you can tell if an iceberg is or is not rolling is to line yourself up with a part of the vessel and watch. You often see a full cycle in 3-5 min. So I find those times very believable, as well as the fact that icebergs can hit the bottom and come back. Returning to the stable condition is an extremely slow process; it is so slow that you can't tell with the naked eye whether or not the icebergs have stopped rolling.

Alan Ruffman, Geomarine Associates Ltd.: Do you ever find icebergs that scour in the middle of nowhere on flat surfaces? I think your craters are from rough surfaces with a certain degree of slope. The craters that I have seen certainly are. Professor Chari's second model, where he proposes that after rolling into the bottom an iceberg would scour on forever, is applicable to flat bottoms. This second model does not need any slope at all.

Chris Woodworth-Lynas: Where are you seeing your scours?

Alan Ruffman, Geomarine Associates Ltd.: On a mosaic from the Rut wellsite.

Chris Woodworth-Lynas: I haven't looked at that sufficiently yet, but I will. I did not see any significant change in slope on that mosaic.

DYNAMICS OF ICEBERG GROUNDING AND SCOURING (DIGS) EXPERIMENT

C.F.M. Lewis
Atlantic Geoscience Centre
Geological Survey of Canada
P.O. Box 1006, Dartmouth, Nova Scotia, B2Y 4A2

INTRODUCTION

We have heard many comments at this workshop and at earlier meetings that documentation of iceberg-seabed processes and verification of scour-depth prediction models is an important requirement for present and future research. We propose to address this problem by monitoring two or more icebergs through their natural grounding and scouring modes in contact with the seabed. Such an exercise is not without difficulties. As considerable planning has been done and some commitments have already been made toward the experiment from various organizations and agencies, we think it is timely to present the plan and to solicit comments, support, and suggestions. Individuals who have participated in the experiment planning are H.W. Josenhans, K. Moran, and D.R. Parrott of Geological Survey of Canada, Bedford Institute of Oceanography (BIO), S. Smith of Atlantic Oceanographic Laboratory (BIO), J. Lever, C. Woodworth-Lynas and J.V. Barrie of C-CORE, Memorial University of Newfoundland, and S. Hotzel of Petro- Canada Resources.

The overall purpose of this experiment is to observe iceberg- grounding processes, to measure and then to relate the iceberg forces to seabed response for validation of scour formation models. As now planned the DIGS program will commence during the 1985 season.[1]

OBJECTIVES OF DIGS

In attempting this program, we feel several objectives should be addressed. The first objective is to determine the iceberg forces on the seabed and the second is to determine the seabed response to those forces. The third objective is to determine the effects of the seabed on iceberg motion and drift trajectory. The fourth objective is to observe possible hydrodynamically induced sediment redistribution effects during scouring events. The fifth and final objective is to identify a scour mark of known age so that its future degradation with time can be determined.

[1] The DIGS program was conducted on Makkovik Bank, Labrador from 28 July to 28 August 1985 as a project of the Environmental Studies Revolving Funds.

OPPORTUNITY EXPERIMENT ON GRAND BANK

Clearly the main interest in terms of the application of results of the case history studies will be verification of scour prediction models for development of the Hibernia oil field on northeast Grand Bank. The problem with the Hibernia area as a testing ground is that iceberg incursions are rare and difficult to predict. What we need is an area where icebergs are almost sure to appear and where grounding events are likely to occur. We have, therefore, divided this experiment in two parts. We are projecting an experiment of opportunity at Hibernia if suitable icebergs become available and a dedicated experiment on Makkovik Bank off central Labrador where we can expect about eight groundings during the month of August.

The experiment of opportunity in the Hibernia area would be keyed to a program already planned by Dr. Stu Smith (BIO), who has been studying iceberg dynamics for the last three years. This program concerns the response of icebergs to currents and winds on the ocean surface. These observations will occur in late April and we hope that if icebergs do go aground, their scour marks will be detected for a follow-up survey using a Pisces submersible. Surveys using this equipment are scheduled by BIO for July and October. If no groundings are reported the submersible would be available for other tasks.

DEDICATED EXPERIMENT AT MAKKOVIK

There are four phases planned for the dedicated experiment at Makkovik. The first phase would involve a dedicated iceberg-observing ship during the period from late July to late August. At that time of the year, following the decay of sea ice cover, icebergs are in a free-drifting state and are generally abundant and accessible. We would then establish a system of iceberg monitoring. Selected large icebergs that appear to be heading for the Makkovik Bank area and which we would expect to ground or scour would be instrumented to measure tilt, rotation, and acceleration. This iceberg motion sensing will be handled by the ice group headed by Jim Lever at C-CORE. Continuous monitoring of the instrumented icebergs, and the currents, winds, and waves applied to them is intended. We are planning to use an Amatek Straza acoustic doppler system mounted on the same observing ship to monitor the current profile continuously. Shape and size of the iceberg above water will be determined by stereo-photography whereas that below water will be profiled using acoustic systems.

Observations are planned to evaluate the extent of a possible sediment plume set into suspension during the scouring process and the nature of sediment failure mechanisms around the grounding iceberg. Both these phenomena would be investigated using video, turbidity metering, and water sampling capabilities of a ROV (remotely operated vehicle) deployed from the observing ship. The seabed scour mark would be mapped by side-scan sonar surveys and precisely positioned for follow-up studies.

Phase two of the program would be a follow-up survey, probably in late August. This survey would involve geophysical mapping in which high-resolution, heave-compensated seismic profiles would dimension and place the scour mark into the context of the local geology. A bathymetric grid would be surveyed and several photographic cross-sections of the scour would be obtained.

Phase three which is now committed, is a Pisces submersible investigation of newly formed scour marks to be supported by the Geological Survey of Canada and Bedford Institute of Oceanography. With this facility, scientists will document surficial sediments, ice-scour marks,

and their character through sampling, video photography, and a shallow penetrometer. At selected locations tracer sediments and depth of disturbance rods will be established on the seabed to assist in evaluating sediment dispersal, erosion, and deposition as processes of ice-scour degradation.

The fourth phase involves a transect of boreholes, or penetrometer probes, or both across the scour mark to document the nature and extent of ice-related sediment deformation.

The fifth phase would be the continuing study of the degradation of scour marks. This study would be accomplished by follow-up examination in subsequent years.

DISCUSSION

T.R. Chari, Memorial University: Are the currents in the area being monitored?

Mike Lewis: The currents would be determined directly from the observing ship using an acoustic doppler current meter. Current meters may also be moored in the area as part of the continuing long-term study by BIO on the Labrador Current. Those data would supplement the DIGS iceberg and environmental measurements.

Bill Roggensack, EBA Engineering Ltd.: The plan then is to restrict the program to natural groundings and not necessarily to tow an iceberg onto a predesignated spot on the sea bed.

Mike Lewis: It is a natural grounding experiment, in water depths of 90 m or greater.

Bill Roggensack, EBA Engineering Ltd.: Is phase four yet committed?

Mike Lewis: No, that is a future requirement. The committed portions are services provided by BIO. Thus a ship with submersible is available from BIO. Support for part of phase one, phase two, and phase four is still being sought.

REGIONAL GEOLOGY AND SEABED DYNAMICS AT THE PROPOSED ICEBERG SCOUR (DIGS) EXPERIMENT SITE

Heiner W. Josenhans
Atlantic Geoscience Centre
Geological Survey of Canada
Box 1006, Dartmouth, Nova Scotia, B2Y 4A2

INTRODUCTION

The physical properties of the seabed have a significant impact on the shape, width, and depth of iceberg scour marks. It is important for detailed process-oriented studies of iceberg scouring to understand the nature of the seabed where the scouring has occurred. This brief report outlines the seabed properties in the vicinity of the Dynamics of Iceberg Grounding and Scouring (DIGS) experiment proposed for Makkovik Bank, Labrador.

GENERAL SETTING

Makkovik Bank, situated on the central Labrador Shelf (Fig. 1), was chosen as the most suitable site for three reasons: it is inundated annually by many icebergs; it has depths similar to the Hibernia discovery area; and it comprises a variety of geological units within the depth range of modern iceberg-scouring. A Labrador iceberg draught distribution (Hotzel and Miller 1983) suggests that icebergs can ground in up to 230-m depth within the Makkovik area. Within this depth range on Makkovik Bank the following geological units are known to occur: over-consolidated bouldery till (designated as Unit 3A); well-stratified silty clays (designated as Unit 4); and a lag gravel up to 60-cm thick resting on the over-consolidated till of Unit 3A. The regional distribution of these units is shown in Figure 2.

DETAILED DESCRIPTION OF UNITS

The geological units mentioned (which are described formally in Josenhans et al. 1986) have the following names and physical characteristics.

Lower Till (Unit 3a)

Only the reworked surface veneer of Unit 3a on bank tops has been sampled, and no sub-surface samples are available. The sand fraction (0.053-1 mm) of the till is composed largely (80%) of crystalline rock fragments. Fragments of clastic sedimentary rock and of lithic carbonate comprise the remainder. The proportion of carbonate detritus decreases southward from about 20% on north Saglek Bank, to 5% at Makkovik Bank.

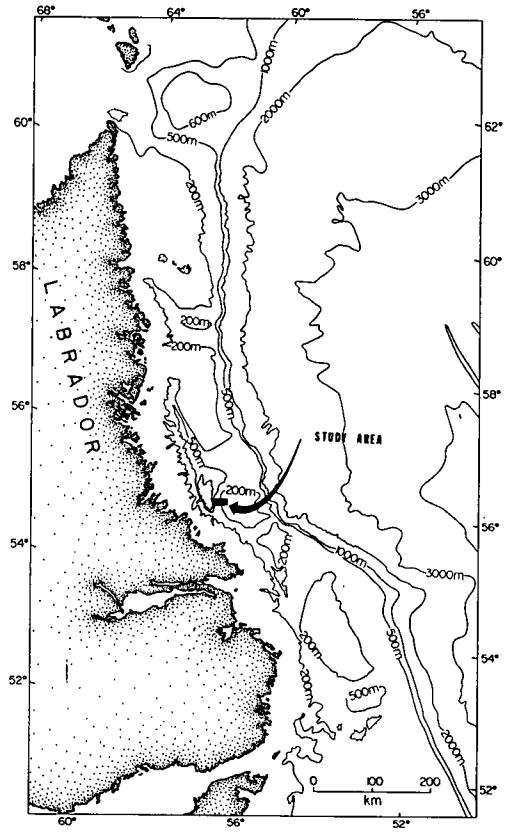

Figure 1. Location of DIGS experiment site on Makkovik Bank Labrador.

Upper Till (Unit 3b)

The upper till is laterally consistent throughout the Labrador Shelf area with regard to its acoustic, geotechnical and paleontological characteristics. Unit 3b is acoustically and physically unstratified and composed of dark greyish brown (Munsell Code 3/2 2.5Y), poorly sorted sandy mud with gravel and boulders. No fragments of lithic carbonate were found within the main bulk of the till, although within two cores some carbonate debris occurs within the uppermost 0.5 m. The break between upper till and overlying Qeovik Silt is clearly recognized by lithological, geotechnical, paleontological, and geochemical character. Geotechnically, the unit is slightly overconsolidated (OCR range 0.8-2.8), and has an average shear strength of 20 kPa, a water content of 25-30% of dry weight, and bulk densities of 1.8-1.9 gm/cc. Liquid limit is typically 34% and plastic limit is 16% (Silva et al. 1984).

The upper part (within 1 m of upper contact) of the till contains occasional foraminifera tests (less than 10 specimens per 35 ml of sediment) that are characteristically fragmented and abraded. The dominant foram species found within Unit 3b are Elphidium excavatum forma clavata, Cassidulina reniforme, Islandiella helenae, and Nonionellina labradorica (Hardy 1985). The species Elphidium excavatum is considered to be an indicator of a cold-water, ice-proximal environment (Vilks 1980; Scott et al. 1984).

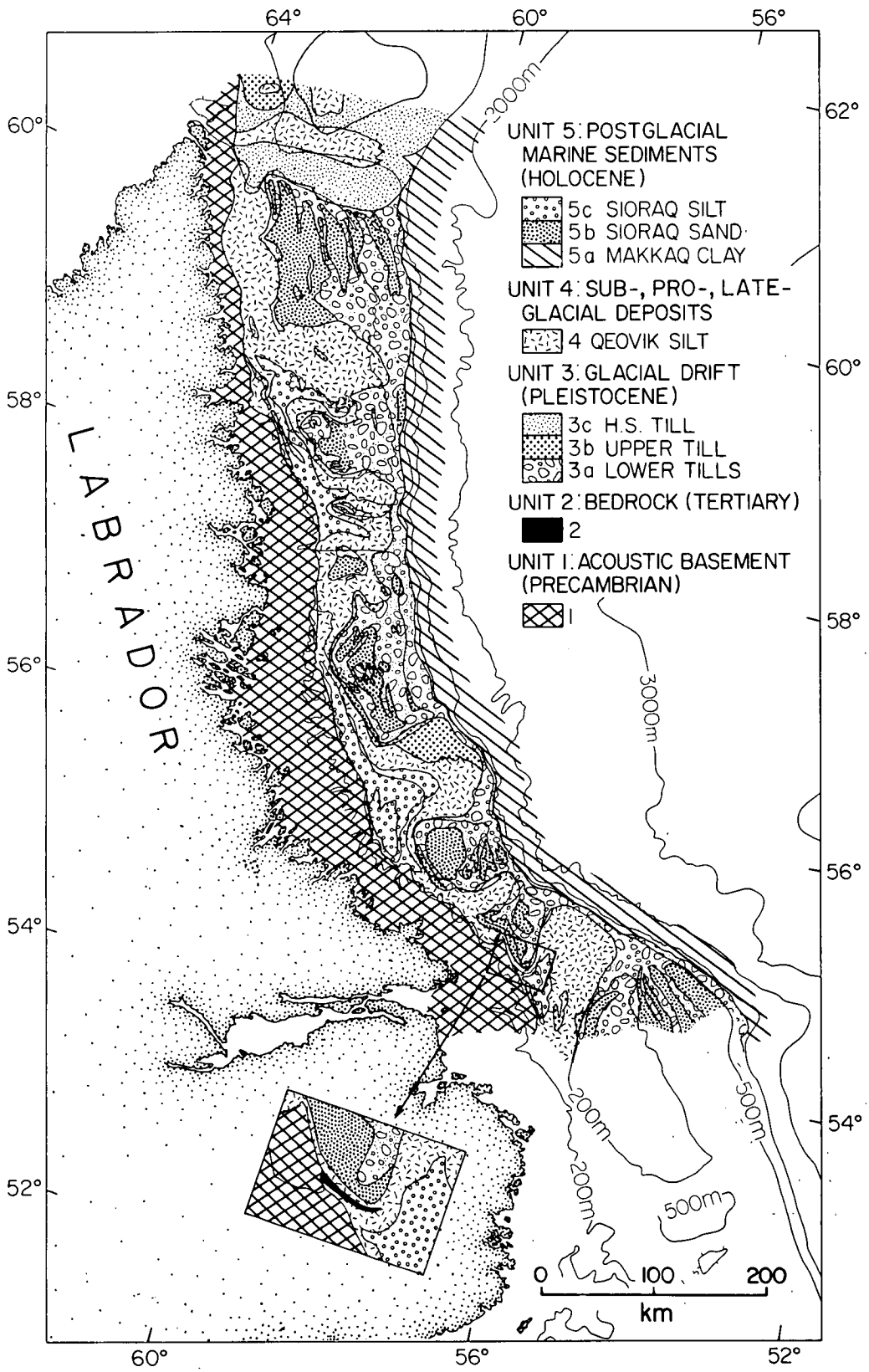

Figure 2. Surficial geology of Makkovik Bank (after Josenhans et al. 1986).

Qeovik Silt (Unit 4)

The Qeovik Silt is a well-stratified olive grey (Munsell Code 5Y 4/2) sandy mud commonly containing coarse clasts presumably ice rafted. Unit 4 typically fines upwards from its lower contact with Unit 3b. In its lower part Unit 4 contains coarse sandy beds and laminae characterized by highly variable, high-angle depositional structures (convolute bedding) and by graded bedding. The unit has a shear strength of approximately 4-18 kPa, water contents of 20-60% of dry weight, and bulk densities of 1.3-1.9 gm/cc. Typical liquid and plastic limits are 33% and 12% respectively. Sand-sized fragments of lithic carbonate occur throughout and are a characteristic component of the Qeovik Silt. The abundance of carbonate debris varies from 50-60% near Hudson Strait to 15-30% in the central region of the Labrador Shelf.

Unit 4 contains abundant, well-preserved, foraminifera tests, including Elphidium excavatum forma clavata, Cassidulina reniforme and Islandiella helena (Hardy 1985), which are indicative of cold-water, ice-proximal conditions. Individual species are represented by 5000 to 10,000 tests per 35 ml of sediment. Scott et al. (1984) described the detailed foraminiferal and palynological data analysis for the upper 8 m of the Qeovik Silt in Cartwright Saddle as well as the overlying Makkaq Clay. On the basis of their independent evidence they pick the clay-silt boundary at the same location and infer detailed paleoenvironments during their deposition.

Sioraq Sand (Unit 5b)

Unit 5b is a thin, locally variable and patchy veneer of sand to muddy sand which occurs on the top and periphery of the banks. The sand is frequently reworked by modern grounded icebergs. Lithologically, the unit resembles the underlying till and ice-rafted debris. The amount of limestone decreases from north to south. Geotechnically, the unit is highly variable and generally too sandy for detailed analysis.

SEABED PROCESSES

The bottom photographs, representing shallow areas, shown in Figure 3, show consistently a gravel-sandy seafloor with many well-developed bedforms indicative of active sediment transport and erosion. In the deeper areas, between 160-130 m, coarse sediments (sands and gravels) form only a veneer above the underlying clays and fills. In water depths between 130 m and the bank top at 85 m, patches of mobile sand appear to migrate over the lag gravels. The well-developed lag gravels and freshly formed gravel and sand waves indicate considerable disturbance and reworking of the seabed by bottom currents and bedload transport and suggest that fresh scours may be rapidly obliterated. The presence of one scour mark at 154 m with clearly visible and sharply defined groove markings suggests a newly formed scour which was probably formed in the same year (1983) as the photograph was taken.

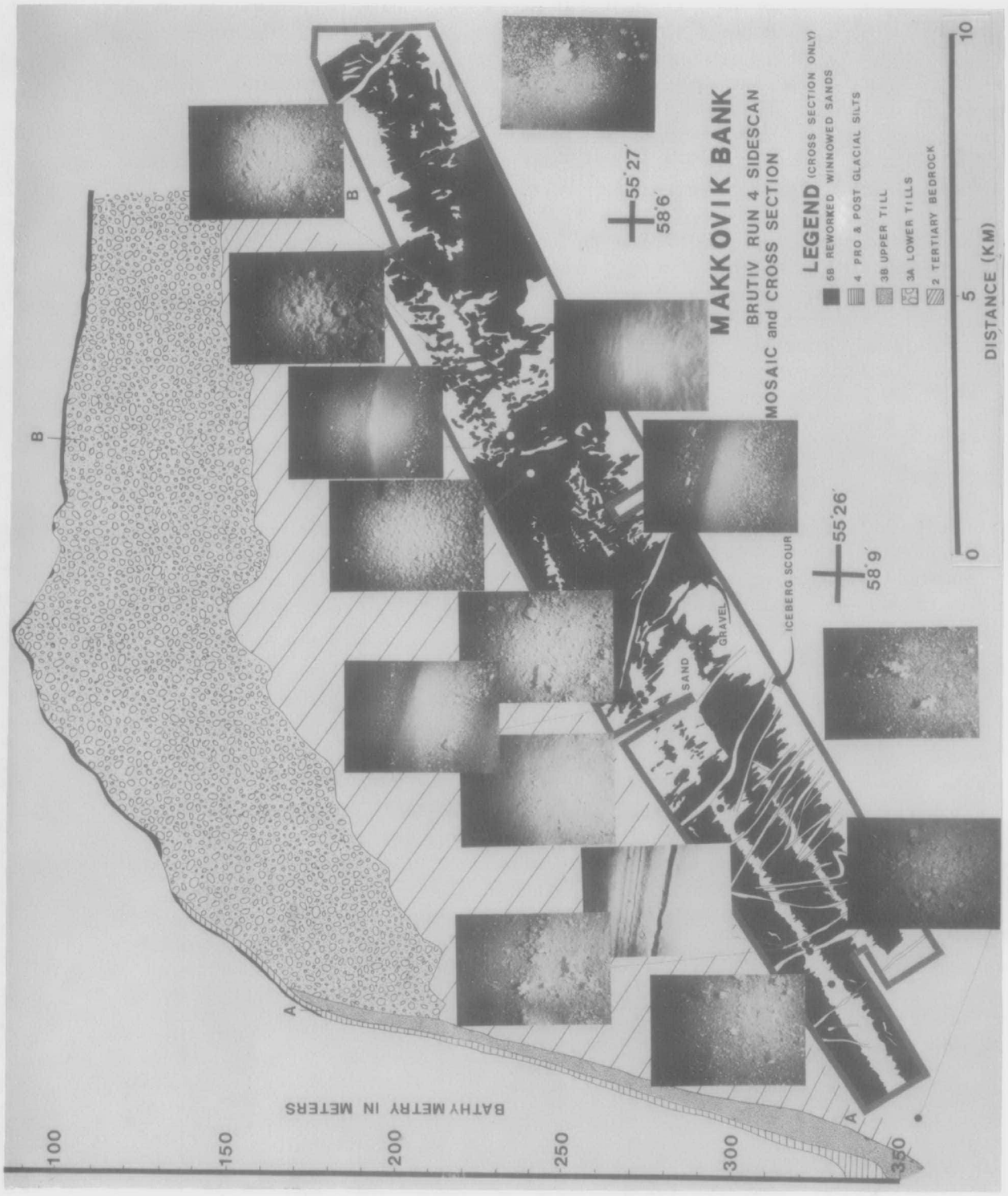

Figure 3. Bottom photographs, sidescan sonar mosaic and seismic section of Makkovik Bank.

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ICEBERG DYNAMICS OF THE DIGS EXPERIMENT

Jim Lever
C-CORE, Memorial University of Newfoundland
St. John's, Newfoundland, A1B 3X5

INTRODUCTION

My main interest is in the motion of small ice masses and waves for the Dynamics of Iceberg Grounding and Scouring (DIGS) experiment (Lewis, this volume). This involves time and length scales considerably different from those usually associated with the geological processes of iceberg scour. The icebergs, bergy bits, and growlers that I am considering are not necessarily involved with scouring, but the techniques that are being developed should be applicable in monitoring iceberg motion during a scouring event. This report summarizes our recent activities.

FIELD PROGRAMS

To appreciate the problem areas in iceberg dynamics, we decided to measure wave-induced iceberg motion directly. A sensor package was developed for these measurements. This unit is about 1 m in diameter, and includes a six-degree-of-freedom sensor package with three linear accelerometers, two tilt sensors, and a compass. The sensor outputs are recorded directly on an eight-channel tape deck, and the entire package is enclosed in a watertight sealed hemisphere.

The package can be deployed by helicopter onto very small ice masses. This package was tested in the field off Labrador last summer. Even in the calm sea, we were able to measure very small accelerations and clear indications of wave-induced motion. The results are being analysed, and will be presented at the Conference on Port and Ocean Engineering under Arctic Conditions (POAC) in September 1985 (Lever and Diemand 1985). The package was also deployed on some larger bergy bits. In fact, the instrument package recorded the behaviour of two icebergs during the last few minutes before each rolled. This information was an unexpected side benefit of the program.

FORCES INVOLVED DURING SCOURING

The relevant questions are: What are the forces acting on an iceberg during scouring, and how can we measure those forces? The forces acting on an iceberg are summarized in Figure 1. There is wind drag, water drag, and gravity. There is the Coriolis force, and what is shown in Figure 1 as the buoyancy force offset from the centre of gravity. It is anticipated that when the seabed forces act on the keel of the iceberg, in general a rotational moment will be induced. Although models have been developed that ignore this, in the general case it should be included.

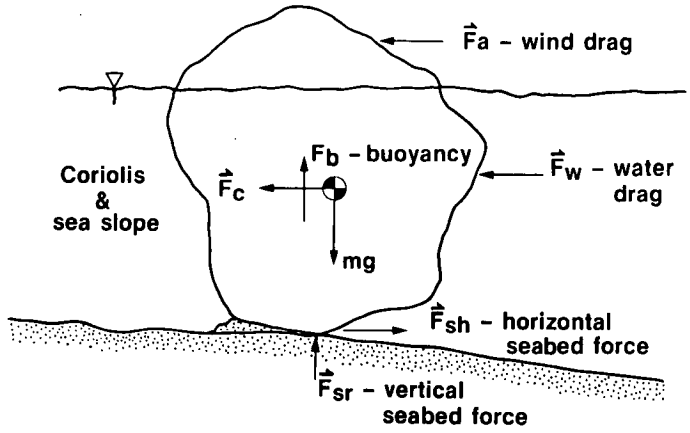

Figure 1. Forces acting on an iceberg during scouring. See text for explanation.

The seabed force can be broken down into horizontal and vertical components. Environmental forces such as wind and water drag inherently involve the iceberg shape. For simplicity, we assume that the drag forces increase as the square of velocity. The Coriolis force is related to the mass multiplied by the Coriolis parameter, which is a function of the earth's rotation, latitude, and the relative velocity of the body in water.

These forces change temporally and spatially, and they also change as the relative velocity of the iceberg changes. Thus, there is significant variability in the environmental forces acting on the iceberg. The buoyancy force will be equal to the weight of the displaced water if the vertical seabed force is small compared with the total weight of the iceberg. These gravity and buoyancy forces are not difficult to deal with if you have good shape information. But inherent in the whole problem are the uncertainties in the environmental forces.

Measurement of Forces

We can put an instrument package with six degrees of freedom on an iceberg and can measure its motion when free-floating. If we can anticipate which iceberg will scour, we can then measure the transition or the change in the behaviour when the scouring process begins. In principle, by comparing the two, we are able to obtain the total force on the iceberg. However, the question remains, can the seabed forces be extracted from the total force?

There appear to be three possibilities for obtaining a solution. We can apply a method that Smith has developed at the Bedford Institute of Oceanography (BIO) which models these different environmental forces (Banke and Smith, 1984). The result is given by the difference between the observed behaviour and the behaviour predicted by modelling the effect of the environmental forces, this difference being the seabed force. It is a simple model and it assumes one degree of freedom. It does not account for the rotations or uplift of the iceberg, or for temporal

variability of the seabed force. Thus, the model has inadequacies, but it does produce a number. It represents a baseline effort to obtain seabed force.

The next possibility assumes that the seabed force is large compared with the environmental forces, or certainly as large as the environmental forces involved. This assumption suggests that linear decelerations during scouring could be substantial, and that the uncertainties in the estimates of the environmental forces will not overly influence the uncertainty in the measured or the calculated seabed force. This may give reasonable estimates of the total force, providing environmental forces based on measured currents are used along with best-fit drag coefficients from free-floating behaviour.

However, the more likely situation is that the seabed force is not large compared with the other forces. In fact, it could conceivably be an order of magnitude smaller, because the very long, straight, scour marks of constant depth suggest that the seabed is not slowing down the iceberg very rapidly. Iceberg drift trajectory work undertaken at C-CORE indicates that you cannot easily distinguish between a free-floating iceberg and one that is scouring. Changes in current forces could easily account for the transition to a stationary state. The seabed may not necessarily be the reason why the iceberg stops. In the general case, the seabed forces are not necessarily large compared with other forces.

ONSET OF SCOURING

In this general case, uncertainties in the environmental forces will have a big effect on the uncertainty in the calculated seabed force. In trying to reduce these uncertainties, we have to consider all the possible techniques that have been discussed today. It is felt that the elimination of degrees of freedom in modelling scouring icebergs is wrong. Only in certain restricted circumstances can an iceberg be considered to be ploughing at constant water depth. Only in certain circumstances can the iceberg be considered to scour and uplift without roll and without reorienting itself.

In the general case, we will have a situation where the contact of the seabed with the iceberg will not be directly below the centre of gravity (CG). Also, the two environmental forces, wind drag and water drag, will not necessarily be coincident with the centre of gravity. If we look at the transition between the free-floating condition and when the iceberg begins to scour, we should be able to determine how far off centre and therefore how important these are. Presumably, the rotations of the iceberg in the horizontal plane (yaw) are small when driven by the environmental forces.

Once in contact with the seabed, an imbalance occurs, and initially the other environmental forces will not counterbalance the seabed force. Therefore, an angular rotation is set up (Fig. 2). We have largely eliminated uncertainties in the environmental forces from influencing our calculated seabed force. The environmental forces will not necessarily be negligible, but their effects will be reasonably constant until the tilt angle increases significantly.

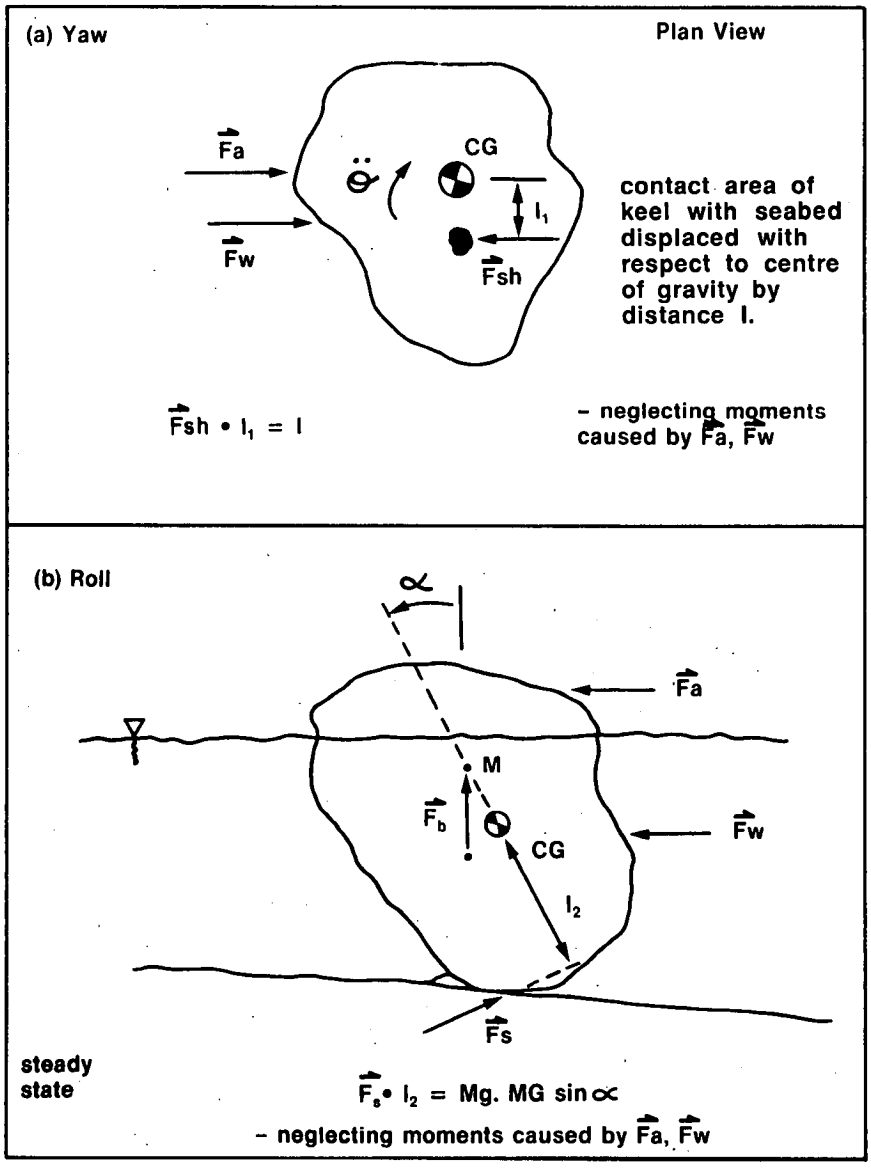

Figure 2. Angular motion of a scouring iceberg.

Whether the iceberg will first yaw or pitch is unclear. The seabed force acts at a distance from the centre of gravity. Whether the angle is small or large depends on the stability of the iceberg. Once equilibrium is reached, the buoyancy force acting upward through the metacentre (M), counterbalances the seabed force. This shift in the buoyancy force is a function of the angle of rotation and the stability of the iceberg. If the iceberg is very stable, then the angle is small, and the seabed force is quickly counterbalanced by the shift in buoyancy force. If this iceberg is not very stable, then a large rolling effect will be generated by the same seabed force. From the steady-state inclination and rolling characteristics, we should be able to calculate the seabed force. For roll behaviour, the seabed force becomes very much more dominant than in the previous case where all environmental forces were considered.

My understanding of the problem suggests that this will be the norm. You will get rotations in both planes. In fact, only if the iceberg is very stable about all axes will the keel not move significantly during scouring. From seafloor observations we know that, even when bathymetry is changing, fairly uniform constant-depth scours of 1-2 m are produced. This suggests that for a bathymetry change of 8-9 m there are 8-9 m of either uplift, which I think is unlikely, or rotation. I think the norm will be a combination of both. If the iceberg is very stable in all configurations, the keel will not be able to move out of the way, so the iceberg will either uplift a long way or ground very quickly. If it grounds very quickly, we will be able to measure the forces. If it uplifts a long way, we will be able to measure the uplift from our aerial photography work. The only circumstance that remains is the situation in which the iceberg rolls however, this condition can also be measured. We are quite satisfied that we will be able to measure the motions of the iceberg and infer the seabed forces, even if all the circumstances mentioned above occur.

CONCLUSIONS

This program is not without uncertainty. However, I feel the correct approach is to consider the situations where the seabed force is dominant. The seabed force is the dominant force inducing angular motion of the iceberg. It should be possible to obtain accurate estimates of the seabed force based on observed rotational behaviour and measured iceberg shape data. The advantage of this method is that we get independent estimates of the seabed force to compare with an estimate based on the method used by Banke and Smith (1984) using environmental data.

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GEOTECHNICAL ASPECTS OF THE DIGS EXPERIMENT

Kate Moran
Atlantic Geoscience Centre
Geological Survey of Canada
Box 1006, Bedford Institute of Oceanography
Dartmouth, Nova Scotia, B2Y 4A2

INTRODUCTION

The physical property measurements of the Dynamics of Iceberg Grounding and Scouring (DIGS) experiment (Lewis, this volume) are important for two reasons: to help understand the scouring processes that occur at a specific site, and to provide verification for modelling programs.

This discussion centres on the types of tools that are available for this experiment. During August, the Bedford Institute of Oceanography (BIO) has access to the Pisces submersible, and we are at present, having a cone penetrometer built by Dr. Campanella at the University of British Columbia that will be mounted outside the vehicle. This part of the field program is an excellent opportunity to measure the relative variations in sediment properties across the scour. The cone penetrometer is 1.3 cm^2 in area, and measures tip resistance. It has a 1-m penetration capability. At the selected site, we will be using the cone penetrometer to obtain data from the surface of the scour. The primary consideration in the design of all such tools is the limited amount of reaction force available from the submersible. We will also be collecting surface samples from the submersible.

The second part of the sediment property measurement program will involve tools that are, as yet, undefined. There are parts of this program that are incomplete, and we are hoping for some input from this meeting. We are considering the new NORDCO corer with a cone penetrometer option, which has a potential penetration to 10 m. Depending on the availability of funds, there is the possibility of drilling several deep boreholes for continuous sampling and testing. This would tie in the ice-scour measurements with the known geology of Makkovik Bank.

SPECIFIC MEASUREMENTS

In the case of the site-specific measurements on the scour using the Pisces submersible, the only measurement apart from temperature that we have is tip resistance. This parameter is quite useful. However, there may be some features of the scour that would merit further investigation, for example, relative strength properties of the undisturbed zone versus properties at the centre of the scour and at the berm.

It would be useful to have a three-channel cone penetrometer to collect information on stratigraphy or bearing capacity and strength for particular sediment types. In addition, it would

be advantageous to collect samples for classification purposes and to get the stress history, present stress regime, and shear strength at the location of, and within, the scour.

There are still some questions to be answered if the NORDCO drill or similar equipment is to be used. Positioning may require an acoustic transponder network. If a borehole program is to be undertaken, then an offshore positioning system such as Syledis or Argo would be necessary to tie in the drillship location with the Pisces coverage.

This summary covers the extent of the planning to date. We would be interested in suggestions and comments from the floor.

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DISCUSSION

Walter Bobby, Newfoundland Petroleum Directorate: I have two questions on instrumentation. First, I understand that basically you have three accelerometers. What happens if during the scouring process the iceberg does not have, or exhibits too much, acceleration. Will there be sufficient output from the iceberg instrumentation? The second question concerns the geotechnical measurements. Are we confident that the affected zone is within 10 m?

Jim Lever, C-CORE: On the issue of the accelerometer output, I indicated that the accelerations and decelerations are small. It may be advisable to extract the seabed force utilizing the rotational motion from the linear decelerations. You run out of possibilities quickly if you do not have rotation. What happens if there is no rotation, but the bathymetry changes 8 m? You must assume uplift, in which case we will measure the force. We must be able to see the above-water portion rise 8 m out of the water.

Bill Roggensack, EBA Engineering Ltd.: It seems to me that there may be some advantage in selecting the iceberg that you measure on the basis of shape, because the response, particularly to rotation, is going to be enhanced if the iceberg is slender.

Jim Lever, C-CORE: The issue of deciding which icebergs will eventually go aground during the test period is a difficult one, involving environmental uncertainty. We can collect the same information if we put a package on an iceberg which is scouring and then leaves the shelf. We expect that an iceberg which goes from the scouring mode to the free-floating mode will also give us the same information.

Bill Roggensack, EBA Engineering Ltd.: That is why I raised the question earlier. If it was not completely impractical from an economic standpoint, it would be interesting to select the iceberg with the best hydrodynamic features, and then tow it so that you would have all the preconditioning in place. You would know where it was going to ground, and could possibly extract more data from the experiment with greater certainty.

Kate Moran: The second question about the 10-m penetration figure is because the present NORDCO drill is limited to a 10-m extension. If we were interested only in a 3-m scour, then the 10-m capability might be adequate. It is a question of costs; obviously, a borehole would be better.

From the floor: When does the penetrometer go out to be tested?

Kate Moran: Probably in early March 1985.

John Miller, Petro-Canada: One important point not developed in the discussion is the underwater shape. In considering the angular component and moment of inertia you must have very good estimates of the three-dimensional shape of that iceberg. You also have to take the free-body motions measured at the upper surface and correct them down to the centre of gravity or the centre of buoyancy. Therefore, the shape is absolutely mandatory for that type of program. This does not mean vertical profiles using a sidescan on five or six faces. It will involve an operation similar to that described by Dave McGonigal (this volume; McGonigal, D., A.F. Stirbys, and J.L. Lussenberg. Grounded ice features and their associated scours in the Beaufort Sea) using the OSNL or another type of acoustic system.

Peter Barnes, U.S. Geological Survey: I want to comment on Heiner Josenhans's model of the gouging processes with the strong hydrodynamic forces (this volume; Josenhans, H. Regional geology and seabed dynamics at the proposed iceberg scour (DIGS) experiment site). Could the model accommodate what we have seen in the Beaufort Sea and off Norway where you do get squishing out, i.e., actual displacement, of subsurface materials to create the ridges, with the lag deposits transported laterally except at the front end where the material is pushed aside?

Heiner Josenhans, Atlantic Geoscience Centre: We have seen lineations in the bottom of the scours and clean cobbles sitting on the seabed. In between those cobbles were occasional residual clay lineations which have exactly the same orientation as the well-preserved ones at the bottom of the scour. That is why I conclude that there has not been any injection or remoulding of the sediment in that zone. I think those things are in situ. I think Reidar Lien's model is a very realistic possibility (this volume; Lien, R. Iceberg scouring and its influence on seabed conditions: investigation and proposed model for the Norwegian Shelf).

Alan Ruffman, Geomarine Associates Ltd.: There are a significant number of items that haven't been funded at this point. How much of your budget is committed and how much of that is firm?

Mike Lewis, Atlantic Geoscience Centre: I would like to take that in reverse order. We would like to determine if this is a worthwhile experiment. If it is worthwhile, and if it will answer some of the questions that have been raised today, and if it will give confidence to some of the models and perspectives that people hold for the scouring process, then it is worth funding.

Alan Ruffman, Geomarine Associates Ltd.: What level of funding are we talking about? I suspect that the Canterra program to look at moraines was of the same order in terms of the ultimate cost to the taxpayer. That project didn't make it.

Mike Lewis, Geological Survey of Canada: I think the budget is adequate to do what we are proposing to do.

T.R. Chari, Memorial University: I have a question for Jim Lever. You are assuming that you are going to determine the hydrodynamic forces fairly accurately, and then estimate the soil forces. This may be a problem, because of the question of the drag force and the added mass. Probably your objectives should be a little more flexible in the sense that if you correlate the size measurements with estimated side forces, you may obtain a better estimate of the hydrodynamic forces.

Jim Lever, C-CORE: I do not want to give the impression that we can do any better than other people in estimating those hydrodynamic coefficients. You can estimate those components and still be left with a large uncertainty in the seabed force. What I meant was that we can look for circumstances where the seabed force predominates; that is the reason for the interest in rotational motion. This is not always the case, but I think in most of them, it will be.

Peter Simpkin, IKB Technology Inc.: Is there any merit in measuring the acoustic noise generated by the iceberg, probably with a sonobuoy or a similar device?

Mike Lewis, Atlantic Geoscience Centre: I think that is one parameter we neglected to mention, but I believe it can be included as one channel in the sensor package. I'm not sure what the frequency range could be.

Jim Lever, C-CORE: That subject has been discussed, and I think we are going to take a good look at trying to do just that. John Miller's comment concerning iceberg shape is very valid. We appreciate the importance of iceberg shape.

Alan Ruffman, Geomarine Associates Ltd.: I think there would be a value in deploying an acoustic navigation net out around a grounding iceberg. It would also act as a positioning system for the geotechnical sampling and, in the long term, for the degradation studies. Also, if the budget could afford it, it would be valuable to consider some of the same documentation techniques that were used in the search for the Thresher. These are relatively inexpensive compared with operating a submersible and give you a much more visual representation of the seafloor.

From the floor: Would Geomarine fund that part?

From the floor: Much laughter!

George Comfort, Arctec Ltd.: I was considering the uncertainty in hydrodynamic forces, and wondering if it might be useful to include a series of model tests to determine the current drag coefficient once we know the iceberg's shape?

Jim Lever, C-CORE: I wonder whether scale models are really useful. I am not convinced that you can control the model experiment or understand what is happening at reduced scale well enough to improve the estimates in the coefficients. Perhaps the estimates for added mass can be improved, but in terms of drag I think the best methods of estimating the coefficients are those in current use which optimize the drift trajectory and the drag coefficients against the observed drift trajectory. If the wind vector and current vector can be measured, then I think you can do as well as with any model tests.

John Miller, Petro-Canada: The problem I have with the data collection program on the iceberg is that you are taking the uncertainty, including the many variables and combining them all in one parameter at the end. This method may be a good way to optimize your solution, but then you cannot include the drag coefficient. I think that uncertainty is another point to consider with Jim Lever's model. It is really important that the sum of the forces equals zero. You have to remember that for every wrong coefficient, for every incorrect value, or for every force missing, there is a residual term that enters into that equation. It is really the sum of the forces that equals the residual. If that residual is large relative to the seabed force you are trying to measure, then you will get a number out, but it will not be the true seabed force. You have to be very careful in interpreting that number, but do not be too hasty in calling it the seabed force.

T.R. Chari, Memorial University: There was a series of model tests done with values of the drag coefficient, C_d, between 0.63 and 0.9. Other model tests have been done with values of C_d of 0.52

and a multiplication factor of 1.4 if the iceberg is close to the seafloor. Another series of model tests indicated that C_d is 1.4 and 1.5. So the drag coefficient does vary, but I do not think one can use those values for a real iceberg, as there are some limitations.

SEABED RESPONSE TO ICE FORCES: SUMMARY AND DISCUSSION

W. Roggensack
EBA Engineering Ltd.
14535-118th Avenue, Edmonton, Alberta, T5L 2N7

and

T.R. Chari
Memorial University of Newfoundland
St. John's, Newfoundland, A1B 3X5

SUMMARY

From the presentations so far, we have highlighted in Figure 1 two main areas for further discussion as follows:

- the geotechnical effects of ice scour on the seabed; and
- the understanding of morphology and the making of predictions for the future as they might apply to design projects.

Geotechnical Effects

The effects we have characterized include the chaotic morphology of the seabed, for which ice scour is an attractive explanation, and the physical effects that large strains may have on soil properties. The results presented by R. Lien, (this volume, Iceberg scouring and its influence on seabed conditions, investigation and proposed model for the Norwegian Shelf) of substantial reductions in shear strength in the vicinity of a scour trough are possibly the first direct evidence we have seen of shear strengths being significantly affected.

Another aspect, which is perhaps of more geological interest, is the mixing, over-turning, and disturbing of surficial sediments that complicates the dating process of some of these features. That in itself has an effect on attempting to develop iceberg frequency relationships that extend to 1,500 year return periods.

Returning to the changes in properties: in both cohesive and non-cohesive soils, there are several types of properties that can be affected, such as strength, compressibility, and stiffness. These factors enter in the areas of pipeline design and with respect to structures on the seabed. I see a division in the geotechnical effects being somewhat directed toward the specific application whether it be a pipeline or a bottom-founded structure.

In the pipeline area we are concerned with depth of scour: How deep can they go in relation to given inputs from the environmental standpoint? What is the frequency? What pressures might these scours exert or what pressures might the ice features exert on pipes? Also, how can the pipeline accommodate soil displacement? Lastly, what structural design factors are necessary to overcome some of the undue effects that ice will certainly produce?

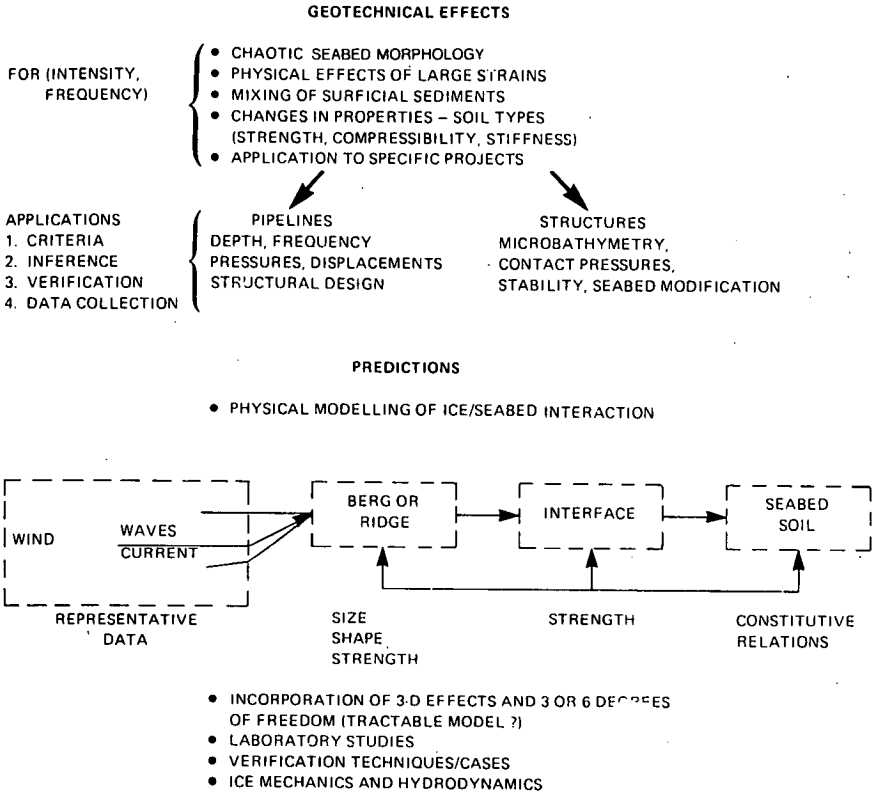

Figure 1. Seabed response to ice scour.

With respect to structures, Bea (this volume, Engineering aspects of ice gouging) has made a good case for having a close look at microbathymetry particularly with respect to the contact pressures that can be developed. Also important is the base contact area which in turn has significant financial implications with respect to bottom treatment, grouting underneath, and so on, to obtain full contact. Also, there have been discussions with respect to stability as affected by a zone of reduced shear strength produced by remoulding. Conversely, evidence in some areas, that the repeated shear straining has, in fact, produced an over-consolidated crust, indicates that the ice-scouring process may, under certain conditions, produce stronger soils. We have some controversy is this respect.

There is also the effect that these features have with respect to seabed modification that might be necessary for structures. We have applications of all of these topics in developing design criteria. Another application is in inferring the extent or effects of ice scour from geotechnical profiles. Other information gathered in this context could provide input for the verification of physical modelling.

Finally, there are requirements in the area of providing better guidelines for data collection. At present, data collection appears to be rather less directed toward the physical side than toward the environmental side.

Predictions

As far as predictions are concerned, modelling is very important. The more complex and realistic the model, the better the prediction of performance will be. To be frank about this, physical modelling of interaction between ice and seabed involves probably more components than any numerical modelling that we have read about in previous years.

Starting with the inputs (Fig. 1), we have all the environmental driving forces with waves and current being the predominant ones for icebergs. In the Beaufort Sea environment, wind shear becomes an additional driving force and has to be incorporated into the model. These forces combine to act on either the iceberg or the ridge. In turn, these forces act on the seabed against the resistance of the soil.

The important question here: What representative data do we input to the environmental side of the model? What need we do to gain a better definition of iceberg or ridge geometry, size, shapes, and, in the cases of ridges in particular, the strength of the ridge. Very little is known about interface strengths between soil and ice. We make gross assumptions with little justification.

The final section concerns the seabed soil which is the ultimate case of interaction between soil and structure. We are dealing with soil models that require fairly complex constitutive descriptions. We are also dealing with very large strains because some of the material is being displaced. To our knowledge, there is no modelling technique that currently addresses that topic. We presume you could apply finite element analyses, as in rock mechanics, but we believe that to be in the future. The jump from three degrees of freedom to six degrees of freedom in a model is big. Ultimately, we may think that it is necessary to go to the full six-degrees- of-freedom model and we have seen plenty of suggestions today that the hydrodynamic effects with icebergs are very important. There are therefore some compelling arguments to bring all six degrees of freedom into play. However, we must bear in mind as engineers and scientists that we have to have a practical model. This problem is analgous to the world climatological model where scientists try to model the entire atmosphere as a three-dimensional boundary layer. There are limits to what you can do.

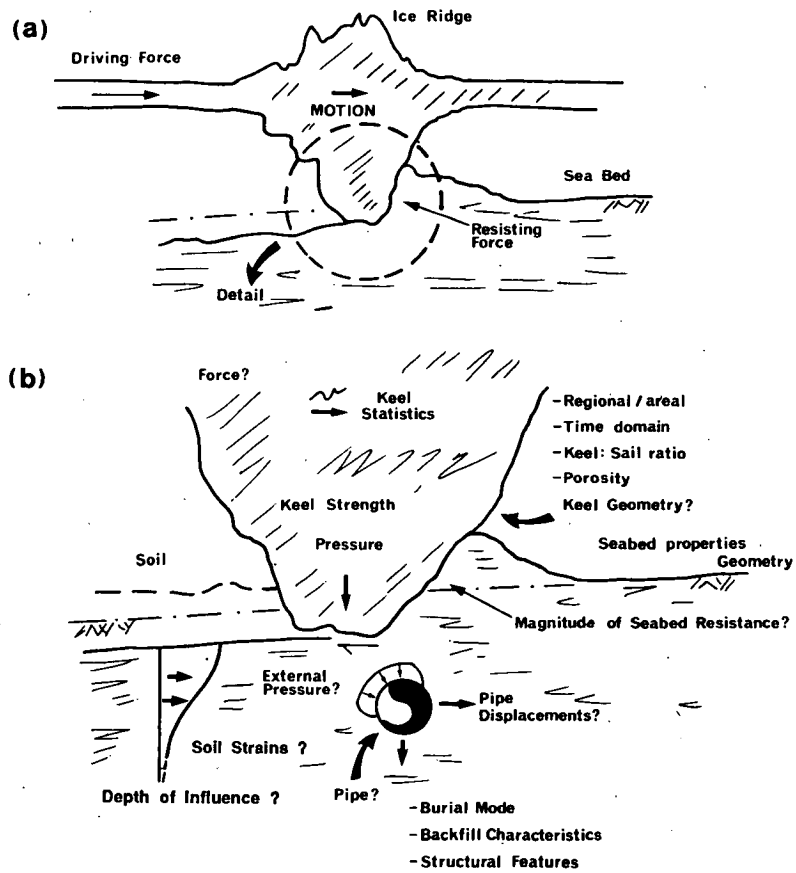

Figure 2. Ice keel scouring a possible pipeline route showing: (a) driving and resisting forces; and (b) detail of ice-soil interaction, and effect on a buried pipe.

Next we come to laboratory studies which include modelling studies and techniques to provide feedback into the ice-strength analysis and into the constitutive relationships for the seabed soils and for the interface. This area of interest is at a very early stage of development.

Lastly, we show the verification techniques and development of cases where we actually have good data. Complete sets of data for model testing still have to be collected. This topic is added as an afterthought but one can only presume that the sister disciplines of ice mechanics and hydrodynamics are also relevant here. We have had questions about damping and about added mass. Once again, some gross assumptions were made about these very important factors that to my knowledge, have not yet come anywhere near verification.

In reviewing the problem areas, it is convenient to look at a simple two-dimensional case of an ice feature scouring a possible pipeline route (Fig. 2). The driving forces include those environmental forces discussed earlier plus the global ice force resulting from the ice sheet. On the seafloor there is the reaction between the keel and the soil. First, we need a description of the keel itself and then a velocity and a driving force. If we isolate these forces we need to get some description of the regional context and areal contact, the time domain records, and the ratios of keel to sail which seem to vary tremendously. The porosity of the keel, which in turn relates to keel strength and the pressure that an ice ridge exerts vertically on the seabed, are other parameters. On the seabed itself, information is required on the geometry and physical properties. These in turn dictate to some degree the magnitude of resistance that is applied. Also the shearing force along the base contact area can affect the global ice forces above.

At depth, we have a pipe. We want to know what external pressures could be applied to it and what displacements both vertically and horizontally may be imposed as a result of the presence of the ice feature. To assist in pipeline design we also want to know how the soil strains vary with depth below the base of the scour. Lastly, we should consider the pipe itself. All of the discussions have ignored the fact that if the pipe goes into a ditch it may have to be back-filled so maybe the in-situ soil characteristics are not relevant at all. The back-fill itself may govern the interaction between the pipe and surrounding soil mass.

A final topic for attention is the modelling of the pipeline itself both with and without structural protection. These subject areas are very extensive and probably beyond the scope of this workshop. But some answers may result from the DIGS project.

DISCUSSION

T.R. Chari, Memorial University: I would like to add to that very full list of topics for discussion the techniques that could be used to fill the gaps in our knowledge of modelling and scour prediction. Where should we concentrate our future efforts? Are we happy with the simple models we have, or how complex should they be made? Finally, how well known is the technique of verification using field data in relation to the models that we will be able to develop?

Terry Day, Day and Associates: It seems to me that one of the big advances this year results from the work we did on King William Island, which indicates to us some of the geological processes that occurred during scouring. That work is still at a very early stage but one implication of our study is the role that water plays in iceberg scouring. Up to now the models seem to be using the effects of ice only and ignoring the effects of water.

Jim Grass, Ontario Hydro: My particular experience in Lake Erie has little to do with icebergs, but I recollect one study where we had to justify burying cables. We had good advice from consultants regarding the maximum depth of scour along the proposed route in Lake Erie and we knew the shear strengths of the soils fairly well. However, the models didn't seem to agree with the scour density obtained from the subbottom profiler records. Finally, I decided that the most important parameter was the depth of scour. I eliminated the soil strength, the ice strength, the pore-water pressure, and the hydrodynamics. I eliminated everything except the depth of scour because I was interested only in the depth of penetration. In reviewing the scour statistics, I took all the depths as being representative points in the population that I was sampling. I used the depth of penetration as my sample. Instead of using one, single, identifiable ice scour as a single scour, I took each individual depth measurement along that scour as being a separate event, which is probably unconventional. I measured the short scours, and the long scours I divided into short segments. Each cross-section was used as a separate scour event. Then I did the probablity analysis on these individual scours and the results were presented as a log-normal distribution. We had some idea of the tail of the distribution, i.e., the maximum depth of scour that one could anticipate, given the circumstances and the population that was sampled. What was the probability of having a scour greater than a certain depth? I would appreciate any comments on the technique.

Bill Roggensack: If I understand correctly what you did there was to develop a relationship that gave you probability of exceedance against depth of scour below the original lake bottom and along the axis of a scour track. You then ruled out any variation in the water depth that might have occurred along the track and ruled out any changes in soil conditions and said: "I'm going to make my ditch deeper than the extreme on my probability relationship."

Jim Grass, Ontario Hydro: Correct! The soil conditions are taken into account by the penetration of the ice into the soil. The iceberg doesn't say, "OK, I've got a strong soil and I've got water pressure etc." It is an accumulation of effects and that iceberg or ice keel scouring is the result of all those events and of all those parameters. Dealing with each parameter individually was intractable, so I simply eliminated them and took the depth of scour as being the ultimate requirement.

Lorne Schoenthaler, Mobil Oil Canada Ltd.: I would like to make a comment on the difference between the ice-scouring problem that you had in Lake Erie and the problem that we have on the Grand Banks. Where you are concerned about scouring by first-year ice, we are concerned about scours that may be relict features and that may have occurred earlier during a lower stand of sea-level. In trying to compare, with any accuracy, iceberg scours that could realistically happen today to relict scours, ultimately, if we were to look at depth only, we may be forcing ourselves into a design criteria for burial depth, which may be unrealistic. So our direction of approach has been that of trying to identify the form of a realistic scour. We could then use the maximum depth profile as a design parameter.

John Miller, Petro Canada: I have some concerns about modelling that I would like to address. For several years I have dealt with icebergs both from a theoretical and a modelling viewpoint. In terms of modelling, there are three areas that I would like to discuss; namely, model inputs, model formulation, and model verification.

First, as far as inputs are concerned, we have to be careful about how we drive our models. Today, we have seen two models presented with water current values of 0.5 m/s and 1 m/s, respectively. Those are certainly possible values but they are not the most common. They are relatively high and drive the models to their ultimate end. For icebergs, I think we see drifting velocities of 0.25 m/s. If we assume that force has a square law dependence on velocity, the estimates for the two models differ from the norm by factors of 4 and 16, respectively. Be reasonable about what goes into your model and also be aware of its limitations. Much

information has certain errors associated with it and that uncertainty will propagate through to your final answer.

Secondly, I have a point about combining model elements, such as a free-floating mode and a scouring mode. It is important to consider all relevant forces. By leaving some out you may change the final result and you also may have a deviation between the model and the real world. Once you have decided on your forces you have to decide which functional relationships you use to drive them. There is still a lot of controversy here. If we take current drag, we assume that it is probably proportional to the square of the difference between the velocity of the iceberg and the corresponding water. Changing that relationship has dramatic effects. Coefficients in the functional relationships vary tremendously. The drag coefficient in the simple Morrison-type equation might vary anywhere from 0.2 to a factor of 2.

Finally, once the model is producing results there has to be a verification process. I do not accept models until I have seen verification. A further point is to keep the data set that you used to generate the model independent from that used to verify it. The modelling is not the end point, it is its application down the line that is ultimately the important consideration. That concern is what is driving the whole modelling effort.

I started my career as a modeller and I have done a lot of modelling at Petro-Canada. I think I am becoming an empiricist. I have two quotes, one is from Confucius who said: "It is better to light a candle than to stumble in the dark." I think that is why we are modelling. The other one is by Thomas Carlyle who said: "Daily I grow to honour facts more and more, and theory less and less."

If your model doesn't reproduce reality, don't blame reality. I think reality is probably right.

REGIONAL ICE-SCOUR STUDIES AND DATA BASES

Session Chairmen:

S.M. Blasco
C.F.M. Lewis

OCEAN-BOTTOM SEA-ICE SCOUR: A COMPUTER-BASED DATA MANAGEMENT SYSTEM[1]

G.R. Gilbert
Geoterrex Ltd.
9865 West Saanich Road
R.R. #2
Sidney, British Columbia, V8L 3S1

and

S.M. Blasco
Atlantic Geoscience Centre
Geological Survey of Canada
Bedford Institute of Oceanography
Box 1006, Dartmouth, Nova Scotia, B2Y 4A2

INTRODUCTION

This presentation describes the Beaufort Sea Ice Scour Data Base, a project of the Environmental Study Revolving Funds which involved Geoterrex, Gulf Canada Resources, and the Atlantic Geoscience Centre. Three aspects of the data base are considered:

- the rationale behind the project;
- the quality control features applied to maintain the integrity of the data base; and
- how the data base can be effective in assessing seabottom conditions for pipeline design.

RATIONALE

In earlier papers, (Bea; McKeehan; Grass; and Allan and Roggensack; each in this volume) the concerns related to potential hazards of ice scouring effects on seafloor installations were discussed in detail. Adequate design for such structures requires a complete understanding of ice-scour processes and accurate statistical representation of the scour parameters essential to risk assessment. Confident interpretation of the ice-scour record is problematic, as it requires a cumulative history of scouring processes, including sea level changes, geological processes of scouring (e.g., scour infill, sedimentation, and erosion), and temporal changes in sea ice conditions.

[1] Presented by R. Quinn, Geoterrex Ltd.

The development of a computerized interpretation system for ice scour involves the recognition of some of the weaknesses of manual interpretation techniques. Manual techniques are invariably slow and often labour-intensive. Bias may be introduced to the data set, either artificially or unconsciously. A reinterpretation requires a second assessment of original analogue data, and reproducibility by separate interpreters can often result in data variability. After consideration, it was decided that digitizing the data set would provide a superior data package with advanced capabilities, such as plotting and statistical analysis. Digitization of the original field records also allows for easy data storage, updates, and reinterpretations.

To generate a data base of the Canadian Beaufort Sea, 5,000 line km of sidescan sonar, bathymetric, and other data were identified as the initial data set. In selecting this 5,000-km data base, considerations were made of the various bathymetric zones of the Beaufort Sea and the variations in surficial geology. The selection process also took into account representative geographical locations.

The computerized technique developed by Geoterrex Ltd. involves initial digitization of the sidescan sonograph by an experienced interpreter. This process involves a precision digitizing table used with a 1.5-m spatial increment, a microcomputer, and a nine-track tape drive for mass storage. The overall sequence of the data digitization procedure is illustrated in Figure 1. The ice scours on each table segment are individually digitized about a pivotal point. The position of this pivotal point is used in subsequent calculations of the scour parameters. Concurrently, the operator tabulates other interpretative values from the sidescan sonographs. These include the form of the scour, its morphology, smoothness, and relative age by a rough assessment of whether it is cut by other scours within the immediate area.

Other parameters that are entered into the data base include:

- identity of the operator (company) collecting the data;
- line information;
- scour identifying number and its position, orientation and statistical information;
- form, morphology, smoothness, and relative age;
- cross-sectional area and scour depth (from the sub-bottom profile records);
- sediment thickness and type, the amount of sediment infill, and the presence of sub-scour deformation;
- bathymetry; and
- assessment of data quality and other points of interest.

The scour data are collected in the computer and are stored in a binary format. They are then merged with the navigation data so that the co-ordinates of each scour can be computed. Scour area, length, and width are computed automatically. At this point, an assessment of data quality is made by plotting a scaled overlay for the sidescan sonograph. An example is shown in Figure 2. Multiple-keel scours are recorded in the original data base and are treated as a single event. Arcuate scours are recorded separately. Tables 1 and 2 list the parameters used in the sidescan sonar and echo sounder data bases.

The bathymetric data from the echograms are carefully digitized at 1.2-mm intervals, scaled, despiked, and combined with the navigation data. Because traditional ice scour depth

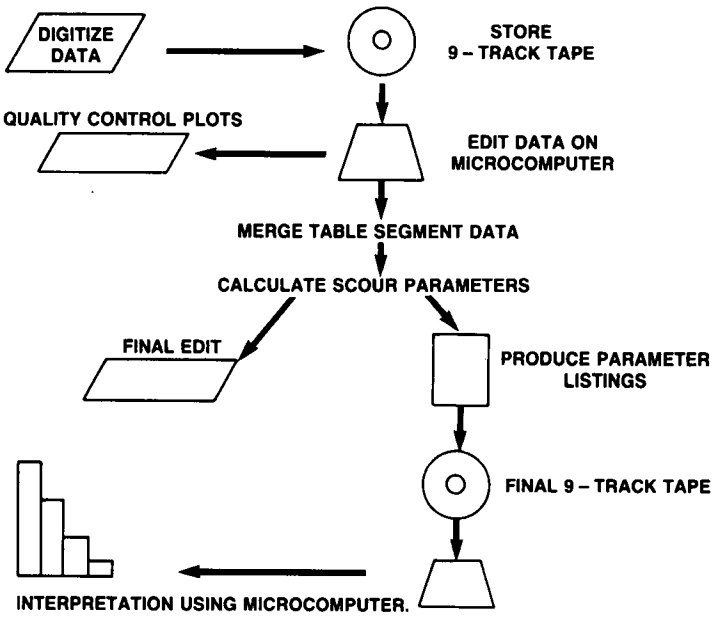

Figure 1. Flow diagram for processing sidescan sonar data.

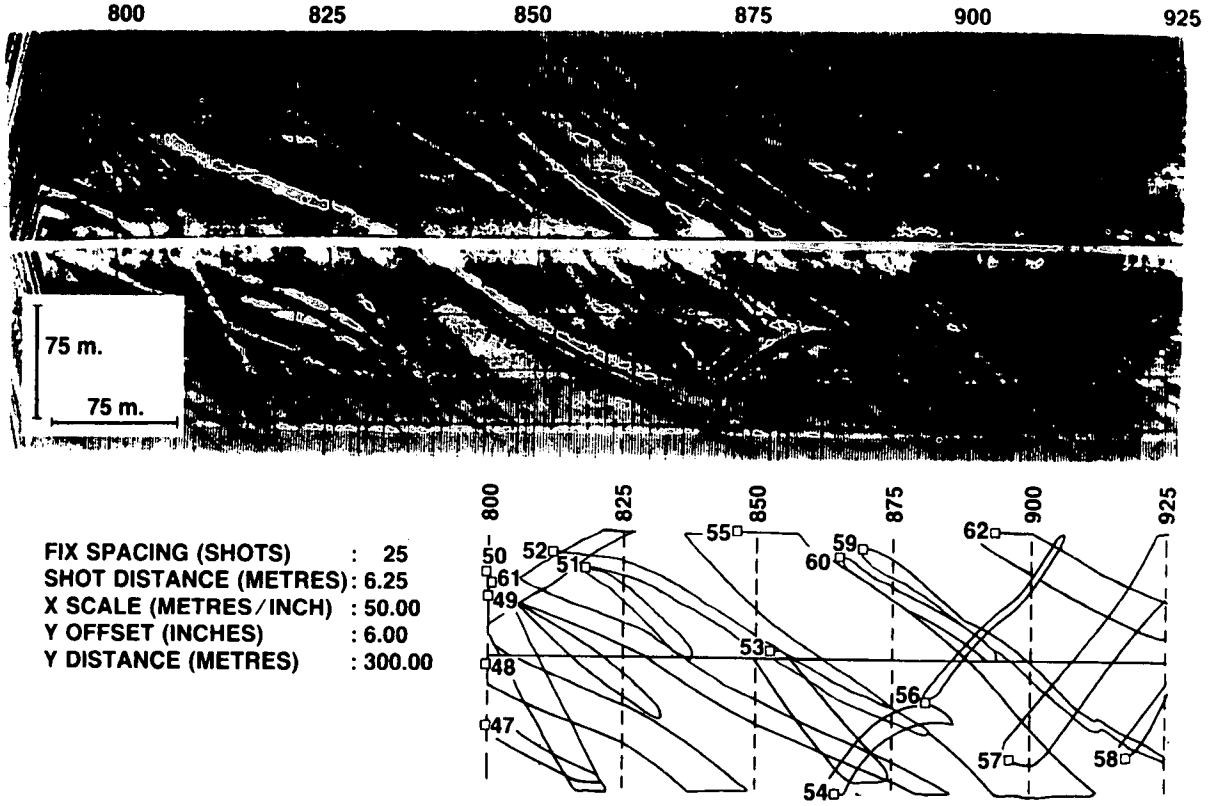

Figure 2. Sidescan sonar quality-control plot.

TABLE 1

Ice-scour parameters (sidescan sonar data base)

No.	Parameter	Description
1	Operator (company)	Operator who conducted survey
2	Year	Year survey was conducted
3	Line Number	Regional line number
4	Part number	Reference number if line is subdivided
5	Fix number	Shot number input for each scour
5	Heading	Ship's heading
7	Easting	UTM co-ordinate for scour location
8	Northing	UTM co-ordinate for scour location
9	Scour number	Specific reference number
10	Orientation	Scour orientation (computed)
11	Standard deviation	Standard deviation of orientation (computed)
12	Form	Single keel, multi-keel, or multi-keel zone
13	Morphology	Straight, arcuate, sinuous, or crater
14	Smoothness	Rough, moderately rough, or smooth
15	Relative age	Old, recent, or uncut
16	Length	Scour length as computed from record
17	Width	Average scour width (computed)
18	Area	Area of scour (computed)
19	Depth	Scour depth; subbottom profile (SBP) if present
20	Fix	Shot number for scour depth
21	Sediment fill	Thickness of scour infill (SBP)
22	Sub-scour deformation	Destruction of sub-scour stratigraphy (SBP)
23	Sediment thickness	Thickness of surficial sediment (SBP)
24	Sediment type	Clay, sand, or silt
25	Bathymetry	Bathymetric zonation, (5.0-m intervals)
26	Quality	Data quality: good, poor, or fair
27	Comments	Appropriate comments

TABLE 2

Ice-scour parameters (echo-sounder data base))

No.	Parameter	Description
1	Operator (company)	Operator who conducted survey
2	Year	Year survey was conducted
3	Line Number	Regional line number
4	Part number	Reference number if line is subdivided
5	Fix number	Shot number input for each scour
6	Easting	UTM co-ordinate for scour location
7	Northing	UTM co-ordinate for scour location
8	Scour depth	Scour depth computed from filtered profile
9	Seabed depth	Bathymetry to filtered seafloor
10	Quality	Data quality: good, poor, or fair
11	Comments	Appropriate comments

assessment is subject to great variability between interpreters, a process has been developed whereby the computer smooths the digitized seafloor and recognizes scour depths as significant departures from the smoothed profile. Tests run with different running average filters showed that a 41-point running average filter gave representative results in areas of moderate relief such as in the Beaufort Shelf (Gilbert et al. 1985). The filtered seabed data field is then subtracted from the original profile to give a field containing departures from the "local" seabed. This data field is used in the automatic detection and measurement of ice scours. Figure 3a is an example of an echo-sounder record, and Figure 3b shows the resulting digitized profile. In automatic detection of ice scour, the occurrence of ice scours with depths that exceed a certain threshold level is recorded, and details concerning, for example, position and water depths are extracted from the data base.

QUALITY CONTROL

Interpretations using the data base outputs have been compared with manual methods of data extraction as a means of assessing performance. The correlation between the two methods is generally high, although some tests using poor original data resulted in poor agreement between manual and computer methods. Comparisons using only one independent interpreter, however, are felt to be inadequate. To judge variability, nine independent interpreters who were accustomed to working with ice-scour data were asked to "pick" a selected echo-sounder record for scour depths. The results showed that the best fit to the nine distributions from the nine interpreters coincided with the computed distribution (Fig. 4). The average of the manually selected curves is compared in Figure 4 with the computed curve. The tests also showed that the most experienced interpreters produced a distribution closest to that of the computer.

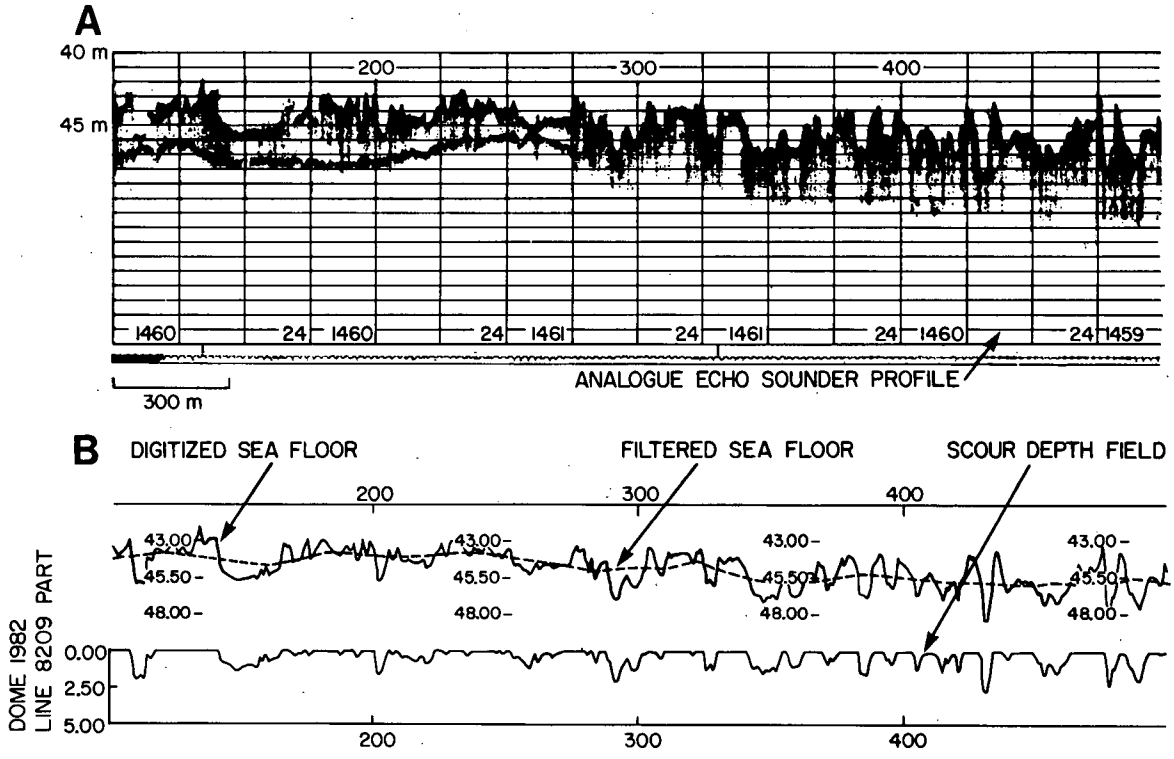

Figure 3. Echo-sounder quality-control plot.

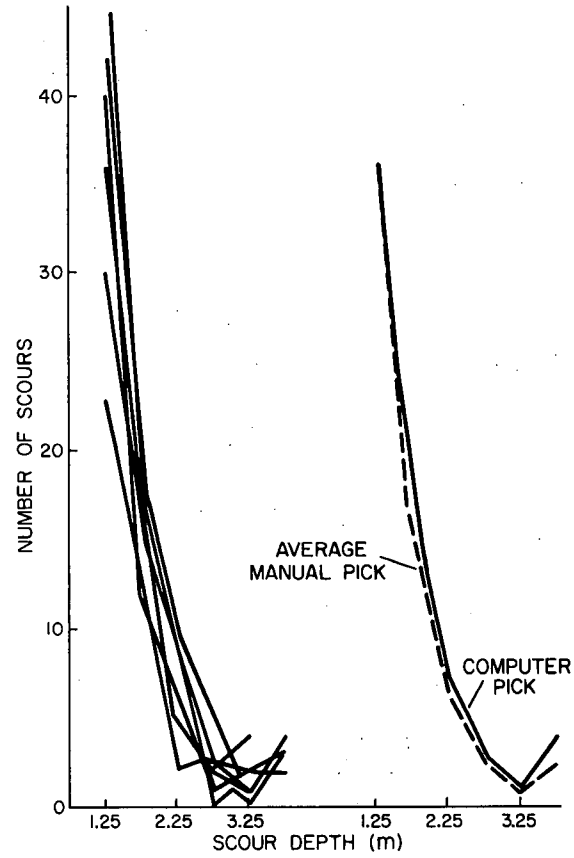

Figure 4. Comparison of a manually selected echo-sounder curve with a computed curve.

ASSESSMENT OF SEABOTTOM CONDITIONS

The creation of a computerized data base lends great flexibility to traditional methods of ice-scour interpretation. The facility of data-sorting routines greatly increases the information potential from the scour data. For example, the data could be sorted to list the orientations and widths of all multi-keeled scours showing a scour depth of 3 m within a particular geographic location. Such specialized software for ice-scour interpretation has been developed over the past 2 years by Geoterrex. This system has been configured on a microcomputer; we used an IBM PC-XT with a 10-megabyte hard disc. Three types of interpretative concepts can be computed and graphically illustrated using the appropriate software routines:

- scour parameters can be interpreted using the whole data set or selected subsets;
- any number of individual scour parameters can be compared with one another; and
- one or more scour parameters can be compared with different environmental parameters.

Figure 5 illustrates the flexibility of the computerized data base. The plot shows the scour depth distribution in 20-cm intervals of all scours found between the water depths of 15.5 and 40.5 m and west of a given longitude in the Beaufort Sea.

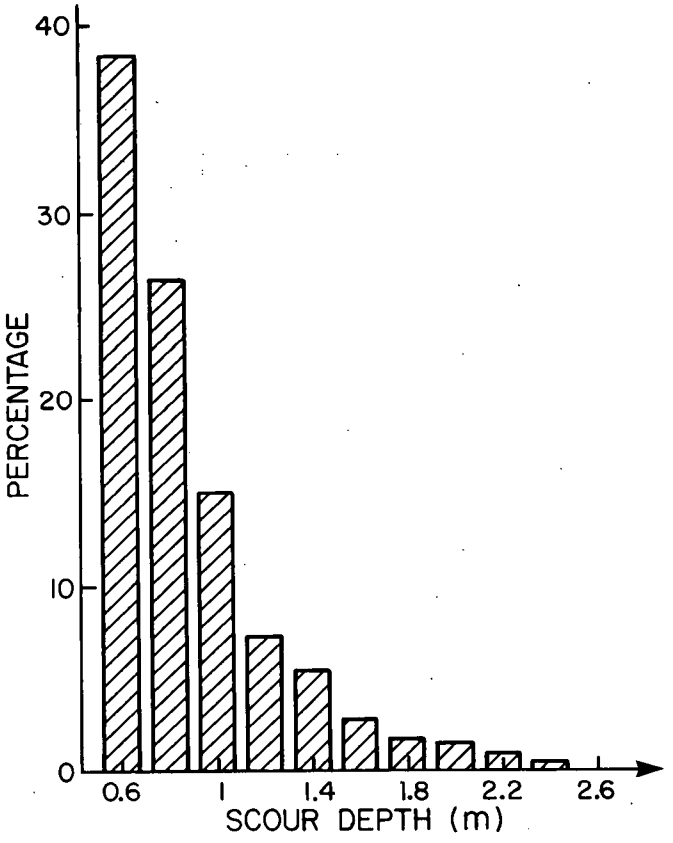

Figure 5. Example of interpretative capabilities.

SUMMARY

To summarize, a comprehensive, computerized, ice-scour data base has been created for Beaufort Sea acoustic seabed data. Scour parameters are catalogued in an organized format allowing for easy modification and updates. Data are input into the data base by digitization, software conversions, and manual interpretation with linkage to a navigational data set. Reinterpretation of data is facilitated through the use of a graphics terminal and user-selected scales, thereby alleviating the reassessment of original analogue records. Scour depths derived from the echo-sounder data base are referenced to a reproducible seafloor datum. Reinterpretation of scour depth may be undertaken by experimenting with different filtering routines, or by modelling the echo-sounder profile within the frequency domain. The data package is compact, less than 10 megabytes, and may be taken to the field for on-board interpretation and survey planning. The data base concept greatly increases the flexibility of ice-scour interpretations, and it is felt that new levels of understanding of ice scours and processes will be reached.

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DISCUSSION

Chris Woodworth-Lynas, C-CORE: You mentioned cross-cutting scours. Are you just looking at the freshest scours, or are you trying to get a sequential picture. What is the purpose of doing this work? Are you trying to come up with some measure of change in scouring through the ages?

R. Quinn: That's a good question. There are really two parts to the answer. The first is the interpreter's treatment of the individual sidescan record. As I've mentioned, we don't go into a full-scale cross-cutting interpretation as the sidescan record is being digitized. We just flag a

scour that is obviously uncut. In addition to digitizing the analogue sidescan record, we've taken three mosaics in various areas of the Beaufort Sea that have been compiled, and have done a full interpretation of the cross-cutting relationship on those using the technique you developed. We have digitized the mosaic to give an appreciation, in a regional sense, of how long some of those major uncut scours appear.

From the floor: We have recognized up to about eight generations of scours in some of those mosaics.

John Miller, Petro-Canada: The records are digitized at a fixed digitizing increment of 1.2 or 1.5 mm, which implies that for different scale originals, we get a different resolution. Is that information on resolution carried anywhere in your records?

Rick Quinn: How do you mean carried?

John Miller, Petro-Canada: Well, if you're giving us a track and it's sampled in nominal 3-m or 10-m or 1-m intervals, then such resolution information could prove useful in later analysis.

Rick Quinn: One thing we do is include resolution into a figure for data quality. If we find that the field-digitized bathymetric data provide sufficient resolution then we accept that. If sampling the echogram at 1.2-mm intervals does not provide sufficient resolution, then we classify the data as poor.

John Miller, Petro-Canada: A second question: looking at the distribution (see Fig. 5) and considering what you said about thresholds for determining scours, do you use a threshold of 0.5 m to decide on a scour or because it gives a beautifully truncated data set?

Rick Quinn: A threshold of 0.5 m is used throughout the data base because we feel it defines the data within the resolution of the equipment and the survey conditions. A wave swell of 0.5 m may be apparent, and the echo-sounder data uncompensated. I expect the distribution would still be a negative exponential if scour depths up to 0.0 m were measured; however, these data would, in our opinion, be meaningless.

Steve Blasco, Atlantic Geoscience Centre: A further comment on the first point is that this concern about data quality is a concern about working with poor-quality data. First of all, in selecting the 5,000 km, we rejected a lot of data where possibly the paper feed rates were not suitable or good samples were not available. To some degree your question concerning accuracy is answered by the fact that, when the echograms are digitized, the operator estimates his error. So if you look at the data and judge the data quality to be fair to good, you can look at the scour depth and say that it was measured to an accuracy of ± 0.25 or 0.5 m. So you'll get some sense of the error.

Peter Barnes, U.S. Geological Survey: Where do the estimates of the number of scours or gouges come from? Are they from the echograms or from the sidescan sonographs? I have a second question on the depths of gouges. You say your computer smooths the seafloor. I wonder if the smoothing operation takes into account the fact that when the gouge is deep, the marks or the ridges are usually less high.

Rick Quinn: In answer to the first question: the numerical designation of each of the scour events was obtained from the individual scours as seen on this sidescan sonar record and from individual scour depths as read automatically from the echo-sounder data. There are two individual data sets that you can call up. Each will give you a certain selection of parameters.

Peter Barnes, U.S. Geological Survey: You get two different densities of scour?

Rick Quinn: We use the echo sounder primarily for scour depth information, and the sidescan sonar records for densities and other parameters of the scour which are flagged as individual events. From the sidescan sonar data you can get a separate distribution of the events. With the sidescan fish being towed astern of the vessel versus the echo-sounder mounted midships on an outboard mount, it's sometimes difficult to correlate major events. You can't always be sure that you're getting the one-to-one correlation necessary to flag both as being one and the same. Regarding your second question about the seafloor averaging routine: part of the routine considers that departures above the mean are equally as important as departures below when calculating the seafloor mean. So the computer will smooth the data and it will look forward and backward and average those points as it attempts to establish the seafloor bottom.

Steve Blasco, Atlantic Geoscience Centre: The bias you're talking about is built into the running mean. That's why we went to a 41 filter, because the berms were in fact of lesser amplitude than the depth of the scour. It took a while to sort that out.

Rick Quinn: In fact, we had to run several test routines of different filter types to be sure the result was representative of the seafloor in different areas.

Peter Barnes, U.S. Geological Survey: I guess my point is that ridge height:gouge depth is not a one-to-one ratio.

Rick Quinn: Correct. That's an important factor. As a final comment, I should mention that the format for the nine-track tape is 1,600 bpi, 132 byte ASCII record, and the record length is 132 bytes fixed-block size.

REGIONAL CORRELATION OF BEAUFORT SEA ICE SCOUR EXTREME DEPTH AND RELATIVE AGE WITH ENVIRONMENTAL FACTORS

Jim Shearer[1]
Shearer Consulting
26 First Ave.
Ottawa, Ontario, K1S 2G2

and

S.M. Blasco
Atlantic Geoscience Centre
Geological Survey of Canada
Bedford Institute of Oceanography
Box 1006, Dartmouth, Nova Scotia, B2Y 4A2

INTRODUCTION

A mapped seabed distribution of known extreme scour depths (scours greater than 2 m deep) and scour relative age (morphological "freshness") was compared to maps of environmental conditions including shelf gradient, seabed morphology, bathymetry, sediment type and thickness, sedimentation rates and sea-ice zonation. From this comparison the degree of correlation between scour parameters and environmental factors was determined for the Canadian Beaufort Sea.

Between water depths of about 10 and 50 m the entire seabed is saturated by ice scours to the extent that the occurrence of any new events would lead to the loss, or partial loss of existing scours. Approximately 510 scours with depths of 2 to 3 m, 100 with depths of 3 to 4 m and 40 with depths greater than 4 m were located on the central shelf. In general these extreme scour depths are found in water depths ranging from 20 to 50 m in the sea-ice shear zone beyond the fast ice. Scours with depths greater than 2, 3, and 4 m were not found in water depths less than 7, 18, and 26 m, respectively.

Although, in general, scouring activity is somewhat uniform, and the sea-ice zonation as well as bathymetry show continuity across the shelf, extreme scour depths are rarely observed east of the Kugmallit Channel at 133.5 degrees West longitude. This absence in extreme scour depths is attributed to the change in seabed sediment conditions. Thicker soft silty clays on the west central shelf thin to the east where scouring ice keels would encounter silty sands. Extreme scour depth occurrences appear to be confined to the thicker soft silty clays.

No apparent correlation was observed between extreme scour depths and shelf gradient or seabed morphology. Seabed depressions were not free of scours as previously thought. Scours were observed to track up, cross over and track down low ridges into depressions. Despite the preferred orientation of scours, there is sufficient variability in their trend that they occur even in depressions aligned perpendicularly to the preferred scour azimuth.

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[1] Presenter.

Based on their appearance on high resolution sidescan sonographs, extreme scours were categorized according to degree of relative "freshness". The freshest-looking scours were thought to be among the most recent events to disturb the seabed. The less fresh or smoother appearing scours were thought to be older and possibly relict. The validity of this approach is based on the observed freshness or crispness of known recent events on sonograph records. In 10 to 20 m of water over 90 per cent of observed scours with depths between 2 and 3 m are in the fresh category compared to only 30 per cent in that category in the 50 to 60 m water depth range. Scours greater than 3 m in depth were subdivided into numbers of events per 100 km and plotted against 10-m water depth intervals for both fresh and smooth categories (Fig. 1). The graph has been corrected for the variation in the number of survey kilometres in each water depth interval. The distributions for the two categories differ, with the fresher scours biased towards the shallower water. This suggests that the distribution of recent extreme scour depths may differ from the older or relict populations, particularly if the fresh scours were young enough that sediment infilling had not altered their depth.

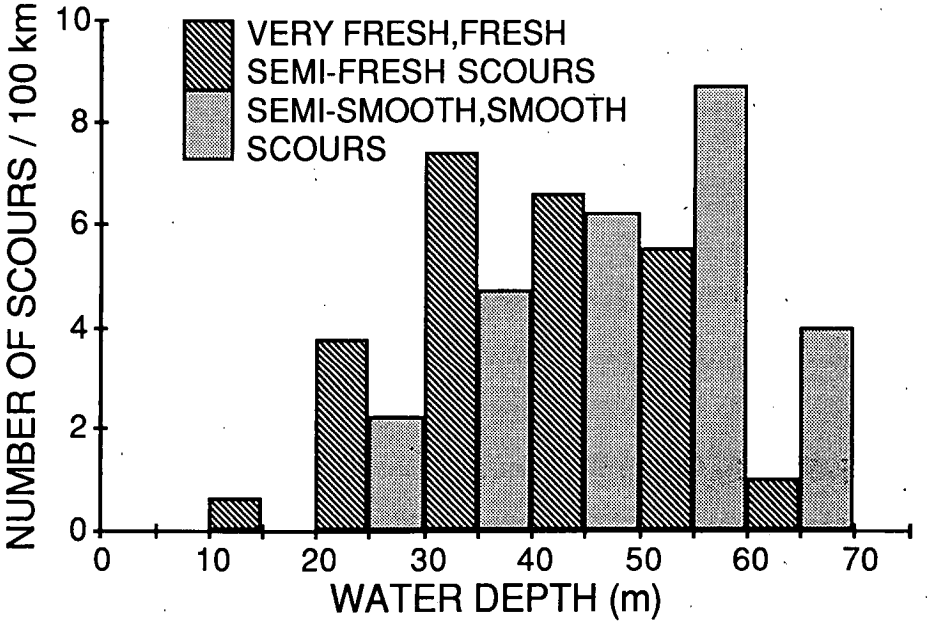


Figure 1. Distribution of fresh and smooth ice scours for different water depth intervals.

Sedimentation rates decrease by an order of magnitude from inshore to offshore water depths greater than 60 m. As sediment infilling occurs, fresh scours tend to appear smoother, and the rate of transformation is a direct function of sedimentation rate. This implies that a fresh-looking scour in shallow water is much younger than a similar event in deeper water. The deeper water scour will look fresher for a much longer period of time due to the low infilling rate. In addition, the higher number of scours observed in the 50 to 60 m water depth interval of Figure 1 does not necessarily indicate that the scouring activity is higher in these water depths, but that the scours have a much higher residence time on the seabed caused by low sedimentation rates which enable the large number of extreme events to accumulate. A partial explanation for the decrease in extreme scour depths in shallow water is the high rate of sedimentation which fills in these features much more quickly than in deep water. A further decrease in observed extreme

scour depths in very shallow water is possibly due to the actual decrease in events inside the fast-ice zone. A more quantitative understanding of the freshness criteria may allow for the discrimination of active versus relict scours and an assessment of the impact of infilling on the extreme scour depth distribution.

This study was funded by the Offshore Geotechnics Program of the Panel on Energy Research and Development through the Geological Survey of Canada.

DISCUSSION

Alan Ruffman, Geomarine Associates Ltd.: Why are your scours shallower now than they were 4 years ago?

Jim Shearer: I think one reason was enthusiasm in looking for deep scours. The estimation error, which is not always present, is between 10 and 20% of the scour depth, or 1 m at the maximum. We are only now learning exactly how to measure scour depths with respect to an average bottom. Earlier we included a portion of the adjacent scour berm in the depth estimate. The depth wasn't taken from the exact top of the mound to the bottom, but some portion of the mound was included. To save time, in determining the depth of average seabottom, we averaged over 200-300 m instead of several kilometres, as is now possible. The error is not great -- maybe 1 m at the maximum.

Steve Blasco, Atlantic Geoscience Centre: From the overlays you'll be able to determine the areas to be correlated, and then you can go back to the computerized data base and establish statistically the degree of correlation that exists, for example, in an area where there is good correlation between scours and sediment types.

ICE SCOUR TERMINOLOGY

S.M. Blasco
Atlantic Geoscience Centre
Geological Survey of Canada
Bedford Institute of Oceanography
Box 1006, Dartmouth, Nova Scotia, B2Y 4A2

INTRODUCTION

Disparity of opinion exists on the use of the terms scour, gouge, ploughmark etc. to describe features on the seabed caused by the passage of ice keels. Thus there is need to consider the use of appropriate terminology to convey precise meaning and to avoid ambiguity on overlapping use. Geomorphologists, geologists, geophysicists, statisticians and engineers all require distinct ice-scour terminologies yet terms are often "coined" in isolation by local communities of researchers within a single discipline. This practice may lead to conflicting usage. Before assigning terms to describe scour features or phenomena, consideration should be given to the suitability of terms from the perspectives of all other interested disciplines.

The double use of terms generates a potential for confusion in the literature. For example, geomorphologists use the term "fresh" to describe the nature of scour morphology while geologists use the term to imply a young age for a scour. In addition, ambiguity becomes a problem with the use of poorly defined terms. As an example, references to scour-frequency information commonly leave the question unanswered as to whether the discussion relates to spatial or temporal characteristics of scour data. There is also the problem of age distribution. Geologists like to discuss relative age because their data, at best, allows for a broad age grouping whereas the design engineer would require scours to be categorized more quantitatively as <100 years, <1000 years and >1000 years old and statisticians would prefer fully quantitative age categories for probabilistic risk analysis. The question then is: what terminology to put in place to accommodate all interests and yet avoid overlap and ambiguity?

As the knowledge base and interest in the subject of ice scouring increases, it will become necessary to establish more rigorous terminology. At present there is a need to identify at least the following categories of terms:

Category		Possible terms
morphology		fresh, smooth, eroded, rough etc.
age:	relative	new, young, active, late, old, relict, early
	statistical	contemporary, historical, modern (<100 years), recent (<1000 years), ancient (>1000 years)
	absolute	actual known age in years

The above terms are listed simply to suggest some possibilities that exist. It is recommended that the researcher be cognisant of the multidisciplinary need for a wide variety of terms to avoid overlapping use and to define the terms used in reports and publications to avoid ambiguity.

REGIONAL ICEBERG SCOUR DISTRIBUTION AND VARIABILITY ON THE EASTERN CANADIAN CONTINENTAL SHELF

E.L. King and R.T. Gillespie[1]
Geonautics Ltd.
P.O. Box 8833
St. John's, Newfoundland, A1B 3T2

INTRODUCTION

The Regional Ice Scour Data Base that currently exists at the Bedford Institute was established initially in 1981 by Mike Lewis and Steve d'Apollonia using Panel on Energy Research and Development funding. This presentation summarizes some of the more pertinent results of an update of the data base by Geonautics Ltd. and funded by Environmental Studies Revolving Funds. The original data base involved an analysis of regional sidescan sonar and Huntec Deep Towed Seismic (DTS) profiler records for the eastern Canadian continental shelf from Lancaster Sound to the Grand Banks of Newfoundland, including the Baffin Island and Labrador Sea regions. The Geonautics Ltd. update of this data base involved an analysis of regional data collected both by government institutions and by industry.

The study of the ice-scour data base involved three main aspects:

- to analyse and compile all relevant information from existing data that had not already been input to the data base;
- to produce four regional maps showing scour data from the updated data base; and
- to make a detailed study of scour morphology and its relationship to various environmental and physical parameters, such as seabed type and water depth, for various regions.

Figure 1 indicates the areas of interest. The available data from these areas, which consisted primarily of Bedford Institute regional survey data, were partitioned in 2-km line lengths, and each sample area was analysed for ice-scour length, width, depth, berm or ridge height, orientation, and density. The sidescan sonographs were also used to group scours as straight, arcuate, or sinuous, to give an estimate of the amount of seabed disturbed and the composition of the seabed material, and to give an indication of hydrodynamic activity (bedforms). The Huntec profiles were analysed for recognizable geological sequences, with particular emphasis on the nature and thickness of the surficial unit. Figure 2 shows most of the parameters extracted from the regional field records and entered into the data base. The measured data were first logged on worksheets, then entered into the System 2000 data base at the Bedford Institute of Oceanography. The data base at present contains comprehensive information on the ice scours in some 3,965 sample areas representing 11,895 km of the eastern Canadian continental shelf.

[1] Presenter.

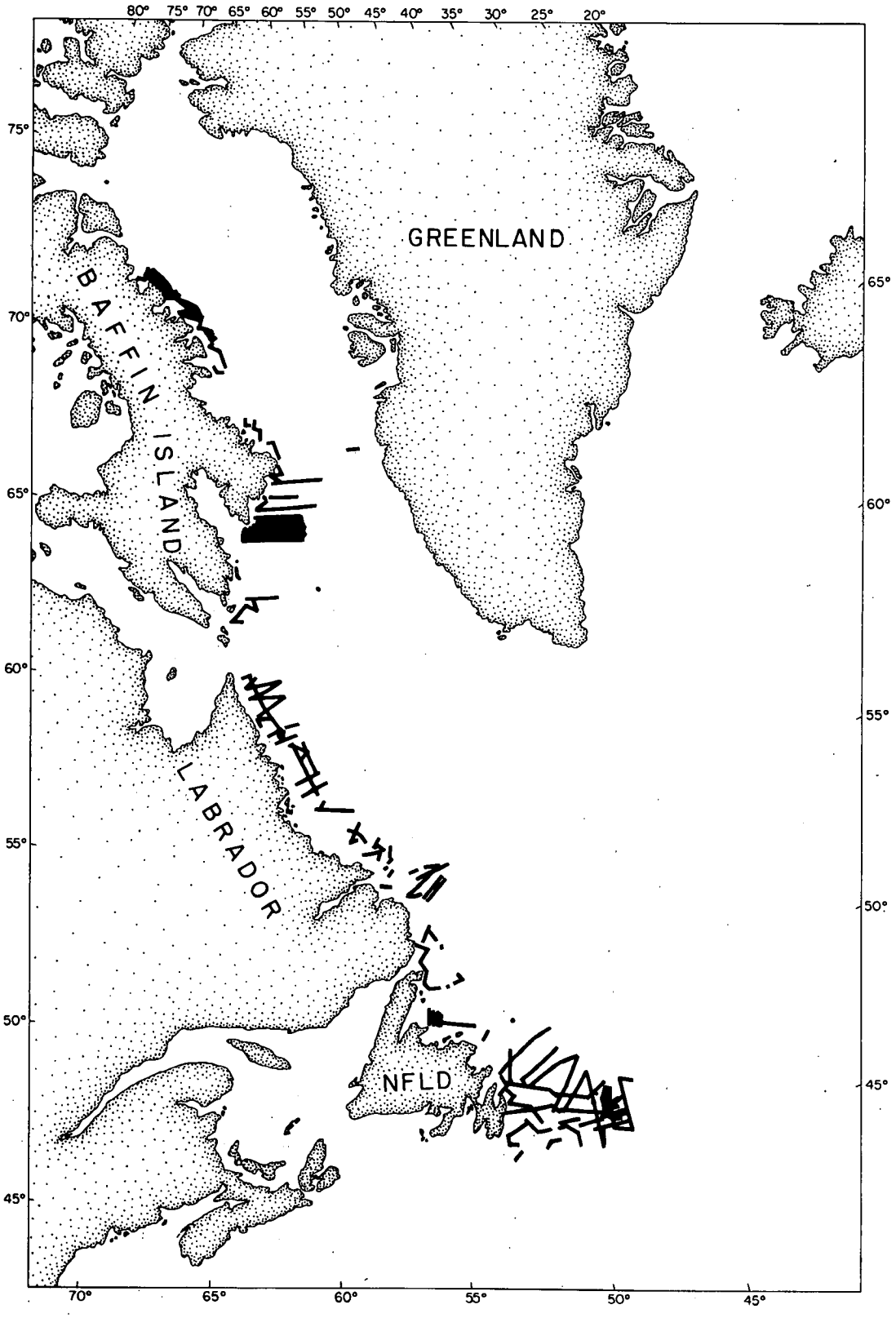


Figure 1. Sample areas along the eastern Canadian continental shelf, that were analysed for iceberg scour characteristics.

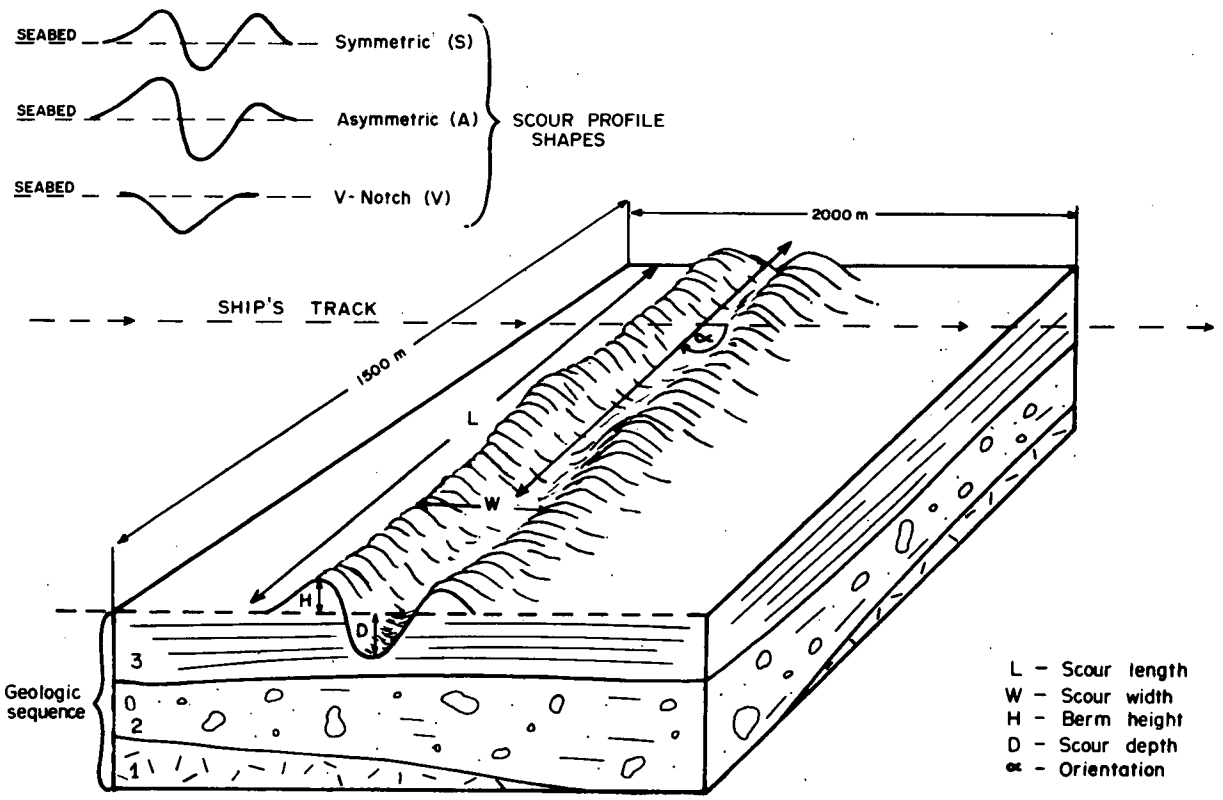


Figure 2. Schematic of a single sample area showing dimensions, ship's track and scour parameters measured. The sample area width, perpendicular to the ship's track, varied from 250-1500 m.

GRAND BANKS REGION

On the broad, flat, bank tops (water depths <100 m), scour densities are very low. This feature is particularly evident in the Hibernia area, where extensive data coverage exists and scours are rare. The scours on bank tops are commonly shallow (usually <1 m) and change direction often. In deeper water, scour density increases and the scours are more linear. A narrow zone of short scours and craters (pits) is commonly observed at the bank edge wherever the break in slope is sharp. Two separate and distinct scour populations, including a relict set found only in water depths of greater than 100-110 m superimposed by a set of younger scours found above and below 100 m, have been well documented on the Grand Banks (Lewis and Barrie 1981; Fader and King 1981), and these findings have been verified during the present study.

Scour orientations on the northeastern Grand Bank are aligned in deeper water (>120 m) but are more variable in shallower water toward the bank top. These observations are believed to reflect an increase in the control of ocean currents on iceberg drift patterns in deeper water. In shallow water, the primary driving forces are more variable, and probably include winds, diurnal tidal currents, and storms. Hence, the scours are more irregular and lack a distinct orientation.

The Avalon Channel area was chosen for detailed study within the Grand Banks region. It was chosen over the Hibernia study area for two reasons. First, it was felt that a substantial amount of analysis had already been carried out in the Hibernia study area, and that any subsequent analysis of the same data would be redundant. Secondly, the Avalon Channel area demonstrates relatively high scour densities and is essential in the consideration of possible pipeline routes from the development area to Newfoundland.

In the area of Avalon Channel the lowest scour densities of 0-1.5 scours per square kilometre correspond to the shallower bank tops, with the highest densities being in the channel itself. An interesting relationship exists at the northern end of Avalon Channel. In deep water to the north, scour densities are low, and scour depths high. As the seabed rises southward into Avalon Channel, water depths decrease, scour density increases and scour depths decrease. This illustrates nicely the effect of bathymetric filtering on southward drifting iceberg population which has more shallow than deep draughts (Lewis and Benedict 1981; Hotzel and Miller 1983).

The deepest iceberg scour observed during this entire study was found in an isolated basin in Avalon Channel east of Cape Race. This scour measured 8-9 m in depth and was oriented transverse to the channel. The scour is definitely part of the relict population mentioned earlier, and its size, orientation, and location all point to it having been made by an iceberg calved off a nearby glacial margin, probably to the east.

A direct relationship between an upper limit of deeper scours and deeper water is found to hold in the southern Avalon Channel south of latitude 47°N (Fig. 3). However, for a more regional data set analysed (Fig. 4), scour depths attain a maximum value at some given depth, in this case 240-260 m, beyond which depths then decrease. This cut-off depth depends on local bathymetry, sea level history (because the existing scour record, especially in deep water, is an accumulated population), iceberg draught distribution, and seabed geology.

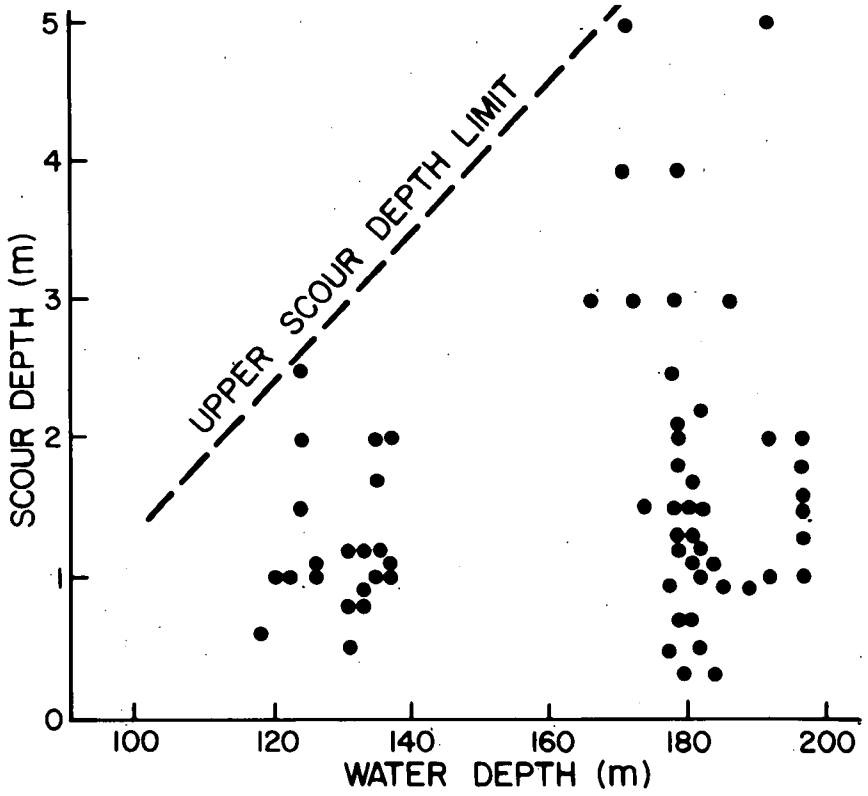


Figure 3. Plot of scour depth versus water depth for scours in southern Avalon Channel area (south of 47°N latitude).

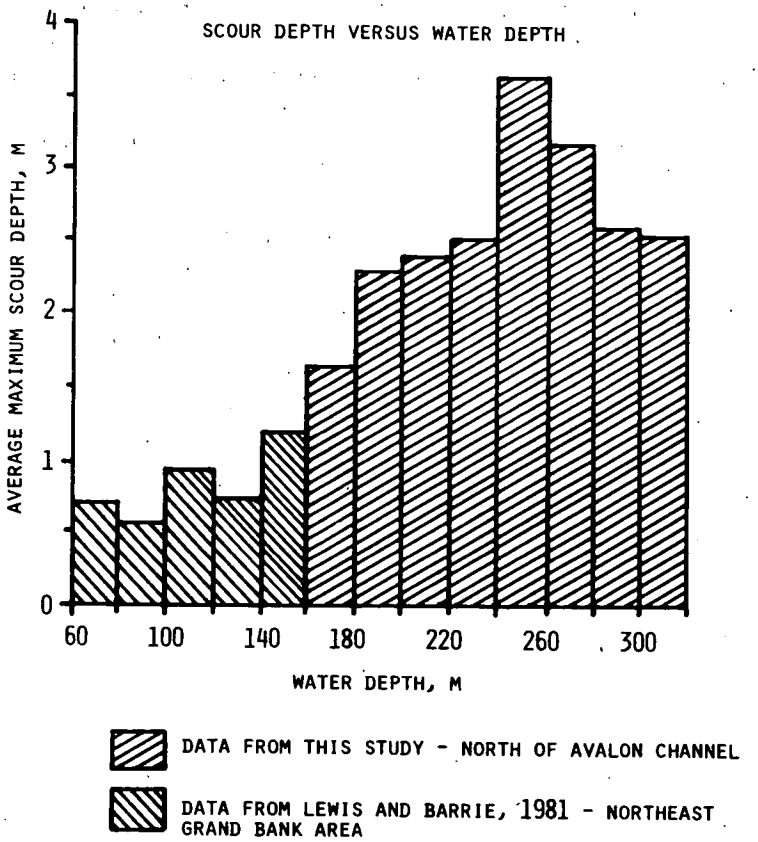


Figure 4. Scour depth vs the mean of the maximum scour depths measured in each 2-km sample area within a particular 20-m interval of water depth.

LABRADOR SEA REGION

In general, scour densities on the Labrador Shelf are highest to the north and decrease southward. Unlike the Grand Banks, high scour densities are found on the tops as well as on the shoulders of the banks. Local areas on the banks with low scour densities probably reflect some combination of bathymetric sheltering (such as in Karlsefni Trough on Saglek Bank), local deflection of icebergs by currents, seabed sediment that does not preserve scours well (such as sand), or a hydrodynamic regime that obliterates scours rapidly. Preliminary analysis of data reveals that there is commonly a marked change in scour appearance from fresh-looking above 200 to 220-m water depth to a more degraded appearance below this depth, commonly with a difference in orientation between relatively "older" and "younger" scours, where the two are superimposed. This portion of the study is still continuing, and lacks orientation data. In addition, analysis of width and depth data as they relate to water depths remains to be done.

Because of the availability of a number of high-quality sidescan mosaics, a detailed study of Karlsefni Trough on Saglek Bank was undertaken. The best-quality mosaic is the Saglek east mosaic, which was compiled by C-CORE (Woodworth-Lynas 1983) from data collected during the BIO 79-019 cruise of CSS Hudson. A detailed interpretation of this mosaic was carried out (Fig. 5), and the data were then combined with geologic, and bathymetric controls for

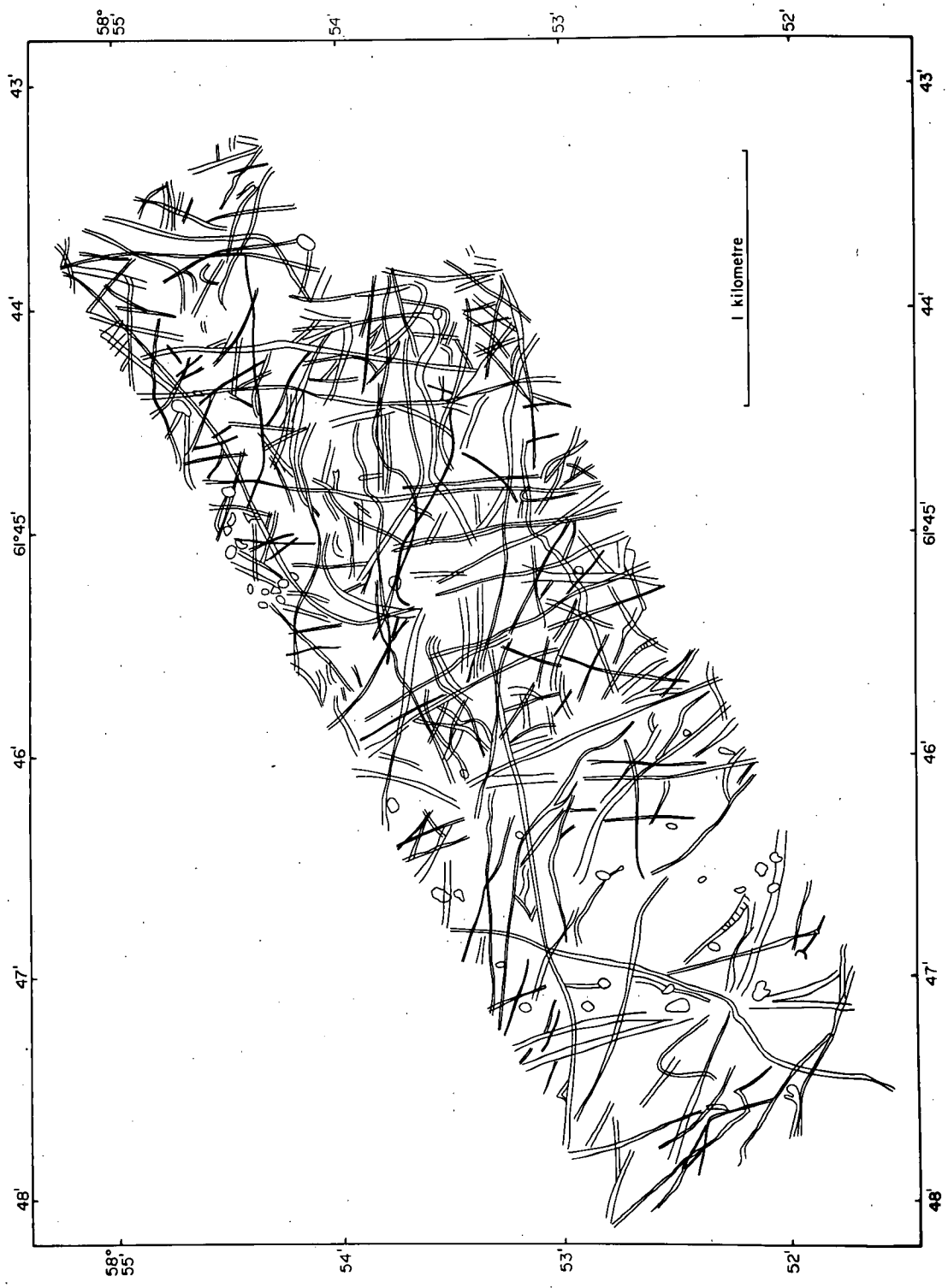


Figure 5. Tracings of iceberg scours from the Saglek mosaic.

the same area provided by H. Josenhans.[1] This combination allowed for a detailed analysis of the interrelationships between scour depth, scour width, water depth, and geology. For instance, Figure 6a illustrates a good correlation between increasing water depth and decreasing scour density. Figure 6b illustrates an exponential-like decrease in the number of deep scours, independent of water depth, whereas Figure 6c illustrates the range in water depths traversed by observed scours. Not only do some scours traverse a range in water depths of up to 15 m (it is not known if this is upslope or downslope motion), but it is also found that there is often a variation in the interpreted amount of material displaced within individual scours, for example by a factor of 4 to 5 in 16% of scour occurrences in the mosaic area (Fig. 6d). In addition to the relationships already discussed continuing work is concentrating on comparing the data collected from the same area in different years, the differences in results when the same data are analysed by different workers, and the differences in data quality between a mosaic and a single, regional-type line over the same area.

BAFFIN-DAVIS REGION

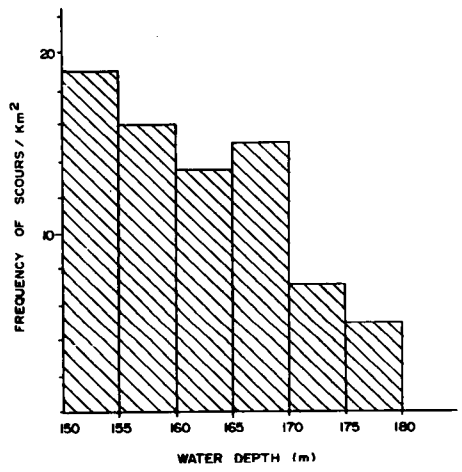
Preliminary results indicate that scour densities are high on the Baffin Island Shelf, and that scour depths are on the average greater than those on the Labrador Shelf. Intense scouring of the seabed is common in water depths of 300-400 m or more. This deep-water scouring is almost certainly relict.

The area east of Cumberland Sound was selected for detailed analysis because of the good regional coverage and tight control on the surficial geology and bathymetry (Praeg et al. 1985).

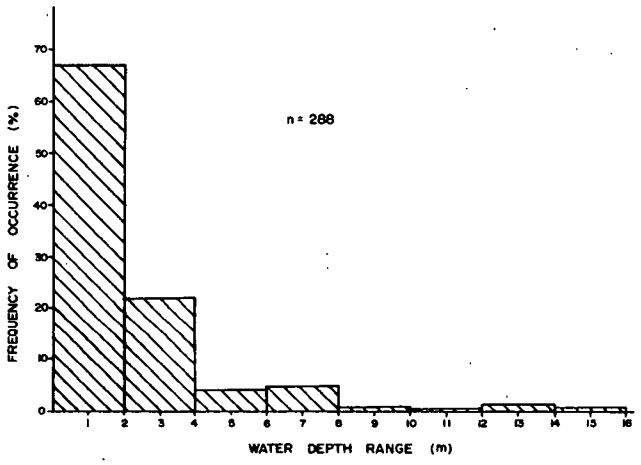
In general, scour orientations appear to reflect the present configuration of the Baffin Current in the region. An exception to this occurs in deep water at the mouth of Cumberland Sound where scours trend northwest-southeast. Based on preliminary analysis, we interpret these scours as being relict, probably produced by icebergs drifting out of Cumberland Sound at some time during the past. An interesting pattern of scour densities occurs over an elongate ridge. This ridge appears to be heavily scoured on its upstream and downstream ends (with respect to present iceberg flux) with very few scours along its flanks. Intense scouring on the upstream end of this ridge is understandable. However, the high scour densities on its downstream end and lack of scours on its flanks are more puzzling. We interpret this pattern as being the result of large- scale current eddies created by the local topography that carry drifting icebergs around the sides of the ridge and drive them against its southern end. A similar phenomenon has been reported on Makkovik Bank on the Labrador Shelf (Woodworth-Lynas et al. 1985).

As part of this detailed study, an attempt was made to relate scour depths to surficial geology, but no direct correlations could be made immediately. We felt that part of the problem is that scour depth is also controlled by water depth, and therefore an attempt was made to separate these two effects. To do this, the mean maximum scour depth for each geologic unit was plotted against water depth. Unfortunately, it was found that any given geologic unit did not traverse a wide enough range in water depths to give a representative picture. However, when all data for unit 3 of the surficial geology (a glacio-marine sediment) are combined, there is some suggestion that a mean-maximum scour depth for this unit occurs at a water depth of 250 m. This finding indicates some potential for this method, given a sufficiently complete data set.

[1] H. Josenhans, Atlantic Geoscience Centre, personal communication, 1984.



(a)



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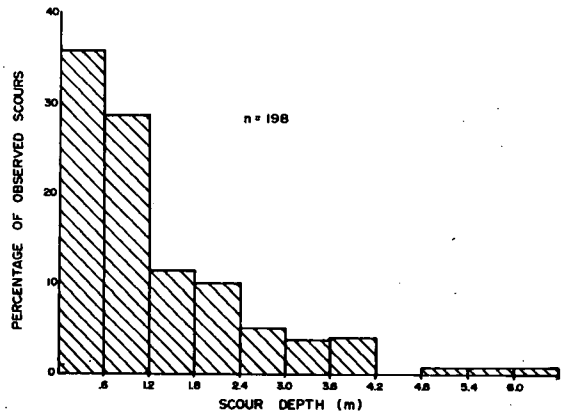

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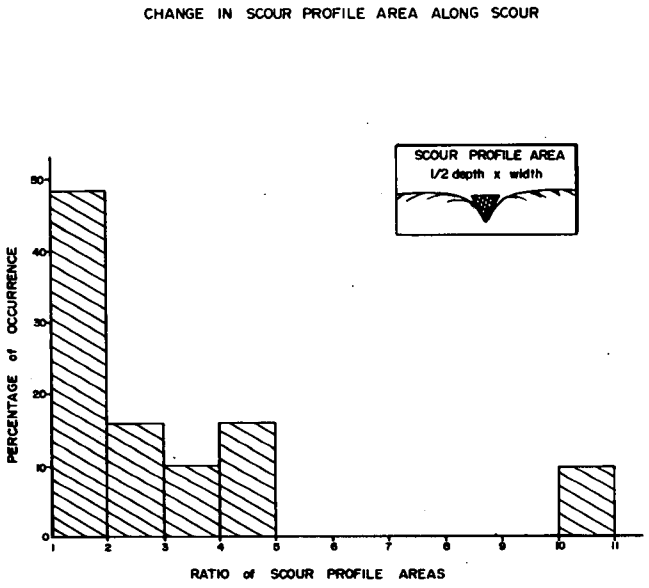

(d)

Figure 6. Scour character on Saglek East mosaic showing: (a) frequency (density) of scours vs. water depth; (b) scour depth distribution; (c) distribution of ranges in water depth along individual scours; and (d) distribution of the ratio of change of profile area within individual scours.

LANCASTER SOUND REGION

Data coverage in Lancaster Sound and surrounding waterways is sparse. A few regional lines run by the Bedford Institute of Oceanography (BIO) across Lancaster Sound show typical iceberg scours in 200 to 250-m water depths. A number of detailed studies at glacier outlets on southern Devon Island have been carried out by the Atlantic Geoscience Centre. Data collected during these studies indicate high numbers of scours in shallow, nearshore areas that were most likely produced by drifting sea ice.

FUTURE CONSIDERATIONS

Analysis of the data is by no means complete, and there is room for a great deal of work to be done, especially with respect to relating ice-scour characteristics to environment, sea level history, and surficial geologic conditions. A further update of the data base is currently being carried out by Geonautics Ltd[1]. which will add data from the SeaMarc system collected in 1984, thereby increasing our knowledge about deep-water scours. In addition, a concerted effort is being made to obtain the release of industry, and additional government data. A quality assessment program in progress will provide valuable information concerning the quality, accuracy, and reproducibility of the data thus far compiled.

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DISCUSSION

Alan Ruffman, Geomarine Associates Ltd.: You said you had trouble getting commercial data, presumably well-site survey data. Would you outline the problems you've had and just what success you did have?

Randy Gillespie: We've had no success thus far. I wasn't really involved in that portion of the project. I suppose Mr. Hodgson of NORDCO or Mike Lewis would be able to give a better answer.

Mike Lewis, Atlantic Geoscience Centre: There is a plan to input the industry data, but it requires time to obtain permission. Each operator has to obtain permission from partners, etc., so the work has been progressing with the readily available data, to be followed in the future with an update involving industry data.

Alan Ruffman, Geomarine Associates Ltd.: The update is putting in industry data?

Randy Gillespie: That's the plan if the industry data are released for this purpose.

Chris Woodworth-Lynas, C-CORE: I'm interested that you did a reanalysis of one of two sidescan mosaics from Saglek Bank. Would you be prepared to make a brief comment on the differences or similarities between your analysis and that done by C-CORE in 1981? What were the differences and what was significant about the differences you found?

Randy Gillespie: There were certain differences with respect to that mosaic. The most striking difference concerned the scour depth and the problem with scale. Scour depths measured by C-CORE were consistently 2 to 2.5 times greater than those measured by us, because of an error in measurement scale used by C-CORE.

ICEBERG SCOURING ON SAGLEK BANK, NORTHERN LABRADOR SHELF

Brian J. Todd
Department of Geology
Dalhousie University
Halifax, Nova Scotia, B3H 3J5

INTRODUCTION

This presentation describes the first use of the Bedford Institute of Oceanography (BIO) Ice-Scour Data Base in a regional geological setting. It reviews the combined efforts of C.F.M. Lewis, Steve d'Apollonia, and the author, and supplements similar studies described in this workshop (King and Gillespie; d'Apollonia and Lewis; this volume).

The papers presented so far have indicated that the continental shelves adjacent to the glaciated continents show extensive scouring attributable to icebergs. However, most of the published data assume that scours are aligned with the prominent currents. This assumption, we thought, needed verification.

We know that about 85% of the icebergs that reach the Labrador Shelf are calved from the tide-water glaciers of Greenland and flow from the northwest in a southeasterly direction, along the shelf, under the influence of the Labrador Current. Saglek Bank, which is located on the northern end of the Labrador Shelf, was chosen as the study area for a number of reasons, the most important being that this area has been the subject of a regional surficial geological study at BIO for several years, and significant amounts of geological, iceberg, and ocean-current data are available. Our objectives were to describe the iceberg-scour record and to attempt an interpretation of some of the features that relate the iceberg scours to the known ocean currents.

REGIONAL SETTING

Saglek Bank is the most northerly bank on the Labrador Shelf (Fig. 1). It is about 300 km from northwest to southeast, and about 100 km wide at its widest point. The water depths range from 125 m on top of the bank to over 400 m on the bank edges. The line locations used in the study were selected from BIO regional survey data collected in 1979, 1981, and 1982. Geophysical data included the Huntec Deep Towed Seismic (DTS) high-resolution profiler, side-scan sonar, and airgun and echogram records. The 1979 lines are oriented from northwest to southeast, whereas the 1982 lines are east-west. This gives several cross-over points for cross-checking. Saglek Bank is actually two different banks, defined as North Saglek Bank and South Saglek Bank, that are separated from the coastline by the Labrador Marginal Trough, a depressional feature running the entire length of the Labrador coast. North and South Saglek banks are separated by Karlsefni Trough, an east-west trending depressional feature. Okak Bank, which is separated from South Saglek Bank by Okak Saddle, another east-west oriented depressional feature, was also included in the study area. In places, the water depths in Karlsefni Trough and Okak Saddle are greater than 200 m.

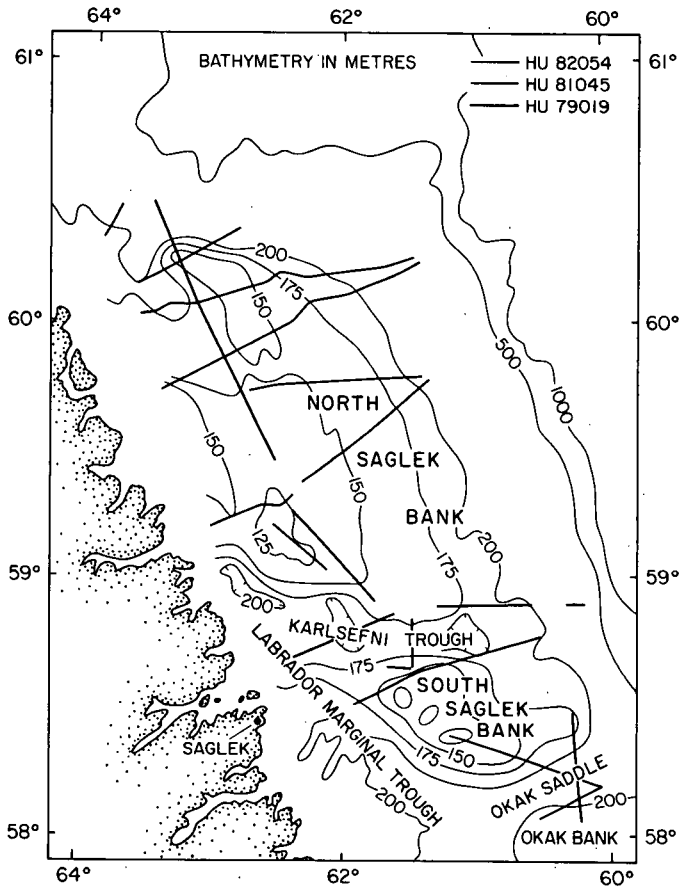

Figure 1. Bathymetry and cruise tracks in the study area.

RESULTS FROM THE STUDY

The sidescan records were processed in 2-km-long sections throughout the entire Saglek Bank area. An example section on a sidescan sonograph from North Saglek Bank is shown in Figure 2. The BIO ice-scour data base, originally developed by C.F.M. Lewis and S. d'Apollonia, facilitated the processing of the information. In total, more than 6,000 scours were measured and entered into the data base, and vector diagrams of direction were produced for every 6 km along the track.

A number of different scour features were recognized in the data set. Figure 3 shows examples of sinuous scours (scours that curve back on themselves), simple linear (straight) scours, arcuate scours, and crater or pit-type scours. Along with the many smoothly curving scours there exist scours that exhibit abrupt changes in direction. In many instances we found that the iceberg had dragged its keel and "wallowed" at a particular location before moving off in a different direction, possibly as a result of tides (Fig. 4). Examples of internal ridges within scours can also be seen in Figure 4.

The analysis of the iceberg scour directions on a regional basis was facilitated by radar iceberg-tracking experiments run by Memorial University in 1972 and 1973. The radar system was set up and operated from Saglek (see Fig. 1). Figure 5 combines the results of the radar observations and the directional trends of the scours extracted from the regional sidescan sonographs in the same area. The correlation between these data sets is considered to be good, although iceberg data from only one season were included. One noticeable feature of the iceberg tracks was that on top of the banks there appeared to be an appreciable amount of looping, whereas in the deeper water areas and Karlsefni Trough the tracks by comparison are straight. This difference was interpreted as being the result of the dominance of rotary tidal currents in the areas of shallow water, whereas the translatory oceanic currents are more dominant in areas of deeper water. Similarly, the trends shown by the vector diagrams for the entire survey area support this theory. In the shallower water on the tops of the banks, there appears to be a more even distribution of scour direction than in areas where the translatory currents are quite strong. In these areas of strong, translatory currents, there is evidence in the sidescan sonographs of icebergs riding up and over bottom features (scarps) in the order of 10 m in height. An example of this phenomenon is found on the offshore (eastern) side of North Saglek Bank. However, the icebergs in this region were not able to scour up and over scarps that exceeded 25 m. In areas of weak, translatory currents such as on the edges of the Labrador Marginal Trough and on the tops of the banks, local relief and local seabed slope appear to exert greater control over the ability of an iceberg to scour up and over bottom features.

BATHYMETRIC SHELTERING

The distribution of iceberg draught (Fig. 6) indicates a marked dropoff in the number of icebergs with draughts over 200 m. The scour action in these water depths is shown in Figure 7, which is a sidescan sonograph from a north-south line across the Karlsefni Trough. Icebergs appear to lift off and touch down again in water depths around 185 m. In the corresponding Huntec profiles, no evidence of subbottom disturbance due to scouring was detectable within at least the upper 32 m of bottom sediment at water depths greater than about 185 m.

RELICT SCOURS

Modern and relict scour regimes were observed in two areas. The Huntec (DTS) record and the sonographs from Okak Saddle, between South Saglek Bank and Okak Bank (Fig. 8), show an older, more-subdued scour regime to the south. The relief seen in the Huntec profiles is quite subdued in the north, but increases in the shallow water on top of the Okak Bank. On the north-eastern edge of the North Saglek Bank, a similar situation was observed and interpreted as being an older scour regime cross-cut by a younger, fresher-looking regime.

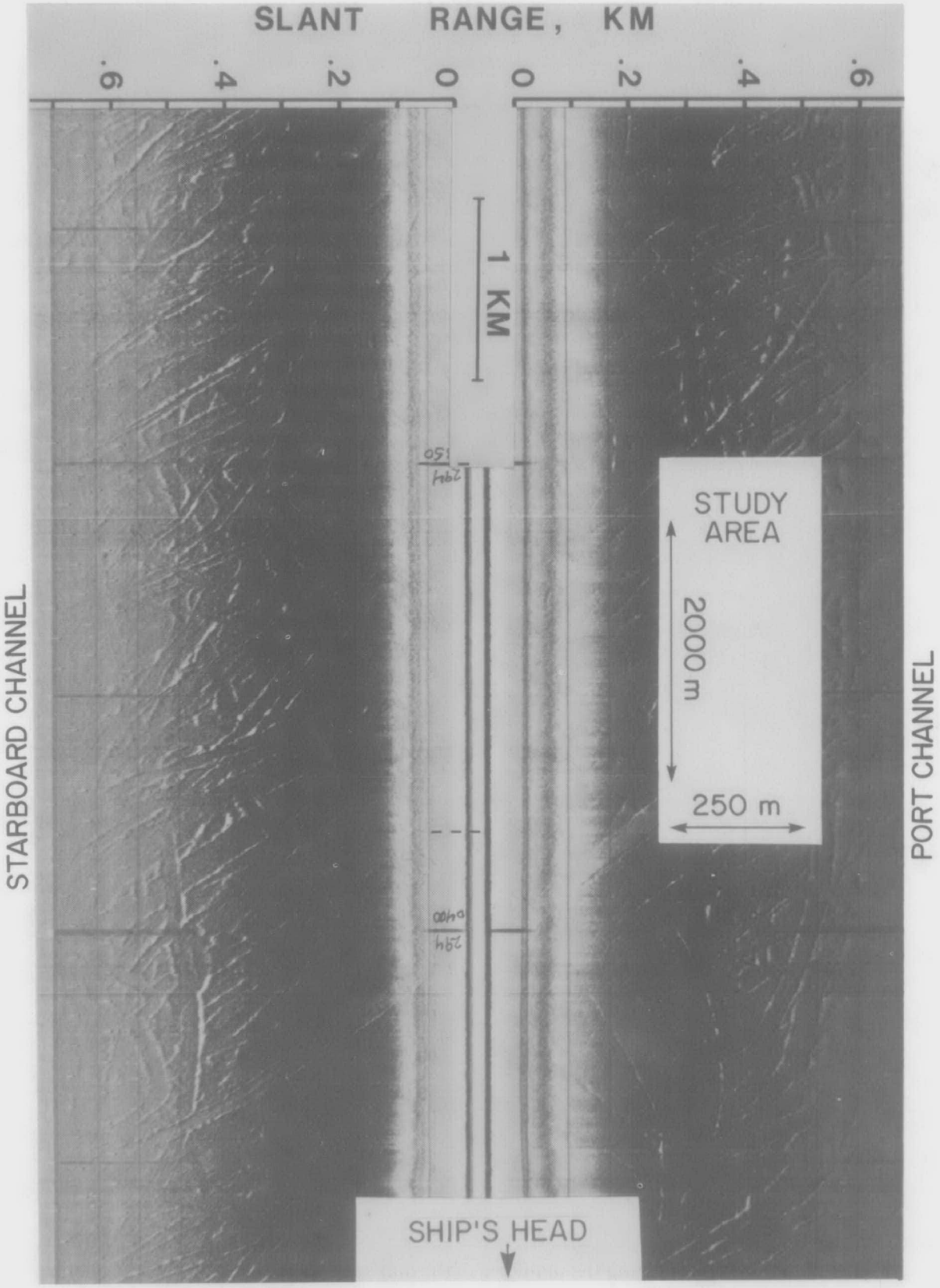

Figure 2. An example of a sidescan sonograph from North Saglek Bank.

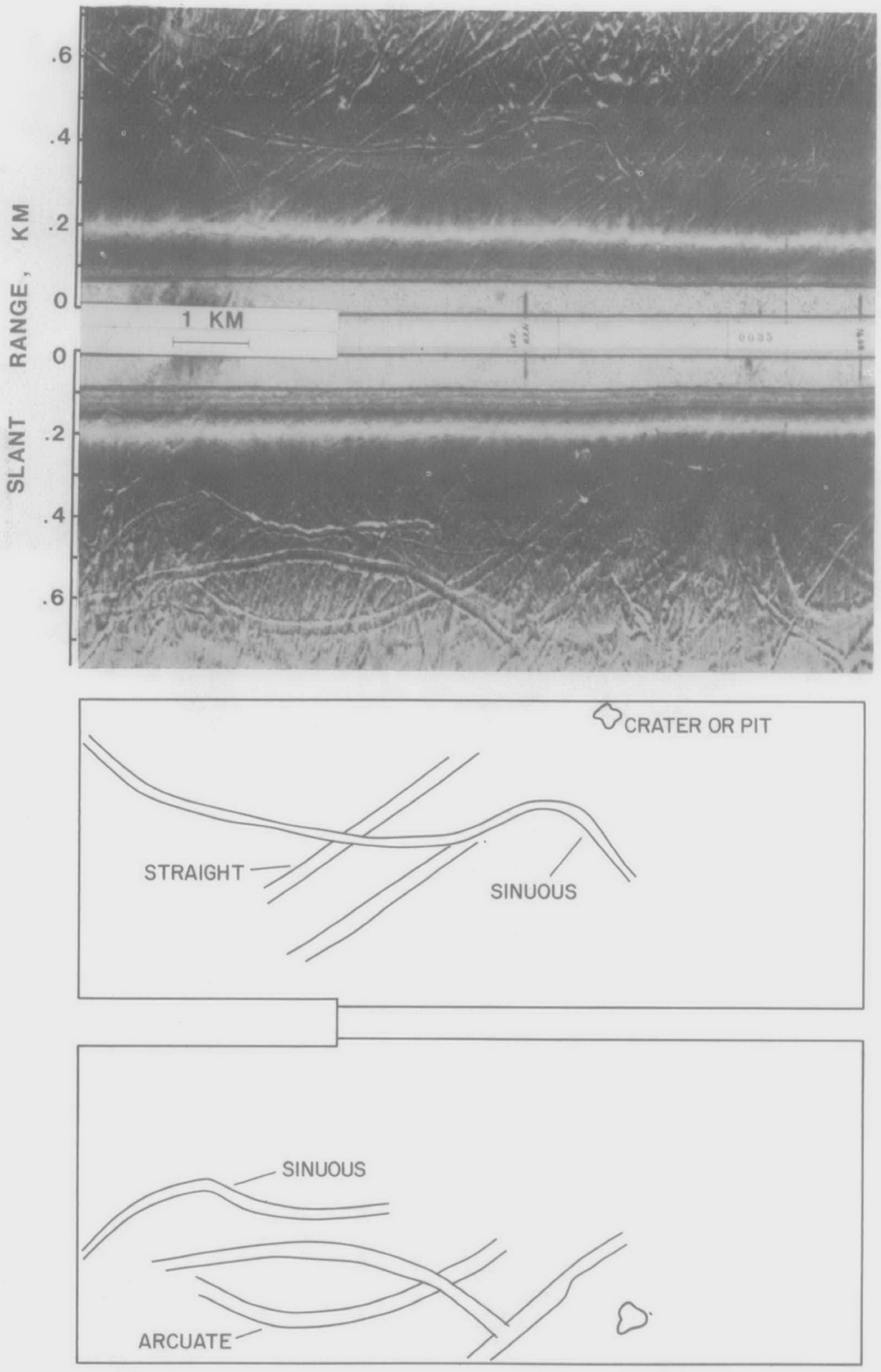

Figure 3. Sonograph showing the planform of the four scour types observed on the eastern Canadian continental shelf.

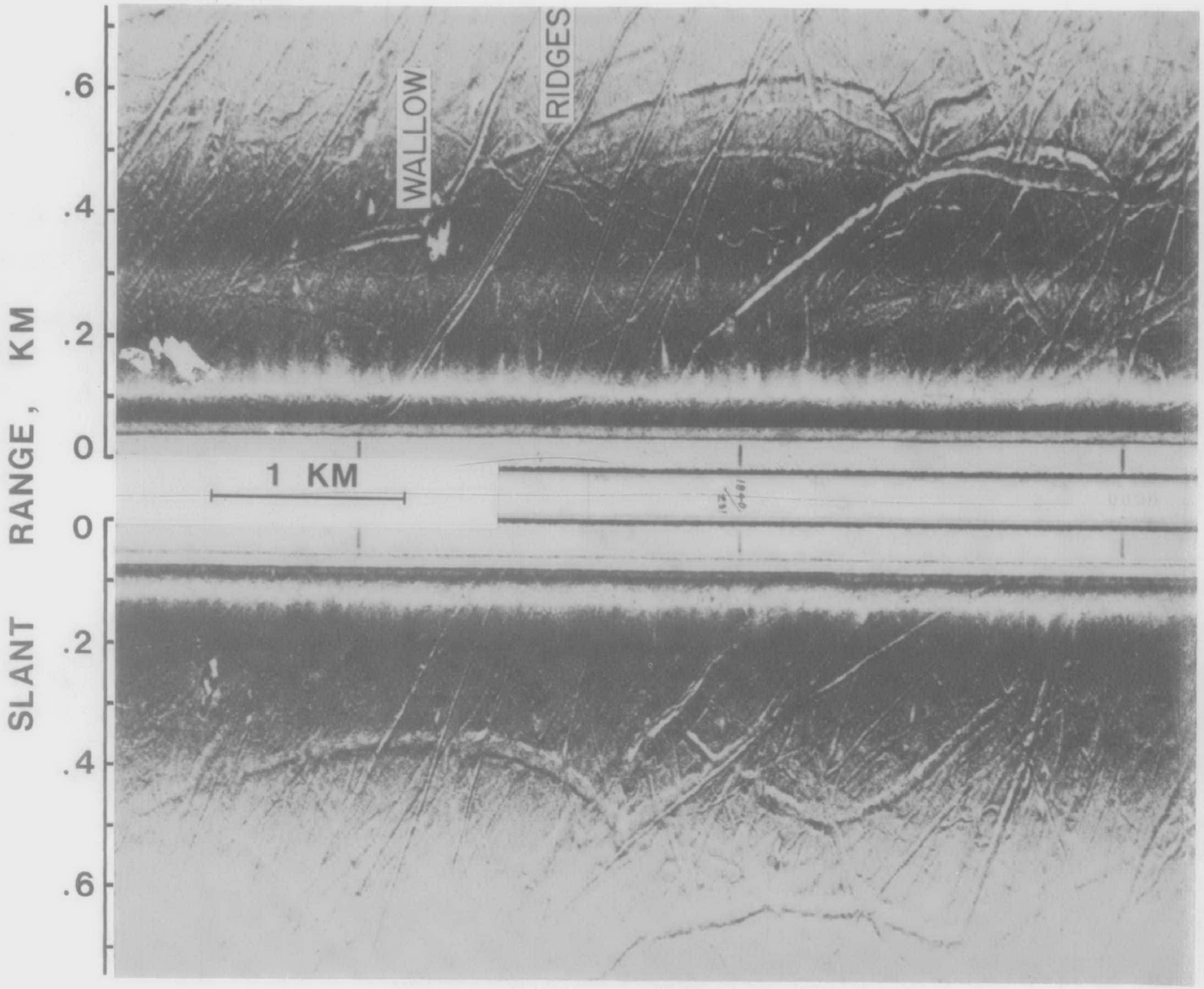

Figure 4. Example of an iceberg scouring in one direction, coming to rest, 'wallowing', and moving off in another direction. Note the mid-scour ridges in the scour below the wallow.

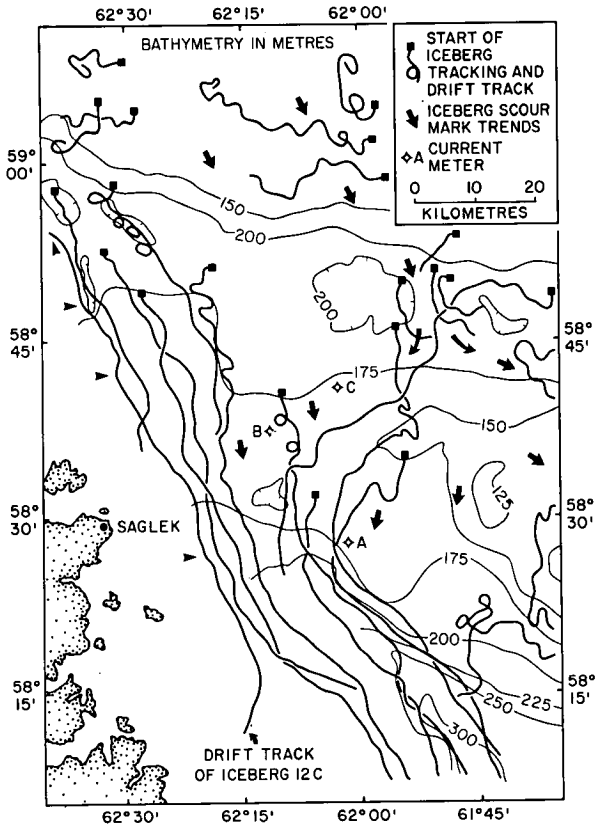

Figure 5. Radar-tracked iceberg drift patterns off Saglek, Labrador. The peaks on the drift path of iceberg 12c, high-lighted by arrows, occur at intervals of 12 h and 25 min, which is the period of the semi-diurnal tide off Saglek (modified from Dempster 1974 and Gustajtis 1979).

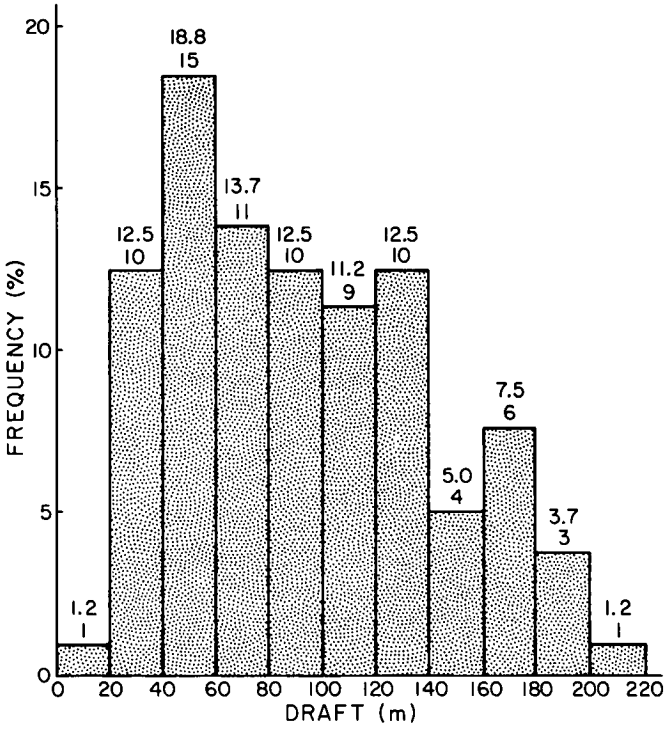

Figure 6. Frequency distribution of iceberg draft observations. Frequency per cent and number of observations shown for each draught interval (after Hotzel and Miller 1983).

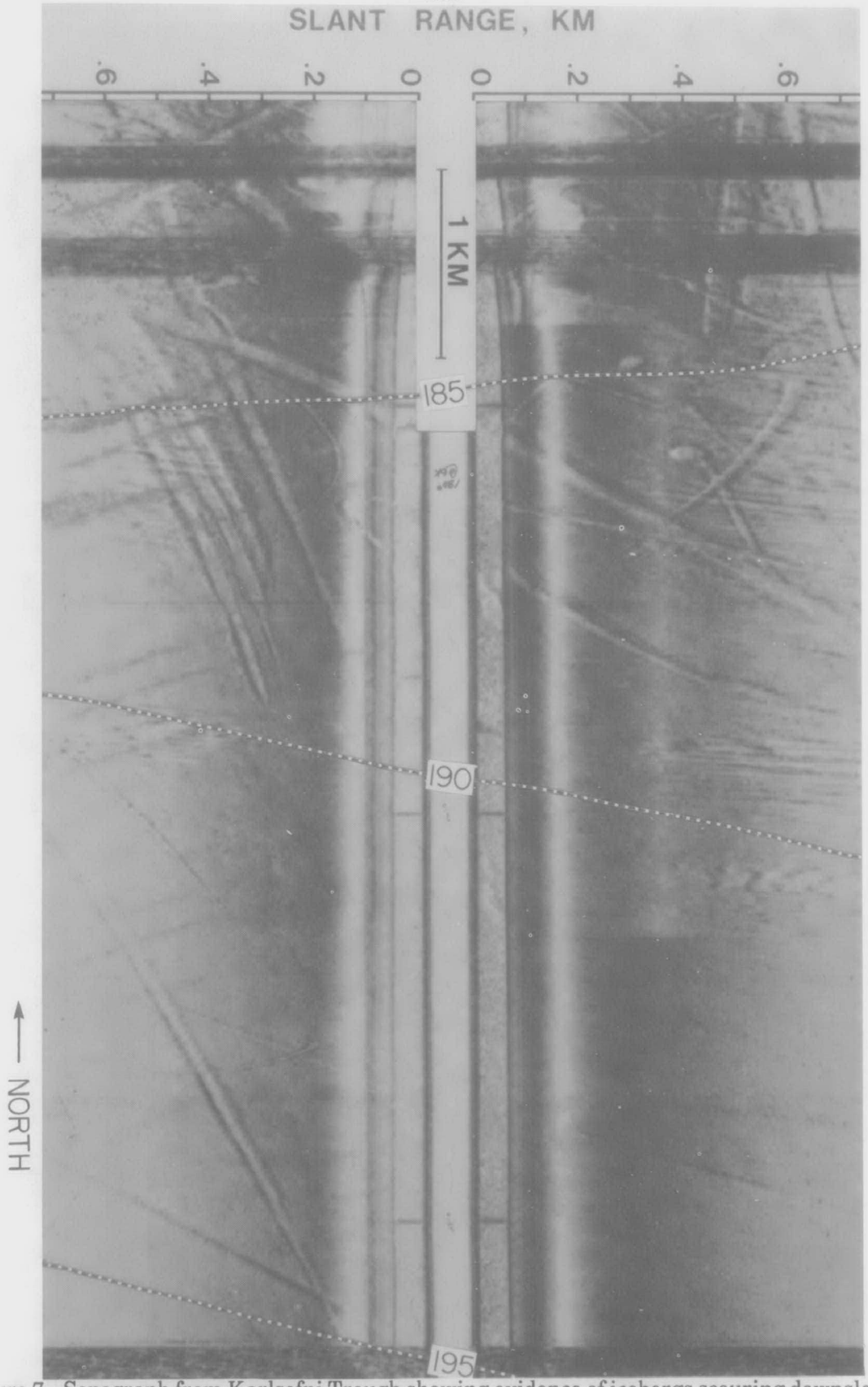

Figure 7. Sonograph from Karlsefni Trough showing evidence of icebergs scouring downslope (south) into the trough, 'lifting off', and 'touching down" on the southern slope of the trough. Superimposed isobaths are in metres.

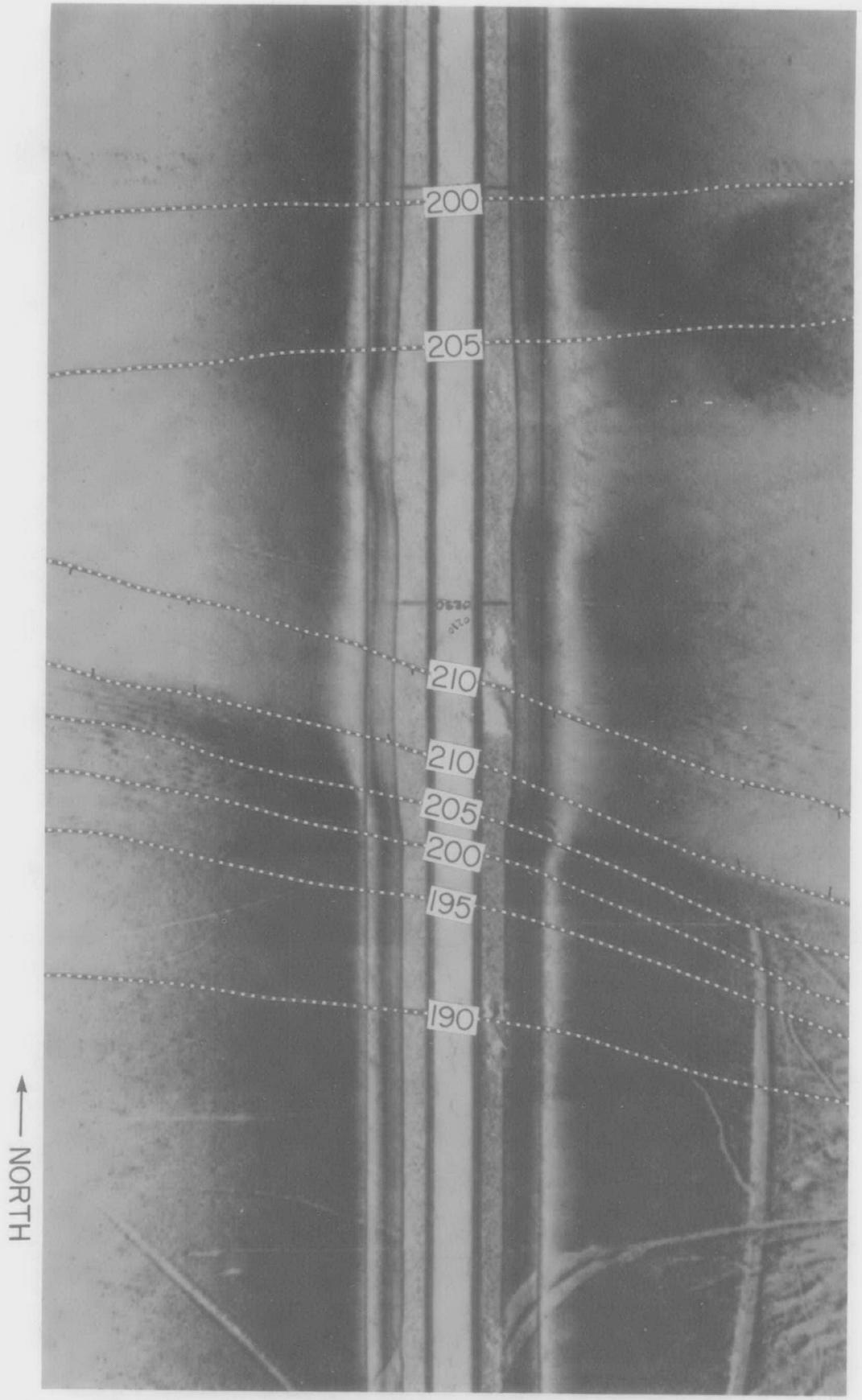

Figure 7. (continued)

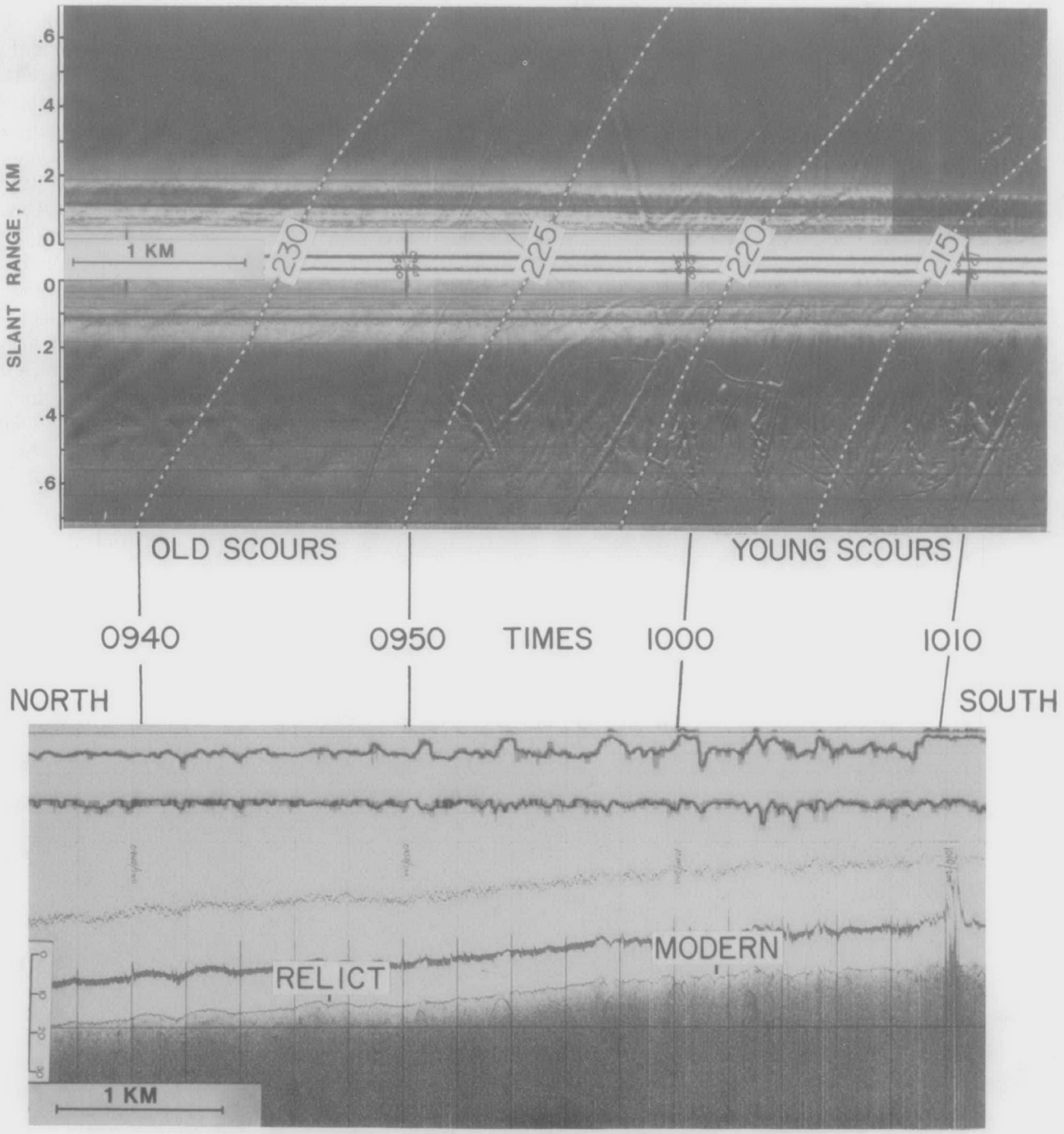

Figure 8. Sonograph from Okak Saddle showing older, wider, relict scours cross-cut by younger, narrower scours. Superimposed isobaths are in metres.

CONCLUSIONS

In conclusion, the strengths of the rotary and translatory ocean currents in different areas are reflected by the directional distribution of scour orientation. The amount of vertical bathymetric relief over which an iceberg can scour is controlled, in part, by the magnitude of the driving current. In areas of bathymetric sheltering, the modern iceberg flux does not inscribe the seafloor. Comparisons of current iceberg trajectories and scour orientation on both the regional and local scales have indicated that currents are the major control on scour orientation. In the summary diagram (Fig. 9), the size of the vectors reflects the relative strength of the translatory currents. In the deeper-water areas, large, dark arrows indicate a stronger translatory current than on the shallow-water bank tops. On these local highs and in areas of weak translatory currents, the scour orientations were more widely distributed, whereas they were far more consistent in areas of deeper-water, stronger translatory currents. The open arrows in Figure 9 reflect what is interpreted as relict populations. On the northeast edge of North Saglek Bank, the paleocurrent regime is interpreted as being similar to today's current regime because the scours are very well aligned. However, in Okak Saddle between South Saglek and Okak banks, a difference of nearly 90 degrees exists between the modern current regime and what is interpreted as the paleocurrent regime. This difference indicates that icebergs were calving off tide-water glaciers to the west and drifting out into the open Labrador Sea, similar to the present-day calving process along the coasts of Greenland. The timing of this regime, however, has not been determined.

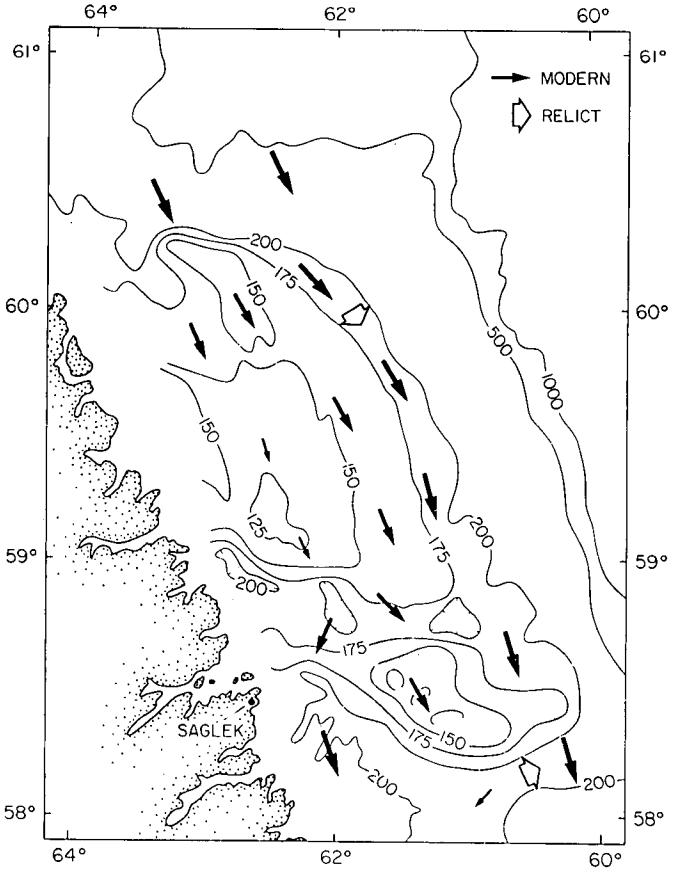

Figure 9 Interpretation of generalized currents and iceberg drift trajectories over Saglek Bank based on scour trend analysis, moored current meter and current drogue data, and observed iceberg trajectories. The larger the size of the arrow,the greater the ratio of translatory to rotational current in an area. Bathymetry is in metres.

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DISCUSSION

Drew Allan, Petro-Canada: I was just wondering how you inferred the direction there in Okak Saddle?

Brian Todd: We measured all the scour directions on the sidescan records, corrected them for ship's heading etc., and entered them into the data base. We ended up with two directions relative to true north for all the scours.

Drew Allan, Petro-Canada: How do you know which end was the start of the scour and which end was the finish?

Brian Todd: We don't.

Drew Allan, Petro-Canada: I don't think you have showed anything other than the fact that the predominant directions of the scours are the same.

From the Floor: Question not heard.

Brian Todd: It is very unlikely that the wide, older, relict scours would indicate very large icebergs going into much shallower water in times past. I don't think they could have got there. I think it is far more likely that icebergs calved from this region (tide-water glaciers in Okak Saddle) and drifted east, i.e., out to sea.

DOCUMENTATION OF ICEBERG GROUNDINGS

M. El-Tahan and H. El-Tahan[1]
FENCO Newfoundland Limited
189 Water Street
St. John's, Newfoundland, A1C 5S2

and

K. Moran[2]
Atlantic Geoscience Centre
Geological Survey of Canada
Bedford Institute of Oceanography
Box 1006, Dartmouth, Nova Scotia, B2Y 4A2

INTRODUCTION

The objective of this study (El-Tahan et al. 1985), supported by ESRF, was to compile all the iceberg-grounding information pertaining to the east coast of Canada, for the Grand Banks, Labrador Shelf, and Baffin Bay regions.

In this paper, several of the data sets compiled during the study are discussed with emphasis on the criteria that were established to identify groundings. Some data analyses that have been completed are then reviewed.

ICEBERG-GROUNDING DATA SETS

In total, there are five major data sets, two of which contain a significant amount of data. One data set consists of iceberg observations made using drill-rig radar between 1973 and 1982 and contains details of about 3,000 icebergs. Other data sets resulted from shore-based radar, one covering Saglek Bank and two others covering the Strait of Belle Isle. The International Ice Patrol (IIP) also has a file of about 65,000 iceberg sightings which is available.

Other sources of information were also included in the study, such as earlier iceberg studies in which data about icebergs sightings and groundings were collected from ship reports, and repair records for breaks in submarine cables, primarily telecommunications cables, 25 of which were recorded between 1960 and 1982.

An important aspect of the data from drill-rig radar is the fact that there can be significant errors in the calculation of the velocity of icebergs. FENCO analysed radar systems

[1] Currently with Arctec Newfoundland Limited.
[2] Presenter.

and found that uncertainties in the order of 0.5 km over a range of 35 km were typical for drill-rig radar systems. This uncertainty, or error, was taken into account in subsequent calculations of the drift velocity of icebergs.

DRILL-RIG RADAR OBSERVATIONS

The grounding criteria established for the tracking information from drill-rig and land-based radars are presented in Figure 1. The first step was to screen all the tracking data to identify icebergs that might have been grounded. Icebergs with consistently low velocities were identified as being potentially grounded and were further analysed. Icebergs identified as being stationary for a period of 6 hours or more were subjected to detailed analysis using the grounding criteria. Drill-rig reports and observer's logs were examined to determine whether groundings had been verified by ice observers or by supply vessel personnel, using constant bearings to known landmarks (when within sight or radar range of the coast). Current, wind conditions, and movement of other icebergs in the vicinity were analysed. Changes in ocean currents, winds, waves, or tides may temporarily slow or even stop a drifting iceberg and may give a false impression that it has grounded. Therefore, iceberg tracking data and plots were checked to determine if there were other icebergs moving in the vicinity (within 8 km) of the iceberg under consideration. When iceberg draught measurements were available, they were compared to information on water depth obtained from hydrographic charts to confirm grounding events.

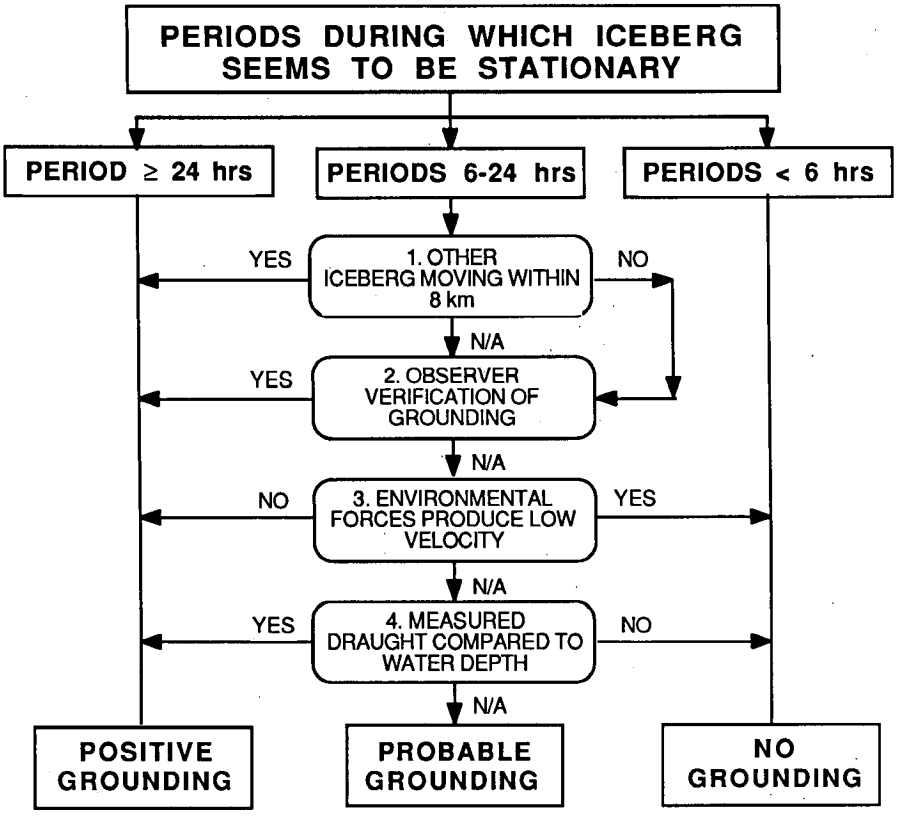

Figure 1. Grounding criteria for iceberg tracked by drill-rig or shore-based radar.

Based on this analysis and on the grounding criteria, a stationary iceberg was identifed as being either positively grounded or probably grounded (see Fig. 1).

Figure 2 shows the location and frequency of positive groundings near each well site for all years. To summarize the groundings from all available well-site radar observations (Table 1), 4.5% of the icebergs tracked were identified as being positively grounded and 1.8% as being probably grounded.

SHORE-BASED RADAR OBSERVATIONS

In the past, stations have been set up to cover the Straits of Belle Isle, Saglek Bank, and the Baffin Island area. These stations collected data for several seasons and the information has been used primarily to measure the flux of nearshore icebergs. These data have been reviewed to extract information on velocities and groundings. In the Saglek Bank area, 20% of the icebergs were identified as being positively grounded and 7% were probably grounded. Similar percentages of groundings were observed for the Strait of Belle Isle area even though it lies further to the south.

SATELLITE TELEMETRY

A total of 40 icebergs were tracked by the IIP and by Petro-Canada in Baffin Bay and the Labrador Sea between 1977 and 1980. Of the 40 icebergs tracked, only 3 were never grounded.

CABLE BREAK DATA

This data set is based on information on breaks in active cables operating in the various regions. Most cable breaks have occurred around the tip of Greenland where 16 breaks have been recorded between 1960 and 1982 out of a total of 25 breaks for the region studied.

INTERNATIONAL ICE PATROL DATA

One of the largest data sets is that of the IIP which includes observations from both aircraft and ships. To date, there have been about 65,000 sightings which form a different type of data set from those mentioned previously. In effect, an observer goes to a region, locates icebergs there and returns later to repeat the process. Of the 65,000 sightings, several hundred icebergs were identified again in the same location. Ten of these were identified as being positively grounded and five as being probably grounded.

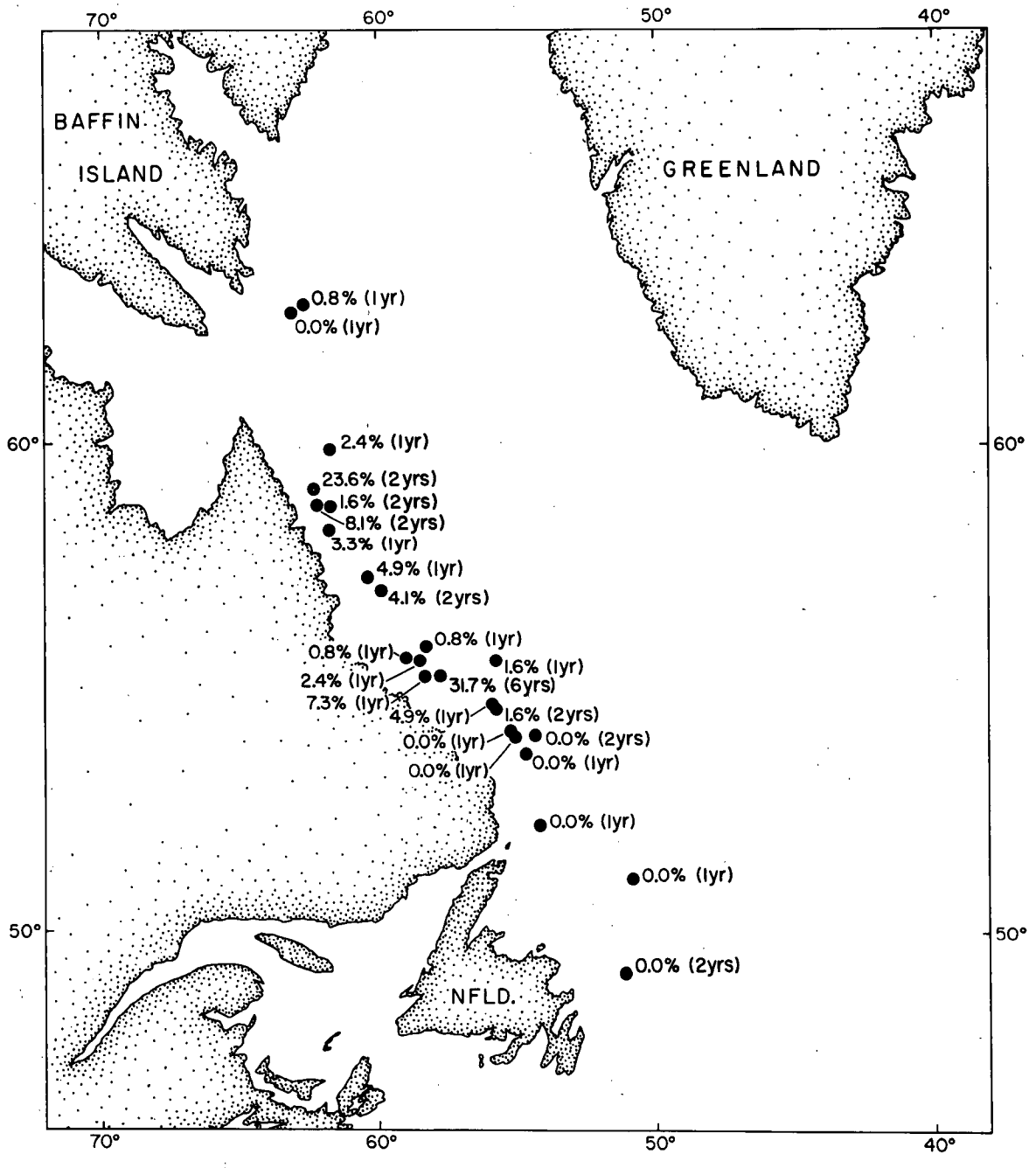

Figure 2. Distribution of iceberg groundings as a percentage of the total icebergs tracked.

TABLE 1

Yearly summary of grounding events for well-site data

Year	Number of tracked icebergs		Positive groundings		Probable groundings	
	Total	Mean per site	Total	%	Total	%
1973	67	22	2	3.0	1	1.5
1974	416	139	6	1.4	1	0.2
1975	149	30	3	2.0	7	4.7
1976	229	38	9	3.9	0	0
1978	123	61	5	4.0	3	2.4
1979	442	88	23	5.2	5	1.1
1980	286	41	19	6.6	6	2.1
1981	633	211	48	7.6	17	2.6
1982	383	97	7	1.8	8	2.1
Total	2,728	72	123	4.5	48	1.8

PRELIMINARY DATA ANALYSIS

The data analysis is considered preliminary because this study concentrated on the compilation and checking of data. The preliminary analysis shows little correlation between the percentage groundings and the number of actual sightings. On the other hand, the percentage groundings versus water depth shows significant numbers of groundings in water depths less than 200 m. The deepest grounded iceberg appears in 220 m of water. Some data suggest that icebergs have been grounded in 500 m of water but positional uncertainties may have led to incorrect results.

CONCLUSIONS

All the grounding data that have been compiled and all the other basic information are now stored in computer-compatible form in a single file. The next step is to compare this data set to others. Preliminary manipulation of the data has been completed and this will be of greater value with better information on water depth. Future correlations could incorporate the locations of ice scours. This data set could also be compared with other environmental data sets. It could also, in future, be used with bathymetric and meteorological information.

The data set will be accessible to scientists and engineers. Thus, in addition to the report (El-Tahan et al. 1985), there is a nine-track tape that will be available from the Bedford Institute of Oceanography.

REFERENCE

El-Tahan, M., H. El-Tahan, D. Courage, and P. Mitten. 1985. Documentation of iceberg groundings. Environmental Studies Revolving Funds, Report No. 007, Ottawa, 162 p.

DISCUSSIONS

Peter Barnes, U.S. Geological Survey: When you are talking about the percentage of icebergs, what was the smallest size of the group?

Kate Moran: What percentage of icebergs?

Peter Barnes, U.S. Geological Survey: For example, those from the radar. Many grounded icebergs were seen in this area. Did you select the size of the icebergs that were tracked -- the ones that were completely grounded -- because of water depth? How small was the distribution?

Kate Moran: Of the draught? I don't know.

Peter Barnes, U.S. Geological Survey: What was the percent of the total? What does the total include?

Kate Moran: All the bergs.

Peter Barnes, U.S. Geological Survey: It is a truncated distribution. Was the radar preferential in picking out the larger icebergs? He is suggesting that the smaller ones which don't ground don't necessarily show up on the radar.

Kate Moran: What is included in this data set are all icebergs that are observed on the radar.

From the floor: Right. That is a very unique distribution. It's a sample. It is certainly not the population of icebergs.

Peter Barnes, U.S. Geological Survey: How small a target can you see on the radar?

Kate Moran: I don't know. Do you know that, John (Miller)? How small a target can the radar detect -- the lower limits?

John Miller, Petro-Canada: How small a target can the radar detect? You have just got about a million dollars in studies from the ESRF Iceberg Committee to look at that. It is a function of course of the size of the target, the sea state, the range, and the resolution cell. Basically, you have to be in closer to see the small ones because at greater range you can't see them. The radar that was used at Saglek in 1972 was operated for about two weeks resulting in a relatively small sample. The radar that operated in Lancaster Sound in 1979 was of limited power (25 kW), and is typical of drillship radars. These systems are probably good to 35-55 km, beyond that they are only picking up very large icebergs, about 100 m in dimension.

GRAND BANKS ICE-SCOUR CATALOGUE

Lorne Schoenthaler
Mobil Oil Canada Ltd.
Box 62, Atlantic Place
St. John's, Newfoundland, A1C 6C9

INTRODUCTION

Over the last 6 years, Mobil has conducted many well-site surveys on the Grand Banks of Newfoundland, in and around the Hibernia field. The well-site surveys are conducted over relatively small areas around prospective drilling sites, and consist of survey lines laid out in a grid pattern with spacing between 250 and 1,000 m. As a result, large quantities of bathymetric, subbottom profiler, and sidescan data have been gathered. These data, were used as the starting point for establishing a computer-based ice-scour catalogue. Data from other Mobil surveys, such as along pipeline routes, as well as regional data from groups such as Bedford Institute of Oceanography (BIO) and Centre for Cold Ocean Resources Engineering (C-CORE) were also used.

Mobil's objectives in compilation of a Grand Banks ice-scour catalogue were to determine the areas where surveys exist, and to catalogue actual scours for use in statistical calculations.

ICE-SCOUR CATALOGUE

The area encompassed by the Grand Banks Ice-Scour Catalogue (Fig. 1) was divided into 30 separate corridors on the basis of bathymetry. Water depths in the area vary between 60 and 260 m. All usable scour data in each corridor were entered into the catalogue. The survey data consisted of high-resolution, Huntec Deep Towed Seismic (DTS) subbottom profiles and side-scan sonar data (70 and 100 kHz).

The data base consists of scour data taken from about 16,300 line kilometres of surveys. About 5,800 km of these data were obtained from selected regional survey data from BIO and C-CORE during seven cruises. The remaining 10,500 km of data were taken from Mobil surveys, which included 25 well-site and several pipeline surveys.

The catalogue was begun in 1981 and was updated in 1984. Typical parameters catalogued are:

- feature number
- type -- pit or scour
- survey identifier
- latitude/longitude; start and end
- depth (m)
- length (m)

- width (m)
- water depth (m)
- orientation
- scour type identifier
- sediment type
- sediment thickness.

The scour types are divided into two categories indicative of the two distinct populations: pit or scour. The origin of the pit is uncertain. A scour identifier is used to describe scour appearance as either linear or meandering.

Scour lengths are recorded only when the entire scour is continuous on a sidescan sonogram. In the case where starting and end points are not visible, the length of scour is not documented.

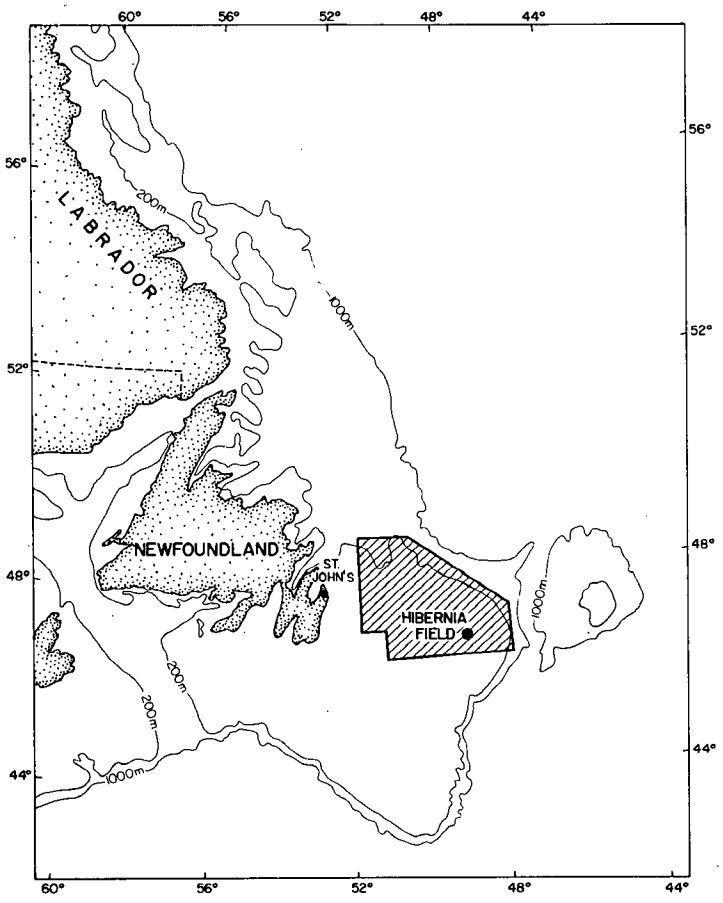

Figure 1. Location of the Grand Banks Ice-Scour Catalogue area.

Scour widths are obtained from the side-scan records after being corrected for distortion. Scour depths are measured from Huntec (DTS) records, and may not represent maximum depth, unless the DTS passed directly over the deepest part of the scour.

Where possible, sediment type and thickness are documented and evidence of any bedforms are also noted.

Histograms were drawn, showing the following types of information:

·number of scours versus water depth
·maximum scour depth versus water depth
·scour width versus water depth
·scour density versus water depth
·scours per line kilometre versus water depth.

An example of a sidescan sonogram used in the study is presented in Figure 2. It shows a sidescan sonogram of an iceberg scour and the iceberg that actually created it. The location was 40 km northwest of Hibernia. The scour is 1.8 m deep in a water depth of 86 m. The iceberg's mass is estimated to be 1.4 million tonnes.

DISCUSSION

Alan Ruffman, Geomarine Associates Ltd.: Have you returned to the area to document what changes to the scour have taken place? Did you run the same type of sidescan sonogram along the same track?

Lorne Schoenthaler: We returned to the site about seven months later, and reran the sidescan sonograms. They looked very similar to the original ones.

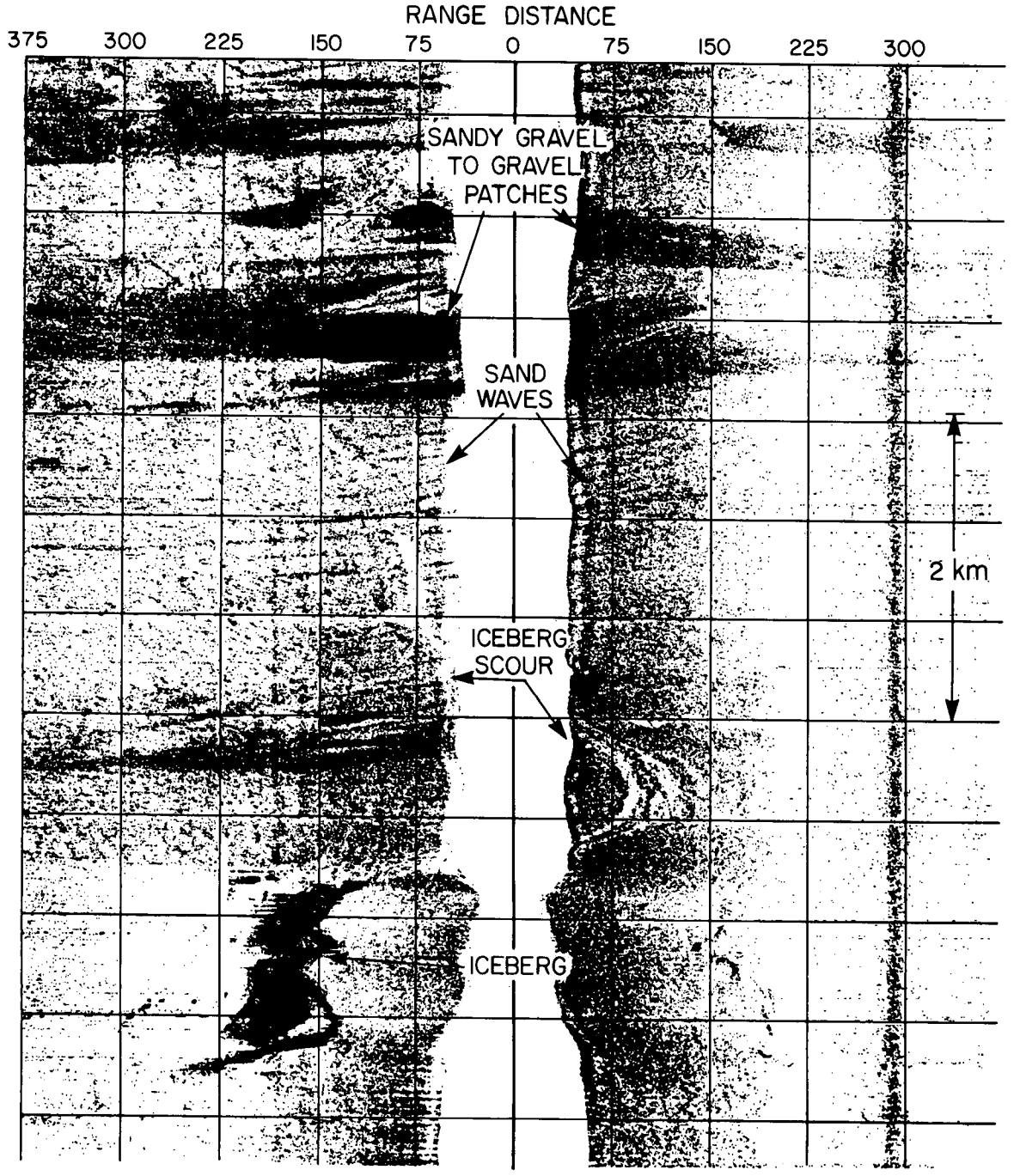

Figure 2. Sidescan sonar record of a portion of the line showing an iceberg scour along with the berg itself. Sand waves and patches of coarser material, possibly sandy gravel or gravel, are also evident.

THE ESRF/ASTIS ICE-SCOUR BIBLIOGRAPHY

Ross Goodwin
The Arctic Science and Technology Information System (ASTIS)
The Arctic Institute of North America
The University of Calgary
Calgary, Alberta, T2N 1N4

INTRODUCTION

The purpose of the joint project between the Environmental Studies Revolving Funds (ESRF) and the Arctic Science and Technology Information System (ASTIS) is to build a data base that will act as a central source of environmental and social information relating to the Canada Lands. This project is using as a starting point the existing bibliographic data base of ASTIS which contains 16,000 citations, most of which are relevant to Canada. This data base is being enhanced to meet the needs of ESRF/ASTIS by expanding its geographic coverage to include the east and west coasts, and by systematically improving the data base's coverage of the ESRF's priority subjects.

The ASTIS data base can be easily searched on line, both by professionals in information, such as librarians, and by end users, such as managers and engineers. The main purpose of the ESRF/ASTIS project is to provide a comprehensive data base for on-line searching. A useful way of measuring the progress of the data-base enhancement, however, is to produce printed bibliographies on each of the ESRF priority subjects as enhancement in that subject area nears completion. Each of these bibliographies will then be updated periodically to include newly published material.

Ice scour was chosen as the first ESRF priority subject to be enhanced. Our experience with this ice-scour pilot project will guide us in planning the enhancement of other priority subjects.

CITATION OF REFERENCES

Work on enhancing the ice-scour coverage in the data base began late in October 1984. Lists of references from most of the significant reports on ice scour were examined. On-line data bases that might be expected to contain citations on ice scour were searched. Whenever possible, the original document was examined for relevancy before being included. A small number of documents could not be obtained in time and were indexed sight unseen. By the end of January 1985, the number of ice-scour citations in the data base had been increased from 97 to 287.

ICE-SCOUR BIBLIOGRAPHY

A first draft of the resulting Ice-Scour Bibliography was circulated to the ESRF Seabottom Ice Scour Program Study Committee in December, 1984. A second draft is on display at this workshop and will be distributed to some of you for detailed comments. This second draft is probably close to being comprehensive, at least for the literature in English. We would appreciate your help in pointing out reports that have been missed, as well as your comments on the format of the bibliography.

We expect to close off the bibliography in June, 1985, and the final result will be released as an ESRF report as soon as printing can be completed (Goodwin et al. 1985). ESRF/ASTIS will add new reports, and any overlooked reports, to the data base on a continual basis. Thus, an updated on-line version of the Ice-Scour Bibliography will always be available in the ASTIS data base.

REFERENCE

Goodwin, C.R., J.C. Finley, and L.M. Howard. 1985. Ice scour bibliography. Environmental Studies Revolving Funds Report No. 010. Ottawa, 99 p.

DISCUSSION

From the floor: How are you handling proprietary and confidential reports?

Ross Goodwin: If the report is actually confidential, we are not entering it into the bibliography. Many reports that were at one time proprietary are now in the public domain, yet are only available in small quantities. These we like to have in the bibliography as long as it is theoretically possible for someone to obtain a copy.

From the floor: Are you going to become some kind of distribution centre for proprietary reports?

Ross Goodwin: No. What we are doing is putting location codes on the citations, indicating libraries that have copies for interlibrary loan. In addition, there is always the publisher's statement, which indicates where the report can be obtained. Any feedback on that subject would be useful.

REGIONAL ICE-SCOUR STUDIES AND DATA BASES: ISSUES AND CONCERNS

S.M. Blasco
Atlantic Geoscience Centre
Geological Survey of Canada
Bedford Institute of Oceanography
Box 1006, Dartmouth, Nova Scotia, B2Y 4A2

SUMMARY

The topics that have been discussed in this session of the workshop have led to the identification of several issues concerning the acquisition and analysis of ice scour data. Of principal concern are: the recognition of the need for collecting high quality data through the optimization of both instrumentation and operating conditions; the integrity, consistency and accuracy of interpretations and analyses; and the identification and accommodation of inherent biases associated with many data (e.g. truncated data sets). For example, small, shallow ice scours less than 0.5 m in depth may go undetected on sonar records. This limitation should be reflected in subsequent analyses.

Of additional concern is the identification and proper measurement of all scour parameters that may be required for engineering design. Interaction among engineers, analysts and data collectors is required to prevent gaps or misuse. Should, for example, total scour length or berm width information be routinely collected or included in data bases?

The advantages of computerized data bases include the elimination of subjective interpretations, the potential standardization of measurement and analytical methodologies and the tremendous versatility in statistical manipulation. However, there is still a major concern relating to the level of confidence in the accuracy of computer derived parameters such as scour depth and width, etc. as well as the cost effectiveness of such derivations.

The need for valid regional information on the spatial and temporal distribution of individual scour parameters and their interrelationships is well known. However, the regional correlations of scour parameters such as depth, width and orientation with environmental factors such as sea-ice zonation, sediment properties, sedimentation rates and seabed morphology, etc. are not well understood nor are they being examined to any extent at present. It would seem reasonable to assume that, if subsea pipeline trenching depths are to be designed kilometre by kilometre to minimize cost, then a more precise knowledge of the effect of environmental factors on scour depths would be valuable in optimizing estimates of trench depths along prospective routes. A regional understanding of such correlations should give the design engineer a valuable perspective for site specific assessments.

Finally, as mentioned at the 1982 Montbello Workshop (Pilkington ed. 1985), it is important to pursue a wide variety of methodologies such as repetitive mapping, iceberg flux etc. to resolve the ice scour problem. The shorter term solution is not likely to come from any single technique but from the convergence of results from independent methodologies applied to appropriate data.

REFERENCE

Pilkington, R. 1985. Workshop on ice scouring, 15-19 February 1982. Associate Committee on Geotechnical Research. National Research Council Technical Memorandum No. 136. 251 p.

DISCUSSION

Walter Bobby, Newfoundland Petroleum Directorate: Todd (this volume; Todd B.J. Iceberg scouring on Saglek Bank, Northern Labrador Shelf) has described briefly the type of scouring process on the Saglek Bank. He indicated that there were scours on the northern and southern sides of the bank but that the centre of the bank, where the water depth increases by 10%, did not have any scour marks at all. I was wondering if this was because of the fact that the icebergs in that region do not show a tendency to increase in draught, or whether the reason is that the icebergs are more stable? The other alternative is that if instability does occur then draught may not increase considerably?

The other comment I wish to make is that there have been a lot of indications of rolling icebergs. This rolling is a great problem for people who have tried to tow icebergs because of line slippage from a rolling iceberg. I was wondering if there is any information on icebergs of near-scouring draught that did roll and ground?

Brian Todd, Dalhousie University: The icebergs are filtered somewhat by drifting over north Saglek Bank, so that smaller-sized icebergs approach Saglek Bank from the North. The icebergs scour from north Saglek Bank down into the Karlsefni Trough. We saw a change in draught of the scouring icebergs in the order of 15 m so they did scour up- and downslope, at least by 15 m, but not into the very bottom of the Karlsefni Trough itself. In Okak Saddle, which has significantly deeper water than Karlsefni Trough, we did see that larger icebergs on the outer (eastern) edge of the bank were scouring deeper and showing draught changes in the order of 20-25 m as they scoured up- and downslope.

From the floor: But they hadn't come across the bank?

Brian Todd, Dalhousie University: No. They hadn't come across the bank. They were deep-water icebergs that had come down the east side of the bank. This population differs from those icebergs entering Karlsefni Trough. The top of Okak Bank has a water depth in the neighbourhood of 125-150 m, but it drops off to 225 m in Okak Saddle.

Steve Blasco: Did anyone else have any comment on the second question that was raised?

John Miller, Petro-Canada: You mentioned that people towing icebergs are familiar with them rolling. You implied that the rolling took place first. I think it is important to remember that under tow you are applying a force that's creating a rather large overturning moment. This moment is located high relative to the to the centre of gravity of the iceberg, and that it is this external force creating the rolling.

As a personal comment, we are talking as though draught increases after rolling are commonplace, but I, personally, remain somewhat skeptical about that. The two-dimensional models that have been mentioned in publications indicate draught increases up to 50% with

averages of 10 or 12%. If we look at some of the data and we use what's called the Brooks' criterion for draught versus length, we still haven't yet been able to exceed that from known observations. We get a few outliers that are within the range of the instrumental errors in the measurement. I would like to support the suggestion that increases in draught upon rolling are neither a wide-spread nor a well-documented phenomenon.

Peter Barnes, U.S. Geological Survey: I have a comment about the documentation of data bases. We have seen lists of parameters that should be documented, but have not discussed how those parameters are defined. I believe that there are differences in how people define depth, for example, if we can define how those numbers are getting into the data base, it would be helpful in comparing different data sets.

Steve Blasco: I think that is a very good point. The problem of terminology raises questions about the parameters in the data bases. In all our Beaufort Sea reports a full section is devoted to the definitions of the terms we've used and what the terms mean in the data base. Unless definitions of terms are included, the results could be misused. I can think of an example that is relevant to this workshop. From the standpoint of data acquisition, we consider "scour width" to be the zone of removed or displaced sediments. This information could be used by a design engineer to give some indication of the length of pipeline that may be damaged. But in the "scour width" we do not include the zone of displaced sediments on either side. Now there is the "berm" which, although smaller in size, is not included in the data base. If, for example, you are estimating the length of a pipeline that may be disrupted or covered by a huge berm, it should in fact be recognized that the scour width is simply the zone of displaced sediment, say 100 m. When you include the berm on either side the zone may be 120 m or more. If you are considering jumper pipelines, and you need to know the length of the jumpers, I suspect you would have to include the total zone in the definition. Unless we can ensure that we have conveyed to the designer what we have measured during the data acquisition, substantial errors could prevail.

Roger Pilkington, Gulf Canada Resources: In line with the consistency of terminology, I would like to see results plotted in a similar fashion. For instance, for probability distributions, I would like to see exceedance plotted instead of just differential. I have spent a great deal of time trying to compare distributions with 0.1-m intervals against distributions with 1-ft intervals. The intervals make a lot of difference to the actual result. If we all plotted exceedance then we would be compatible provided that we all use metric units.

Steve Blasco: That is another relevant point. I am somewhat concerned that certain terms can be overlooked during interpretation. In comparing different data sets, we have particular problems with depth distribution function parameters (k values) that have been derived by a variety of means.

David McKeehan, INTEC Engineering: With reference to pipelines and scour width, it is important to remember that if a pipeline is damaged by a keel, then that pipeline is out of commission. This could possibly relate to a situation in which a very wide keel would cause the replacement of a 100-m section of pipe, for example. In any event, the loss of production would be the same even if a 10-m keel had caused the damage. Yesterday, there was some discussion on multiple keels within the same scour (this volume; Barnes, P.W. and E. Reimnitz. Ice-gouge studies, Alaskan Beaufort Sea). As far as repair is concerned, a 10-m scour produced by two keels penetrating down 6 m is the same as one keel penetrating 6 m.

One final comment on sinuous or arcuate scours. If a deep, single keel is forced across a pipeline several times during a single season, the pipeline is still out of commission for the same amount of time as if it had been crossed only once. You may be forced to mobilize repair crews,

but the tradeoff between cost of repair and cost of installation is about the same. It is therefore, important to keep characteristics such as directionality in mind, as well as width.

ICE-SCOUR FREQUENCY AND RISK

Session Chairmen:

R. Pilkington
R.W. Marcellus

ESTIMATING ICE-SCOUR FREQUENCY AND RISK TO BURIED PIPELINES

Roger Pilkington
Gulf Canada Resources Inc.
401-9th Avenue, SW, Calgary, Alberta, T2P 2H7

INTRODUCTION

One of the most important factors in the burial of pipelines beneath Arctic seas is the estimation of the return period of ice ridges with deep keels that may cause damage. Various physical models and data bases have already been discussed that seem ideal for understanding processes taking place (Barnes and Reimnitz; Gilbert and Blasco, this volume). However, in risk assessment, in which the problem of estimating the return periods of ice keels arises, these models may have certain limitations. For example, statistical data form the parameters that are entered into the models, and these may not be as well known as the results that are being predicted. In the Beaufort Sea, for instance, statistics on the distribution and shapes of ice keels and on soil interactions are not as well known as the actual number and distribution of scours on the seafloor. This argument suggests that statistical methods of obtaining return periods from ice-scour information may be preferable. In looking at the application of statistical methods, five philosophical questions need to be answered before attempting to estimate and define burial depth.

(a) What return period should be used; 100 years as is used for most engineering projects, or 1,000 years, to further minimize risk?

(b) Should we consider a percentage risk factor over the lifetime of a structure (for example, a 2% risk, which amounts to a 1,250 year return period)?

(c) Should we be looking at cost optimization by which we minimize the cost of pipeline burial over the lifetime of the project?

(d) Should we be looking at a return period on a "per pipe" basis, or at a return period "per project", or at a return period for overall projects?

(e) How do we consider the risk of laying a pipe through different risk zones?

DIRECT METHODS OF DETERMINING BURIAL DEPTH

Maximum Scour in Area

One method of determining burial depth is to bury the pipe below the maximum scour in an area, which has the advantage that results can be obtained with relative ease and speed. It is also comforting to know the depth of the deepest scour; however, the question arises as to whether the scour is, for example, a 100-year scour or a 1,000-year scour. Another question that

arises concerns the definition of a 100-year scour. Does a 100-year scour occur somewhere in the Beaufort Sea every year? If we find the deepest scour, what is the return period on that scour, and is that scour near a planned pipeline route? Also, can we look at the deepest scour in 10,000 km of independent scour tracks (each track being the average length of a scour, 10-12 km), and will the result be the 100-year scour for our particular 100 km of pipeline? It is felt that this approach is not very reliable.

Dating

This method involves taking a core sample of the infilled material within a scour, then attempting to date subsamples using standard methods, such as radiocarbon and pollen analysis (Kenting, 1975; Mudie 1986, this volume). This method relies on identifying the base of the scour and on obtaining good samples of suitable material. The results estimate the age of the scour, which is useful; however, the fundamental problem, apart from cost and the possible lack of results, is that the infilled sediment itself is probably reworked by ice or current action. This mobility of sediments means that deeper samples could be younger in age than those less deep. Also, for a statistical result, this method is extremely expensive, as many scours must be dated. However, dating does have merit in deeper waters (e.g. 60 m in the Beaufort Sea) where recent scouring is unlikely. Estimates of sedimentation rate can be obtained on the basis of a small number of samples.

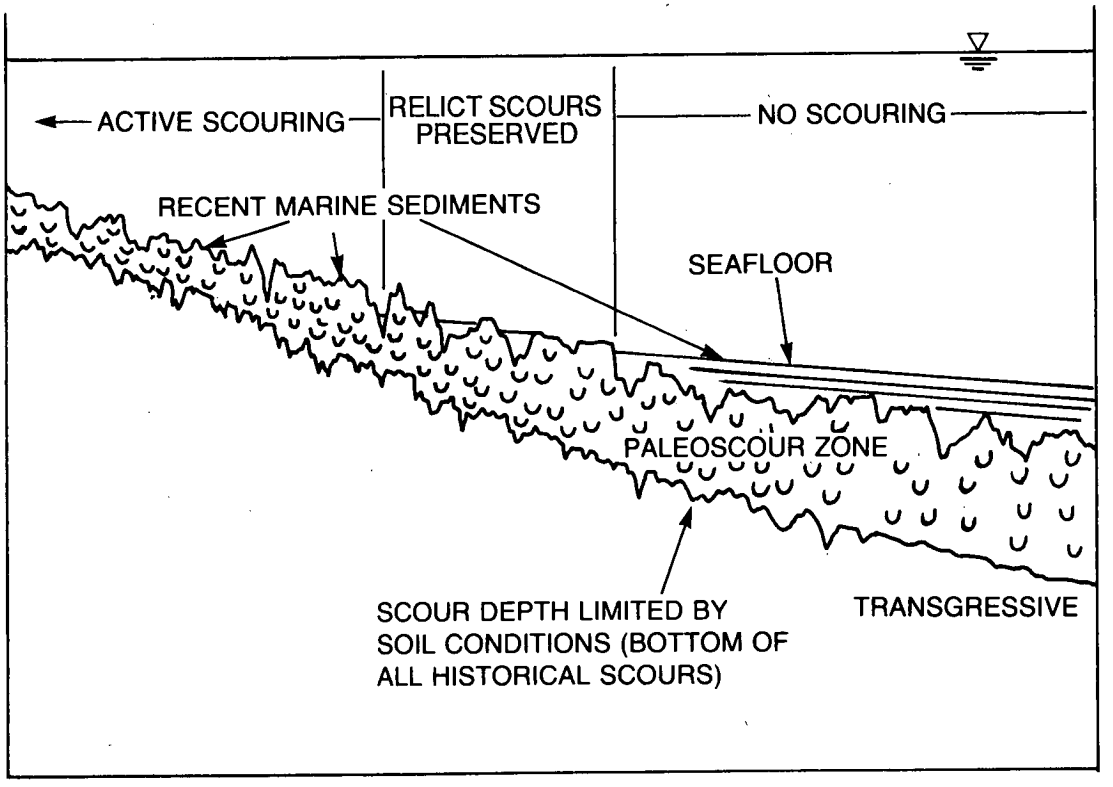

Figure 1. The paleoscour zone method of determining burial depth.

Paleoscour Zone

The paleoscour zone (PZ) method (S. Blasco, personal communication) involves the delineation of the zone of surficial sediments that have been redistributed in recent times by the action of ice scour. Because sea-level in the Beaufort Sea has risen to inundate the shelf as a result of the recession of Pleistocene glaciers, all scouring must have occurred during the last 15,000 years. Scouring activity produces a zone of small disturbances which extends to a certain depth (Fig. 1). If this zone is detected, then it is reasonable to assume that a pipeline buried deeper than the depth of the "PZ" would not have been damaged in the last 15,000 years. Extending this argument to shallower areas, to water depths of about 10 m, the PZ will correspond to a more recent time period, perhaps 10,000 years, and may represent a return period of 5,000 years. The suggestion is that if the PZ can be delineated in the shallower areas, then a pipeline buried beneath it would be safe. One problem with this technique is that it requires cohesive sediments that retain detectable features. The advantages of the PZ is that the results are immediate and specific to location. However, the lower boundary of the PZ is difficult to detect in some areas with present shallow seismic techniques, and the results are conservative and are applicable only to shallow water areas.

SCOUR-DEPTH DISTRIBUTION METHODS FOR DETERMINING BURIAL DEPTH

In plotting the scour-depth distribution functions, it is convenient to plot the probability on a log-linear scale to obtain a straight line relationship. The range of available data is shown in Figure 2. The multi-keel or "rake"-type scours are probably scours caused by first-year ice, whereas single scours are probably caused by multi-year ice. If these data could be separated, it is very likely that they would exhibit different exponential functions. The first-year features can scour only to a limited depth, being weaker, whereas the multi-year features being stronger, possessing a single and narrow ploughing point, can plough deeper. Unfortunately, it is not yet possible to separate out the two exponential functions.

For multi-year ice-scouring events the design depth is probably much deeper than for first-year events, the first-year ice being weaker than multi-year ice. This means that pipeline burial depth estimates based on shallow scours are not conservative. The only known solutions to this problem involve either collecting a large number of data, or analysing the collected data in two blocks representing first-year and multi-year ice-scouring events respectively. The problem changes when stiffer soils exist below the surface (Fig. 3). Again, the bulk of available data is biased towards the shallow scour range, and an extrapolation would give a conservative estimate of design depth.

Another problem with the interpretation of the scour-depth distribution arises from the effects of scour infill. Figure 4, shows the probability of scours deeper than a certain depth prior to, and after, a period of sedimentation. With uniform infill, where the scours would be reduced in depth by a fixed amount every year, the probability curve would be lowered. After normalization (adjustment of the distribution upward so that its zero depth has a probability of 1.0) however, the line would return to its original position. When infill occurs preferentially into the shallower scours, the distribution becomes less steep, and more shallow scours are lost preferentially from the distribution. After normalization, this line differs from the original distribution and, having a lesser slope suggests a more conservative design scour depth. Unless the deep scours have steeper sides there appears to be no simple mechanism that could explain how deep scours could be infilled preferentially to shallow scours.

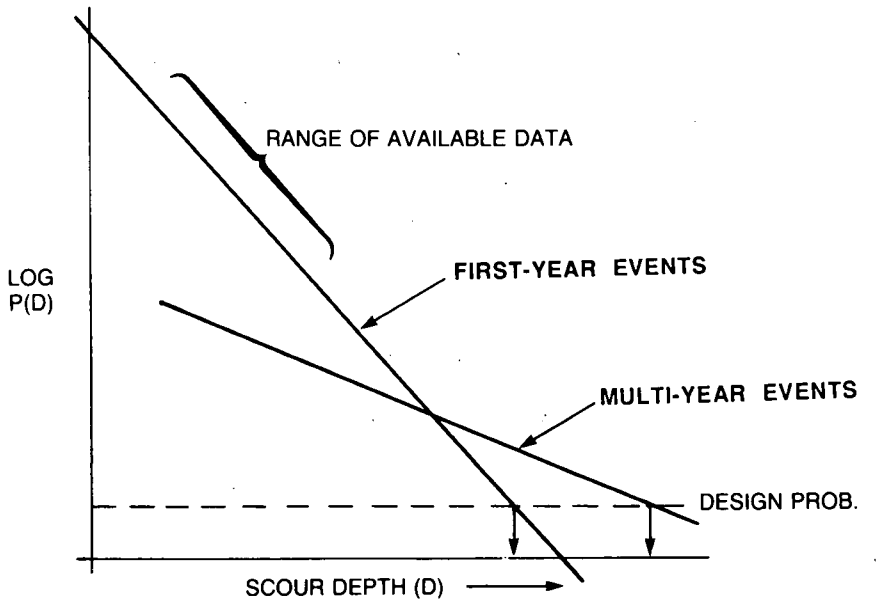

Figure 2. Scour-depth distributions showing how a distribution based on first-year pressure-ridge ice scouring events may lead to non-conservative estimates for pipeline burial depth.

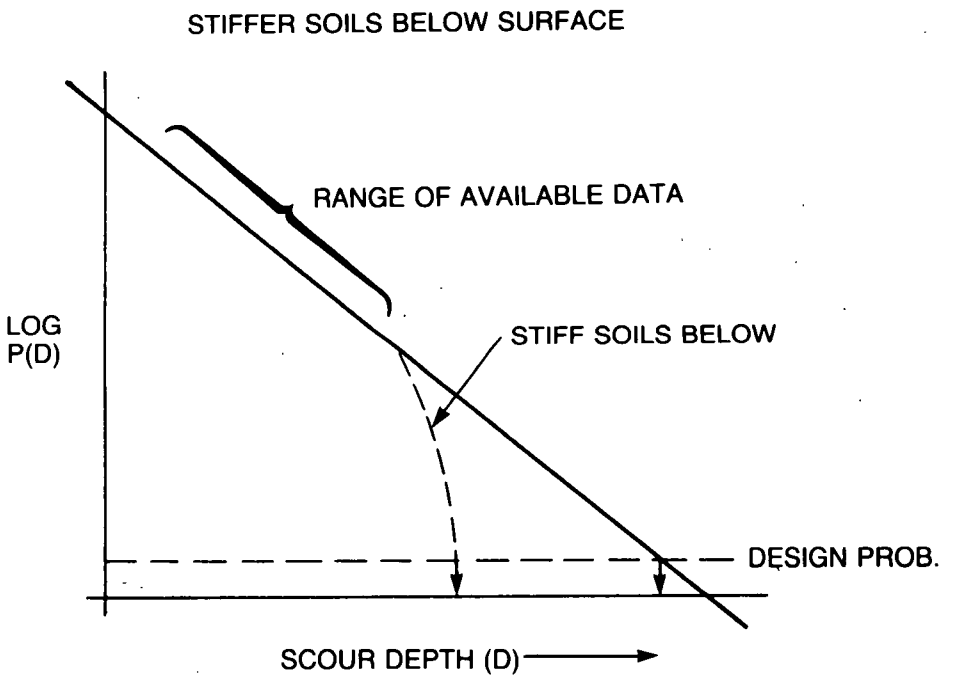

Figure 3. A scour-depth distribution leading to conservative estimates for pipeline burial depths, where stiffer sediments underly weaker surface sediments.

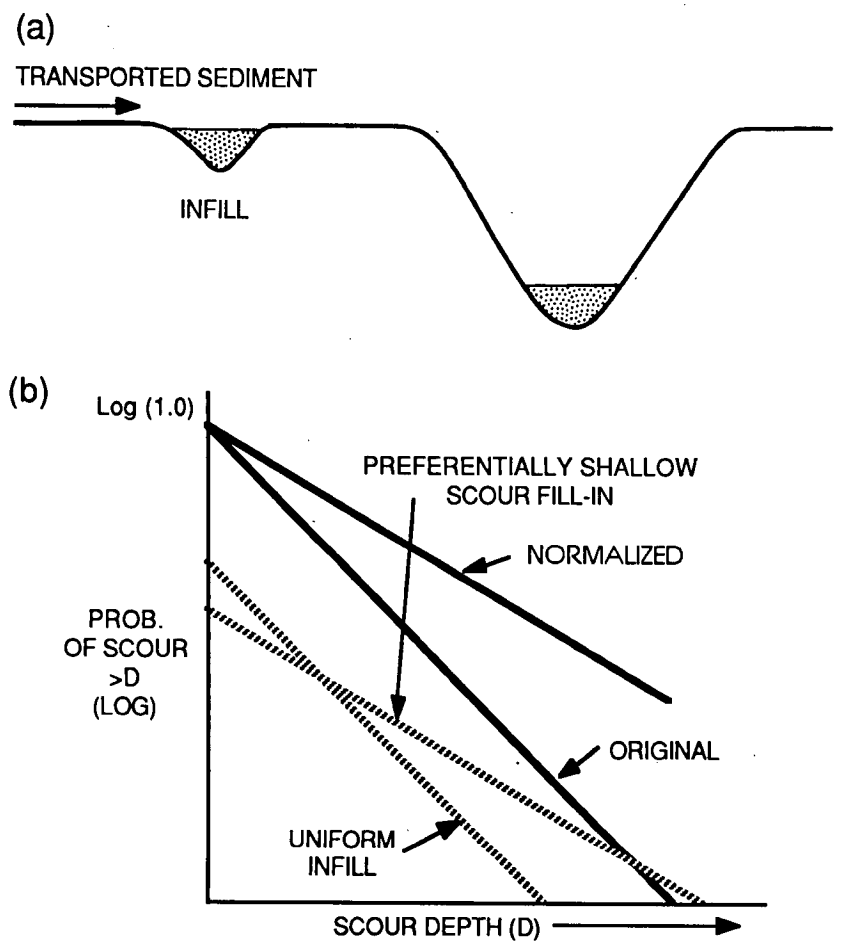

Figure 4. (a) Preferential shallow scour infill. For a given volume rate of bedload sediment transport, narrow, shallow scours will infill more rapidly than wide, deep scours. (b) the probability of scours greater than a certain depth prior to (line labelled "original"), and after a period of infill, showing the effects of two styles of sedimentation: uniform infill in which scours of all depths are diminished uniformly with time and preferential shallow-scour infill as a result of bedload transport.

Steady-State Scour Infill

A method developed several years ago, mainly by Lewis (1977), is known as the steady-state scour infill method. This method assumes that the number of scours on the seabed is constant at any time. If the infill rate is known, then the rate of rescouring can be estimated. This method which can be extended to give a depth for pipeline burial has the advantage that an immediate answer is obtained. A disadvantage is that a steady-state situation may not exist, and that an infill rate, which is dependent on the scour shape and frequency, may not be known. This process is also location-dependent. For example, close to the mouth of the Mackenzie Delta, the sedimentation rate will be high; in shallow water, scour infill will be affected by wave action, the effects of which may not be well known. Scour infill rate is probably very difficult, if not impossible, to measure because it is episodic. If the measurement is not taken at the correct time and in the correct location, the results will be in error.

Repetitive Seafloor Mosaics and Ice-Scour Depth Distribution

The method that is probably creating the most interest at the moment is the use of repetitive seafloor mosaics and the ice-scour depth distribution (Weeks et al. 1983). The relationship:

$$N_D = N_0 L T e^{-KD} \quad (1)$$

indicates that the number of scours, N_D, that reach a depth, D, is equal to the annual frequency of scouring (all depth) per unit length, N_0, multiplied by the length of the pipeline, L, multiplied by the lifetime, T, of the project (e.g., 25 years), multiplied by the probability, e^{-KD}, of any one of these scours reaching some depth, D. The frequency of scouring, N_0, can be obtained from repetitive mapping by measuring the number of new scours appearing on the seafloor over a given period of time, and the exponent K can be obtained from the scour-depth distribution. For example, to estimate the depth of burial of a 100-km pipeline with an expected 25-year life span, known information can be entered into Equation 1 leaving an explicit function in D. The method seems reasonable given data obtained over a certain period; the possibility exists for extrapolating outside that period. The results are dependent on the current scour rate and on the local soil type. However, the distribution function may not be truly exponential. The current rate of local scour may be affected by bathymetric variation within the area of interest but this is taken into account in the repetitive mapping process. The disadvantage is that the method requires data for many years, because extrapolation beyond two return periods is not desirable.

As far as repetitive mapping in the Canadian Beaufort Sea is concerned, important sites were surveyed in 1984, and the initial scour maps already exist. The sites will be resurveyed in the future, and the new scours will be mapped.

OTHER METHODS FOR DETERMINING BURIAL DEPTH

Present methods for the estimation of pipeline burial depth appear to be very sensitive to the scour-depth distribution, i.e., the exponential coefficient K in Equation 1. This coefficient can be measured fairly accurately, leaving the problem of infill, which is fairly insensitive to scour-depth distribution, as the major obstacle. Another problem is in the definition of multi-keeled ice features. For example, does a multiple keel represent one event or many events? One aspect of repetitive mosaicing is that, if the scour density is low, a large area has to be surveyed.

An alternative method of obtaining the scouring rate consists of scour counting and sediment dating. This involves counting the number of scours occurring over a certain distance in areas where the scour density is low (water depths greater than 60 m, for example, in the Beaufort Sea) at various depths in a sedimentary section (as seen in a seismic reflection record). The sediments would then be dated, and a figure for scours per line-kilometre per year would be obtained. There is no record of this method having been used to date.

Another technique for estimating the number of scouring events in certain water depths is the ice-keel/ice-scour statistics method, which uses the relationship.

$$N_D = N\ L T\ e^{-KD} \quad (2)$$

Where:

N_D = number of scours penetrating to depth D over the life of the project (T) and the length of the pipeline (L),

N = the number of ice keels hitting the seabed/km/year obtained by integrating the keel distribution from the water depth down, times the velocity of the ice

e^{-KD} = the scour exceedence probability.

The ice-keel information could be obtained from upward-looking sonar, from submarine data, or from estimates of sail areas of the ice above. This method has been applied, but the results do not agree with those obtained using the repetitive mosaicing method. There are inherent difficulties in the method in that one deep keel will dominate over many small keels. Also, ice-keel statistics are general, and are not necessarily relevant to a particular area. However, the method does give an immediate result.

COST OPTIMIZATION

The statistical methods discussed are necessary for the cost-optimization calculation for a particular development. In general, the total cost of a project is equal to the cost of pipe, plus the cost of trenching, plus the cost of disruption, multiplied by the probability of a disruption occurring. The various parameters can be entered into this equation, and the cost minimized with respect to the depth of burial. Figure 5 summarizes a cost optimization for a pipeline between Kopanoar and shore in the Canadian Beaufort Sea. The repetitive mapping method produces a much shallower depth requirement in shallower water than does the ice-keel ice-scour statistics method or cost-optimization method. In deeper water, scour infill would be uniform, so a scour would possibly never disappear. In deeper water, therefore, repetitive mapping would tend to overestimate the depth of scours. However, the statistical method suggests that, using a 100-year return period in water depths greater than 50 m, burial of a pipe line would not be necessary.

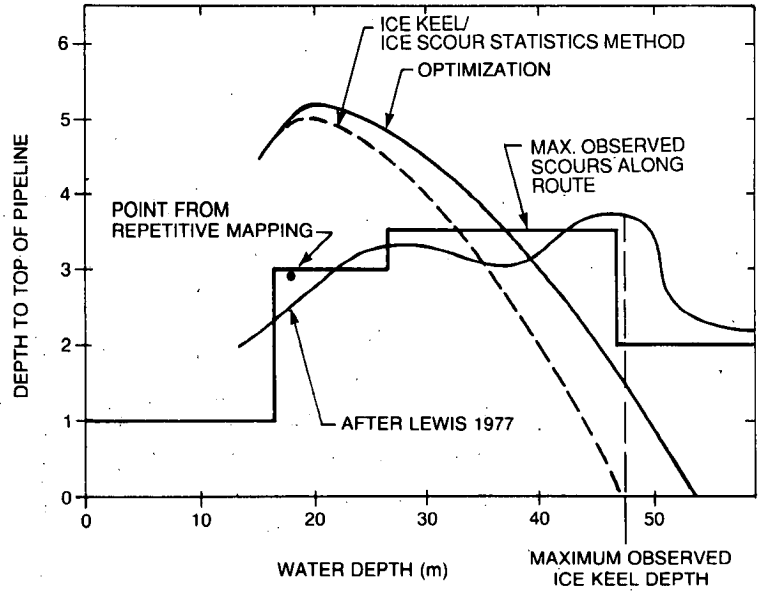

Figure 5. Summary of a cost optimization for a pipeline between Kopanoar and shore in the Canadian Beaufort Sea (from Pilkington and Marcellus 1981).

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DISCUSSION

From the floor: My recollection is that there is a very severe cost penalty in the optimization equation for the clean-up of an oil spill. I would like to point out that, in the case of a gas line, the clean-up penalty would not have to be as severe, and therefore the cost-optimization curve would fall significantly, because the consequence of damage would be reduced.

Roger Pilkington: At the time, a figure of one billion dollars was felt to be realistic.

From the floor: With respect to the repetitive mapping, one point that wasn't made was that it is very important to ensure that repetitive mosaics represent the entire pipeline.

NUMERICAL MODEL FOR CALCULATING SPATIAL DISTRIBUTION AND MEAN FREQUENCY OF ICEBERG GROUNDING EVENTS

S.J. d'Apollonia[1] and C.F.M. Lewis
Atlantic Geoscience Centre
Geological Survey of Canada
Bedford Institute of Oceanography
Dartmouth, N.S., B2Y 4A2

Geological studies of the eastern Canadian continental shelf show the seabed to be extensively marked with iceberg scours (Harris 1974, Harris and Jollymore 1974, King 1976, Lewis et al. 1980, Fader and King 1981, Lewis and Barrie 1981). We are interested in testing the idea that the observed pattern of iceberg scours, in particular the areal density of presumed Holocene (less than 10,000 years old) scour events, can be accounted for by the historical average southward flux of icebergs to the Grand Banks of Newfoundland from Greenland and arctic Canada.

This presentation describes a simple numerical model that calculates spatial distribution and mean frequency of iceberg groundings based on information about long-term mean iceberg flux, iceberg draught distribution, and the interaction of these parameters with local bathymetry. Other influences on the scour population which should be investigated in future research, such as rescouring and sedimentary obliteration as well as variations in the detection capability of the mapping technique, are not dealt with in this preliminary study.

The area initially selected to explore the model is situated on the northeastern margin of Grand Bank east of Newfoundland between 46° and 48° N latitude, and spans a bathymetric range of approximately 70 to 1000 metres (Fig. 1). This area was selected primarily because of the large quantity of data available, including iceberg sighting data by the International Ice Patrol (IIP) dating back to the early 1900s and recent observations of iceberg scours by acoustic seabed mapping (d'Apollonia and Lewis 1981; King and Gillespie 1986, this volume).

MODEL STRUCTURE

The modelled area was divided into 9.3 by 9.3 km (5 by 5 nautical miles) cells oriented in east-west rows. The number of iceberg groundings is dependent on the iceberg flux, distribution of iceberg draughts, and the range of water depths in each cell. The derivation of these input data is described below. It is assumed that each iceberg entering a cell grounds once if its draught lies between the maximum and minimum water depths for that cell.

[1] Presenter.

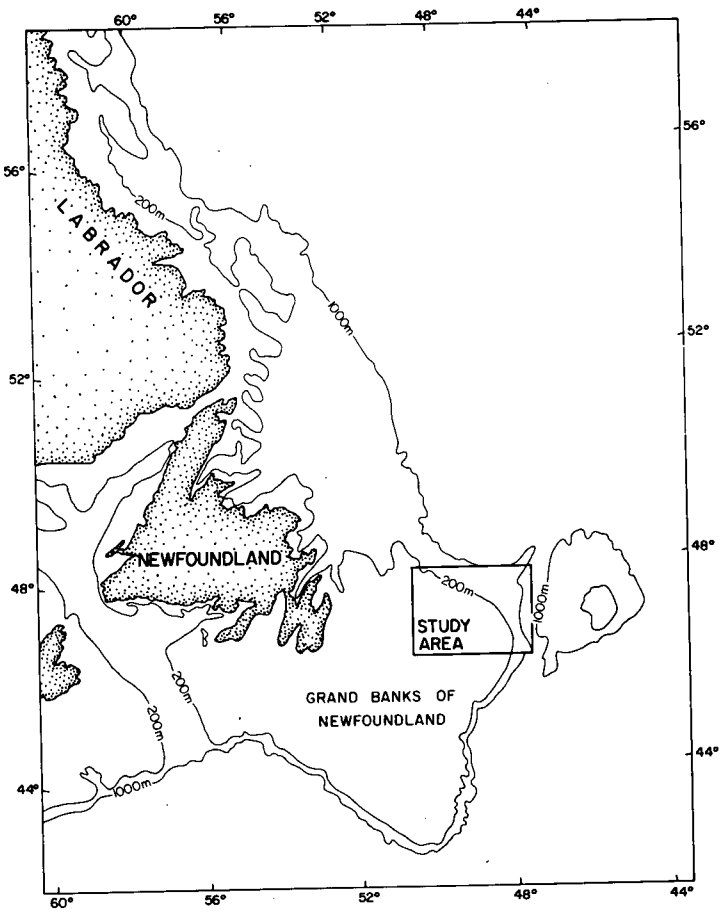

Figure 1. Location map showing study area and the continental shelf adjacent Newfoundland.

Iceberg Flux

The annual number of icebergs crossing latitude 48°N observed by the IIP (Fig. 2) is the basic data for deriving iceberg flux into each cell (Murray 1969, Morgan 1974, Mobil Oil Canada Ltd. 1985). A mean flux of 400 icebergs per year crossing 48°N was used in this study. Work by Anderson (1971) suggests the total annual iceberg population crossing successive latitudes between 67° and 48°N decreases approximately linearly with latitude at an average loss rate of 2 icebergs/km. Ebbesmeyer et al. (1980) developed a stochastic iceberg drift model for the area between Baffin Bay and the Grand Banks. This statistical model agrees with Anderson's estimate for loss rate and predicts the annual number of icebergs crossing latitudes 67° to 48°N as a random exponential sequence. For our study, a loss rate of 2 icebergs/km southward was assumed. Under this assumption, the southerly iceberg drift limit for a flux of 400 icebergs crossing 48° N occurs at 46° 12' N. This boundary agrees generally with the mean limit of southerly iceberg drift as mapped by Markham (1980).

For application to our model the IIP cross-latitude flux is subdivided and distributed to each cell adjoining the latitude to which the flux applies. The flux of icebergs into each cell is derived by multiplying the relative proportion of icebergs in each cell by the cross-latitude flux. This proportion is based on the average number of sightings by IIP during the 11-year period 1968-1978 and is the ratio of the average number of icebergs in a cell to the total number of icebergs in the east-west row of cells containing the cell in question. In areas where the mean southerly currents (and iceberg drift speeds) vary, the iceberg flux is influenced by both relative iceberg drift speed and relative iceberg density. In such areas the cross-latitude flux is distributed along the east-west row of cells in proportion to both the relative iceberg density and the

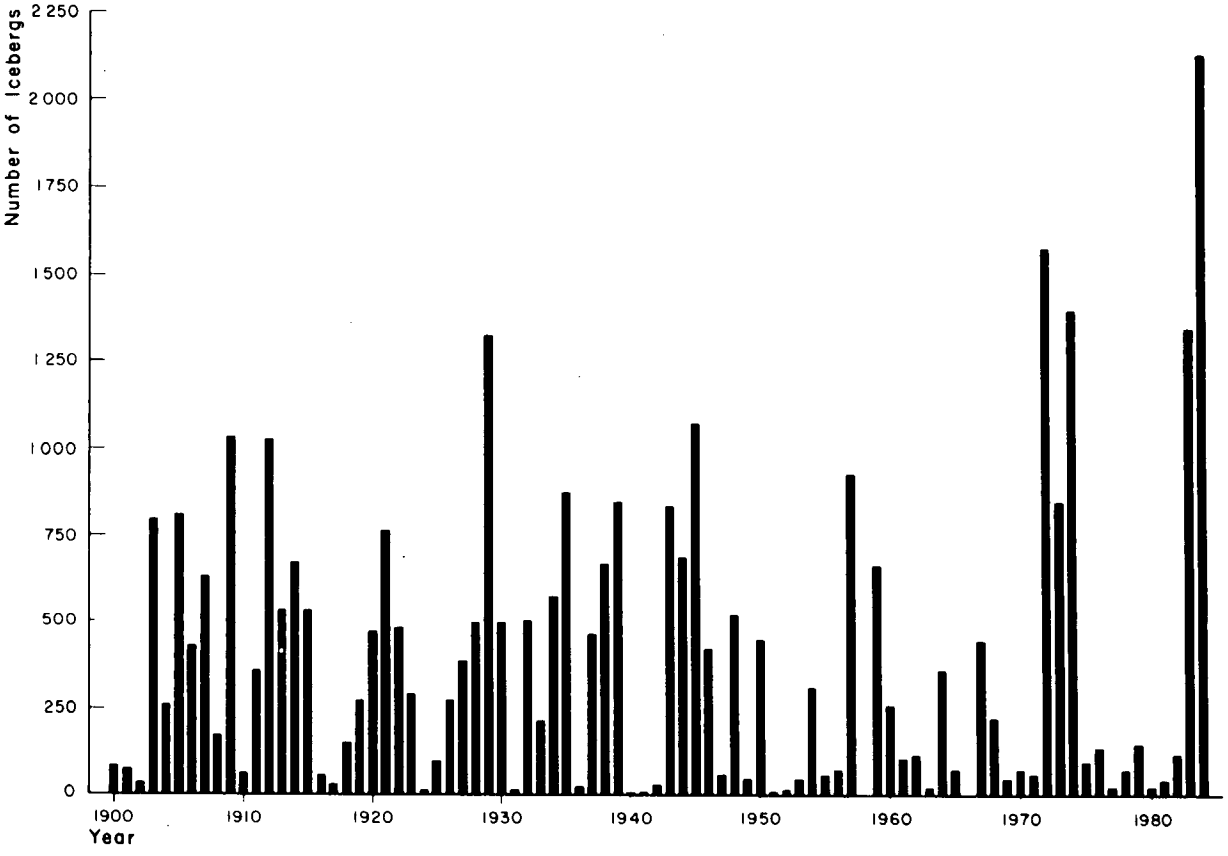

Figure 2. Number of icebergs crossing latitude 48°N between 1900 and 1984 based on reports of the International Ice Patrol. Adapted from Mobil Oil Canada Ltd. 1985.

relative southerly speed of iceberg drift in each cell. For the northeastern Grand Bank, approximations of southerly iceberg drift speeds are based on mean current speeds (Petrie and Anderson 1983) and are related to each cell by its water depth (Table 1). The faster speeds in deeper water reflect the presence of the Labrador Current flowing around the northeastern margin of Grand Bank. This current brings icebergs to the area from Greenland and arctic Canada.

TABLE 1

Mean southerly iceberg drift speeds for northeastern Grand Bank

Cell Water depth metres	Mean southerly iceberg drift speed metres/second
<110	0.1
110-150	0.3
>150	0.5

Iceberg Draught Distribution

The other critical parameter upon which the model depends is iceberg draught distribution. Three iceberg draught distributions for different regions between Baffin Bay and the Grand Banks were selected for preliminary input to the model (Fig. 3). The minimum draught distribution (D1) was adapted from work by Hotzel and Miller (1983) in which they estimate the draught distribution for icebergs drifting across the top of the Grand Banks. Their estimate is based on a function relating iceberg keel depth to the above water-line shape and size parameters. The function they derive is based on the analysis of 80 icebergs on the Labrador shelf whose areal dimensions and keel depths were known. The second draught distribution (D2), used as the baseline in this study, was modified from Hotzel and Miller's estimate described above by adding a deep tail to the distribution from 90 to 245 m. This was done to allow for the possibility of icebergs with draughts deeper than 90 m drifting into the study area. A third and maximum draught distribution (D3) is based on the analysis of 214 icebergs measured between latitudes 49° and 75°N during the period 1973 to 1979 (El-Tahan and El-Tahan 1982).

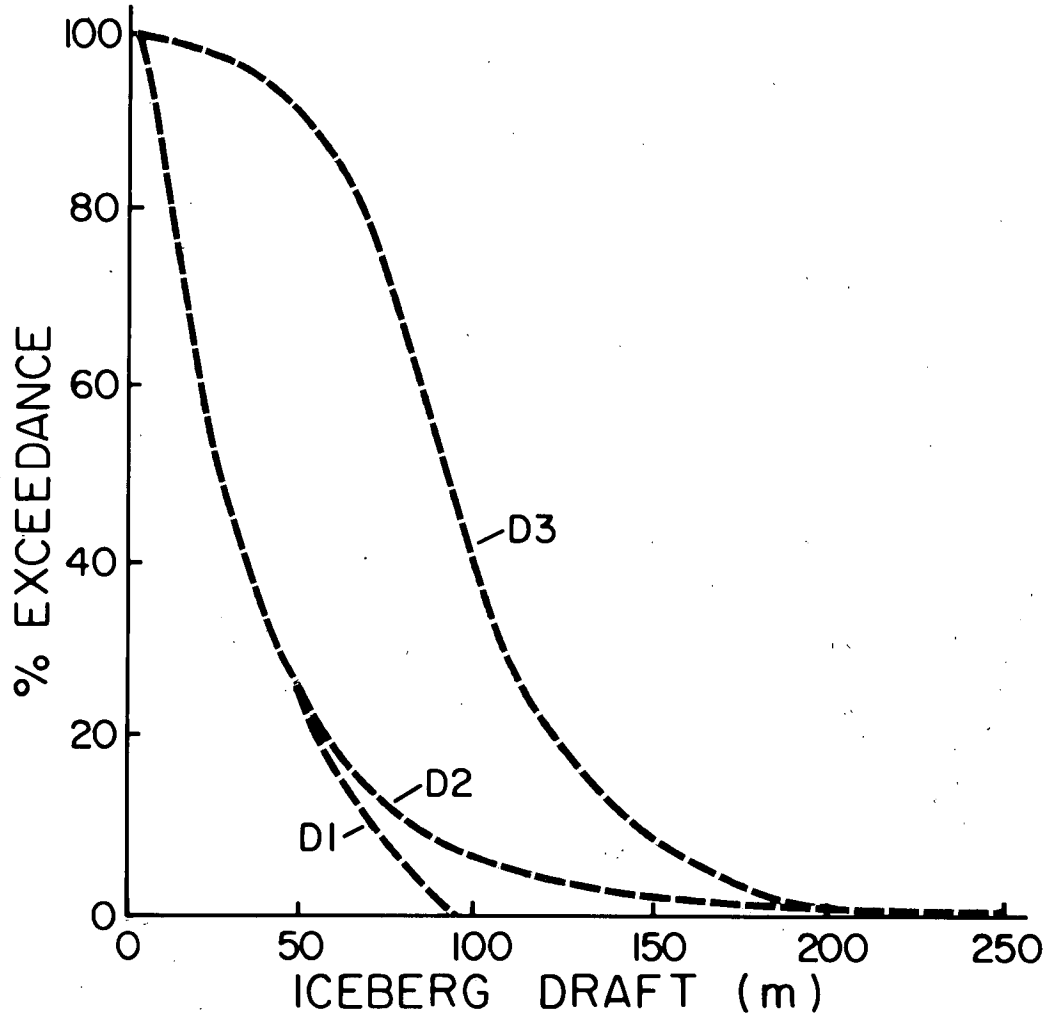

Figure 3. Iceberg draught distributions, plotted as per cent exceedance, used in the model runs for northeastern Grand Bank. See text for source of distributions.

Calculations of Iceberg Groundings

The model is driven by calculating, for each cell, the number of icebergs that occur within a segment or "window" of the selected draught distribution (Fig. 4). The "window" size is set by the range of water depths within each cell and can be selectively increased to account for potential upslope scouring or scouring below the seabed at the maximum cell water depth. It is assumed that all icebergs with draughts shallower than the minimum water depth in the cell pass through without grounding, whereas all icebergs having draughts deeper than the maximum water depth in the cell are excluded. Icebergs with draughts between these limits are assumed to ground once. Therefore the total number of groundings that occur within a cell is the product of the fractional frequency of iceberg draughts within each "window" and the mean iceberg flux through each respective cell (Fig. 4). Expressed in the form of an equation,

$$G_{ij} = p_j \cdot q_{ij} \cdot d_{ij} \quad (1)$$

where G_{ij} = annual number of iceberg groundings in cell ij

p_j = annual iceberg flux into row j
$= p_1 - (j - 1) \cdot l \cdot r$ (2)

q_{ij} = mean annual fraction of icebergs in cell ij relative to total mean annual icebergs in row j

d_{ij} = fraction of icebergs having drafts within range w_{min} to $w_{max} + x$

p_1 = annual flux of icebergs into row 1

l = length of cell in kilometres

r = average rate of loss of icebergs southward per kilometre

w_{min} = minimum water depth in cell

w_{max} = maximum water depth in cell

x = maximum ice scour depth

The model has two options for controlling the manner in which the draught distribution is utilized. In one option the selected draught distribution is used without modification for each cell. The other option simulates the selective removal of deeper keels from a population of icebergs that drifts upslope onto a shallow bank. This is done by truncating the initial draught distribution at the maximum water depth in cells of the first row, then normalizing the truncated distribution to 100 per cent for application to the second row of cells. The truncation procedure is repeated for each successive row of cells.

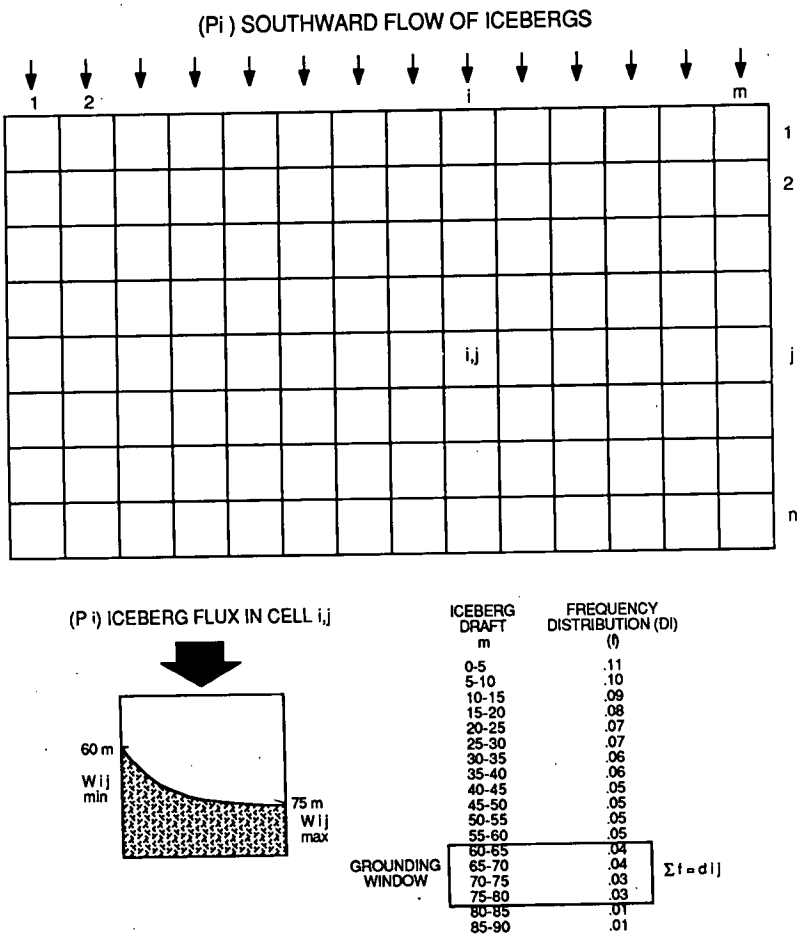

Figure 4. Pictorial illustration showing grid lay-out and method of calculation used in the iceberg grounding model. The grounding window is deeper than the maximum cell water depth to allow for a maximum scour depth of 5 m.

RESULTS AND DISCUSSION

The model was run with each of the draught distributions described above and with the other parameters set at baseline values (Table 2). The results, expressed as groundings/year/100 km^2), were plotted and contoured (Fig. 5) using a standard oceanographic contouring program. The form of the contoured distribution of groundings compares favourably with the form of similarly plotted scour densities based on analysis of 1200 km of acoustic data (Fig. 6). Good agreement exists for gross features of the contoured patterns between the measured scour densities and the spatial distribution of calculated groundings for the run using the second (baseline) distribution. These baseline results are summarized in Table 2 for specific water depth intervals of the model area. In Figure 7 the summary results are plotted for 10-metre water depth intervals.

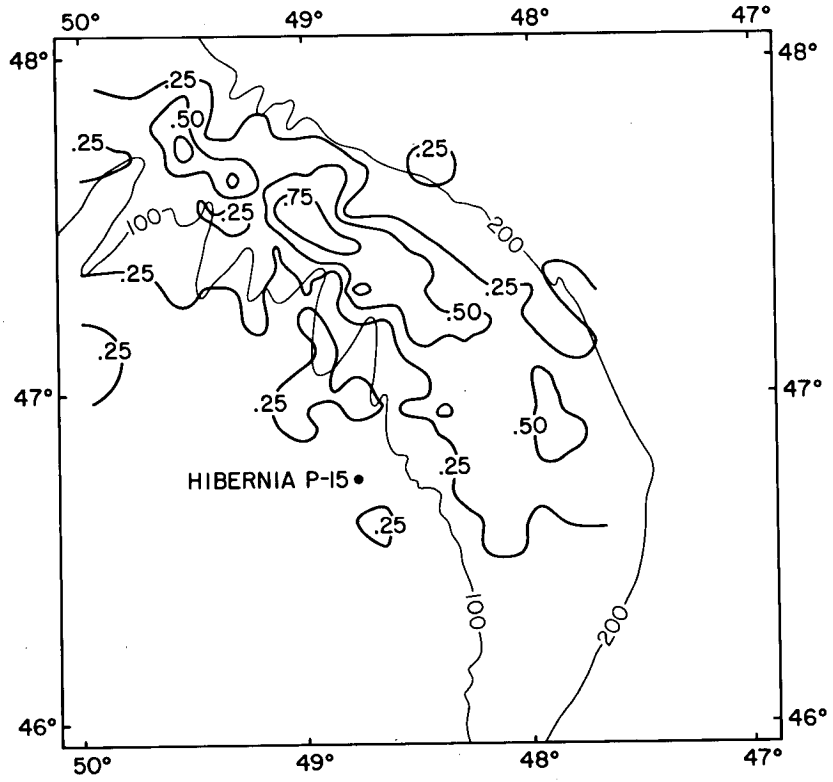

Figure 5. Spatial distribution of iceberg groundings after one year (groundings/100 km^2) calculated for the northeastern margin of Grand Bank using baseline parameters. Dots indicate centres of model cells.

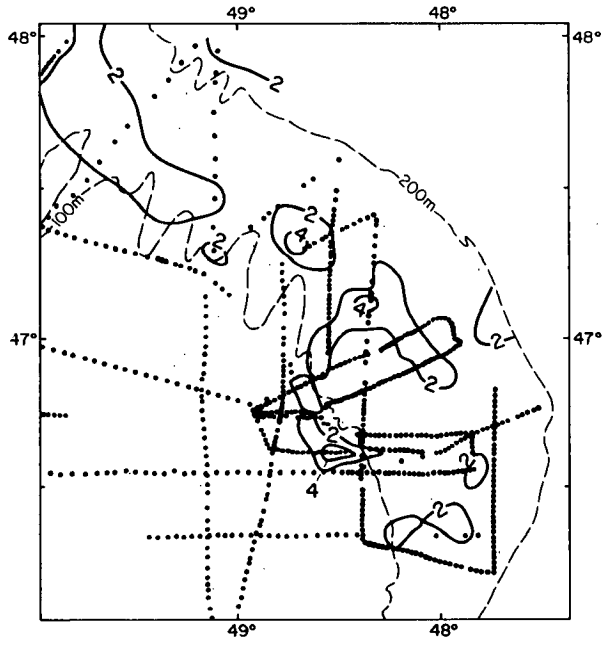

Figure 6. Iceberg scour densities (scours/100 km^2) based on analysis of sidescan sonographs from the northeastern margin of Grand Bank. Dots indicate areas of counted iceberg scours.

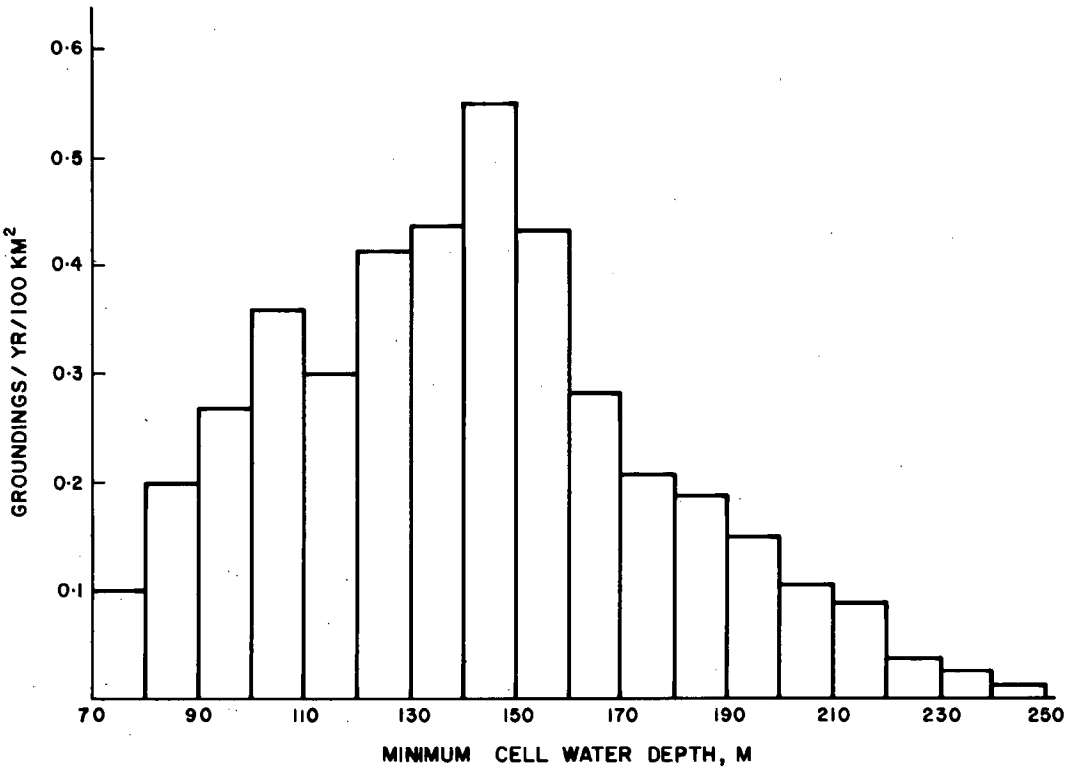

Figure 7. Calculated frequencies of iceberg groundings using model assumptions and baseline parameter values averaged in 10-m intervals of water depth for the northeastern margin of Grand Bank.

TABLE 2

Model results using baseline parameter values[1]

Mean Cell Water Depth, m	Groundings/Year/100 km²
70-90	0.1
120-140	0.5
160-180	0.4

[1] The baseline values are: flux at 48°N = 400 icebergs/year; loss rate = 2 icebergs/km southward; unmodified D2 draught distribution (Fig. 3); and maximum scour depth = 5 m.

Model Sensitivity

Model sensitivity tests were run by varying the different parameters that drive the model. The results of these tests are summarized in Table 3 for three different water depth ranges.

TABLE 3

Model sensitivity

Parameter		Results (Groundings/Yr/100 Km^2)		
		70-90 m	120-140 m	160-180 m
Draught Distribution	D1	0.2	0.0	0.0
(All Truncated)	D2	0.1	0.5	0.4
	D3	0.4	2.2	1.1
Scour Depth, m	10	0.2	0.5	0.4
	1	0.1	0.5	0.4
Iceberg Flux	2000	2.3	3.3	2.5
Crossing 48°N	400	0.1	0.5	0.4
	80	0.0	0.0	0.0
Iceberg Loss	1	0.2	0.7	0.6
Per Km Southward	2	0.1	0.5	0.4

The D1 draught distribution is a bank-top distribution and thus it is not surprising that groundings are found only above 120-m water depth. The deepest distribution D3 yields the greatest frequency of groundings, as expected, since this distribution contains the largest proportion of icebergs for the range of water depths in the model area. The grounding results are essentially insensitive to differences between the truncated and unmodified draught distributions for this test area. Despite having median values of less than 100 m, both the D2 and D3 draught distributions produce their greatest grounding frequencies in the 120- to 140-m depth range. As icebergs are more numerous in the deeper water area than on the bank top, this illustrates the joint control on grounding frequencies by the high density of iceberg sightings and the draught distribution. A subsidiary contribution to higher grounding frequencies in the 120- to 140-m depth range may also arise due to the effect of wider "windows" into the draught distribution induced by the steeper seabed gradients in this water depth range.

Variations of the scour depth allowance have little effect on the grounding results. There is a slight effect in the shallower water where seabed gradients are less. In that area the scour depth allowance has a proportionately greater influence on the magnitude of the "window" into the draught distribution thereby inducing more groundings.

Grounding frequencies increase, as expected, with an increase in iceberg flux and a decrease in iceberg loss rate. There is a flux threshold below which no groundings occur. For the

region tested the threshold flux is between 80 and 400 icebergs per year. Grounding frequency and iceberg flux vary linearly in the deeper water (160 to 180 m) but less so in the shallower water (70 to 90 m) to the south because of the joint effect of loss rate and flux on grounding frequency. Loss rate reduces flux and distorts its linear relationship with grounding frequency. This effect accumulates southward and thus is greatest in the shallow bank-top region.

Absolute Grounding Frequency

The fact that mapped scours (Fig. 6) and modelled groundings (Fig. 5) are most abundant within the same 130- to 160-m bathymetric interval (Fig. 7) lends support to the model and its baseline parameters. The high density of these features in this zone is interpreted to reflect the route by which most icebergs pass through the region via the Labrador Current. The upslope decrease may signify a lesser flow of water and ice onto Grand Bank relative to the core of the current - hence fewer groundings. Alternatively, the upslope decrease may be due to scour degradation by currents induced by storm waves and swell. The downslope decrease in scour density is interpreted as the limiting zone in which even the deepest iceberg keels contact the seabed infrequently.

For the zone of maximum scour density a period of 800 years only is required, at the indicated (Fig. 7) annual grounding frequency to generate the observed scour density assuming all scours are preserved (Fig. 6). This result cannot be verified as the scours, are not dated and the actual period of scouring is unknown. The model annual scouring rates (Table 2) are about an order of magnitude greater than rates derived by Gaskill (1986, this volume) and Gaskill et al. (1985) using iceberg arrival data also and a model of scour depth degradation. The apparent scour buildup period of 800 years is rather short compared to the potential scouring period following the last marine transgression about 10,000 years B.P. (Fader and King 1981). Thus the model frequencies are significantly higher than expected. Several possibilities exist which might explain this discrepancy. (1) The inception of iceberg scouring on Grand Bank may be more recent than expected; (2) It is possible also that the grounding criterion in this model is too conservative and should be altered to allow only a fraction of keels, whose draughts lie within the range of cell water depths to ground. This alteration would reduce the apparent grounding frequency; and (3) Other influences, not yet modelled or corrected, such as incomplete scour detection, scour obliteration by sedimentary processes, and unknown variations in iceberg draught, flux, or trajectories, etc., may account for the remaining differences. All these possibilities are points for future research.

CONCLUSIONS

Use of an unidirectional deterministic iceberg arrival model shows that the spatial distribution of iceberg scours on the seabed is controlled jointly by the iceberg flux, population density, and draught distribution parameters. As a result, the bathymetric zone of most frequent scouring on the margin of a continental shelf does not necessarily align with the modal depths of the iceberg draught distribution but may be shifted toward areas of high iceberg population density and flux.

For the northeastern margin of Grand Bank the combined model results and seabed record indicate that the most rapid iceberg scouring occurs generally between the 130- and 160-m isobaths close to the edge of the ice-bearing Labrador Current. Scouring rates decline upslope from this bathymetric zone possibly due to a lesser flow of water and ice onto the bank or to wave and current-induced scour degradation. They decline downslope due to a lack of deeper iceberg keels.

The iceberg grounding model calculates unexpectedly high rates of scouring for its baseline parameters. Under these conditions the model accounts for the observed ice scour distribution within about 800 years. The confidence to be placed on these results is low as verification is lacking and greater understanding of the following topics is required: model grounding criteria, the efficiency of mapping techniques for scour detection, the age of iceberg scour marks, the role of sedimentary processes on scour obliteration, and post glacial variations in iceberg draught, flux, and trajectories.

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PALYNOLOGY AS A METHOD FOR DATING ICEBERG SCOURS

Peta J. Mudie[1]
Atlantic Geoscience Centre
Geological Survey of Canada
Bedford Institute of Oceanography
Box 1006, Dartmouth, Nova Scotia, B2Y 4A2

INTRODUCTION

Analysis of fossil pollen and spores has long been used as a powerful tool for dating Pleistocene sediments. Techniques for palynological dating of terrestrial sediments are well documented (Birks and Birks 1980), and it has been shown how pollen and dinoflagellate assemblages in marine sediments can be dated by cross-correlation with radiocarbon-dated onshore palynofacies (Vilks and Mudie 1978).

In 1980, discussions between Dalhousie University's Department of Geology, the Atlantic Geoscience Centre (AGC), and Petro-Canada led to a pilot study to investigate the possible use of palynology for dating of ice scours on the eastern Canadian continental shelf. The northeast Newfoundland Shelf (Fig. 1) was recognized as an important test area because shallow seismic profiles (Dale and Howarth 1979; Fader and King 1981) indicated the presence of several scours, the nature and age of which might have a significant bearing on the construction of offshore pipelines.

The study had three objectives:

- to locate scours containing deposits of mud that might be suitable for palynological study;
- to determine the feasibility of target coring at the scour sites, using conventional shipboard navigation and coring systems; and
- to conduct palynological studies of the cores recovered and to determine whether or not the boundary between scour base and infill sediments could be dated by correlation with onshore and offshore stratotypes (reference sections).

[1]Presented by C.F.M. Lewis, Atlantic Geoscience Centre.

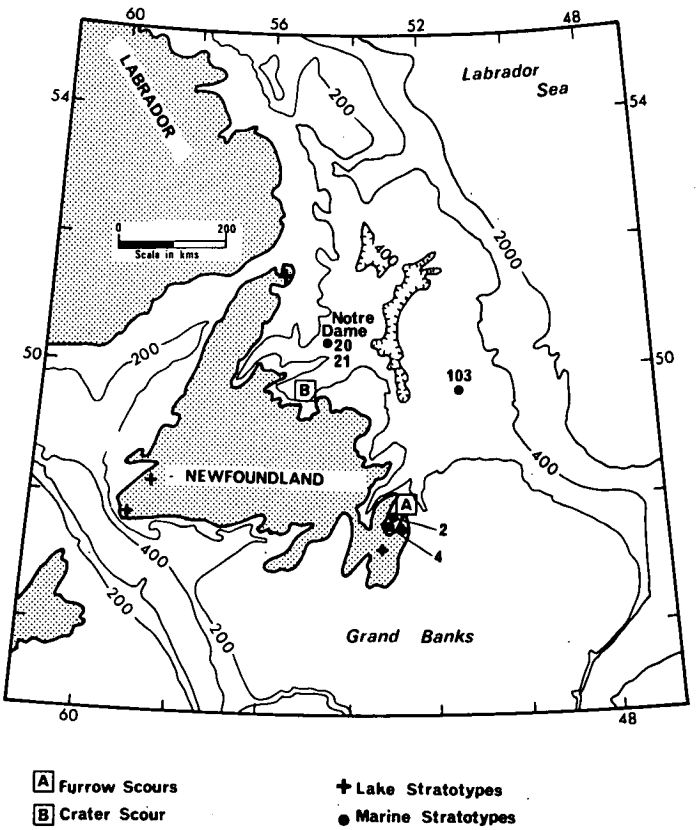

Figure 1. The northeast Newfoundland shelf.

The northeast Newfoundland Shelf (Fig. 1) proved to be suitable for the pilot study for several reasons.

(a) Dated onshore palynostratigraphies had been established for late-Wisconsinan sediments (Fig. 2; column 1, top) by the work of Joyce Macpherson on Newfoundland lakes (Macpherson 1981) and for early Wisconsinan sediments (Fig. 2; column 1, base) in southwest Newfoundland (Brookes et al. 1982).

(b) Offshore palynostratigraphies had already been established for central (See Fig. 2; Core 78-20) and outer (see Fig. 2; Core 103) shelf regions in studies by Piper et al. (1978), Mudie and Gilbault (1982), and Scott et al. (1984); core locations for these studies and for new reference cores obtained from Conception Bay are shown in Figure 1.

(c) Apparent scour features with mud fill, such as crater-like scours at 260-m water depth in Notre Dame Channel (see Fig. 1, area B) and furrow scours at 183-m depth off Conception Bay (see Fig. 1, area A), could be identified from Huntec Deep Towed Seismic (DTS) high-resolution seismic surveys that had previously been carried out by AGC.

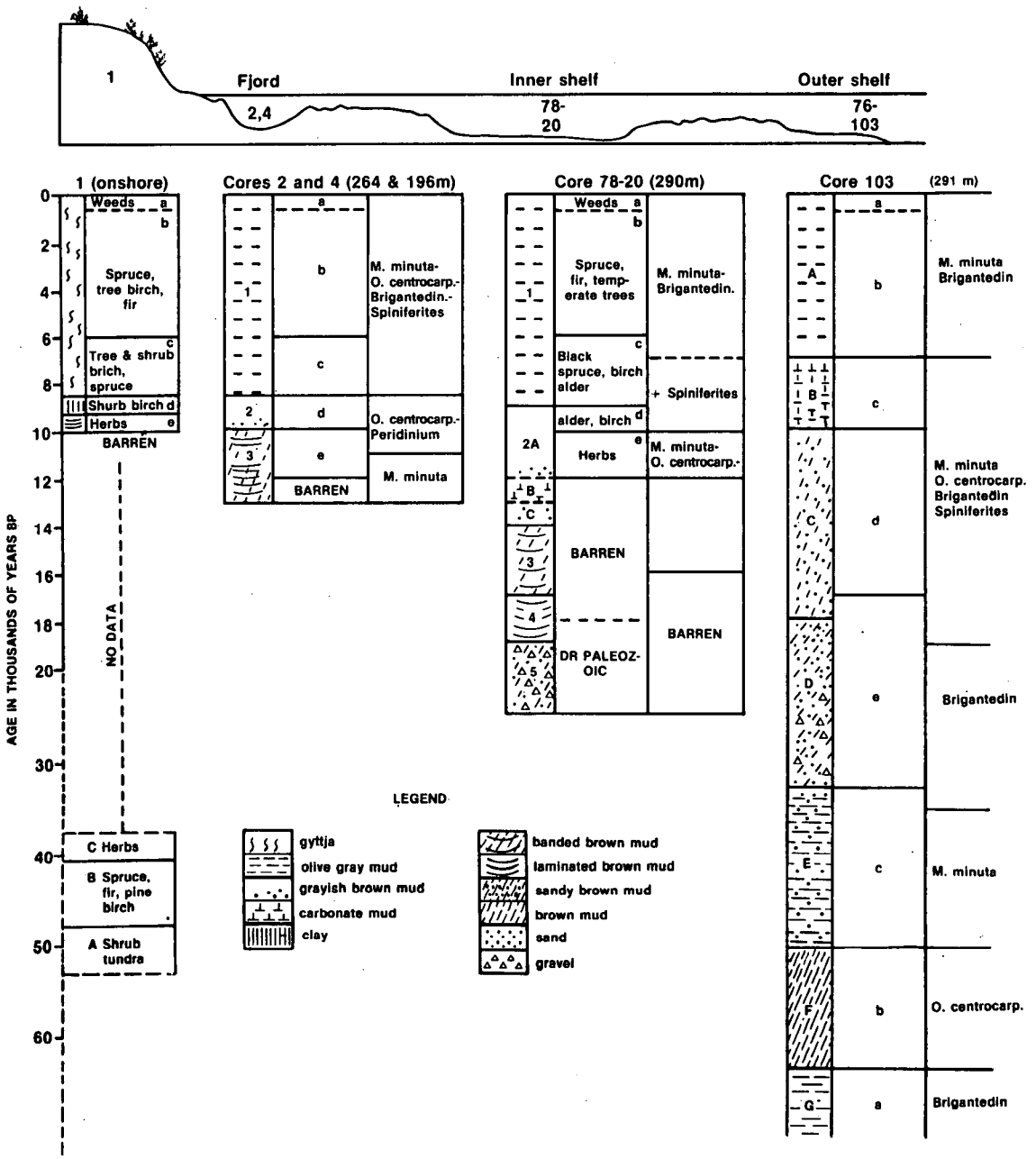

Figure 2. Onshore and offshore palynostratigraphies for the northeast Newfoundland shelf.

FIELD PROGRAM

The field work was carried out from CSS Dawson in November 1980 (Keen 1980), and consisted of steaming to the target areas identified from the Huntec DTS records and mapping the sites in detail over an area of about 1 km using a 1,000-J sparker. After selecting the target core sites within the scour areas, we sampled the surface sediment with a Van Veen grab to make sure that the sediment fill was muddy and probably suitable for palynological study (for example, sediments with less than 60% silt and clay rarely contain enough pollen for analysis). Finally, we cored the target sites using a pinger on the wire above the piston corer to position the corer precisely 50 m above the target before allowing it to free fall. With the CSS Dawson, a 60-m (195-ft) vessel with good station-holding capability, we were able to target successfully in winds up to 74 km/h (40 kts) and in waves 2-3 m (6-10 ft) high.

The cores were split, X-rayed, described, and correlated by lithofacies. Palynology samples of 5 cm^3 of wet sediment volume were taken at 1-cm intervals in the olive-grey surface lithofacies and at 5- to 10-cm intervals in the other lithofacies. The samples were processed using methods that were developed for Pleistocene marine sediments by Mudie (1982) and that allow good recovery of delicate dinoflagellate indicator species as well as of pollen and spores.

RESULTS

Figure 3 summarizes the palynostratigraphy obtained for Core 80-030-22 from the V-shaped crater scour in area B (see Fig. 1). The gravity core (GC) contained abundant pollen and dinoflagellates. The relative abundance of indicator species (spruce, fir, and birch tree pollen; birch and alder shrub pollen; herb pollen; and fern spores) changed down-core in a systematic manner that corresponds closely to the palynozones (see Fig. 2, a-e) found in Holocene lake sediments and in marine stratotypes established for Conception Bay (Cores 2 and 4, see Fig. 2). The pollen assemblages in the gravity core of Core 80-030-22 clearly correspond to palynofacies b, c, and d of the five palynozones present in the reference sections. The lower boundaries of the palynozones a, b and c have radiocarbon dates of ca. 6,500, 8,500, and 9,500 years respectively before present (B.P.). The piston core (PC) recovered a longer section of palynofacies d and 3 m of brown silt (litho facies 4) with diamicton at the base (lithofacies 5). There is an abrupt change in palynomorphs at the contact between lithofacies 2 and 4: facies 4 contains no Quaternary pollen, although reworked Tertiary and Paleozoic spores are present, and Pleistocene dinoflagellate assemblages are typical of late-Wisconsinan sediments dated as 12,000 to 23,000 years B.P. in the stratotype for Notre Dame Channel. Hence, the palynology and lithostratigraphy indicate that the ice scour was cut into late Wisconsinan glaciomarine sediment with a minimum age of 12,000 years, and that in-fill began at a maximum date of 9,500 years B.P.

Figure 4 shows the palynostratigraphy for Core 80-030-5 from a trough of a scour furrow off Conception Bay. Here, the palynofacies present are pollen zones a, b, d, and e. Although the lithological discontinuity is less obvious than in Core 80-030-22, it can be stated that sediment deposition was disrupted between ca. 8,000 and 3,500 years B.P., i.e., between palynofacies b and d; the most likely time that the scour was formed is an intermediate 6,500 years B.P.

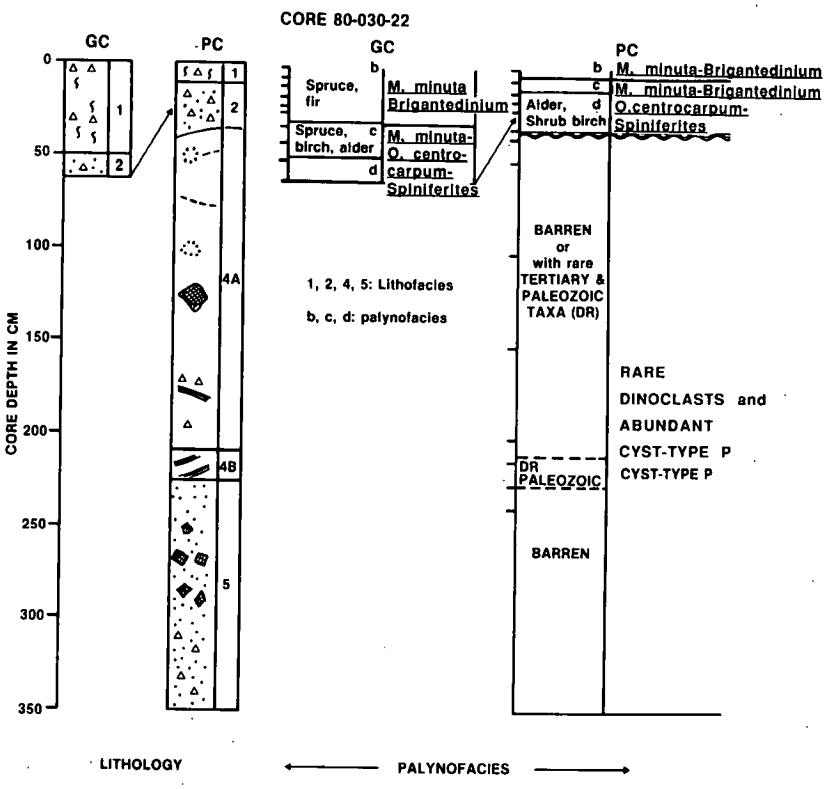

Figure 3. A summary of the palynostratigraphy and dinoflagellate stratigraphy obtained for Core 80-030-22 from the V-shaped crater scour in area B. GC = gravity core; PC = piston core.

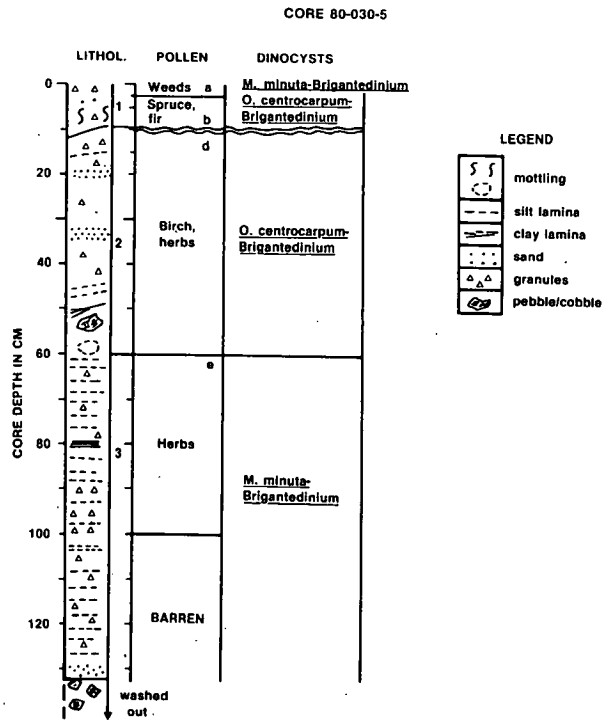

Figure 4. The palynostratigraphy and dinoflagellate stratigraphy for Core 80-030-5 from the trough of the scour furrow of Conception Bay.

In summary, preliminary studies indicate that palynology can be applied to dating of the boundaries of intervals to a precision of about ±1,000 years. However, its application requires that two conditions be met.

(a) The scour must contain progressively accumulated pollen-bearing muds that can be cored.

(b) A regional palynostratigraphy must exist that is reliably dated.

In the northeast Newfoundland Shelf region, the palynology indicates a period of possible disruption between 8,000 and 3,500 years B.P., with an interpreted age of 6,500 years B.P. for the termination of furrow scouring at 183-m water depth off Conception Bay. The method shows another period of possible disruption between 12,000 and 9,500 years B.P., with an interpreted age of 9,500 to 10,000 years B.P. for a crater-like scour feature at 260-m water depth in Notre Dame Bay.

CONCLUSIONS

Palynology can be used as a tool for dating ice scours within the age range spanned by dated onshore and offshore late Pleistocene stratigraphies. Greater resolution of scour age might be obtained if statistical methods (Birks and Birks 1980) were used to analyse the depth of sediment mixing by bioturbation, and dating resolution might be increased if enough calcareous microfossils could be extracted from the sediment to permit carbon-14 dating of small sediment samples above and below pollen or lithological boundaries using an accelerator mass spectrometer. As a rapid method for estimating the age of a scour feature, involving a minimum of core destruction, however, palynology appears to be the best available dating method.

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DISCUSSION

Mike Lewis: This study supports comments made earlier by Roger Pilkington (this volume; Pilkington, R. Estimating ice-scour frequency and risk to buried pipelines) that this method (which provides absolute ages of low to moderately high precision) may be suitable for confirming that scours thought to have been infilled over thousands of years are indeed old.

From the floor: How was the lake sediment carbon dated? You said organic carbon. Was that total organic?

Mike Lewis: Yes, the sediment is gyttja, an algal detritus of high organic carbon content, which can be accurately dated by the radiocarbon method.

RISK ASSESSMENT FOR ICEBERG-SCOUR DAMAGE: LABRADOR SEA AND GRAND BANKS

Drew Allan
Petro-Canada
P.O. Box 2844
Calgary, Alberta, T2P 3E3

INTRODUCTION

Our work has involved determining burial depths or alternative measures for protection required to provide an acceptable level of risk of scour damage for subsea facilities in the Labrador Sea and Grand Banks.

In the assessment of ice-scour risk (Fig. 1), the aim is to use environmental and statistical data in a model, to determine the probability of damage linked with the consequences of damage, and then to decide whether the particular design is acceptable.

Intra-field subsea facilities are generally concentrated within a small area, as opposed to pipelines to shore, which span long distances. The intra-field gathering system is usually governed by reservoir requirements; therefore, there is little flexibility in their relocation to mitigate risk. There is little variation in water depth, soil conditions, and environmental conditions, primarily because of the small area involved. Usually, exploration drilling projects and the associated data-gathering programs produce a significant data base of information on icebergs and scour in the small area of interest. In addition, because facilities are concentrated in this small area, it is likely that damage events will not be isolated. Thus, if an iceberg enters the field under development, it is highly probable that damage to more than one facility will result. Therefore, predicted damage events may not be independent, and this possibility must be taken into account in the risk analysis.

For pipelines, there is much more flexibility in selecting the route and there are other considerations in going from A to B aside from iceberg scour. Apart from the desire to minimize the length of the pipeline, there are the soil conditions along the route and the various advantages and disadvantages of alternative landfalls. Over the route, large variations in water depth, soil, and environmental conditions can be expected. In addition, there is usually less data available with respect to the parameters required to carry out an analysis of ice-scour risk, particularly in the nearshore areas far removed from the drilling operations.

RISK EVALUATION

Figure 2 shows the main features of the risk assessment program being considered by Petro-Canada. The approach used in determining the risk of scour damage is to compare the iceberg keel draught with bathymetry and the expected frequency of icebergs at a particular site. This produces the iceberg-bottom contact frequency. The distribution of scour depths is then examined to determine how many of those scours would be deeper than the proposed burial depth

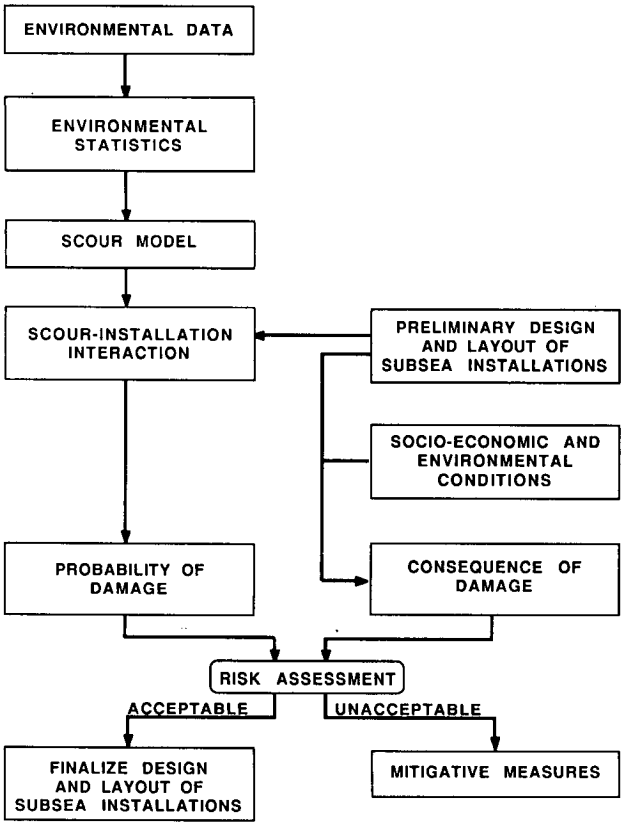

Figure 1. Elements of the ice-scour risk assessment process.

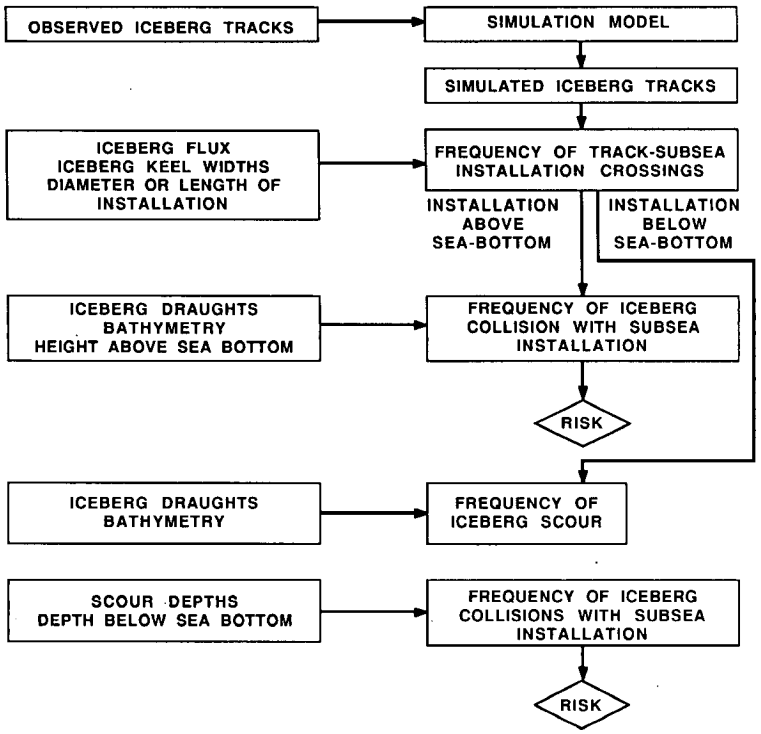

Figure 2. Main features of the risk assessment program for iceberg - subsea installation collisions being considered by Petro-Canada.

of the facility. This approach is similar to that described by Roger Pilkington (this volume) although there is a difference in the input data parameters.

INTRA-FIELD RISK ANALYSIS

For intra-field risk analysis, there is the advantage that observations of iceberg trajectories are available from the drilling operations. From these observed trajectories, changes in velocity and direction can be examined, and Markov transition matrices can be formulated. These matrices can then be used to simulate iceberg trajectories for use in the scour-risk analysis. Figure 3a is an example of simulated iceberg trajectories on the Grand Banks of Newfoundland. Eight trajectories are plotted. Validation tests are made to ensure that the model compares well with observations. Figure 3b is an enlargement of the area of interest. To get a general understanding of the effect on underwater facilities, overlays, as shown in Figure 4a and b, can be superimposed, and the number of crossings for a certain diameter of facility or orientation of pipeline are obtained. In these simulations, it is assumed that the scouring process does not have a significant impact on the path of the iceberg as it scours. This is a conservative assumption, as the scouring process should dampen the meandering of the iceberg which would reduce the risk to the facilities. A matrix of circles is used in the overlay because it is simpler to use many circles and one trajectory than to use one circle and many trajectories.

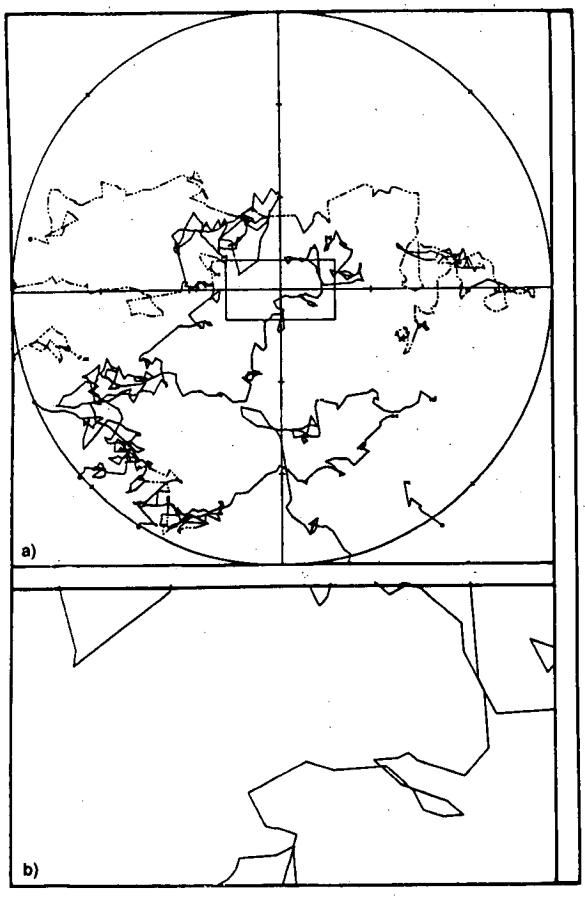

Figure 3. (a) An example of eight simulated iceberg tracks on the Grand Banks of Newfoundland. The zero marks the exit and an x marks the beginning of the tracks.
(b) A enlargment of the area indicated in (a).

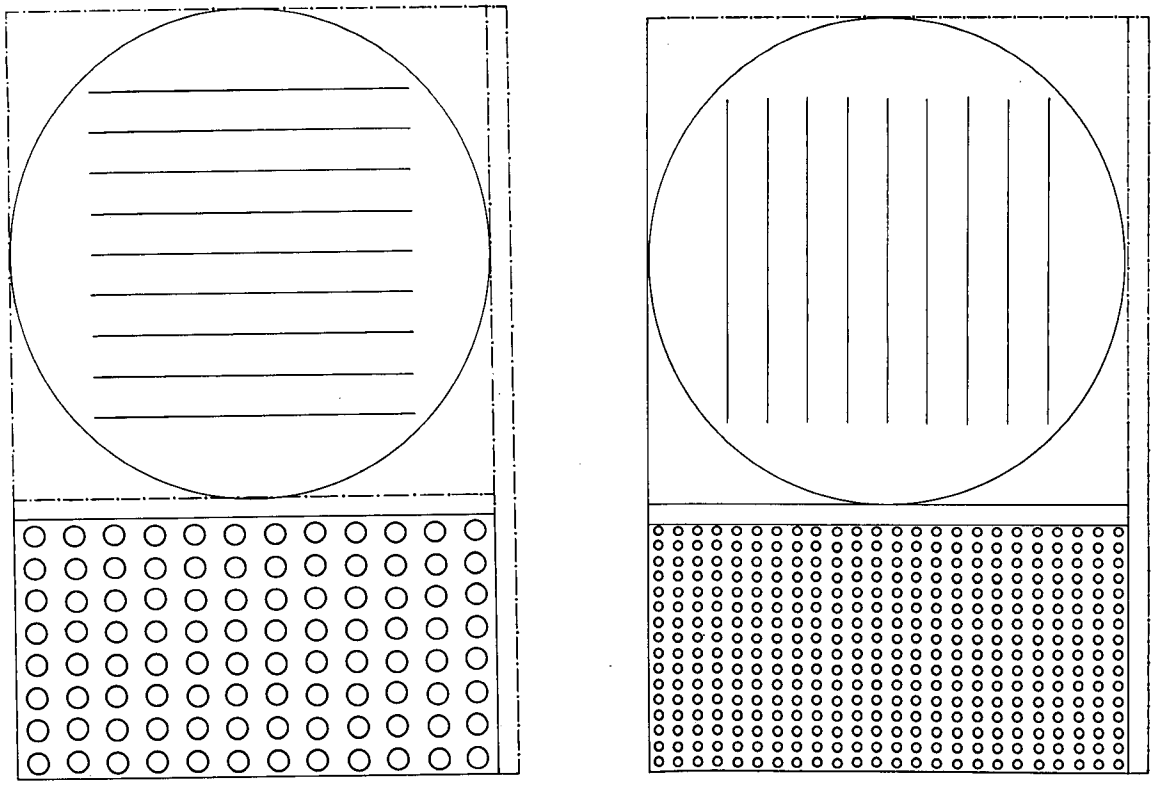

Figure 4. Overlays for Figure 3, allowing the calculation of the number of crossings for a certain diameter of facility or orientation of pipeline.

Using the simulated trajectories and overlays, the number of iceberg-pipeline crossings for a given iceberg flux and pipeline orientation can be calculated. A meander coefficient can be calculated by dividing the number of crossings by the flux. This coefficient is used to indicate the increase in iceberg-pipeline crossings resulting from variance from a completely linear trajectory. Using the simulated iceberg trajectories, the iceberg flux, the keel widths, and the diameter or length of the installation, the frequency of trajectory-subsea installation crossings can be calculated. If the installation is above the sea bottom, then the bathymetry, the draught, and the height above the bottom are included in the model, and the frequency of iceberg collision with the subsea installation is calculated. If the installation is buried, the iceberg draught and bathymetry are considered to determine the frequency of iceberg scour. This is combined with scour-depth distribution data and the depth of the facility below the seabottom to give the frequency of collision for buried installations. This is then available for inclusion in the risk analysis for subsea installations.

PIPELINE TO SHORE RISK ANALYSIS

For pipelines to shore, the variance in the water depth over the length of the route must be taken into account. To accomplish this, the pipeline is divided into various segments along the route, as shown in Table 1 for a proposed route from the Grand Banks prospects to the shore. The number of icebergs crossing a given segment over a 20-year period is calculated. This is determined using the flux distribution, which is inferred from iceberg density maps and International Ice Patrol (IIP) flux data. A projected length factor is used to calculate the number of iceberg-pipe crossings for pipelines that are not perpendicular to the north-south flux. In

TABLE 1

An example analysis of scour probability for a pipeline

Point	Station (km)	Segment No.	No. icebergs crossing segment in 20 yr	Average water depth (m)	Draught dist. D < d D + 10 (probability)	Scouring icebergs over 20 yr (no.)	Depth to TOP (m)	Scour dist. SD> TOP (probability)	Ice-pipe collisions over 20 yrs
Nfld.	0.0	1	46	10	0.0254	1.167	2	0.0357	0.042
	3.0	2	15	30	0.2057	3.085	2	0.0357	0.110
	4.0	3	77	50	0.1803	13,881		0.0357	0.495
	9.0	4	153	70	0.0676	10,339	2	0.0357	0.369
54°W	19.0	5	38	90	0.0162	0.616	2	0.0357	0.022
	21.5	6	30	110	0.0030	0.089	2	0.0357	0.003
	23.5	7	53	130	0.0004	0.024	2	0.0357	0.001
	27.0	8	53	150	0.0001	0.003	2	0.0357	0.0
	30.5	9	225	160	0.0	0.005	2	0.0357	0.0
TP1	45.5	10	558	160	0.0	0.012	2	0.0357	0.0
	67.0	11	130	150	0.0001	0.008	2	0.0357	0.0
	72.0	12	78	130	0.0004	0.035	2	0.0357	0.001
	75.0	13	78	110	0.0030	0.230	2	0.0357	0.008
	78.0	14	60	90	0.0162	0.073	2	0.0357	0.033
	81.0	15	330	80	0.0345	11.394	2	0.0357	0.406
	97.0	16	180	90	0.0162	2.918	2	0.0357	0.104
	106.5	17	50	100	0.0071	0.356	2	0.0357	0.013
52°W	109.0	18	385	100	0.0071	2.739	2	0.0357	0.098
	141.0	19	145	90	0.0162	2.351	2	0.0357	0.084
	153.0	20	412	80	0.0345	14.225	2	0.0357	0.507
51°W	187.0	21	596	80	0.0345	20.578	2	0.0357	0.734
50°W	265.0	22	412	80	0.0345	14.225	2	0.0357	0.507
49°W	342.0	23	129	80	0.0345	4.454	2	0.0357	0.159
	361.0								
			4233			**103.71**			**3.17**

Where: TOP = top of pipe; d = iceberg draught; SD = scour depth; yr = years; D = water depth; TP = turning point; dist. = distribution

TABLE 2

Pipeline-to-shore scour probability analysis - burial depth calculation

Point	Station (km)	Segment No.	No. icebergs crossing segment in 20 yr	Average water depth (m)	Draught dist. D < d D + 10 (probability)	Scouring icebergs over 20 yr (no.)	Depth to TOP (m)	Scour dist. SD > TOP (probability)	Ice-pipe collisions over 20 yrs
Nfld.	0.0	1	46	10	0.0254	1.167	3.93	0.0014	0.002
	3.0	2	15	30	0.2057	3.085	4.34	0.0007	0.002
	4.0	3	77	50	0.1803	13.881	5.11	0.0002	0.003
	9.0	4	153	70	0.0676	10.339	4.52	0.0005	0.006
54°W	19.0	5	38	90	0.0162	0.616	3.66	0.0022	0.001
	21.5	6	30	110	0.0030	0.089	2.63	0.0124	0.001
	23.5	7	53	130	0.0004	0.024	1.51	0.0808	0.002
	27.0	8	53	150	0.0001	0.003	0.26	0.6464	0.002
	30.5	9	225	159.70	0.0	0.005	0.30	1.0	0.005
TP1	45.5	10	558	160.00	0.0	0.012	0.00	0.9926	0.012
	67.0	11	130	150.00	0.0001	0.008	0.64	0.3463	0.003
	72.0	12	78	130.00	0.0004	0.035	1.83	0.0475	0.002
	75.0	13	78	110.00	0.0030	0.230	2.0	0.0357	0.008
	78.0	14	60	90.00	0.0162	0.073	3.83	0.0017	0.002
	81.0	15	330	80.00	0.0345	11.394	4.30	0.0006	0.009
	97.0	16	180	90.00	0.0162	2.918	3.79	0.0018	0.005
	106.5	17	50	100.00	0.0071	0.356	3.33	0.0039	0.001
52°W	109.0	18	385	100.00	0.0071	2.739	2	0.0065	0.016
	141.0	19	145	90.00	0.0162	2.351	2	0.0028	0.007
	153.0	20	412	80.00	0.0345	14.225	2	0.0013	0.019
51°W	187.0	21	596	80.00	0.0345	20.578	2	0.0021	0.043
50°W	265.0	22	412	80.00	0.0345	14.225	2	0.0030	0.043
49°W	342.0	23	129	80.00	0.0345	4.454	2	0.0024	0.011
	361.0								
			4233			**103.71**		**3.22**	**0.200**

Where: TOP = top of pipe; d = iceberg draught; SD = scour depth; yr = years; D = water depth; TP = turning point; dist. = distribution

addition, in areas where significant meandering of icebergs is common, the meander coefficient has to be taken into account in calculating the number of iceberg crossings. Then the percentage of icebergs whose draught will exceed the average water depth within a segment can be calculated. The draught distribution used is truncated by limiting the amount an iceberg can scour uphill to 10 m, an estimate based on scour observations. For example, this means that icebergs with draughts greater than 90 m will not be considered for subsea facilities at a site with an 80-m water depth. Using the number of crossings, and truncating the depth distribution, the number of icebergs that contact or scour the bottom can be computed. In this example, a constant burial depth of 2 m over the pipeline route has been selected. Multiplying the number of scouring icebergs crossing the pipeline by the fraction of scours expected to exceed the burial depth gives the expected number of ice-pipe collisions. In the example, out of 4,233 crossings, about 100 scour events occurred, out of which 4 would scour deep enough to collide with the pipeline.

This procedure can be reversed by setting a constant probability of damage per metre or per kilometre of pipe, and then the required burial depth can be determined by reworking the calculations. Essentially, the model can be run in two different modes, as shown in Table 2. The probability that corresponds to one collision in 100 years, i.e., an average of 0.2 damage events in a 20-year period, has been selected, and the depths of burial along the pipeline sections have been calculated.

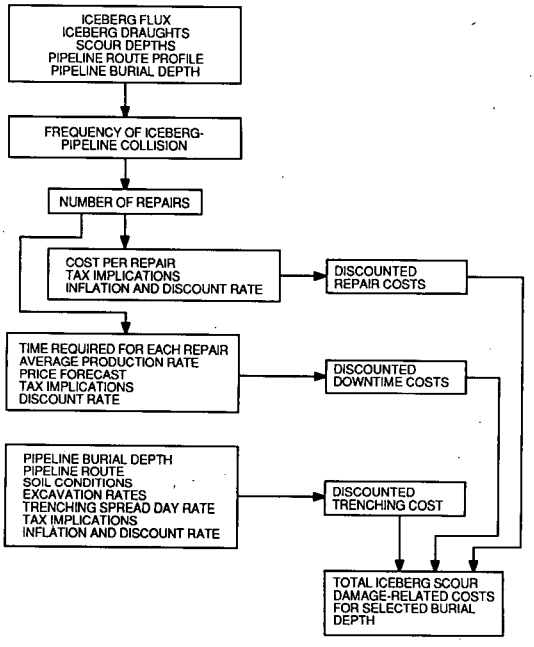

Figure 5. Iceberg-scour damage-related costs.

FUTURE WORK

At present, we are working on integrating the probability of damage with scour-related cost models. Because the risk to human life and environment is low for scour damage to a gas pipeline, an approach using cost optimization was used. An algorithm to calculate the overall total scour-related cost, including protection, downtime, and repair, has been developed. The process involves an iterative procedure which examines different burial depths to reach an optimum cost. In addition to the data requirements for the scour-risk model, the following inputs are required for the cost models: the number and cost of repairs, the burial depth, the pipeline route, the soil conditions, excavation rate, trenching spread rates, inflation and discount rates, and tax implications. This cost-minimization approach (Fig. 5) is used to determine the optimum burial depth.

Future work required on scour risk assessment includes determining confidence levels of environmental statistics used as input into scour models, updating environmental data bases, and revising statistical inputs as required. Additional work should include refining existing scour models; by coupling probability of scour damage with consequences of damage; by defining acceptable risk criteria; and by evaluating alternatives for mitigation of risk of scour damage.

REFERENCE

Pilkington, R. 1986. Estimating ice-scour frequency and risk to buried pipelines. In Lewis, C.F.M., D.R. Parrott, P.G. Simpkin, and J.T. Buckley (eds). Ice Scour and Seabed Engineering: Environmental Studies Revolving Funds Report No. 049. Ottawa. 322 p.

DISCUSSION

Mahar Nessim, Det norske Veritas: I like this approach very much. We have done something similar for the Beaufort Sea, and I would like to comment about the risk levels. In this approach, the risk level falls out if you do the optimization. The risk level becomes a result of your model rather than something that you input into the model. So whether the collision rate is one in 100 years, it is a result of the model. I think this is very important in the case of ice scour, where we have very little experience with building installations, for example. We have tried 100- and 150-year return periods for installations in other environments, which over the years have seemed to work. That is why we use them. But with ice cover, we have very little experience, and I think this approach is appropriate. But I have a couple of questions. The first is, did you find that truncating the draught distribution for the water depth make much difference?

Drew Allan: It depends on the water depth. If you are in water depths where you truncate the distribution in the middle, say around the median, then the amount of area (in the distribution) you eliminate is quite significant. In other words, you could go from a 0.05 to 0.15 probability of exceedance by varying the truncation. But if you are in the tail area of the distribution, the impact of that truncation is not as significant because you are only truncating a smaller and smaller area. The answer to your question is that it depends on the draught distribution and the water depth.

Mahar Nessim, Det norske Veritas: My other question is, are some of these parameters that you input in the model subjective?

Drew Allan: No. They are directly measured or inferred from related data. However, there are questions as to the representativeness and accuracy of the data bases on which these parameters are based, but the values used in the analysis are the best we have at this time. We have to work with what we have in terms of data. To address this problem, we are going to cycle through the simulation and see which parameters are the most sensitive. In that way I can feed back information into engineering and environmental programs.

Mahar Nessim, Det norske Veritas: That was my question. Have you examined sensitivity, of the parameters? If so, would you make any comment?

Drew Allan: One comment I can make is that in general you should get the pipeline as deep as you can, as fast as you can. It is intuitively obvious, but the analyses confirm it. Even though you experience higher iceberg fluxes in the north, the advantage of going north and getting the pipeline deeper seems to outweigh the smaller fluxes of a shallower pipeline to the south. The cable companies get their cables as deep as they can, as fast as they can.

REPORT ON A NON-DETERMINISTIC MODEL OF POPULATIONS OF ICEBERG SCOUR DEPTHS

Herbert Gaskill
Department of Mathematics and Statistics
Memorial University of Newfoundland
St. John's, Newfoundland
A1B 3X5

also of

NORDCO Limited
P.O. Box 8833
St. John's, Newfoundland
A1B 3T2

INTRODUCTION

This presentation describes work that is a joint effort between myself, Linda Nicks, and David Ross. A full report on our work, together with a discussion of relevant literature, is contained in Gaskill et al. (1985).

The modelling effort described here grew out of attempts to answer a number of questions related to iceberg scours and include, What depth is "deep enough" to protect a pipeline from iceberg scours? and How old are the iceberg scours we see on the seafloor?

In an effort to address these questions, we began by listing the data sources related to the problem. The two most reliable sources of available data were the total number of scours present in an area at sample time, i.e., now, and the distribution of depths of scours in the observable iceberg scours for the area in question. Thus, we created a model that would make predictions about these two measurable parameters, which can be the most reliably measured among all those which relate to the questions posed.

An immediate problem in developing design criteria based on these data sets is that the scours being observed have been subject to a variety of forms of aging. Over the time interval since the contact between the iceberg and seabed, a period of decay has taken place during which the scour has become less deep than it was initially. Thus, an immediate question is, How do the numerical characteristics of the present population of "observable" iceberg scours relate to the numerical characteristics of the population of "initial" iceberg scours?

Evidently, everything we know about the initial distribution of iceberg-scour depths must be inferred from the observable population, which has decayed to some extent from its original structure. Thus, we must understand the effect of the decay process on the numerical parameters of the population as it changes from an initial population to a mature observable population. If the relationship between the parameters is understood, and if the rate of decay is known, a method can be developed to generate estimates of the required probabilities and the resultant risks.

Because field studies to investigate these matters thoroughly are expensive and require several years of duration, we decided to create a model of populations of iceberg-scour depths for the Grand Banks of Newfoundland, and to use it to generate educated guesses with which to answer the questions posed above.

MODEL DESCRIPTION

The modelling effort rests on four basic assumptions.

(a) The mean annual iceberg scouring rate has been constant throughout the last 8,000-10,000 years, i.e., since the rise to present sea levels.

(b) The primary mode of scour deterioration has been from sedimentary degradation, as opposed to reworking by later scours, or other effects.

(c) The mean annual iceberg-scour decay rate resulting from sedimentary degradation has been constant throughout the last 8,000-10,000 years, and can be estimated by a fixed infill rate.

(d) The form of the initial depth distribution for iceberg scours has been unchanged for the last 8,000-10,000 years.

A complete discussion of these assumptions is contained in Gaskill et al. (1985). We must emphasize that because we are interested in the population parameters, we do not need to know the details about how a particular scour degrades. What we want to know is, What would be the gross effects on the population if scours were to disappear in 100 years on the average, instead of in 5,000 years on the average?

The model is constructed on the assumption that, as an iceberg scours the seabed, it produces a trench of depth, d. The initial value of the trench depth is determined by the initial distribution. Each year thereafter, this trench is infilled by processes of sedimentation at a fixed annual rate, c. When d/c years have elapsed, the trench will be infilled, and the scour will disappear from the population of observable scours.

The model actually works as follows. At year 1, an annual scour rate, ρ, an infill rate, c, and an initial distribution of scour depth, ε, are specified. Each model year, ρ icebergs scour. Each new iceberg scour is assigned an initial depth, d, which is chosen in a random fashion subject only to a weighting factor specified by the initial distribution, ε. These new depths are added to the population of observable scour depths. Each year thereafter, each observable scour is infilled by a fixed amount, if this infilling results in zero depth, the scour is removed from the population of observable scours. At any time, then, the model has two products: the distribution of depths associated with observable scours present at that time, and the total number of observable scours present at that time. These two products can be related to the initial distribution of depths and, more importantly, to actual data on the distribution of scour depths derived from deep-towed seismic reflection measurements collected in the field.

MODEL RESULTS

Most important among the initial data supplied to the model was the distribution of initial scour depths, ε. Three distributions were employed during the course of the study. These three distributions were chosen to represent three significantly different shapes. The purpose here was to address the question of whether the observable distribution would have the same basic shape as the initial distribution.

The distributions chosen were an exponential distribution (E), a distribution with a single mode (M), and a flat distribution (F). Probability density and cumulative frequency curves for the three distributions are presented in Figures 1 and 2.

Number of Observable Scours

As the model years pass, the number of observable iceberg scours grows. Clearly, if the infill rate is zero, then this number will grow without bound. However, if the infill rate is positive, then eventually scours are infilled, and the number of observable scours is less than the number of scours that have occurred, the latter being given by the product of scour rate and the number of model years. For non-zero infill rates, we wanted to determine what happens to the number of observable scours as a function of time.

We have plotted a 10,000 year history of the number of observable scours, at time increments of 500 years; at year 0 we assumed that the sea bottom was free of previous scours. In Figure 3, curves are presented for two scour rates. In both cases, what we see is a period of rapid growth followed by what appears to be a continuing period of random oscillation about a mean value. Both curves were generated using the exponential distribution. This behaviour, rapid growth followed by a levelling off and oscillation about an apparent mean, is typical of all the models. For a fixed infill rate, if we were to double the scour rate, we would expect a simple linear relationship to exist between the two variables; this is exactly what is observed, subject, of course, to the fact that the model is not deterministic. Moreover, we would expect progress toward the long-term mean to be essentially the same in all cases. This latter fact is also illustrated in Figure 3.

The infill rate is also of prime importance in determining the long-term mean number of observable scours. We examined this relationship for a fixed scour rate of one per year (Fig. 4); the maximum infill rate is 0.1 m/year, and the minimum is 0.001 m/year. The value of the long-term mean appears to be inversely proportional to the value of the infill rate; thus, if we were to halve the infill rate, we would double the long-term mean. This relationship seems transparent in retrospect; moreover, it is not dependent on the probability distribution governing the initial scour depths.

We also investigated the effect of the infill rate on the rate at which the number of visible scours approaches the long-term mean (Fig. 5). For a scour rate of one per year, we studied a 10,000-year period for infill rates ranging from 1 cm/year (0.01 m/year) to 0.05 cm/year (0.0005 m/year). Evidently, the smaller the infill rate for a fixed scour rate, the more rapid will be the initial buildup in the number of visible scours, and the greater will be the length of time required to approach the long-term mean.

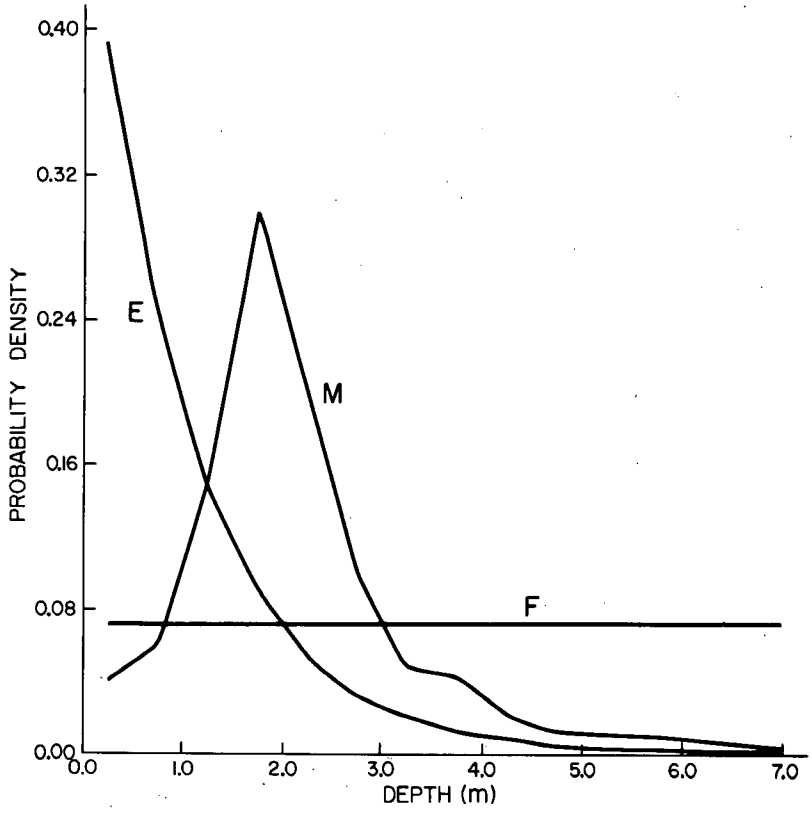

Figure 1. Probability density for the three initial distributions studied: E - exponential; M - modal; F - flat.

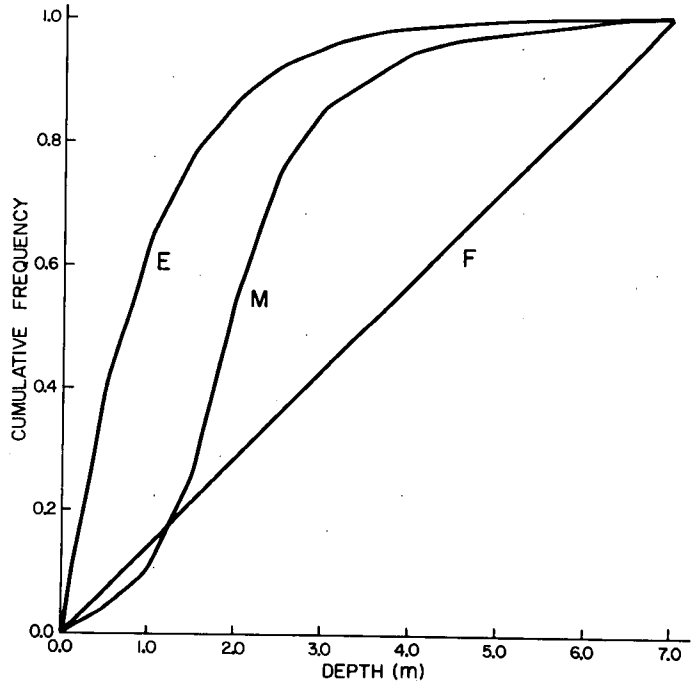

Figure 2. Cumulative frequency for the three initial distributions studied: E - exponential; M - modal; F - flat.

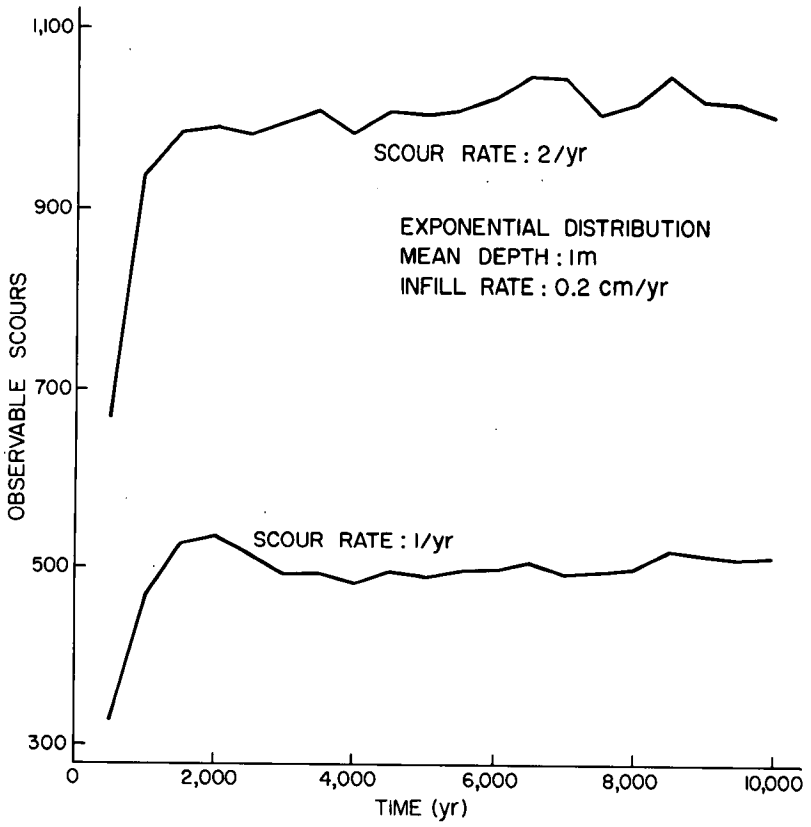

Figure 3. Number of observable scours plotted as a function of time for a period of 10,000 years; initially there are no scours.

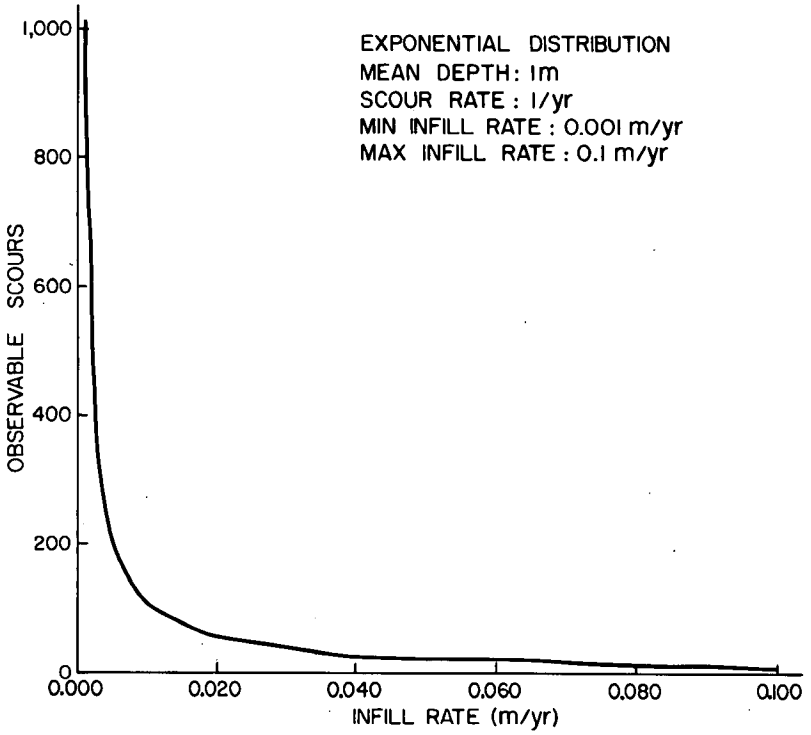

Figure 4. Graph of the long-term mean number of observable scours as a function of infill rate.

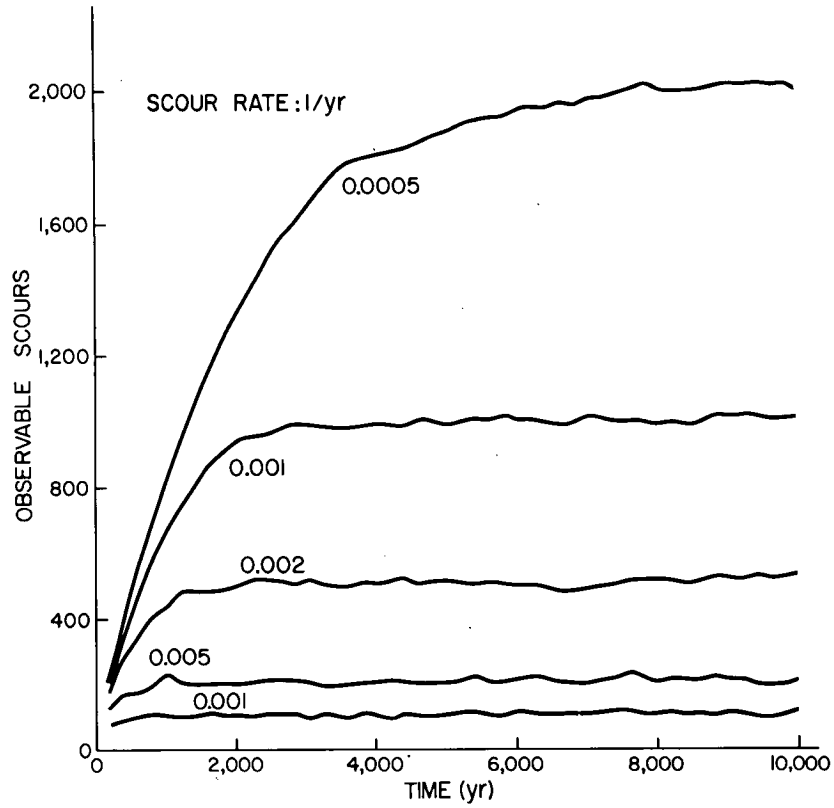

Figure 5. Graph showing the number of observable scours as a function of time for various infill rates.

Distribution Shape Change Over Time

The next question we posed about the relationship of an observable population distribution of iceberg-scour depths to the initial distribution from which it is derived is: To what degree does the gross shape of the observable distribution reflect the shape of the initial distribution?

We plotted the probability density function of visible scour depths, for over 500 scours that would be obtained after 5,000 model years (Fig. 6). For the exponential distribution, the sample distribution of visible scours quite closely reflects the initial distribution. The same cannot be said of the other two distributions. The modal distribution has lost its peak, and could quite possibly be mistaken for an exponential distribution. The flat distribution is still defined by what appears to be a straight line, but it now has a negative slope.

We then estimated the mean asymptotic distribution, which is calculated by averaging the class values for particular instances of the distributions (Fig. 7); in each case, we averaged the 500 year distributions from the period between 5,000 and to 10,000 years, inclusive. The effect of averaging is to smooth the curves by focusing on the locus of means; as can be seen, a nearly smooth curve results. It is interesting to note, with respect to the modal distribution, that the break-away from an exponential shape occurs in the modal class. These results suggest that if the underlying distribution were exponential, the resultant distribution of observable scours would also appear to be exponential. If the underlying distribution were modal, then we should see reduced class values for a population of observable scours in the classes associated with depths less than the modal depth, compared with the expected number based on a postulated initial distribution, which is exponential.

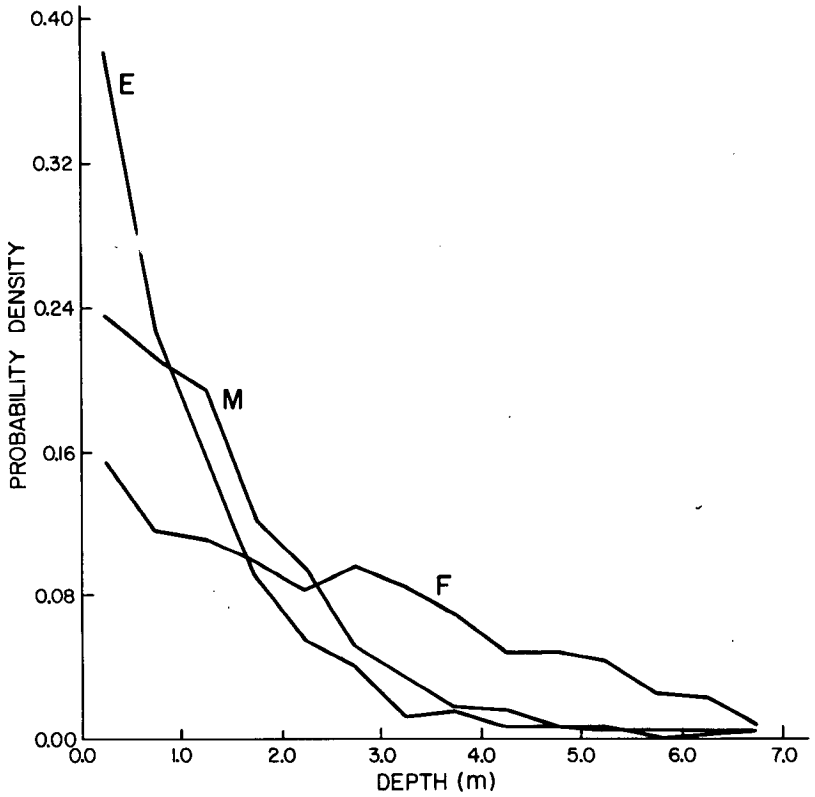

Figure 6. Observed distribution of observable scour depths sampled at 5,000 years for a single model run for each of the three initial distributions: E - exponential; M - modal; F - flat.

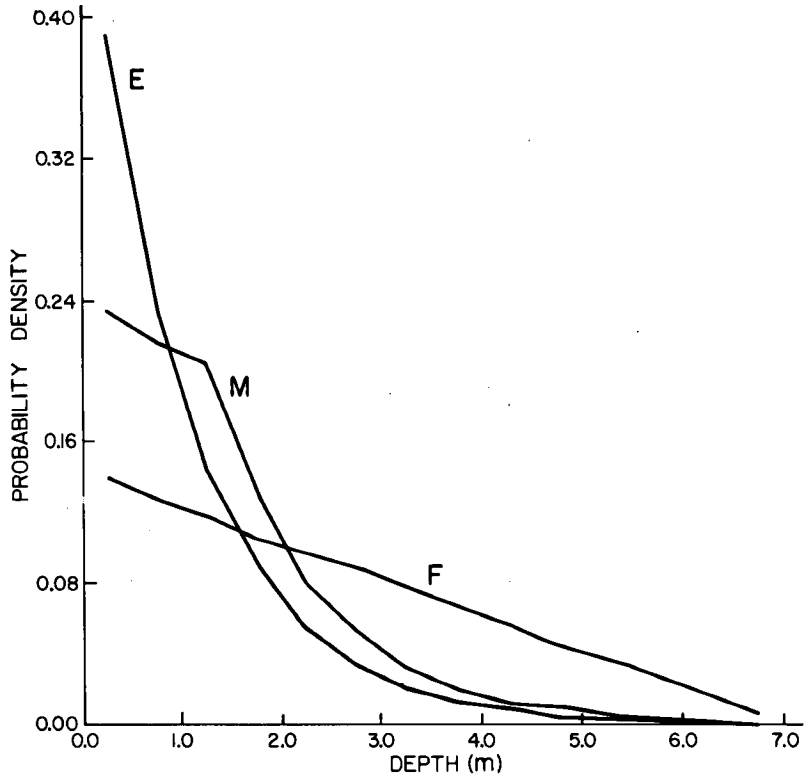

Figure 7. Composite distributions of observable scour depths after 10,000 elapsed model years. The composite distribution was obtained by averaging over several model runs for each distribution: E - exponential; M - modal; F - flat.

APPLICATIONS OF THE MODEL

From this discussion, we believe that, we can, with confidence, infer the nature of the initial distribution from the type of dis tribution observed. Indeed, as shown in Gaskill et al. (1985), we can also infer its mean. If we can also get information about the infill rate, we can use the model to predict scour rates. From the scour rate and the distribution of depths, we can directly calculate burial depths for pipelines and set levels of risk.

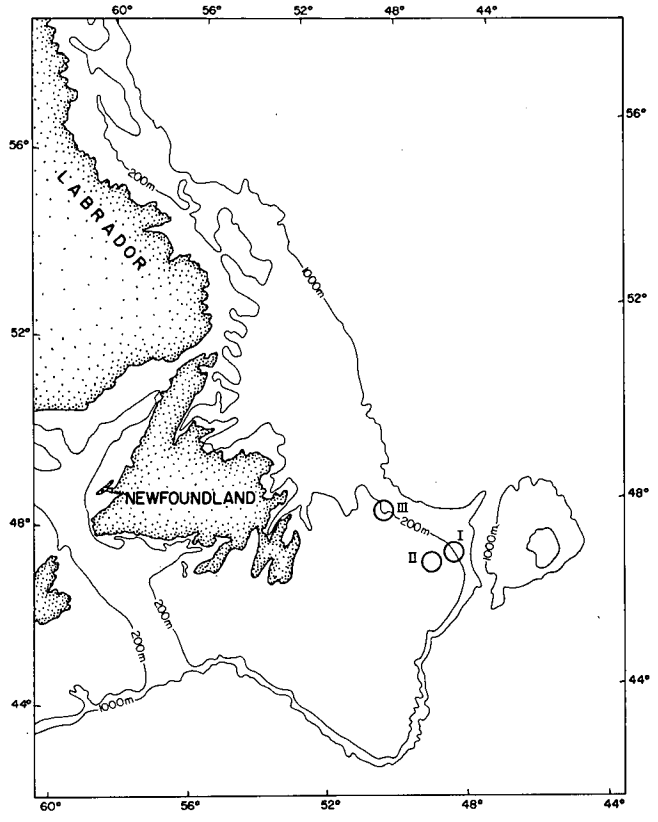

Figure 8. A map of the Grand Banks showing the location of the three regions studied.

As an application of the model, three regions were chosen on the northeastern Grand Banks area. These regions are presented in Figure 8. In each region, comprising 2500 km^2, it was found that an exponential distribution reasonably represented the observable population of scour depths. From this, an initial distribution was inferred. An infill rate of 10 cm per 1,000 years was adopted, which was consistent with a rate based on a core taken in the area by Lewis[1]. The model was then used to calculate a scour rate for the three areas (Table 1). As well, scour rates were calculated from iceberg arrival data; the details of the calculations are described in Gaskill et al. (1985) and employ data contained in Hotzel and Miller (1983). As can be seen from the table, good agreement is found for regions I and III. A discussion of the predicted scour deficit for region II is contained in Gaskill et al. (1985), and a plausible explanation for the deficit is developed.

[1]C.F.M. Lewis, Atlantic Geoscience Centre, personal communication, 1985.

TABLE 1

Predicted annual iceberg scour rates per 2500 km^2

Region	Water depth	Model calculations	Iceberg arrival data
I	110 - 130 m	0.24 - 0.27	0.20 - 0.68
II	70 - 90 m	0.021 - 0.023	0.39 - 0.88
III	170 - 190m	0.24 - 0.28	0.14 - 0.39

FURTHER WORK

The modelling effort described is being extended so as to deal with situations in which cross-cutting plays a significant role. This further work is being conducted under contract to the Atlantic Geoscience Centre.

REFERENCES

Gaskill, H.S., L. Nicks, and D. Ross. 1985. A non-deterministic model of populations of iceberg scour depths. Cold Regions Science and Technology 11: 107-122.

Hotzel, I.S. and J.D. Miller. 1983. Icebergs: their physical dimensions and the presentation and application of measured data. Annals of Glaciology 4: 116-123.

DISCUSSION

Heiner Josenhans, Atlantic Geoscience Centre: I think it is quite unrealistic to use a 10-cm sedimentation rate in various water depths. I think the rate is highly variable and I see little value in applying that kind of a number. The other comment I have is that we have been looking at the number of ice-rafted fragments found in the Holocene cores. There is a consistently large variability. I doubt that you have had the same iceberg flux rate throughout the past 8,000 to 10,000 years. It is important to go back to some of the real information that does exist and tie those to your model, although I understand it is just a general model at this point.

Herb Gaskill: With respect to the cores, we have information for only one of the test areas supplied to us courtesy of Mike Lewis at the Atlantic Geoscience Centre. I'm not a geologist but if I am told that the rates are highly variable, then I would have to accept that.

Heiner Josenhans, Atlantic Geoscience Centre: I wouldn't think your results are all that exciting at this point because I'm not sure that you are entering real world data.

Herb Gaskill: As far as the geology goes I cannot comment except to say that the geologists who were working on the paper seemed to feel that the geology was consistent with present knowledge.

John Miller, Petro-Canada: We had quick look at your study areas. I didn't get an idea of what their diameter was. My question relates back to the iceberg arrival rates. You have one arrival in five years to one in two years and intuitively those numbers are an order of magnitude too low. In Hibernia,, on a long-term average basis, for a 60-km diameter area we are estimating 30 arrivals or so, so I question your figures. One in five years for your size of study area seems very low, which would make the spread between your observations and the model that much greater.

Herb Gaskill: The figure relates to annual scour rates, not arrival rates. In calculating scour rates, we assumed 100 icebergs would enter a circle of radius 80 km in a given year. This value was adjusted to reflect test circles in the paper.

PRELIMINARY SIMULATION OF THE FORMATION AND INFILLING OF SEA ICE GOUGES

W.F. Weeks and W.B. Tucker III[1]
U.S. Army Corps.
Hanover, N.H. 03755, USA

and

Alan Niedoroda
R.J. Brown and Associates
2010 North Loop West
Houston, Texas, 77018, USA

INTRODUCTION

In contrast to iceberg scouring off the east coast, this presentation deals with sea ice gouging in the Beaufort Sea, in particular off the Alaskan coast. In the United States, we prefer the term "gouge" rather than "scour," so in this paper "gouge" is used.

The discussion concentrates on a probabilistic-deterministic model of gouge occurrence and infilling in a manner similar to that described by Herb Gaskill (this volume), with the exception that we arrive deterministically at infilling rates. Although the computer simulation model will not provide immediate engineering-type results, we feel it is a powerful and cost-effective method of studying the whole gouging process.

OVERVIEW OF THE MODEL

A probabilistic approach is used to generate initial gouge characteristics. Specifically, individual gouge depths and locations, as well as the number of new gouges created each year, are obtained from statistical distributions. In the future, we plan to use a more realistic environmental climatology to describe yearly conditions and, thus, the resulting gouge formation and infilling characteristics.

The deterministic aspects are governed by the laws of physics, which must be simplified enough to include in the computer model. We treat both regional sedimentation and local bedload transport of sediment deterministically, with varying degrees of complexity. To specify regional sedimentation, we simply assume a sedimentation rate of 1 mm/yr over the entire area. These sediments are deposited in the gouges and onto the level seafloor. A more rigorous formulation is used to determine sedimentation in gouges by bedload transport. At present, the

[1]Presenter.

transport is calculated from currents only. Future work will also include the transport resulting from waves, which is an important factor.

COMPUTER ORGANIZATION

Figure 1 shows the overall flow of the computer model. Initially, environmental and distribution parameters that control this model are entered. Bedload parameters that can be calculated independently but that remain constant for all years, are then computed. This step is taken at this time merely in the interest of computer efficiency.

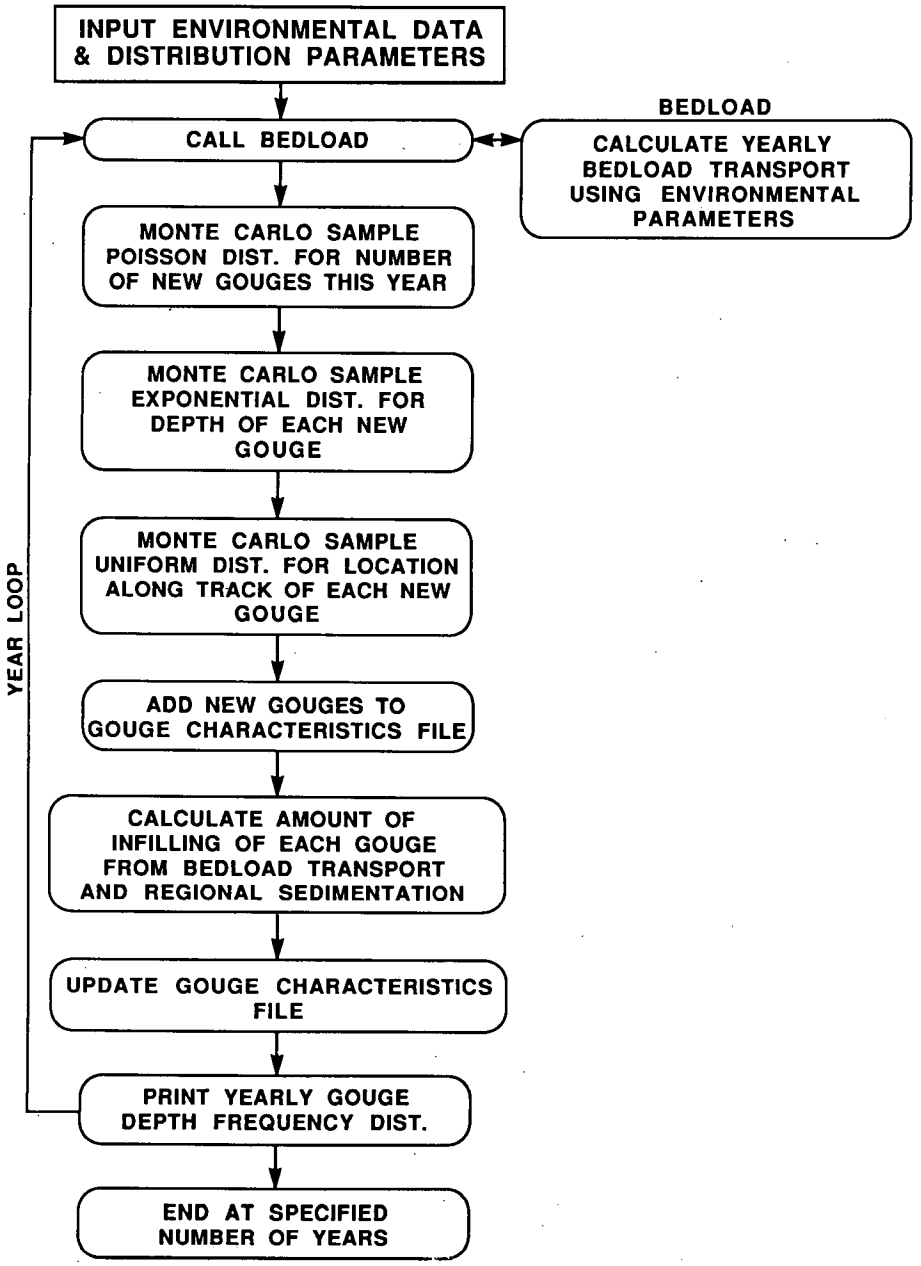

Figure 1. Flow diagram for the computer model.

A Poisson distribution is sampled using a Monte Carlo technique to determine the number of new gouges created each year. The depth of each new gouge is given by similarly sampling an exponential distribution. The location of the new gouge, which is assumed to occur along a 1-km track line, is taken from a uniform distribution. We are assuming an equal likelihood of a gouge occurring anywhere along the trackline. A gouge characteristics file contains the attributes of each gouge: the location, depth, and bottom width, which is initially zero because a triangular-shaped gouge is assumed. Next, the amount of infilling by regional sedimentation and local bedload transport is determined. The gouge characteristics file is updated, and yearly depth frequency distributions are printed. The program then cycles through another year.

THEORETICAL CONSIDERATIONS -- PROBABILISTIC

Number of New Gouges

The number of new gouges is controlled by a Poisson distribution. The Poisson distribution is useful for describing the frequency of random events in continuous time; and it is completely described by one parameter. The number of new gouges is obtained by Monte Carlo sampling Equation 1 in which a is the expected mean number of gouges per year and is an input variable.

$$f_x(x,a) = \frac{a^x e^{-a}}{x!} \qquad x = 0,1,2,... \quad a > 0 \qquad (1)$$

Depth of New Gouges

The depth of each new gouge, Equation 2, is obtained by Monte Carlo sampling a negative exponential distribution.

$$f_x(x) = \lambda e^{-\lambda x} \qquad \ldots x \geq 0 \qquad (2)$$

The parameter λ is an input parameter that varies systematically with water depth. It can be either entered independently or calculated as a function of the water depth. Gouges in the Beaufort Sea have been found to be satisfactorily described with this distribution (Lewis 1977, 1980; Weeks et al. 1983). As mentioned earlier, a uniform distribution is used to generate gouge location.

The new gouges are added to the gouge characteristics file. If a new gouge falls within the area covered by another gouge already in the gouge characteristics file, the deeper of the two gouges wins and the shallower gouge is deleted. This action is taken primarily for computational convenience, and it may be unreasonable to assume that if a new gouge is formed close to an existing gouge, the shallower one is completely eliminated. As this is a special problem, it is discussed later.

THEORETICAL CONSIDERATIONS -- DETERMINISTIC

A formulation for gouge infilling is adapted from a paper by Fredsoe (1979) that dealt with the natural backfilling of pipeline trenches. The volume of infilling material is given by:

$$q_b = \sqrt{(\gamma - 1) g d^3}\ \ 5p\ (\sqrt{\tau_d} - 0.7\sqrt{\tau_{dc}})$$

$$p = \{1 + [0.267/(\tau_d - \tau_{dc})]^4\}^{-1/4} \qquad (3)$$

$$A = 2Dg\ \frac{\sqrt{\delta}}{\sqrt{\pi}}\ (\sqrt{t + t_o} - \sqrt{t_o}) \qquad \delta, t_o = f(q_b)$$

The sediment bedload transport velocity, q_b, is dependent on the sediment density, gravity, the grain diameter, and the term τ_{dc}, which is a function of the bed shear stress τ_d and the critical shear stress τ_d. Finally, the volume of material introduced into the gouge per unit metre, A, is a function of the gouge depth, the parameter δ, the time constant t_o, and the simulation timestep, t. The parameters δ and the time constant t_o are also functions of q_b.

GOUGE GEOMETRY

Figure 2 shows the gouge infilling strategy and the associated equations. In the first year, the gouges start out as a basic triangle. Knowing the regional sedimentation, the amount of infilling can be calculated to give the new depth. The amount of bedload transport and the resulting new depth and width are then calculated. In the gouge characteristics file, only the corrected depth, updated width, and location of the gouge are stored.

RESULTS

Figure 3 shows the number of gouges against time at various surface current velocities for a bottom sediment of unconsolidated silt. Currents were considered to be active for only 3 months, the assumed length of the open-water season. Here the water depth was assumed to be 20 m and the expected gouge frequency was 10/km/year. A gouge-depth distribution parameter of 3.5, a gouge side slope of 15°, and a gouge-current crossing angle of 45° were constant input parameters for all runs. At the lowest velocity, 5 cm/s, very little infilling is taking place, because this velocity is below the threshold level required to entrain sediment. Gouges are formed at the rate specified by the distribution. Here, the overlap effect, in which the shallower of two overlapping gouges is eliminated, greatly influences the results. At the end of 50 years, we have only about 160 gouges when we should have nearly 500, based on the input expected rate parameter of 10 gouges per year, which indicates that many are being eliminated by overlap. At the end of the 50 year period, about 65% or 650 m of the 1-km track is covered with gouges. This presents a high probability that a new gouge will overlap with an existing gouge, eliminating one or the other.

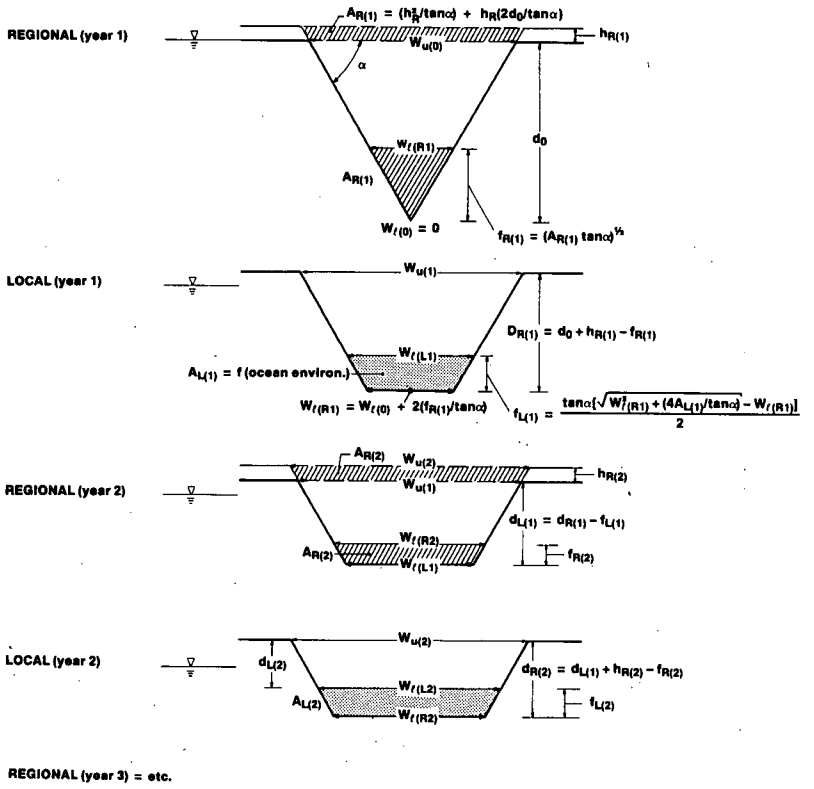

Figure 2. Gouge infilling strategy and associated equations.

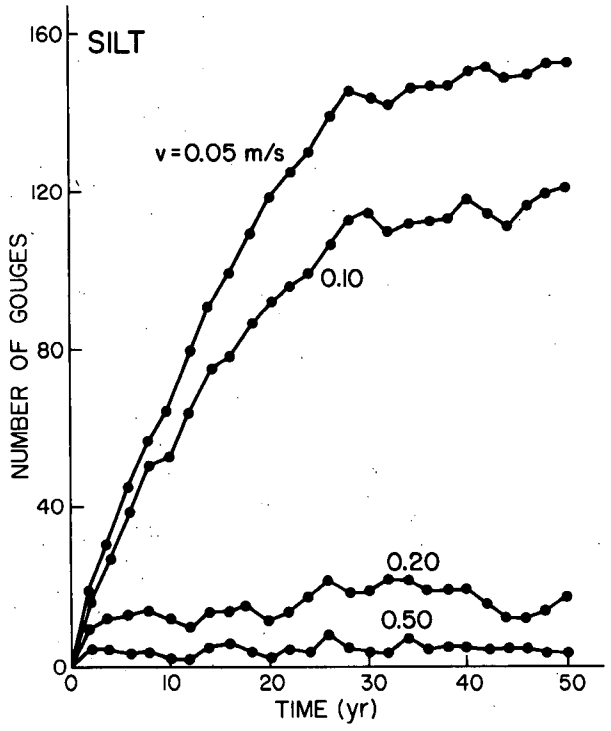

Figure 3. Number of gouges versus time at various surface current velocities for a bottom sediment of unconsolidated silt.

At 10 cm/s, the gouges begin to fill. Silt is being lifted off the ocean floor and transported into the gouges. Although some of the gouges are filling in, the total number is still growing, and an equilibrium state would have been reached had the model run long enough.

However, with a velocity of 20 cm/s, much of the silt that is entrained in the sediment transport process is falling out, maintaining the number of gouges at about 20 per year after 20 years. At a velocity of 50 cm/s, the gouge equilibrium number is about three or four per year, because at this velocity most gouges are filled the same year that they are formed.

Figure 4 is a group of histograms showing the number of gouges against gouge depth for the silt. It shows that as current velocity increases, the number and depth of the gouges decrease. With a current velocity of 20 cm/s, a large number of gouges that existed for velocities of 5 and 10 cm/s is destroyed. Much silt is being deposited into the gouges. At 50 cm/s, only four shallow gouges remain.

A similar set of results for sand is given in Figures 5 and 6. With the increase in grain size, very little infilling takes place even at 10 cm/s. After 50 years, 160 scours are observed, but equilibrium has not been reached. Because of its larger grain size, sand is not being lifted off the seafloor. However, sand has a critical velocity around 30 cm/s, and when it is mobilized, great quantities are capable of being transported as a bedload. At 30 cm/s, about 25 or 30 gouges per year will be maintained. An interesting situation exists with a current of 50 cm/s, in that all gouges are infilled. Obviously, the 50-year histogram shown in Figure 6 carries little information for the 50 cm/s current, whereas at 10 cm/s 161 gouges exist, and at 30 cm/s 24 shallow gouges exist at the end of the 50-year period.

FUTURE DEVELOPMENTS

In the near future, wave information will be included in the simulations, and probably the Fredsoe (1979) model will be abandoned in favour of the Madsen and Grant (1976) model. This formulation is preferred by co-author Alan Niedoroda, and includes wave action. An example of the infilling rate against water depth using this formulation for a 2-m gouge in various sediment types is shown in Figure 7. This formulation shows a tremendous drop in infilling rate with water depth for two reasons.

(a) A climatology has been assumed that has a decreased open-water time with increasing water depth, i.e., the ice retreats only for short period in deep water. On the other hand, in shallow water close to the Barrier Islands, there is a much longer period of open water.

(b) There is a substantial decrease in bottom-wave orbital velocities in the deeper water, so that much less sediment has been entrained.

To give a more realistic model, cohesive-type sediments or a mixture of cohesive and non-cohesive sediments will also be added to the simulations.

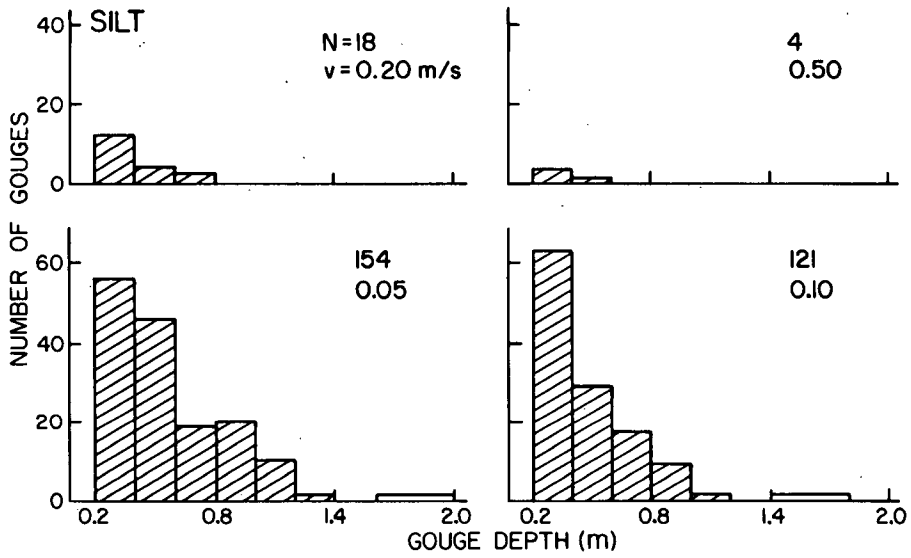

Figure 4. Histograms of the number of gouges against gouge depth at different current velocities for silt.

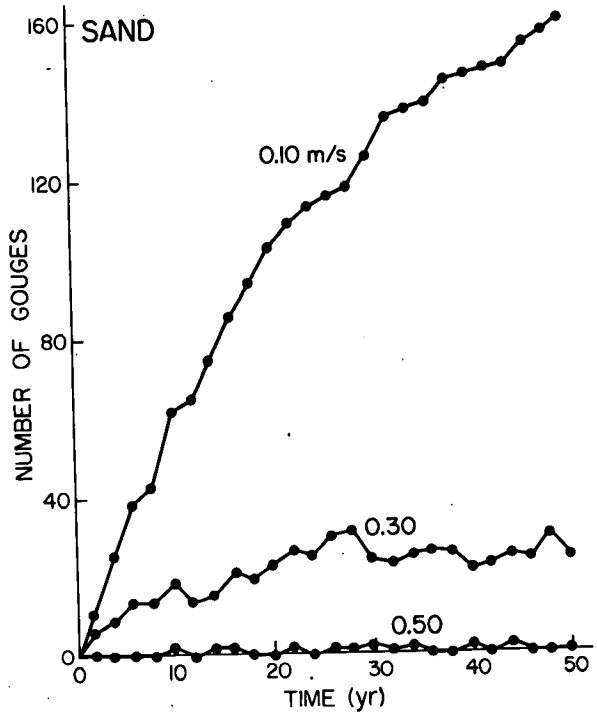

Figure 5. Number of gouges versus time at various current velocities for sand.

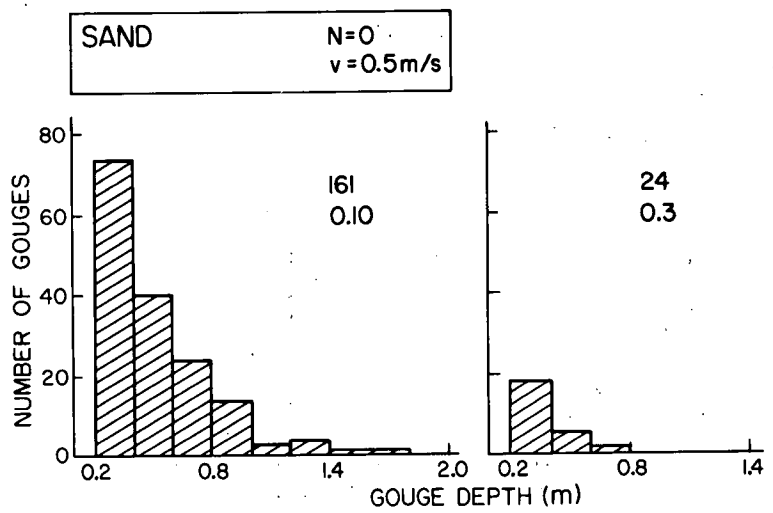

Figure 6. Histograms of the number of gouges against gouge depth at various current velocities for sand.

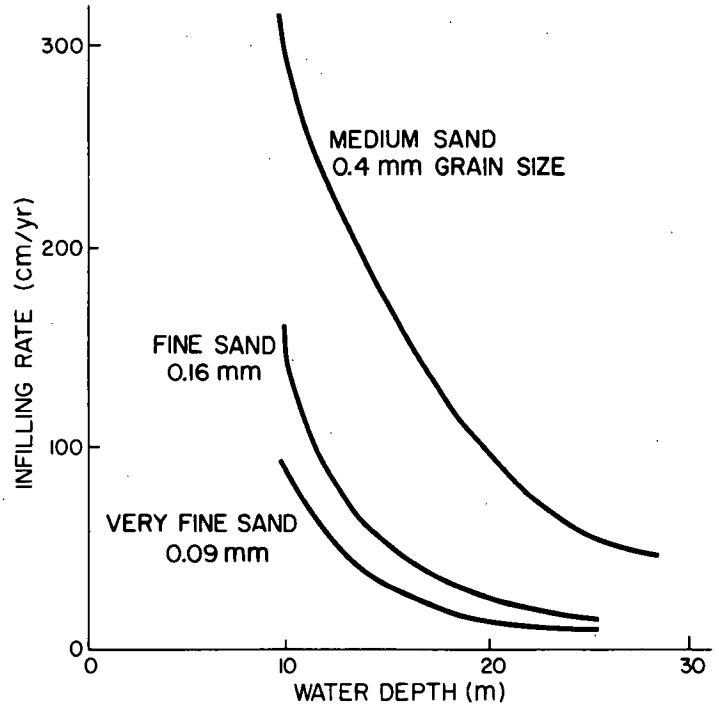

Figure 7. Infilling rate versus water depth for a 2-m gouge in various sediment types.

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DISCUSSION

Bob Bea, PMB Systems Engineering: I'd like to ask you how you are proposing to recognize and handle the dependencies among your probabilistic quantities, i.e., correlations between some of the principal elements you mentioned.

Terry Tucker: Correlations have not yet been addressed, but I imagine we'll run many sensitivity tests.

Bob Bea, PMB Systems Engineering: The sensitivity tests, I assume, do not reflect correlations. In essence you are assuming independence and that there is a correlation between number, depth, and location. Then the results could be very different.

Terry Tucker: They certainly could. We'll have to think hard on that.

Roger Pilkington, Gulf Canada Resources: Some of the work that Gulf has done indicates that reworking of the seabed as a result of scouring is the main reworking mechanism. Is there any way you can include that in your model?

Terry Tucker: The only way we've included it is by the assumption that one gouge wipes out another. Is that what you are referring to?

Roger Pilkington, Gulf Canada Resources: No, I am referring to a scour bringing up the sediment and that sediment being transported.

Terry Tucker: No, the only way at present we could include that and still keep the model fairly simplistic would be to assume a mix of cohesive versus non-cohesive sediments. After a few years, when you have an adequate number of gouges, perhaps you could lower the consolidation of the sediments somewhat.

Roger Pilkington, Gulf Canada Resources: If you compare Mike Lewis's model to repetitive mosaicing (this volume; Pilkington, R. Overview of methods of estimating ice-scour frequency and risk to buried pipelines), I think you require an infill rate of eight times the normal sedimentation rate, and the assumption was that this was because of reworking as result of ice scouring.

Terry Tucker: Then reworking is a very important parameter. We'll have to attempt to obtain a good estimate of it for the model.

ICEBERG-GROUNDING STUDY, LABRADOR WELL-SITE OBSERVATIONS

Chris Woodworth-Lynas[1] and Alvin Simms
C-CORE, Memorial University of Newfoundland
St. John's, Newfoundland, A1B 3X5

INTRODUCTION

This is a study of iceberg groundings using radar data. Most of the data for this study came from the Canada Oil and Gas Lands Administration (COGLA), but originated from industry programs. Where data deficiencies existed, Petro-Canada kindly helped where they could.

The primary aims of this study were to look at icebergs that were sighted at particular wellsites during operations along the Labrador coast and northeast Newfoundland shelf, to delineate grounded and scouring icebergs. We wanted to identify scouring icebergs within this data set, and to examine the bathymetric range of scouring bergs. The highlights for this study are given in this report; full details are published elsewhere (Woodworth-Lynas et al. 1985).

ICEBERG-GROUNDING STUDY

Table 1 lists all the well-site data sets that were available for this study. Ten years of data on between 1,300 and 2,000 icebergs were reviewed and sorted. The data from Saglek Bank (Fig. 1) were collected between the months of July and mid-October. The bar graphs of Figures 1 and 2 represent the times when the drillships were collecting iceberg information. The histogram in Figure 2 represents the average monthly flux of icebergs crossing the latitude of Saglek Bank, and is based on International Ice Patrol (IIP) data. It is interesting to note that the greatest flux is in the early spring and summer months, when there is no commercial activity. This situation has some implications for the rates of scouring that result from this study.

Figure 3 shows a typical iceberg trajectory obtained from radar information. Icebergs move in peculiar loops and gyrations, as Petro-Canada's Drew Allan (this volume) showed in his simulation model. These gyrations result largely from rotary currents caused by tidal oscillations. The loops usually have a period of between 11 and 14 h, with an average period of about 12 h caused by the semi-diurnal tides.

As Kate Moran (El-Tahan et al., this volume) outlined, there are many problems with the data set. One of the problems is the inherent error that is present in a radar system as pointed out by John Miller of Petro-Canada (El-Tahan et al., this volume). Basically, this error concerns the resolution cell of the radar, which has dimensions about 1.5% of the total range. The radar beam width also has an effect. With such resolution characteristics, the greater the range, the greater the uncertainty in size and location of the target. Observations may indicate that an

[1]Presenter.

TABLE 1

Well sites, positions, years, and data used for grounding and scouring study

Year(s) drilled	Well name	Latitute	Longitude	Geographic area	Data missing in this study
1973	Leif E-38	54°17'30"	55°05'22"	Hamilton Bank	
1973	Leif M-48	54°17'46"	55°07'20"	Hamilton Bank	
1973, 1974	Bjarni H-81	55°30'29"	57°42'06"	Makkovik Bank	
1974, 1975	Bonavista C-99	49°08'05"	57°14'25"	N.E. Newfoundland Shelf	
1974	Gudrid H-55	54°54'30"	55°52'32"	Cartwright Saddle	
1975	Cumberland B-55	48°24'13"	56°07'58"	N.E. Newfoundland Shelf	
1975	Freydis B-87	53°56'13"	54°42'31"	Hamilton Bank	
1975, 1976	Indian Harbour M-52	54°21'51"	54°23'52"	Hamilton Bank	
1975, 1976	Karlsefni A-13	58°52'15"	61°46'42"	Saglek Bank	
1975, 1976	Snorri J-90	57°19'45"	59°57'44"	Nain Bank	
1975, 1976	Cartier D-70	54°39'02"	55°40'30"	Hamilton Bank	Missing
1976	Cabot G-91	59°50'20"	61°44'04"	Saglek Bank	
1976	Herjolf M-92	55°31'53"	57°44'53"	Makkovik Bank	
1976	Verranzano L-77	52°26'38"	54°11'51"	N.E. Newfoundland Shelf	
1978	Hopedale E-33	55°52'24"	58°50'52"	Hopedale Saddle	
1978, 1979, 1980	Roberval K-92	54°51'36"	55°44'36"	Cartwright Saddle	Missing 1978, 1980
1978	Skolp E-07	58°26'25"	61°46'10"	Saglek Bank	
1979, 1980, 1981	Bjarni 0-s82	55°31'48"	57°42'34"	Makkovik Bank	
1979, 1980	Gilbert F-53	58°52'26"	62°08'23"	Saglek Bank	
1979	Hare Bay E-21	51°10'22"	51°04'27"	N.E. Newfoundland Shelf	
1979	Tyrk P-100	55°29'49"	58°13'50"	Makkovik Bank	
1980	South Labrador N-79	55°48'46"	58°26'33"	Makkovik Bank	
1980, 1981	North Leif I-05	52°24'39"	55°15'11"	N.E. Newfoundland Shelf	Missing 1981
1980	Ogmund E-72	57°31'29"	60°26'39"	Nain Bank	
1980	Roberval C-02	54°51'07"	55°46'04"	Cartwright Saddle	
1980, 1981	North Bjarni F-06	55°35'29"	57°45'49"	Makkovik Bank	Missing 1980
1981	Corte Real P-85	56°04'49"	58°12'10"	Hopedale Saddle	Missing
1981	Rut H-11	59°10'16"	62°16'47"	Saglek Bank	

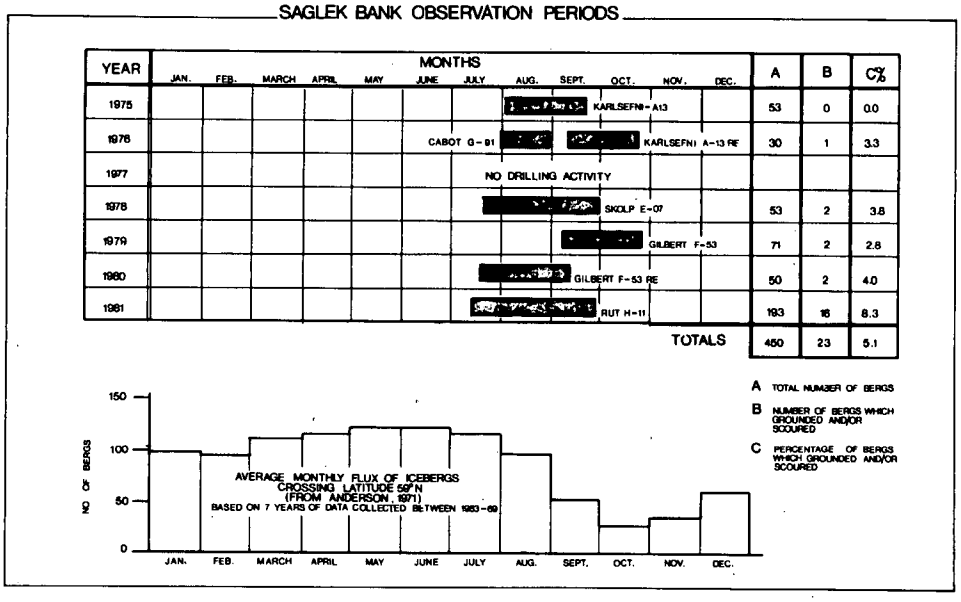

Figure 1. Drilling activity on Saglek Bank, and average monthly iceberg flux (after Woodworth-Lynas et al. 1985)

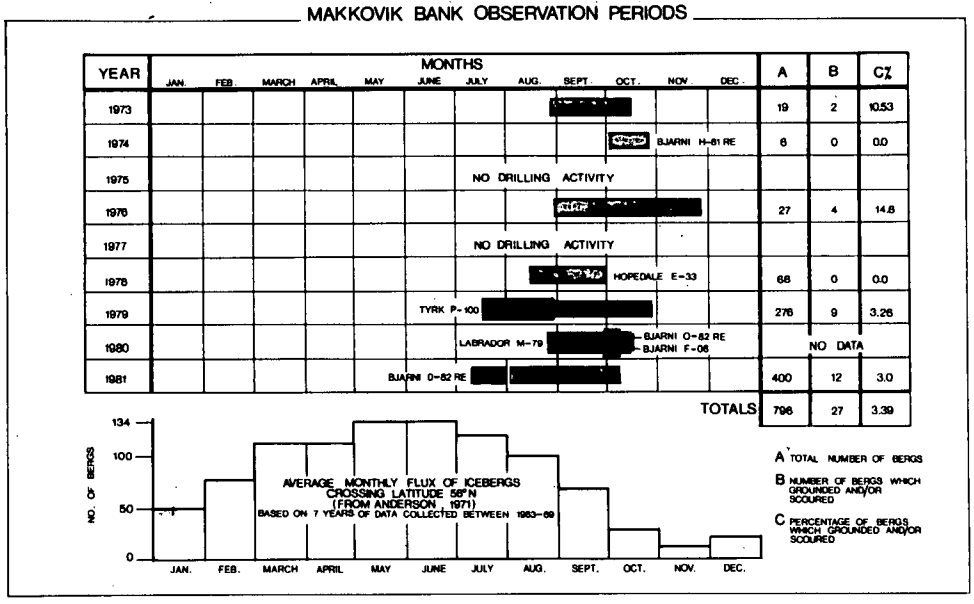

Figure 2. Drilling activity on Makkovik Bank, and average monthly iceberg flux (after Woodworth-Lynas et al. 1985)

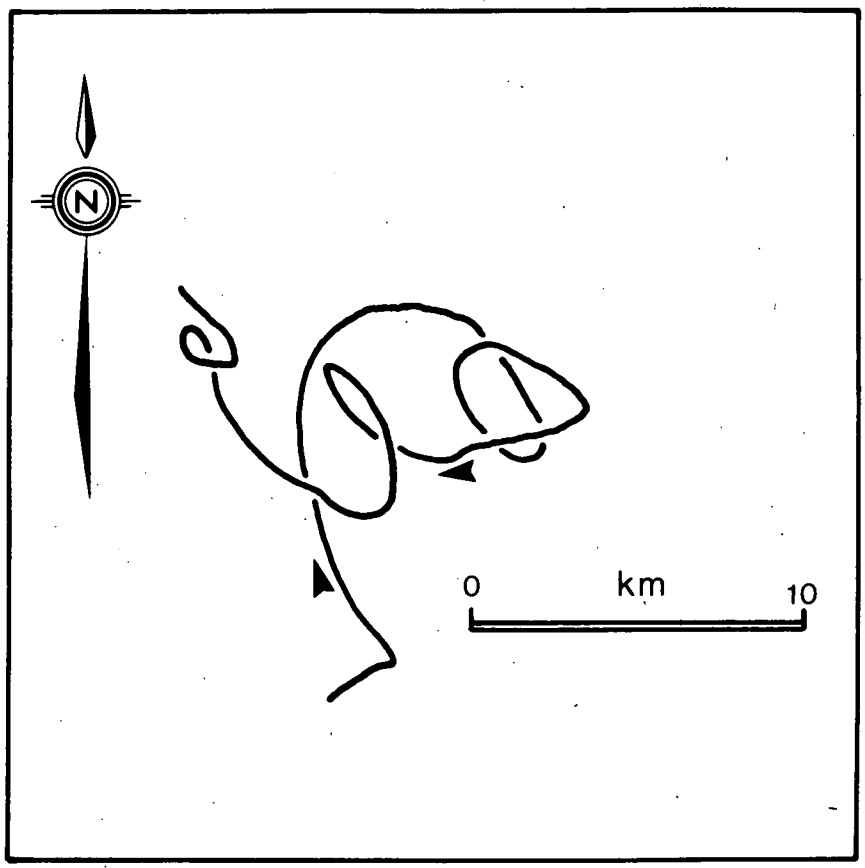

Figure 3. Part of the looped trajectory of iceberg 164 seen at RUT H-11 (1981) on Saglek Bank (after Woodworth-Lynas et al. 1985).

iceberg has moved, when in fact it could well be stationary. This inherent error is taken into account within the plotting routines that provide the trajectory information.

There are also observer errors. For example, one operator could approach the radar screen and measure an iceberg at 43.5 km (23.5 naut. mi), and, after a change of watch, a new operator could measure the same iceberg at 42.6 km (23 naut. mi) with a 1-degree difference in bearing, even though the iceberg has not moved. Another problem area is incorrect logging of measurements. It was estimated that at least 10% of the iceberg data were incorrectly logged. For example, after computation some icebergs were found to be travelling at speeds between 10 and 37 km/h! The average velocity of an iceberg is about 1.8 km/h.

Figure 4 is an example of the interpreted scour-track map for Saglek Bank. The rings represent a range of 46.3 km (25 naut. mi), which is typically the maximum range on the radars used for these observations. The heavy black curved lines represent what are considered to be scouring icebergs.

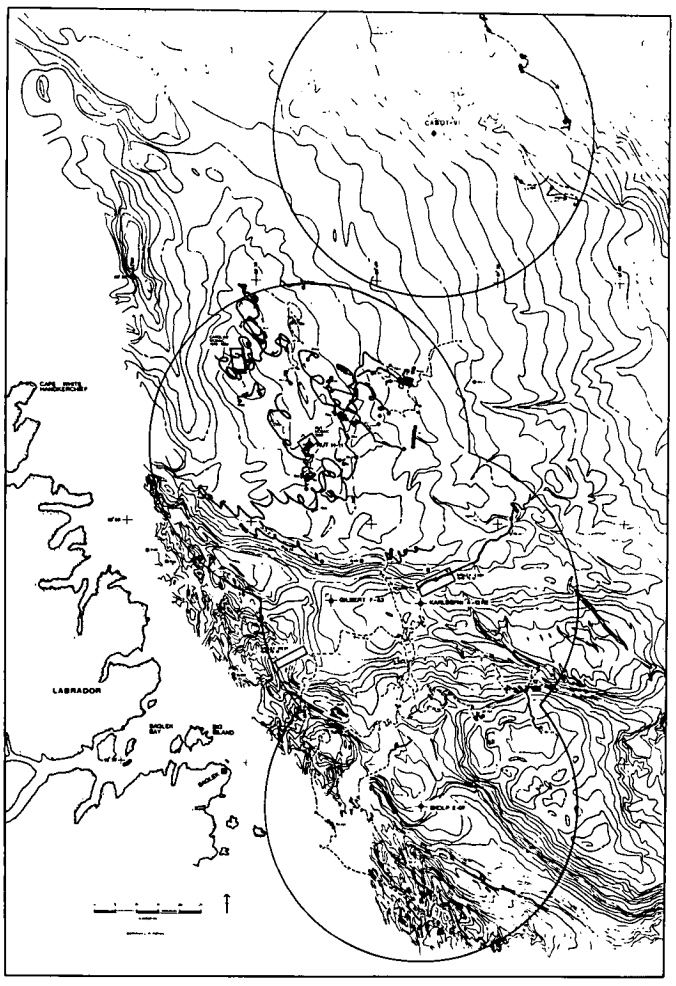

Figure 4. Bathymetry map of Saglek Bank showing all interpreted groundings (dots) and scour tracks (solid lines). Dotted lines are free-floating portions of tracks of icebergs which ground or scour more than once (after Woodworth-Lynas et al. 1985).

IDENTIFICATION OF SCOURING ICEBERGS

Before our model can detect scouring icebergs, it is a prerequisite that an iceberg must first be grounded and completely stationary. If an iceberg is stationary for 12 h, we reasonably assume that because it has not moved through a semi-diurnal tidal cycle, then it is probably wedged on the seabed. If the iceberg then moves into shallow water from its grounding site, and assuming that its keel depth remains the same, i.e., it has not rolled to a shallower draught, then it is interpreted as scouring. If it moves into deeper water, it is not scouring, and if it stays at the same contour, it is also thought not to be scouring.

This simple hypothesis was adopted rather than the null hypothesis, which assumes that from a grounding position an iceberg would just float off and a scour would not be produced. Scouring does occur, particularly since very long linear scours going up and down the slopes are very much in evidence on the seafloor.

Figure 5 is the scour map for Makkovik Bank. The dots represent the iceberg groundings, and the heavy black lines represent the interpreted scour tracks. Of interest here is that all the groundings occur above the 120-m isobath.

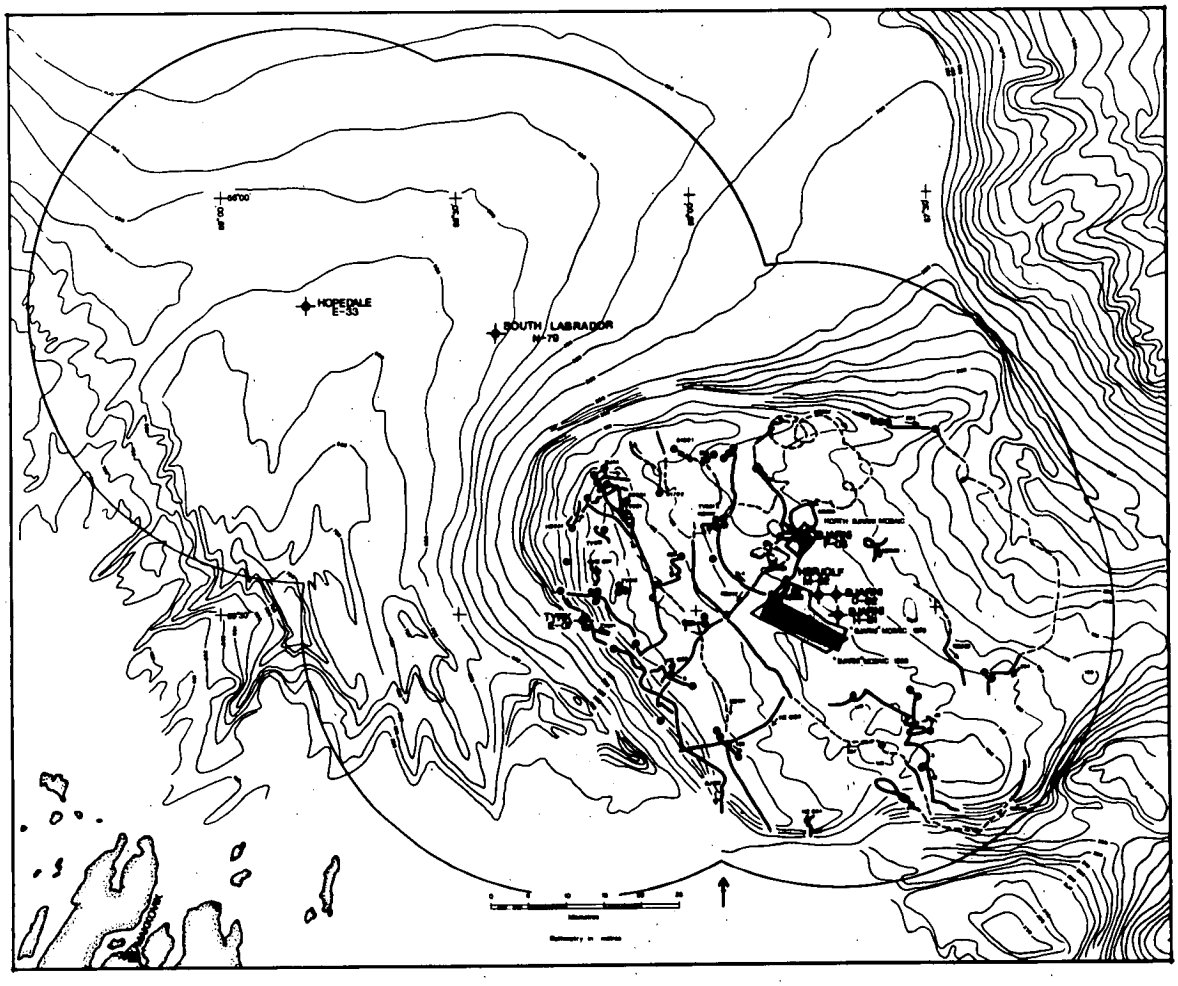

Figure 5. Bathymetry map of Makkovik Bank showing all interpreted groundings (dots) and scour tracks (solid lines). Dotted lines are free-floating portions of tracks of icebergs which ground or scour more than once.

It can be seen that several icebergs were interpreted as scouring both up- and down-slope. Figure 6 shows a track of an iceberg on the west side of Makkovik Bank. The iceberg entered the area showing a rather peculiar confused motion, which is characteristic of some scouring icebergs. The iceberg is scouring at a depth of 135 m. It then travels along the 100 m isobath and across up to point B, where it grounds for at least 12 h. The iceberg then moves up and over the 90-m isobath, with more confused motion, continuing down into 135 m of water: a 45-m change in draught if our model is correct. Here it grounds again for at least 12 h. The 135-m depth was taken to be the actual maximum depth of the keel. Our interpretation of the zig-zag portion of the latter part of the track is that the normal free-floating looping motion is restricted by the seabed forces acting on the keel. The total length of the scour track is 100 km.

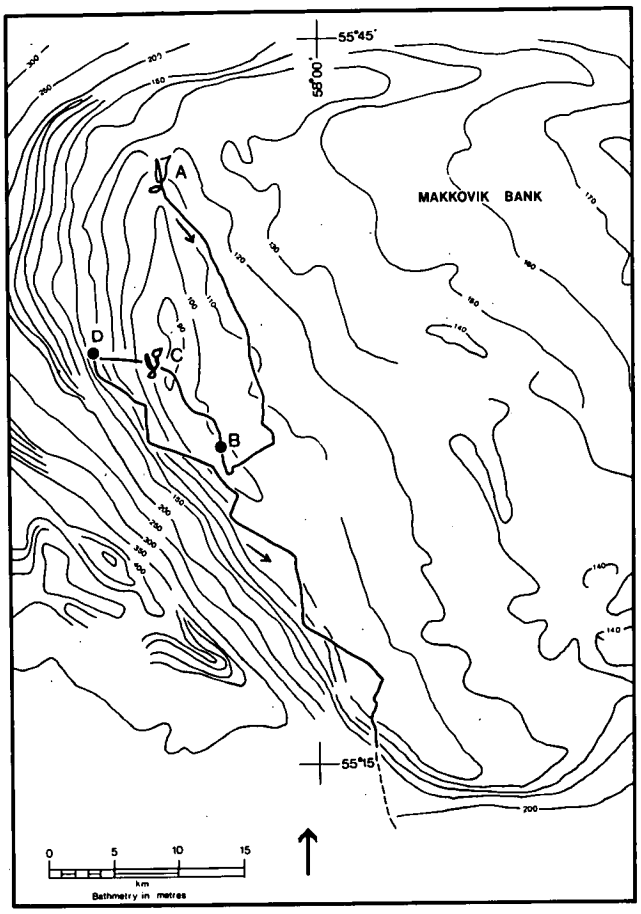

Figure 6. The groundings (dots) and scour track (solid line) of a 25-million-ton iceberg, BJ37, observed from Bjarni H-81 (1973). The berg grounds twice, at point B (98 m) and D (135 m), and scours between them, traversing a ridge at 90 m over a bathymetric range of about 45 m, a dramatic illustration of how icebergs may scour over terrains with large relief. Dashed line is where iceberg is interpreted to become free-floating again (after Woodworth-Lynas et al. 1985).

Figure 7 is an iceberg track from Saglek Bank, where the scouring iceberg is stationary at several points. The iceberg produces a scour with very pronounced semi-diurnal loops. This particular scour is 220 km long.

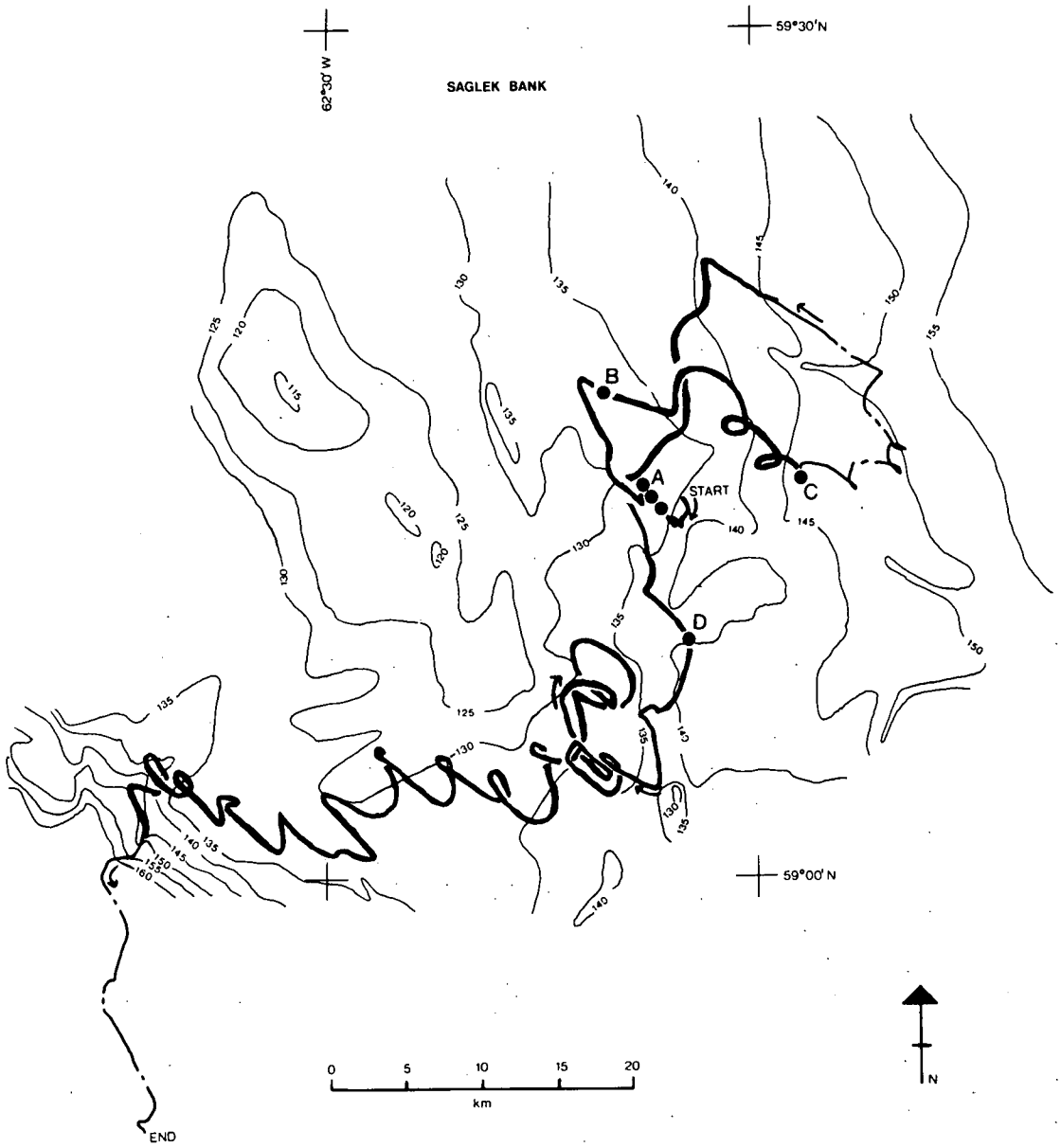

Figure 7. The scour track of iceberg R53 seen from Rut H-11 (1981) showing characteristic looping motion, probably corresponding to semi-diurnal cycles. The looping motion ceases when the iceberg becomes free-floating towards the end of its recorded track in the southwest as it drifts into the deeper waters of the Labrador marginal trough. The iceberg grounds six times, three times at point A, and once at points B, C, and D. Scour track is solid line, free-floating portions are dashed lines.

Attempts were made to incorporate acoustic measurements of draught into the observations. Unfortunately, very few icebergs were measured. However, the three grounded icebergs for which draught data were available (Table 2) did show a reasonable agreement with the water depth where grounding was first observed. This is a good indicator that our criteria correctly interpret grounded bergs.

Tables 3 and 4 show the bathymetric ranges of scouring icebergs off Makkovik Bank and Saglek Bank, respectively. Bathymetric ranges between 10 and 25 m are not uncommon in this data set. This kind of information is not detectable on long, regional, sidescan survey lines or on well-site surveys, because only small segments of scours are seen.

TABLE 2

Comparison of measured iceberg draught with bathymetry

Well site	Iceberg No.	Measured draught (m)	Water depth at grounding site (m)
Bjarni 0-82 (1979)	NB38	156	138-145
Gudrid H-55 (1974)	G122	155	160 (first grounding) 150 (second grounding)
Skolp E-07 (1978)	SK002	107	135 (two other groundings plot outside the area of bathymetry coverage)

TABLE 3

Bathymetric range of scouring icebergs off Makkovik Bank

Well site	Berg No.	Scouring depths (m)	Range (m)
Bjarni H-81	37	120 - 90 - 135	45
(1973)	44	125 - 115	10
Bjarni 0-82	38	156 (measured draught) - 130	26
(1979)	48	139 - 109	30
(1981)	234	175 - 150	25
	308	125 - 110	15
Bjarni F-06	8	108 - 100	8
(1981)			
Herjolf M-92	4	120 - 105	15
(1976)			
Tyrk P100	11	100 - 130	30
(1979)	12	97 - 100	3

TABLE 4

Bathymetric range of scouring icebergs off Saglek Bank

Well site	Berg No.	Scouring depths (m)	Range (m)
Karlsefni A - 13RE	7	164 - 154 - 165	11
(1976)			
Skolp E - 07	44	135 - 152	17
(1978)			
Rut H - 11	-	150 - 133	17
(1981)	11	131 - 116	15
	24	125 - 121	4
	53	146 - 127	19
	102	129 - 132	3
	125	135 - 139	4
	164	120 - 117	3

It is realized that not all scouring icebergs can be identified from the data set, because our model requires that an iceberg must first come to a halt by grounding on the seabed before it can be interpreted as scouring. There must be icebergs that scour without stopping. Figure 8 shows an example of such an iceberg that had an acoustically measured draught which in places exceeded the water depth. As only three icebergs with measured draught have been plotted, we expect that there are a lot more scouring icebergs in this data set than we can detect, so that the actual scour rates we propose are probably underestimated. We estimate scour rates of 4.3% for Saglek Bank and 3.3% for Makkovik Bank.

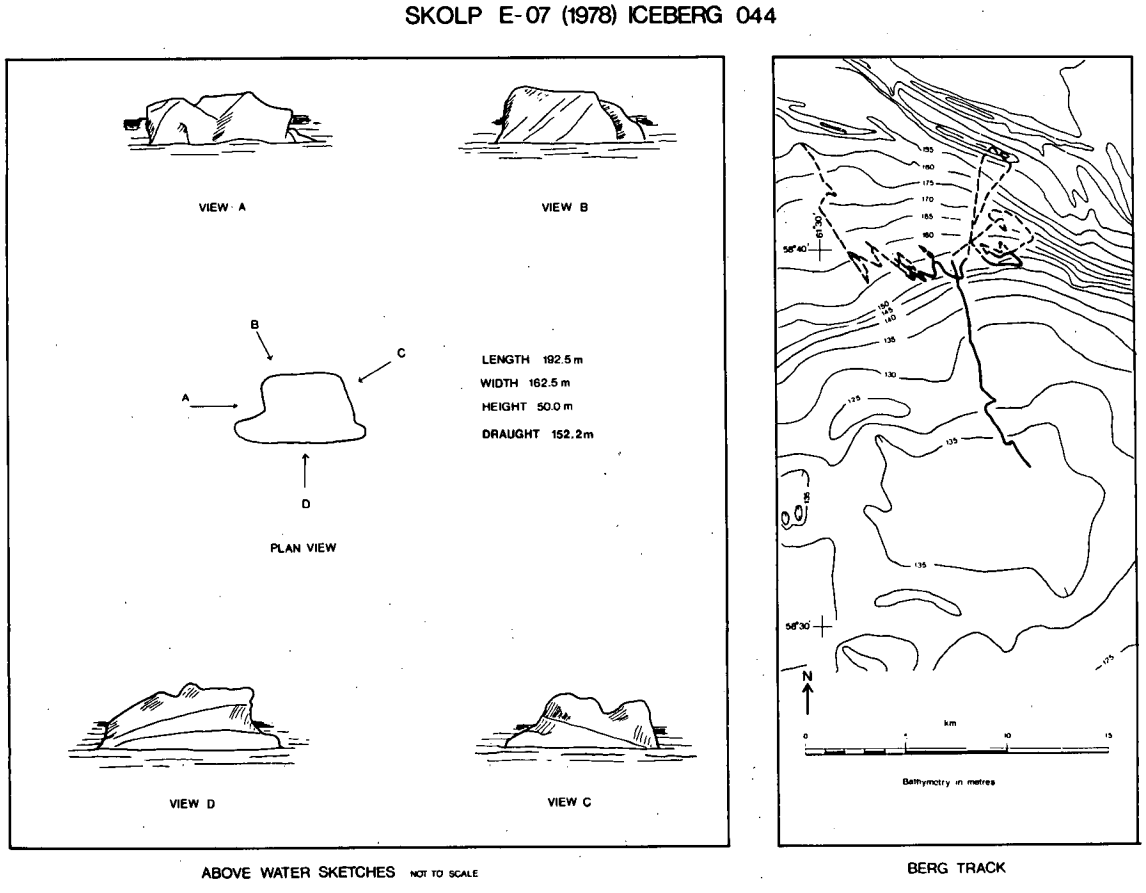

Figure 8. The scour track of iceberg 044 (Skolp E-07, 1978). This berg was not identified as grounded from the grounding algorithm used in the study. However, it is interpreted as scouring (solid line) for parts of its track because its sonically measured draught (152.2 m) exceeds the water depth in places. Note the confused motion of the track between 160 and 145 m. This is probably the result of pronounced drag effects on the berg's scouring keel, slowing it down and compressing what may be resolved as normal tidal looping into apparently erratic course changes (after Woodworth-Lynas et al. 1985).

COMPARISONS WITH PHYSICAL MODELS

There are differences between the scouring processes mentioned above and the simplistic model developed by Dr. Chari (this volume) in the Faculty of Engineering at Memorial University in St. John's, Newfoundland. Chari's model assumes that an iceberg strikes the seabed, starts to scour, and begins to uplift without rotating as scouring continues. In our model, six degrees of freedom are allowed, so that rotation can take place.

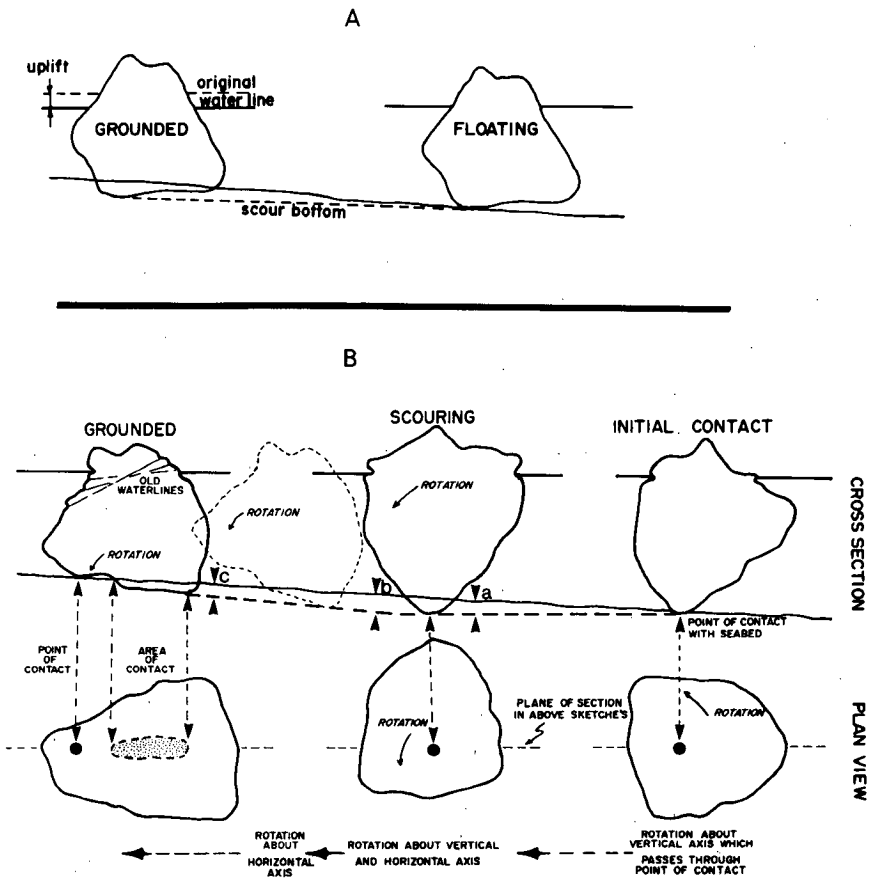

Figure 9. (a) The model of Chari et al. (1980). As the berg scours upslope the keel is driven deeper into the seabed. At the same time soil forces cause gradual uplifting of the keel, raising the iceberg until it eventually grounds (modified from Chari et al. 1980).
(b) Proposed model which allows the iceberg to respond to soil forces by rotation.

Figure 9 shows a side view and a plan view of a simple scouring model. As the iceberg's keel contacts the seabed, soil drag effects cause the berg to rotate slowly about a vertical axis which passes through the point of contact. This continues until the keel is in the optimum position for efficient scouring, i.e., at the aft end so that it is pulled, not pushed, through the seabed. During this period of rotation the keel becomes entrenched in the seabed, as in the model (Chari et al. 1980). At point (a) horizontal rotation is still occurring but increasing upward seabed forces cause iceberg uplift. However, instead of being raised out of the water, the berg, being unconstrained, responds by beginning to rotate about a horizontal axis normal to the movement direction. In this way the keel is uplifted, but the iceberg still maintains its original above-

water/below-water mass ratio. As it continues to scour upslope from point (a), rotation about a vertical axis ceases as the keel becomes positioned aft. Continuing rotation about the horizontal axis causes redistribution of mass forward from above the keel. This results in reduced vertical pressure being applied to the seabed through the scouring keel and, thus, scour depth decreases as the iceberg moves into shallower water, a feature which agrees with observed scour depth distributions. Thus, scour depth at (b) is greater than at (c). The iceberg may eventually ground when it can no longer continue to rotate as it moves into shallower water, in which case it may be uplifted as in the model of Chari et al. (1980). Alternatively, continual rotation may result in a large keel/seabed contact area developing, as shown, grounding occurring as a result of increased seabed frictional forces.

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DISCUSSION

Walter Bobby, Newfoundland Petroleum Directorate: You indicated that there was a 35-m difference in the draught. Can you expand on this?

Chris Woodworth-Lynas: Yes. That actually worked out to be a 33% change in draught.

Walter Bobby, Newfoundland Petroleum Directorate: I think you have a nice model to explain how rotation on the horizontal and vertical axes is possible. In the scouring curves that you presented, do you have any feel for the initial draught and the final draught of the iceberg? What I am trying to get at is this -- does your model show that draught reduces, i.e., is there any simulation in your model where you start with a shallow draught and then go on to ground in deeper water?

Chris Woodworth-Lynas: The data are too insensitive for that. We have to assume that an iceberg's grounding depth is its draught, and we assume that it can always return to that deepest

draught, but no deeper. We believe that an iceberg is not going to hit the seafloor suddenly and ground. Presumably, it is going to have to scour before seabed forces eventually arrest it. So there are probably a lot of scour tracks prior to the grounding positions, but we cannot define these.

Peter Barnes, U.S. Geological Survey: You show your icebergs stopping before you call them grounded, which is usually at their deeper draught. Why do you suggest that they stop there and then suddenly start moving? I was wondering, given the error in the locations, if you had made a comparison between floating icebergs that appear to have stopped for 12 hours versus the ones that you are calling grounded. In other words, there must be some percentage of the population that appear to have stopped but haven't stopped and haven't grounded.

Chris Woodworth-Lynas: Herb Gaskill (this volume, Report on a non-deterministic model of populations of iceberg scour depths) mentioned that he had observed an iceberg on the west coast of Greenland that was stationary for 72 h in 700 m of water, but that couldn't possibly have been grounded. In our data, we discovered an iceberg that was stationary in 500 m of water, and we know it wasn't grounded. It is likely that no iceberg on the east coast has a draught in excess of 220 m.

Peter Barnes, U.S. Geological Survey: Why did they stop initially in deep water and then go shallower? You have to have them stopped for 12 hours.

Chris Woodworth-Lynas: They have to stop before we can detect them.

Peter Barnes, U.S. Geological Survey: And then they get into shallower water?

Chris Woodworth-Lynas: Yes, there are a lot of icebergs that move off into deep water. We interpret only the ones that move into shallow water as scouring.

Drew Allan, Petro-Canada: When the iceberg stops during a long scour and you infer its depth, you count it as a single scour. It will then continue to scour until the water depth exceeds the maximum draught. But inherent in your assumption of iceberg shape is that it is very stable, in that it can experience quite a rotation without rolling. I was wondering if that agrees with what we know about icebergs and their inherent instability?

Chris Woodworth-Lynas: Because of the iceberg that experienced a 48-m change in draught, I would assume that a stable situation exists because it is grounded at the shallower and deeper ends of its scour track. For that reason and because other icebergs go through 10-, 20-, or 30-m changes in draught fairly frequently, yes, why shouldn't the model be feasible?

Drew Allan, Petro-Canada: Did that iceberg ground at the end of its track?

Chris Woodworth-Lynas: No, not at the end of its track. It went over the 90-m isobath and then down, and grounded in 135 m of water before it continued scouring.

From the floor: How good is your bathymetry?

Heiner Josenhans, Geological Survey of Canada: It is ±5 m.

Alan Ruffman, Geomarine Associates Ltd.: A question on terminology: a grounding iceberg is one that is in fact scouring, and it is grounded when it stops?

Chris Woodworth-Lynas: Yes.

Alan Ruffman, Geomarine Associates Ltd.: Grounding is at any other time?

Chris Woodworth-Lynas: Grounding is equivalent to scouring.

TOWARDS REPETITIVE MAPPING OF ICE SCOURS IN THE BEAUFORT SEA

J. Shearer[1]
26 First Avenue
Ottawa, Ontario, K1S 2G2

and

A.F. Stirbys
Gulf Canada Resources
Calgary, Alberta, T2P 2H7

INTRODUCTION

During the summer of 1984, an extensive ice-scour survey, sponsored by the Environmental Studies Revolving Fund (ESRF), was carried out over a large portion of the Canadian Beaufort continental shelf (Shearer et al. 1986). Using sidescan sonar and precision echo-sounding equipment, the main purpose of the survey was to establish an ice-scour network that would serve as the basis for future repetitive ice-scour mapping studies. Accurate resurveying of any portion of this network could then be used to calculate the frequency of new scouring events, and comparison with its earlier surveys should reveal seabed changes during the period between surveys.

IMPACT RATE DATA

Much of the 1984 network covered corridors and control areas that had been surveyed previously. Where overlap occurred, impact rate data were collected. In the western Beaufort Sea, near the southern end of the Tarsiut-Nektoralik corridor, scouring rates as high as four impacts per kilometre per year have been observed in water depths of 20-25 m. The impact rates decrease towards the east Mackenzie corridor, which is located in shallower water in Mackenzie Bay. In this area, the impact rate decreases to about one impact per kilometre per year in water depths between 10 and 20 m. In the eastern Beaufort Sea, the impact rates are even lower in the Tingmiark-Nerlerk and Kaglulik corridors, where rates in the order of 0.2 to 0.4 impacts per kilometre per year have been observed in water depths of about 30 m

SCOUR DEPTH DISTRIBUTION

It is apparent from Figure 1 that even though both the Tarsiut-Nektoralik and Pullen sites have a similar number of very shallow new scours (0-0.5 m in depth) the deeper-water

[1]Presenter.

Tarsiut area (25-35 m water depth) has a much larger number of deeper scours than does the Pullen area (15-20m water depth).

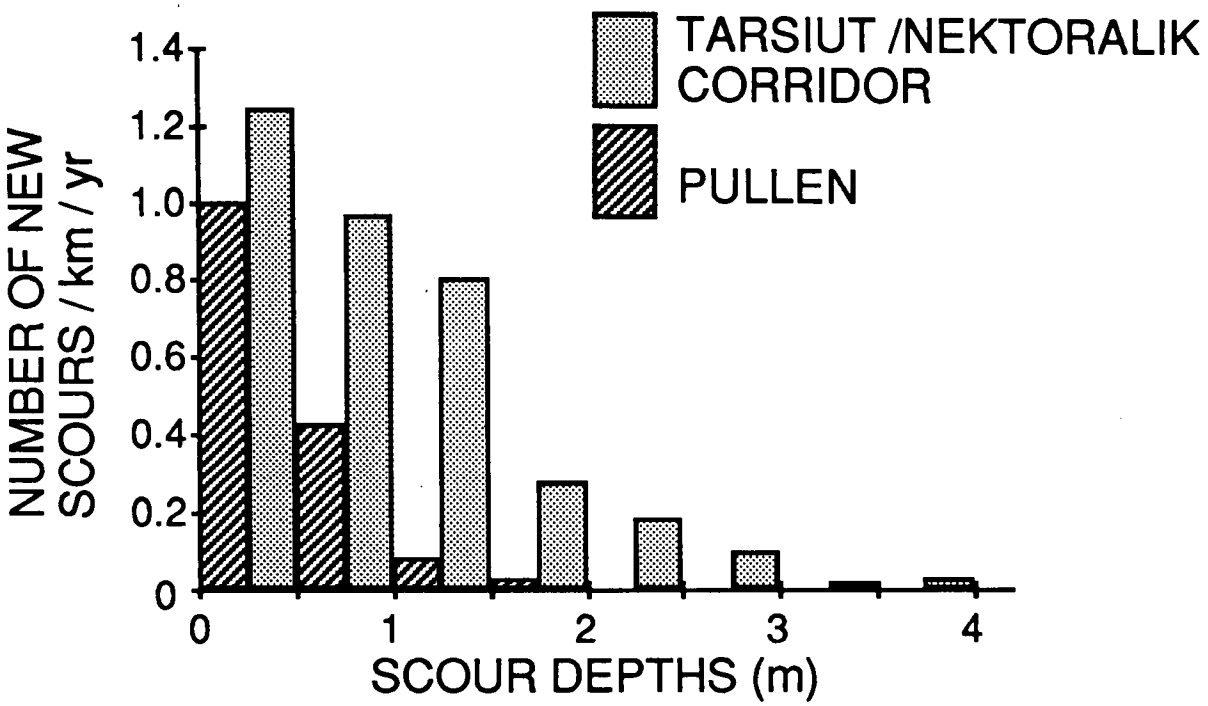

Figure 1. Net distribution of depth for new ice scours in the Beaufort Sea repetitive mapping network.

No new scours were observed in areas where water depths are greater than 40 m. A maximum new scour depth of 3.5 m was recorded in the Tarsiut-Nektoralik corridor.

During the winter of 1983-84, a multi-year ice incursion took place in the southern Beaufort Sea which resulted in the grounding of a number of large ice masses (McGonigal et al. this volume). Accurate locations of the grounded ice were obtained through satellite positioning; during the following summer, the seafloor was surveyed with sidescan sonar and a precision echo-sounder. The data collected during the survey allowed the construction of seafloor mosaics, and their detailed examination showed that the scour depths, associated with individual ice masses, can vary considerably along their tracks; furthermore, significant decrease in depth of the scour base was observed. At one specific location in Kugmallit Channel, a scour with a constant depth of 3 m experienced a net rise in the base of the ice scour of about 3 m. A maximum scour depth of 4.5 m was identified at one of the new scour locations.

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DESIGN OF A REPETITIVE-MAPPING NETWORK FOR ICE SCOUR: EAST COAST

G.J. Hodgson
Geonautics Ltd.
P.O. Box 8833
St. John's, Newfoundland, A1B 3T2

INTRODUCTION

A preliminary assessment of ice-scour data from the east coast of Canada is now being undertaken by Geonautics Ltd. This program will form the basis of a repetitive ice-scour mapping program similar to those currently under way in the Beaufort Sea. The objectives are similar to those outlined earlier (Gilbert and Blasco, this volume) and it will be interesting to speculate how useful this work will be in support of the numerous models that have been proposed at this workshop (d'Apollonia and Lewis; Gaskill; Weeks et al. this volume).

The criteria that Geonautics Ltd. is using are based on several factors that are fairly common in this type of study. We are looking at present-day occurrences of ice scours based on grounding information to support the modelling work being undertaken by d'Apollonia and Lewis (this volume) at the Atlantic Geoscience Centre (AGC).

Although the major considerations in site selection are iceberg flux, bathymetry, and surficial geology, on the east coast there is the additional issue involving potential commercial development on the Grand Banks of Newfoundland. In this context, Labrador is further in the future.

Our approach to the site selection for this study involved forecasting rates of groundings and scouring activity using all available information, including well-site survey data. Our input into the model being evaluated by d'Apollonia and Lewis (this volume) involves compilation of bathymetric data and iceberg density data within 9.3 km cells . Iceberg-draught distributions are being addressed by d'Apollonia and Lewis (this volume). We are also in the process of trying to access the best possible current-meter data for the model. At present, the model uses very general current information.

The results of the modelling are being compared with observed grounding data and with the surficial geology. The former are now being compiled under an ESRF project.[1]

SELECTION OF A SUITABLE SITE FOR REPETITIVE MAPPING

The grounding rates forecast for the northeast part of the Grand Banks seemed to have a higher intensity between the 100 and 200 m isobaths (Fig. 1). This area, which has annual scouring rates of about 0.5 scours per 100 km^2 , may be the most suitable site for a repetitive

[1]ESRF study 011-191-05(S) Regional ice-scour data base update studies.

mapping project. However, with this relatively low scouring rate, defining exactly where to locate the site presents a problem. Preliminary investigations on the Labrador Shelf - Makkovik Bank area indicate an annual grounding rate of about 60 groundings per 100 km, or about two orders of magnitude higher than on the Grand Banks (Fig 2). This site is more realistic for a repetitive mapping project.

The surficial geology on Makkovik Bank is shown in Figure 3. One of the advantages of Makkovik Bank as a site is a fairly large change in bathymetry and surface geology within a small area. A sidescan mosaic will then encompass areas of high scour occurrence and geological variability.

NETWORK DESIGN CONSIDERATIONS

The first consideration in the design of a repetitive mapping program is the determination of the size of the site, which will largely depend on the scour density and the variations in seabed morphology and geology. The orientations of the survey lines will depend on dominant orientation of the scour, the seabed slopes, and the currents in the water column. When running a sidescan mosaicing program, it is very important that the lines be straight and that the position of the sidescan fish be known. If bottom currents are excessive or vary along the line, then accurate positioning of the fish is difficult to achieve.

Line spacing and sonar range setting will depend on the particular sidescan system and on the seabed geology. Also, acoustic propagation anomalies can seriously limit sonar range capabilities. The anomalies are seasonal and site-specific, and can vary within a short period of time. With respect to navigation, it is important that the lines are straight and based on a preprogrammed grid. Ship position would have to be known within the usually accepted standards for site surveys, i.e., within a 10- 20-m circle of error. An important requirement for accurate tow-fish positioning is the ability to run straight lines at a constant speed.

EQUIPMENT CONSIDERATIONS

The use of both 50- and 100-kHz sidescan sonar systems along with a subbottom profiler has been discussed, but no final selection has been made. The operations plan would certainly involve preliminary interpretations and mosaicing on board ship. With regard to echo sounding, heave compensation should be considered to achieve the quality of data necessary for scour depth determination.

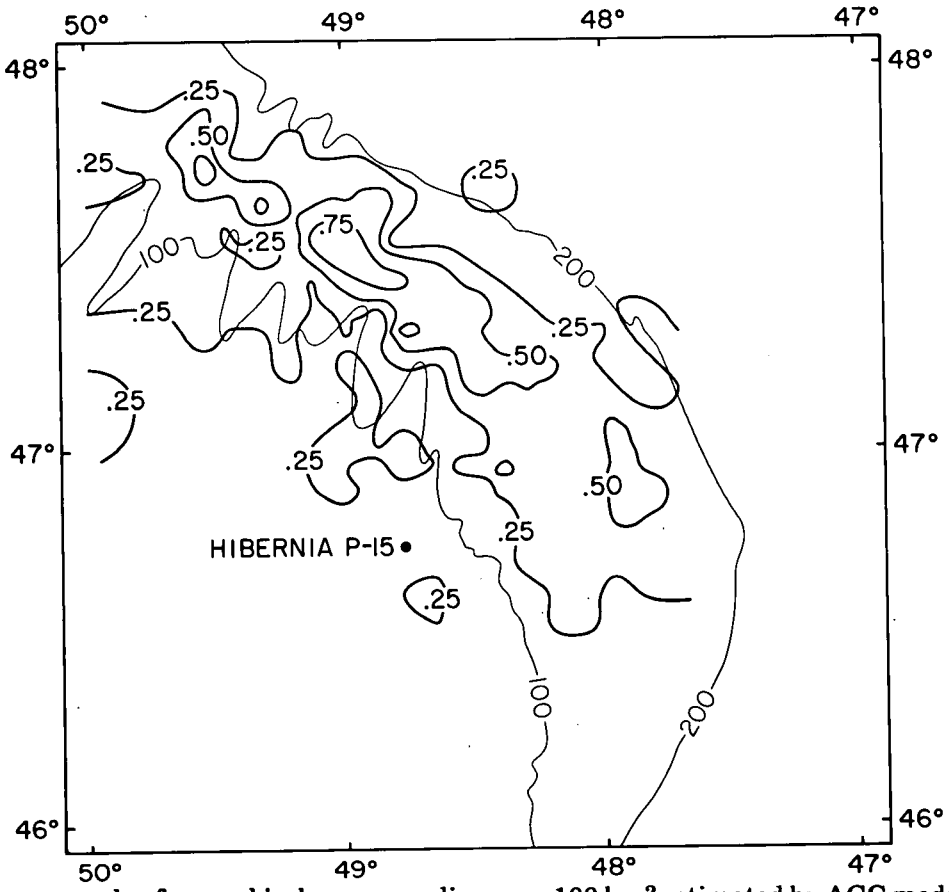

Figure 1. An example of annual iceberg groundings per 100 km^2 estimated by AGC model for northeastern Grand Banks.

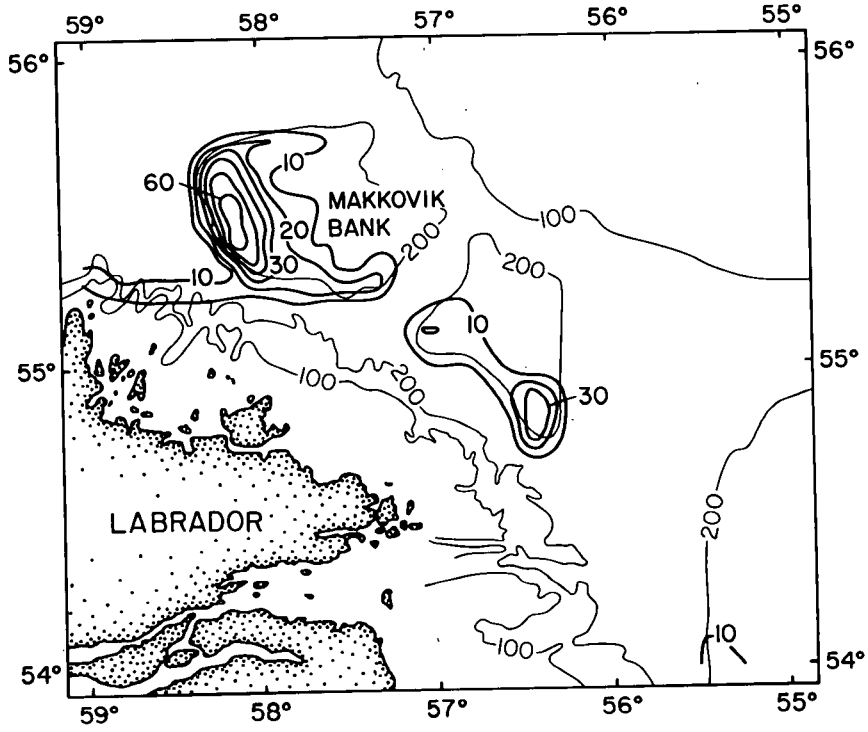

Figure 2. An example of annual iceberg groundings per 100 km^2 estimated by AGC model for Makkovik Bank, Labrador Shelf.

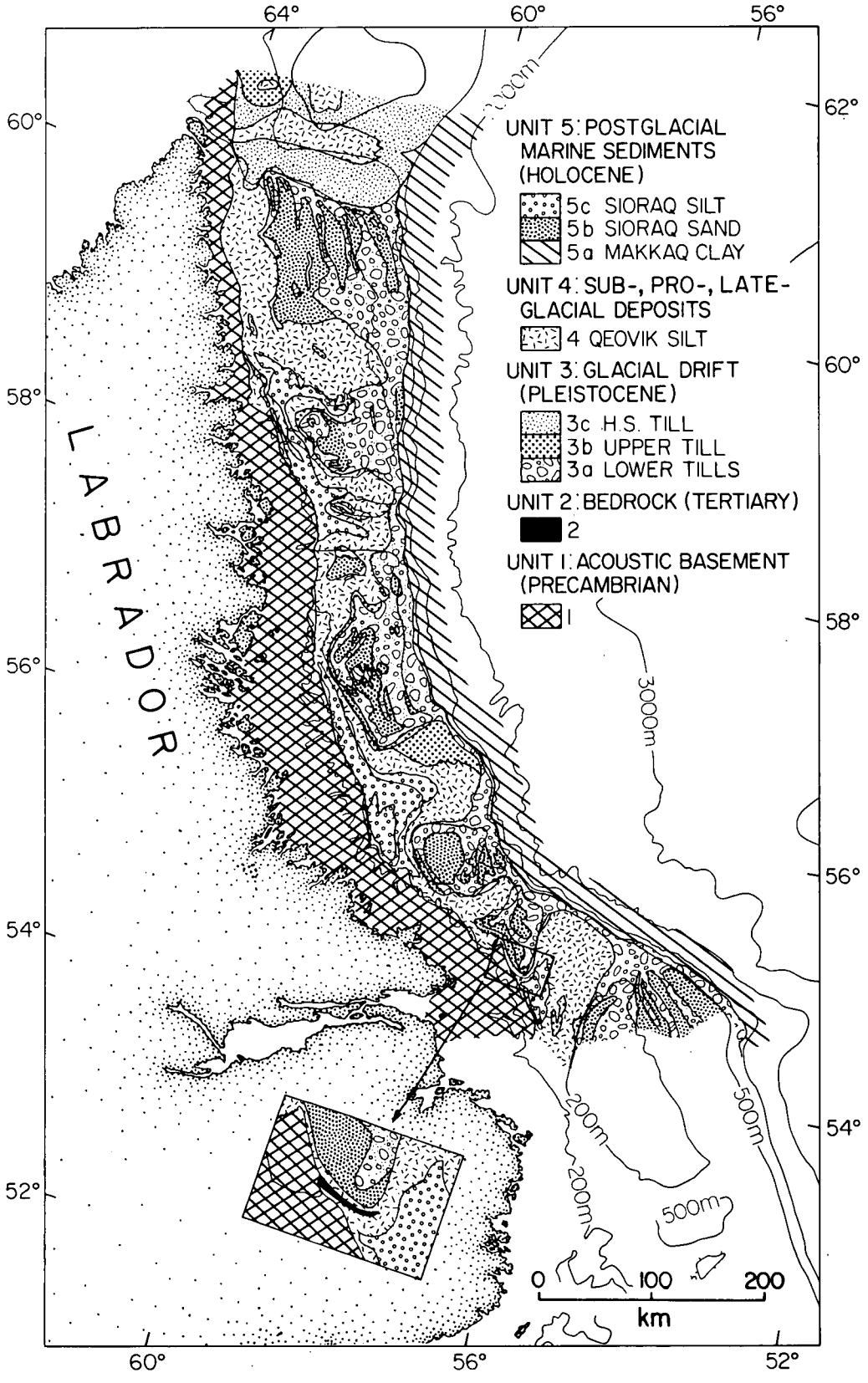

Figure 3. Preliminary surficial geology of the Labrador Shelf (after Josenhans et al. 1986).

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DISCUSSION

Alan Ruffman, Geomarine Associates Ltd.: This approach is quite different from that discussed by Jim Shearer (this volume; Shearer J. and A.F. Stirbys. Towards repetitive mapping of ice scours in the Beaufort Sea). In effect, you are recommending mosaics rather than individual lines. In a mosaicing program, you are involved in more expensive surveying techniques and also with sophisticated equipment such as heave compensation and tow-fish positioning. I think there should be debate as to whether lines or mosaics are needed for iceberg-scour mapping on the east coast. An iceberg scour is really quite a large feature that shows up rather well on a side-scan sonogram. A new iceberg scour is also going to show up quite well. I'm not sure you need a mosaic to see the addition of new scours. I think one idea that Jim Shearer put forward was to look at areas in the Beaufort Sea where no data exist and, in effect, to build up a regional picture. You seem to be suggesting that the place to do the surveying is in those areas where new scours are known to exist because there is a high flux of icebergs and a high frequency of scouring. Perhaps you could just comment on whether we should be looking at the southern Grand Banks, for example? Or is the reason for lack of interest in this area because hydrocarbons have not been found there?

Bud Hodgson: I think regional scour surveys are a continuing part of the Bedford Institute programs which are not part of this program. We are trying to collect data on iceberg scours that we know to be recent, and the only feasible way of doing this is to select a site where scouring is most likely to take place. One result that we are trying to achieve is the determination of the rate of return and the obliteration rate of the scours; however, new scour data for input to all these ice-scour models are also required. In this case it makes little sense to collect data in new areas where only minor scouring may occur.

Alan Ruffman, Geomarine Associates Ltd.: But it was a repetitive mapping network. You aren't putting forward a network, you are putting forward a couple of patches in areas where it looks like we are going to get the scouring.

Bud Hodgson: I didn't mean to imply that the mosaicing is the only means of studying scours. I think that on Makkovik Bank, mosaicing is the only way to go. It might be a mistake to concentrate on only one geographic area, so I think you can complement that by doing some work on Saglek Bank, on Harrison Bank, and on the Grand Banks. I didn't include this in the discussion because I'm not yet sure how to design the program. I'd certainly welcome a discussion on this topic. I think there could be some useful data in a single regional line, but the problem is how are you going to be sure that you can return to the exact line? The Bedford Institute has many regional lines, but I doubt if I could repeat them.

Alan Ruffman, Geomarine Associates Ltd.: That's presumably your recommendation on the navigation network?

Bud Hodgson: Yes. It is for the Grand Banks. When you attempt to relate two mosaics to each other, it is reasonably straightforward if the navigation information is good. The two mosaics can be moved around and features can be correlated. But, if I ran a survey line this year using Argo navigation with 40-m accuracy, I doubt if I could repeat that line next year. It might be possible with four, adjacent, parallel lines; in other words with a long, narrow mosaic.

Peter Barnes, U.S. Geological Survey: Just a comment about linear versus mosaic areas based on my experience. We haven't had good luck with mosaics, but we have been lucky in that all of our features are at right angles to the survey line. We do, therefore, cross a lot more features than if we had taken a mosaic at a particular water depth and covered the same area. A mosaic would not have displayed anywhere near as many new or datable gouges. Looking at some of the gouge orientations that we have seen on the east coast, I would think that you could design a line at right angles to the general trend even in a low-density gouge area, or in an area of new gouge occurrences. You will know that you have one or half of one scour per 100 km^2 as you go at right angles to it. You are therefore going to cross more scours in the same length of time than you would doing a mosaic. As far as navigation is concerned, we haven't been as far offshore as you have, so I can't really comment on that. We've been able to achieve 10-m and 15-m accuracy, and we are not repeating the lines precisely either. But we accept 10- to 20-m offsets without a problem.

Bud Hodgson: I think that for positioning 200 miles offshore 10-m or 20-m accuracy would be pushing current technology.

RISK ANALYSIS AND PIPE BURIAL DEPTHS

Maher Nessim
Det norske Veritas
1110 - 10201 Southport Plaza
Calgary, Alberta, T2W 4X9

INTRODUCTION

This presentation (given at short notice) is a review of a paper (Nessim and Jordaan 1985) that will be presented at the OMAE Conference[1], the work that was carried out at Det norske Veritas on risk analysis during the preparation phase of a submarine pipeline.

METHODS CONSIDERED

The first method we considered was trenching, which introduces depth as a variable, and valve segmentation, for protection. The latter method requires putting pressure-activated check valves in the pipe that would activate in the event of a problem and reduce the amount of oil spilt. In fact, the oil spills that we considered were very small, so this option was not very effective. The third method we considered was twinning, i.e. laying parallel pipelines. This should be conditional on the length of scours and the topography of the site. In other words, we would have to ensure that both branches in the pipeline would not be struck by the same ice feature; otherwise twinning is useless.

RISK ANALYSIS

Our approach involved an optimization technique where the costs of trying to protect the pipeline were weighed against the benefits gained by doing so. The optimization technique using decision theory is well known; it is simply a way of formulating a problem such that you can keep track of decisions and their effects. We need to assess the problem of pipeline damage based on the frequency and depth of new scours. The factors that we considered included trenching costs, the costs of clean-up resulting from damage, and the cost of delayed production, in a manner similar to that discussed by Roger Pilkington (this volume). Also, the environmental aspects which would then include the cost of pollution were considered.

The model we used allowed a sensitivity analysis to be performed. The main purpose of the exercise was to highlight the most important parameters. Roger Pilkington, mentioned that sensitivity to the depth of scour is much more important than sensitivity to the frequency of scour. This relationship is particularly true at the higher scour frequencies. The sensitivity curve is

[1]Offshore Mechanics and Arctic Engineering, Dallas, February 1985.

steep in the low-frequency range, and then levels out. However, the sensitivity increases rapidly with depth, so it is probably very important to determine scour depth accurately.

Pollution costs are another subjective factor. If you talk to environmentalists, they would probably estimate damage resulting from a 1-m^3 oil spill to be much greater than estimates made by non-environmentalists. So again we checked the sensitivity to pollution and found that it is quite important. In addition, the soil properties determine the volume of material that you have to remove to reach a certain depth of trench, which is another important factor. Sensitivities to other parameters have also been examined.

PRELIMINARY CONCLUSIONS

We realized that trenching was indeed the most effective strategy. Twinning was always suboptimal using the data that we put in. We found that twinning would be optimal only if repairs took an excessive amount of time, and that full production or maybe partial production could be maintained through one of the lines. If the repair was to take longer than 3 months, then twinning would be an optimal strategy.

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SOME RECENT STUDIES RELATING TO THE DETERMINATION OF PIPELINE DEPTHS

R.W. Marcellus and T.B. Morrison,
Canada Marine Engineering Ltd.
608 604 - 1st South West
Calgary, Alberta, T2M 2H7

INTRODUCTION

Several issues regarding scour depth distribution require discussion. Before the proper depths for pipeline (or seabed unit) protection can be determined, we need to obtain an accurate idea of the following:

- the effect of the accuracy of the scour depths;
- the true form of the scour depth distribution; and
- the effect of infilling on the scour depth distribution.

Because these items influence the measurement and interpretation of the scour depth distribution, we need a firm understanding of what we are actually measuring when analysing echo-sounder, subbottom profiler, and sidescan sonar data.

Barrie et al. (this volume) mentioned the problem of measuring pit depths. Every measurement they made of the depth of the pit yielded a different depth. This paper describes a methodology whereby the effect of system resolution on the measurement of ice-scour depths can be determined. The methodology described here is not exactly applicable to the problem of Barrie and co-workers, but similarities are evident.

SCOUR DEPTHS

Each and every scour-depth measurement has some uncertainty associated with it. In the past, the error has usually been quoted as 50 cm (meaning that the "measured scour depth" is within 50 cm of the "true scour depth"). For this reason, many researchers use wide intervals in histograms of the data, and do not attempt to correct the data for the uncertainty.

Not to be overlooked is the fact that echo-sounder data are sometimes taken using very small scales, such as 1 cm = 5 m (1:500). In discussions with Peter Barnes[1], it was discovered that the U.S. Geological Survey (USGS) likes to present echogram data with a scale of 1 cm = 1 m (1:100), or about the scale that is required for calculations in pipeline design. The use of small

[1]P. Barnes. U.S. Geological Survey, personal communication, 1985.

scales reduces the observer's capability to determine accurately the depth of the scour, and forces the use of large intervals when compiling histograms of the data.

Determining the depth of a scour is a two-step process: first the seafloor datum is generally estimated (by eye in a manual analysis or by the use of a computer algorithm in the ESRF Beaufort ice-scour data base), and secondly, the depth of the bottom of the scour below the seafloor datum is determined.

To combat these variables (50-cm resolution and small scales on the echo sounder), the data are usually grouped into wide intervals. Thus, the analysis is made easier because the amount of time consumed in processing the data is less because less detail is possible. By placing scour depths in wide intervals the true form of the scour-depth distribution may be masked.

Recently, Canadian Marine Engineering Ltd. (CMEL) has applied a technique of correcting the raw scour depth data for the resolution of the system (i.e., scour depth determination). In this technique, the process of depth measurement is modelled using a Gaussian function with a standard deviation equal to the resolution of the measurement process (i.e., the 50 cm already mentioned). Based on this it is possible to convolve the Gaussian function with the expected scour-depth distribution (negative exponential for simplicity) and to prepare a new probability density function with which to compare the measured distribution.

Figure 1 shows, in a rather abstract way, what we are talking about. Each scour depth has the greatest probability of being measured near its true depth. A shallow scour may not be resolved, and a deep scour will be resolved, but there is still a chance that its depth will be recorded incorrectly. The higher probability of not counting shallow scours in the scour-depth distribution generally changes the measured probability density function.

The convolution of the Gaussian function and the exponential can be calculated using a computer program. The effect of the convolution is to produce a peak in the scour depth distribution. This peak occurs typically between 0.5 and 1.0 m scour depths. Figure 2 shows the theoretical and measured probability density functions for a scour depth distribution with $k = 1$ (an average depth of 1.0 m) where the variable k is equal to the reciprocal of the average scour depth. The change in the distribution for a resolution of 0.5 m is small; however, the change in the probability density function for a larger resolution of 1.0 m is quite noticeable. The object of the analysis is to propose a modified probability density function (the one including the effect of the resolution) and to compare this with the measured scour depth distribution.

Before proceeding it is best to describe some aspects of the scour depth distributions that have been analysed recently by CMEL. The technique is summarized here, and is presented in more detail in Morrison and Marcellus (1985).

Figures 3, 4, and 5 illustrate a typical data set obtained in the Canadian Beaufort Sea. The label "historical" means that the distribution was not adjusted for the possibility of infilling (which is under examination at this time). Figure 3 shows the distribution in large (0.5 m) intervals. This distribution appears to be anything but negative exponential. Figure 4 shows the same data set presented in 10 cm intervals.

The data presented in Figure 4 were passed through the analysis procedure already described, and a different distribution was generated This "modified" distribution has a reduced probability of deep scours compared with the measured distribution (see Fig. 5). Note that the greatest effect of the analysis is to boost the number of scours in the shallower portions of the distribution. The modified distribution is more "negative exponential" than the measured distribution.

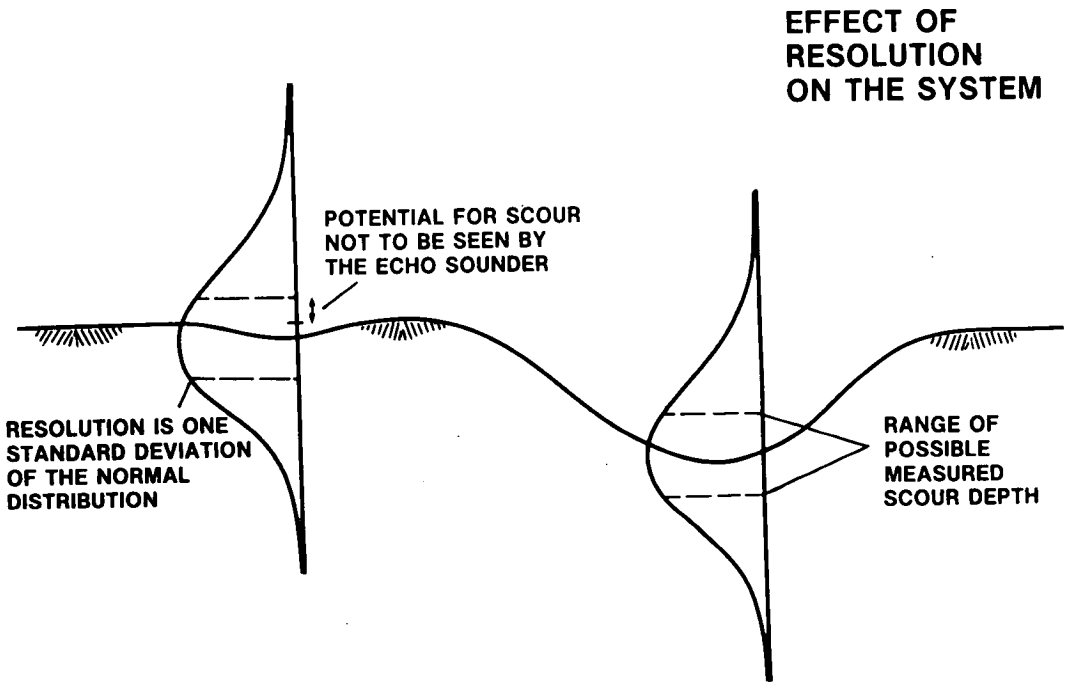

Figure 1. Effect of resolution on the system.

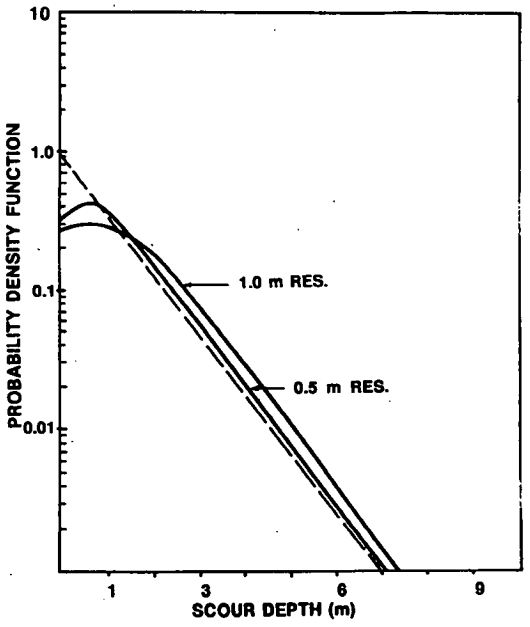

Figure 2. Effect of poor resolution for k = 1.

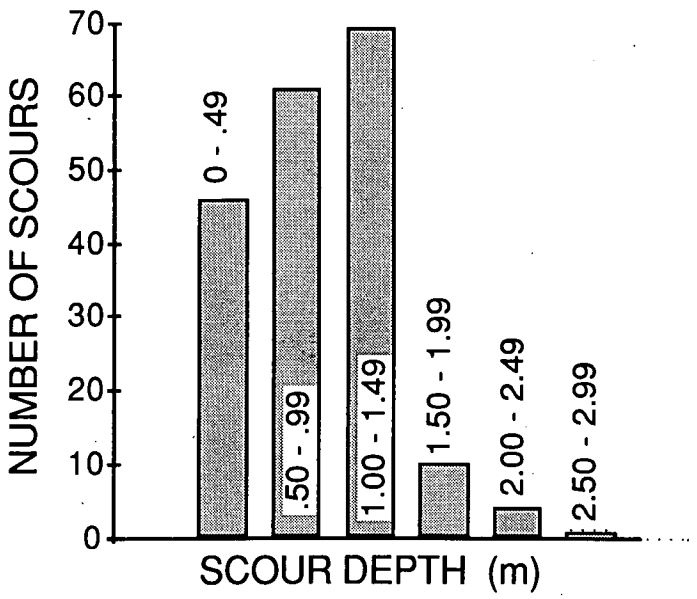

Figure 3. Historical scour depth distribution in large intervals.

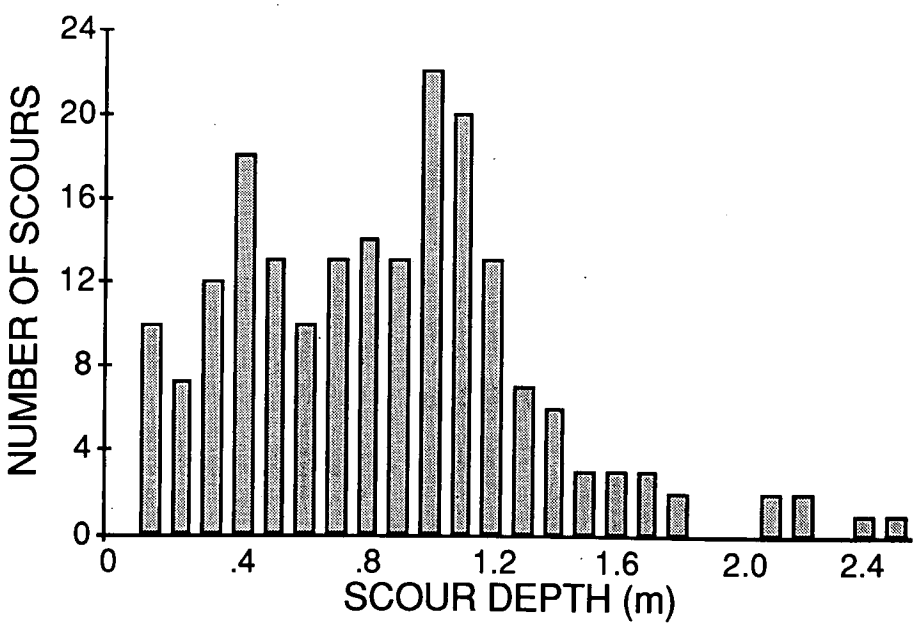

Figure 4. Historical scour depth distribution in small intervals.

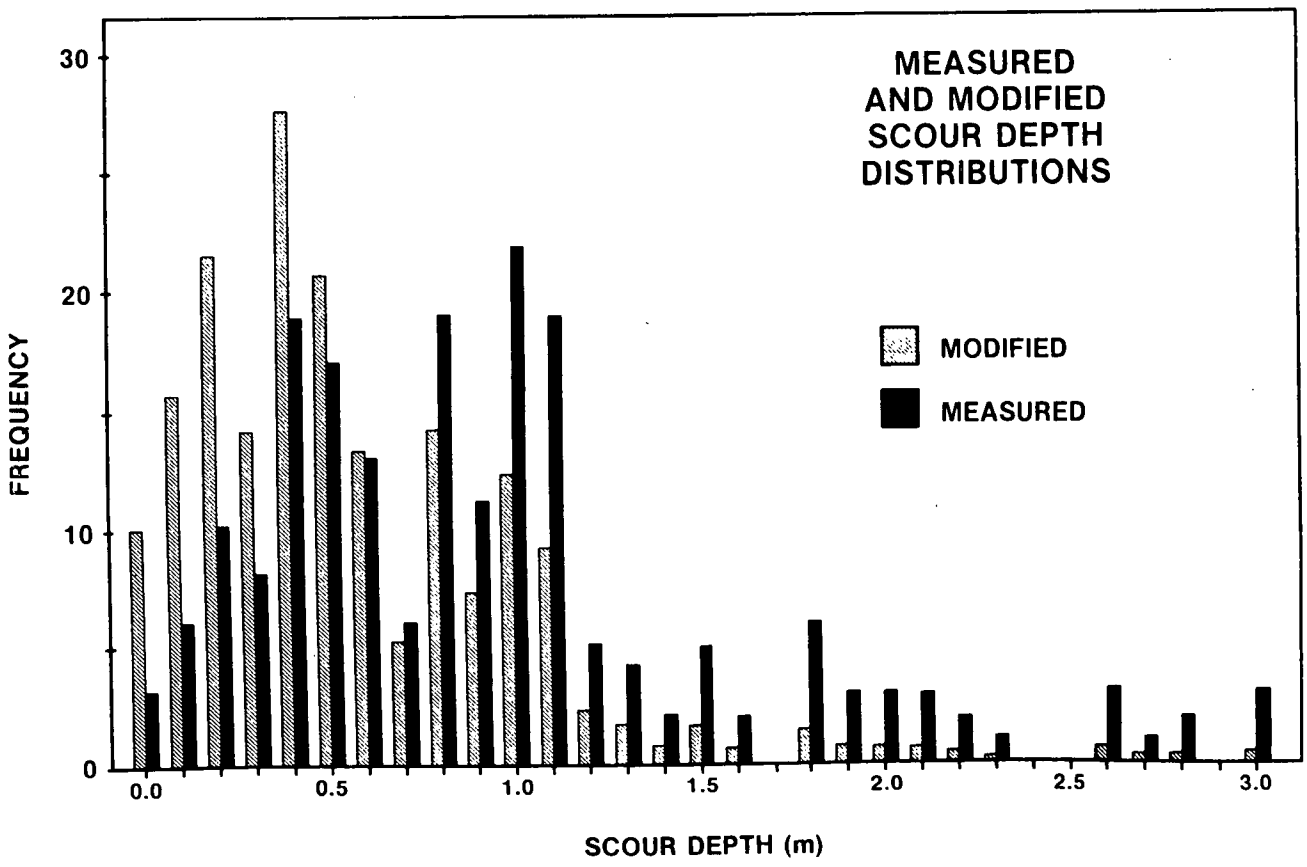

Figure 5. Measured and modified scour depth distributions.

The modification procedure uses the observed number of scours in any given interval to calculate the modified distribution. This is only for illustrative purposes; in reality, the procedure starts from a theoretical distribution and calculates distributions affected by resolution (see Fig. 2). It is the lines on Figure 2 that are compared with the measured distribution.

One other note on the form of the scour depth distribution: It should be realized that the negative exponential is not the only scour depth distribution. It is possible that the scour depth distribution could be modelled using another function. The gamma and Weibull functions are likely candidates, because they include the negative exponential as a special case.

INFILLING OF THE SCOUR DEPTH DISTRIBUTION

Recently, several researchers (Gaskill; Weeks et al.; this volume) have included infilling into analyses of scour-depth distributions using computer models. The effects of infilling, such as whether all scours are infilled at the same rate, or whether only shallow scours are infilled first, are not accurately known.

The biggest question is: What effect does infilling have on the distribution? Could the distribution originally have been negative exponential and have been subsequently modified by infilling? In our opinion, the only way of testing such an hypothesis is to conduct a repetitive mapping program along a line and to obtain the distribution for new scours. Design calculations should be conducted on the distribution of new scours in an area, or on an historical scour depth distribution, modified to correct for the rate of infilling and for resolution of the scour depths.

LINE VERSUS MOSAIC SCOUR DEPTH DISTRIBUTIONS

Sometimes scour depth data are obtained from seismic lines grouped together into mosaics. An analysis was performed to determine if any significant difference between using all scour depth measurements in a mosaic or using only the "deepest depth per scour" was visible. This is the deepest scour observed on several crossings of an individual scour on a mosaic. Figure 6 shows the difference between the two distributions for an area in the Canadian Beaufort Sea. The difference is minimal.

Figure 6 also shows the shape of a peaked scour depth distribution on an exceedance plot (such as that presented on Figure 4). The curve is concave downwards. The curve differs from a negative exponential, which again reinforces the opinion that the distribution of scour depths may not be negative exponential. The curves have been extended by hand.

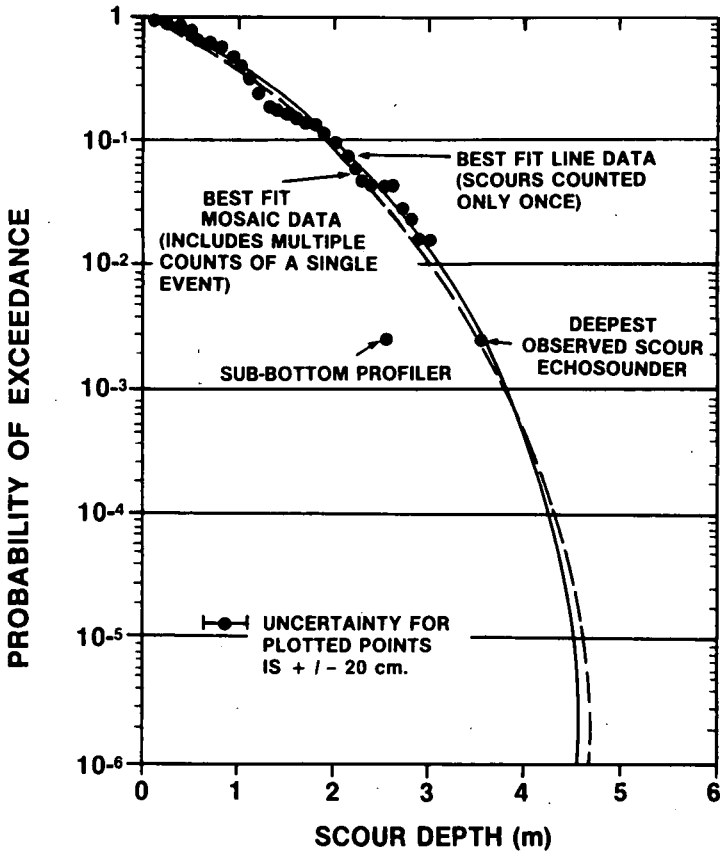

Figure 6. Depth distribution: line versus mosaic.

CURRENT UNCERTAINTY OF TOP DEPTHS

The objective of this analysis is to calculate top-of-pipe (TOP) depths. These are the depths below which the top of the pipeline must be placed. TOP depths have been calculated by many observers (Pilkington and Marcellus 1981; Wadhams 1983; Weeks et al. 1983). Even assuming the scour depth distribution is negative exponential, there is a lot of uncertainty in the ultimate calculation of how deep the top of the pipe must be placed for it to be safe during its lifetime.

Figure 7 shows some results of an analysis of TOP depths for a site in the Canadian Beaufort Sea. The small squares are the scour depth distribution from Figure 6 plotted in 1.0-m intervals. It is possible (using the four points) to fit curves to the data. The two straight lines are fits using the probability density function and the exceedance of the distribution. Note that the k values determined from the two types of negative exponential fits are different (the slopes of the two straight lines are different). The curved line is from Figure 6. The dotted portions of the lines are the extrapolation necessary when calculating TOP depths. Note the wide range in the depths. This is "true" uncertainty as opposed to the "statistical" uncertainty calculated in an individual fit to one of the distributions. The range of calculated TOP depths is from 4.5 to 8.5 m.

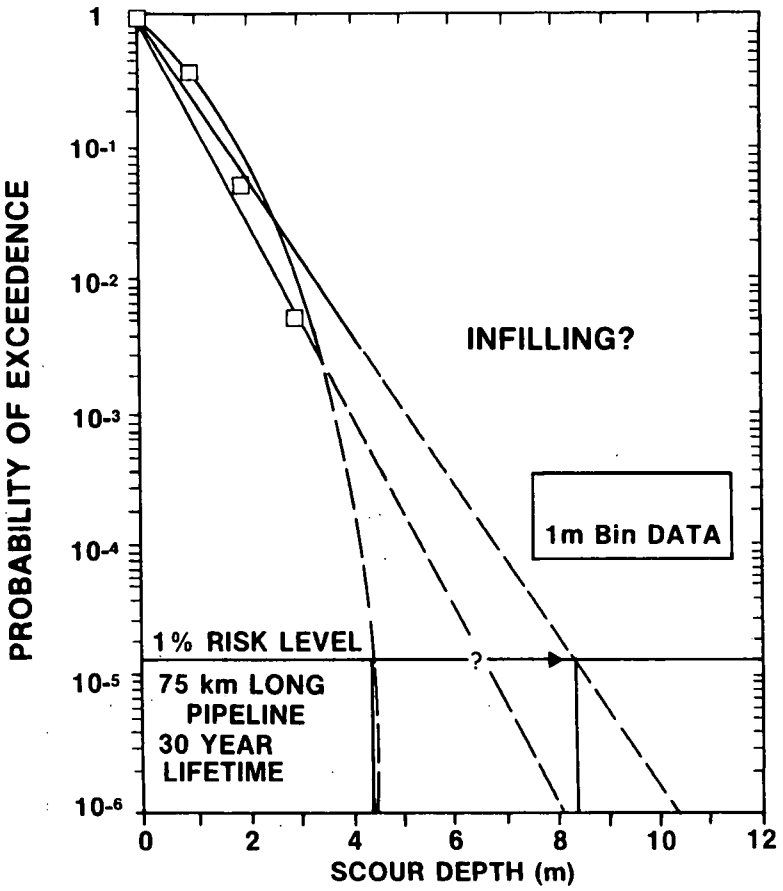

Figure 7. Scour depth distributions: "current uncertainty".

The large range can be reduced by further study of the form of the scour depth distribution, and the scouring process. The "infilling" flag on Figure 7 reminds us of the latter problem.

COMPARISON OF ALASKAN AND CANADIAN BEAUFORT SEA VALUES

In the past, some scour-depth data obtained in one area have been applied to another area usually with the purpose of comparing calculated TOP depths. It was found necessary to explain some of the differences between the calculations.

The original data may be responsible for some of the differences in TOP depths calculated by Pilkington and Marcellus (1981) and by Weeks et al. (1983). Figure 8 shows inverse mean scour depths, or k, values for the Alaskan and Canadian Beaufort Sea areas compiled by Lewis (1977) and Weeks et al. (1983). Weeks et al. (1983) used the symbol "lambda" in their work instead of the k used here. To a first-order approximation, one would expect the k values to be the same because of the close geographical locations of the two areas. Figure 8 shows that k is larger for the Alaskan data than for the Canadian data. The larger k is, the shallower on average are the scours.

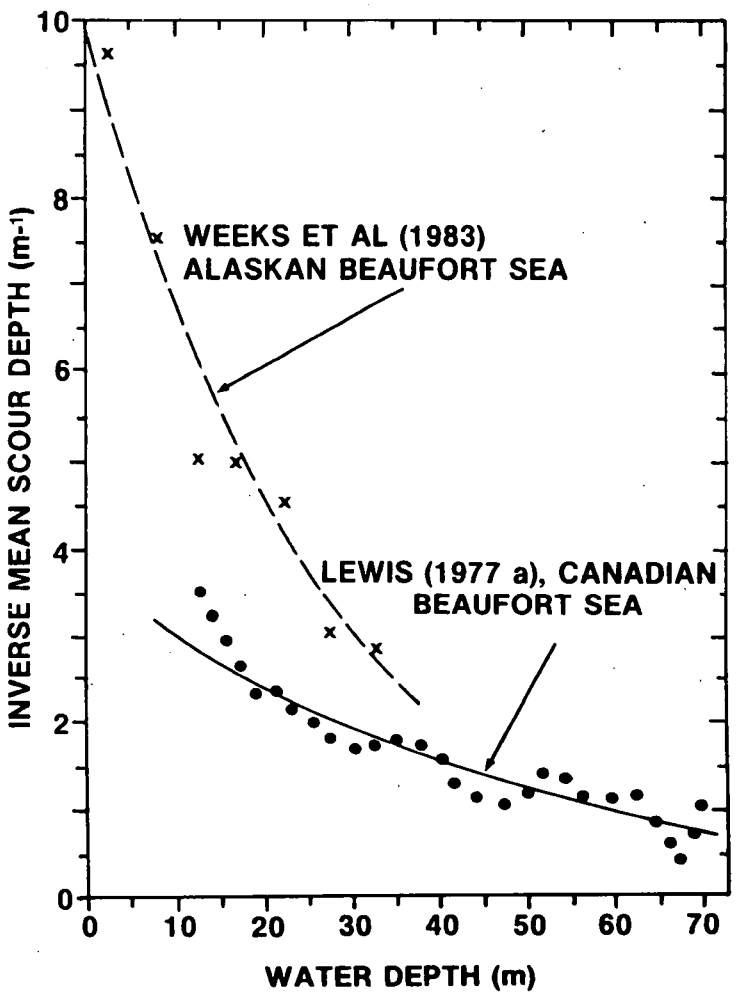

Figure 8. A comparison of U.S. and Canadian values of inverse mean scour depth for the Beaufort Sea.

It is interesting to note that as the water depth increases, the two sets of k values come close together. It may be that differences in the methodology of determining scour depths are responsible for the differences in the k values. For instance, the counting of multiple scours may affect the k values determined by different researchers. In one case, the multiple scours (or multiplets using the USGS terminology) could be counted as one scour with one depth (the deepest), or they could be counted as one multiplet scour with several depths. The addition of the extra shallow scours in the multiplet to the distribution would weight the distribution towards shallower scours and higher k values. This weighting is reasonable because the probability of multiplets decreases as the water depth increases. Note that as the water depth increases, the two lines on Figure 8 approach each other.

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RESEARCH OVERVIEW and COMMENTS

Session Chairmen:

C.F.M. Lewis
W.R. Livingstone

ICE-SCOUR RESEARCH: LONG-TERM PLAN FOR ESRF

W.R. Livingstone
Gulf Canada Resources Inc.
401-9th Avenue, SW
Calgary, Alberta, T2P 2H7

INTRODUCTION

The question that Mike Lewis posed at the final session of the Montebello conference (Pilkington 1985) was:

> "Do you feel that by the time you want to put pipe in the seabed, say in five years time, enough scour statistics will be available to provide acceptable burial depths?"

I would like to use that question as a basis for the structure of this final session. I have asked the session chairmen to spend a few minutes after my summary of the ESRF program to make a few philosophical comments about confidence in ice scour information with regard to their own areas of expertise.

The idea of an ice scour workshop was conceived about five months ago in Halifax. At that time, the ESRF committee was meeting to grapple with the idea of our long-term research plan. Mike Lewis and I thought that once we had this plan together it would be useful if we could get ice scour experts from Canada and abroad together to discuss their various research programs. The result is this very interesting workshop.

ICE SCOUR COMMITTEE

At present, there are four technical committees within the ESRF; one on waves, one on bottom sediment transport, one on icebergs, and, of course, the one on seabottom ice scour.

Each of these committees was conceived for a purpose. The committee on waves was conceived primarily because of wave-related issues that affect east coast development. Similarly, the seabottom sediment transport committee has an east coast focus, particularly on the Scotian Shelf. Icebergs are also an east coast issue. The seabottom ice scour committee is unique in the sense that ice scour has been identified as a "priority topic" in both the Beaufort Sea and the east coast offshore regions.

Mandate and Philosophy

The committee felt that its mandate should be to study regional, or generic issues, or both. We would not, for example, carry out risk analyses along a Mobil pipeline corridor. Instead, we would assess the processes and parameters in the general region so that an operator like Mobil could take our findings and incorporate them into their plan. In other words, if a particular

operator requires data or analyses at a specific site or along a specific corridor, then it is that operator's responsibility to collect site-specific data.

Relationship to Other Research

The committee felt that the most effective means of complementing the research being carried out elsewhere was to concentrate on studies involving data analysis or data acquisition. For example, the committee did not feel that it should get involved in such things as developing an analytical model for ice scour. Rather, the ice scour committee's role was to concentrate on obtaining or analysing data on the relevant parameters that go into such models for calibration purposes.

LONG-TERM RESEARCH PLAN

The ESRF's long-term ice-scour research plan should, more correctly, be considered as a guide. It is not cast in stone. I think that the ice scour committee has to go back and re-evaluate some of the components of the plan based on the results of this workshop. One of the main reasons for the plan is to project the long-term expenditures required for research and to get approval from both government and industry for these levels of expenditures.

The plan is oriented towards subsea facilities such as pipelines and templates. I think we all acknowledge that the effect of ice scours on bottom-founded production structures is also an important technical issue in some cases, as highlighted during the first session of this workshop (Bea, this volume). However, the committee felt that the technology for detection and possible mitigation of this type of problem already exists. As well, this issue tends to be both site-specific and structure-specific. Therefore, it does not fall into the category of a "priority topic" as defined by the ice scour committee.

ESRF's long-term ice-scour research plan is broken into two components that are aimed at providing answers to the following two basic questions:

- How deep are the present-day scours?
- How often do they occur?

How Deep are Present-Day Scours?

The types of studies that will be undertaken by ESRF to address the question of scour depth are summarized in Table 1. The approximate timing of these studies is also presented.

We have heard a number of presentations at this workshop about the ESRF computerized ice-scour data bases for both the Beaufort Sea (Gilbert and Blasco, this volume) and the east coast (King and Gillespie, this volume). These studies we initiated in 1983 and the Beaufort Sea data base is nearly complete. In the future, we shall concentrate either on updating these data bases, or on carrying out detailed analyses to evaluate trends in the data and to investigate interrelationships of the various ice scour parameters, or on both.

TABLE 1

Studies on depth of present-day scours

Methods	Study Descriptions	Timing 1983	1984	1985	1986	1987	1988
Direct Measurement	Computer data bases (Existing Data)						
	· Beaufort Sea	▬▬	▬▬	▬▬	▬▬		
	· East Coast	▬▬	▬▬	▬▬	▬▬		
	Scour-infilling degradation						
	· Beaufort Sea	Bottom-Sediment Transport Committee?					
	· East Coast	Bottom-Sediment Transport Committee?					
	Iceberg pits				▬▬		
	Profiling/Testing of New Scours						
	· Beaufort Sea					▬▬	
	· East Coast			▬▬	▬▬		
Modelling	State-of-art of modelling Method/Techniques	▬▬	▬▬				
	Iceberg motion (upslope/downslope)		▬▬	▬▬			
	Calibrate analytical models with "real" data				▬▬	▬▬	
	Physical Model Studies					▬▬	
	Ice/soil/structure interaction studies				▬▬		

The rate of scour infilling and its effect on the scour depth distribution and frequency has been discussed by several speakers; for example, Gaskill (this volume) and Tucker (Weeks et al. this volume). This year ESRF may initiate a baseline study in the Beaufort Sea which will involve monitoring infill rates in scours and glory holes over the long-term. This project will be co-ordinated by the ESRF bottom sediment transport committee and is an example of interaction between the various ESRF committees. Similarly, the DIGS experiment (Lewis, this volume) which the ESRF will support this summer off the coast of Labrador may provide information on the significance of immediate infilling as postulated earlier in the workshop (Woodworth-Lynas et al. this volume). Longer-term degradation of new scours identified during DIGS will also be monitored.

Iceberg pits is one topic on which I personally have mixed feelings, because I am uncertain as to whether the existence and origin of these pits is a "nice-to-know" or a "need-to-know" item with respect to offshore development projects. I suspect it tends to be more of a site-specific issue. Nevertheless, I have the impression from this workshop (Barrie et al.; Bass and

Woodworth-Lynas, this volume) that this topic is being adequately addressed by other agencies or institutions.

The committee did perceive a need to carry out geotechnical testing in certain existing scours to provide some insight into potential soil failure mechanisms during the scouring mechanisms. These data are necessary for analytical models and would provide information on subscour disturbance for pipeline design. For this reason, the DIGS experiment (Lewis, this volume) will have a geotechnical component. A similar program for the Beaufort Sea has been scheduled tentatively for 1986-87.

Analytical and physical models are another means of predicting scour depths. In 1983, the ESRF undertook a baseline model study which has been described at this workshop (Comfort and Graham, this volume). The intention was to evaluate and compare existing models and to run sensitivity analyses to detect the importance of the various model parameters. Some of these parameters would then be selected for further study. One of the first follow-up studies related to modelling parameters and inputs was the upslope and downslope study described earlier by Woodworth-Lynas (Bass and Woodworth-Lynas, this volume). Eventually, once the information on the geotechnical properties and infilling characteristics are available, the ESRF may play a role in model calibration.

The ESRF is not putting immediate emphasis on physical models. This has been identified as a longer-term objective. The committee does, however, recognize the significant role that physical modelling will play in model calibration.

At the present time, little effort has been directed towards the problem of subscour disturbance (Lien, this volume) and what effect it will have on incremental pipeline burial depths. The ESRF has identified this as a topic for future study.

How Often Does Scouring Occur?

The types of studies that will be undertaken by the ESRF to address the question of frequency are summarized in Table 2. The approximate timing of these studies is also shown.

The ESRF has placed considerable emphasis on the repetitive mapping technique to obtain information on scour frequency. An earlier presentation (Shearer and Stirbys, this volume) described an ESRF-sponsored study which involved the establishment in the Beaufort Sea of a regional repetitive mapping network that was first surveyed during 1984. The intent is to return and re-survey this network in future years. A similar approach has been proposed for the east coast and the ESRF have initiated a study to design a regional network (Hodgson, this volume). This network may be surveyed for the first time this summer.

In 1983, the ESRF established an inventory of all recorded iceberg groundings off the east coast (El Tahan et al. 1985) from a variety of information sources to gain some insight with respect to grounding frequency. As a part of this study, the rate of damage to trans-Atlantic cables was also investigated. Similar studies of this type may be warranted in the future.

Ice-keel draught statistics, which are input to scour-frequency models, deserve further study in certain regions. Although studies of this type have been highlighted on Table 2, I expect that we shall receive assistance from the ESRF Iceberg Committee.

TABLE 2

Studies on frequency of present-day scours

Methods	Study Descriptions	Timing 1983	1984	1985	1986	1987	1988
Repetitive Mapping	Beaufort Sea Programs		▬▬		▬▬		▬
	East Coast Programs		▬	▬		▬	
Iceberg Groundings	Documentation of Iceberg Groundings	▬▬					
	Iceberg-Grounding Update Studies				▬		
Ice-keel Distribution vs. Water Depth	Compare Results of Repetitive Mapping & Grounding				▬	▬	
	Studies with Ice-Keel Statistics - Beaufort Sea - East Coast					▬	▬
Other Methods	Scour Dating/Sedimentation Rates/etc.				▬	▬	

LEVELS OF EXPENDITURE

Figure 1 summarizes the expected levels of expenditure over the next few years. In 1983, $500,000 were invested in studies related to ice scour. In 1984, expenditures rose to about $1 million. Over the next two years, the cost of the ESRF ice scour studies off the east coast and in the Beaufort Sea could be in the order of about $1.5 million.

In conclusion, you now have an indication as to how the ESRF hopes to augment ice scour research in Canada. I shall appreciate any comments on this summary.

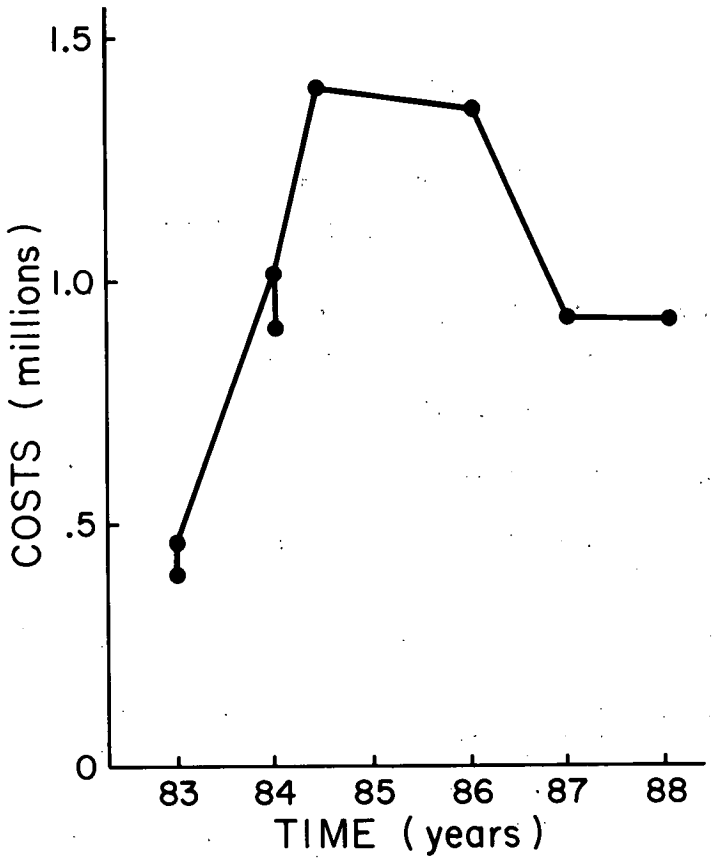

Figure 1. Profile of tentative expenditures on the ESRF ice-scour studies.

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FINAL COMMENTS

Drew Allan, Petro-Canada

I was asked to comment on where I thought we stood in assessing risk for subsea facilities on the east coast. I believe that we have appropriate data, risk assessment methodologies, and engineering mitigative measures to allow us to assess risk and to safely design intrafield subsea facilities, such as satellite wells, templates, flowlines, and so on. Further work could be directed at comparing the ice-keel risk assessment approach with the scour record/infill approach.

With respect to the pipeline to shore (from the Grand Banks of Newfoundland), I think that we should collect additional iceberg and scour data in certain areas along the pipeline route to gain a better understanding of the frequency and depth of scouring. The nearshore and inner shelf regions should be considered as areas for further study. In the shore approach zone, engineering solutions such as tunnels or protective covers could be considered to avoid scour damage, or even the requirement to assess scour damage risk in this area.

Finally, we should assess and incorporate the accuracy with which we are able to determine scour risk into our design methodology.

Bill Roggensack, EBA Engineering Ltd.

One of the advantages of working with the Americans is that you invariably have to work in dual units. Today we have opened new ground with dual terminology; namely, scours and gouges. As a person who is only casually involved in ice scour, I see that we have a lot of disciplines involved. In my career as an engineer, I have always felt that we have to work in an interdisciplinary fashion. We have to be familiar with the problems that other people are working on. I have attempted to list a few of the topics that have been discussed today. As a coincidence, the three main categories are similar to those discussed by Dave McKeehan (this volume). We have scientists who measure and collect data; analysts who qualify, rationalize, and occasionally attempt to simulate real life problems; and lastly the designers who are left with the task of applying the information to specific developments to optimize risk against expenditure.

With that in mind, I shall attempt to respond to Bill Livingstone's request for comments on the following three topics: the direction of research, the timing relative to need, and lastly what the needs are in the long term.

Direction of Research

In my view, the direction of the research that has been described at this workshop is good, but I don't believe that the focus of the research is optimal at this point. First, it probably comes as no surprise that people working in different places on the different problems are not necessarily all going to be looking in the same direction at the same time. Perhaps that is one area in which the ESRF and other agencies engaged in research can reassess the focus of our research activities to get more accomplished in a given period. Secondly, speaking more from a consulting standpoint many of the research activities tend to be brief and fragmented and often without interdisciplinary co-ordination. I believe that has a harmful effect on the outcome of research. Lastly, with respect to the direction, there is a need to set goals in time and those goals

should continue to be set by the ESRF based on the region of application, such as the Beaufort Sea or the east coast, etc.

Timing Relative to Need

Timing raises the question: Are we in a position today to feel that we have made some headway from where we were at Montebello three years ago?

I personally believe that we are not yet at the point at which we can say with any confidence first, that we could collect data for a pipeline route; and secondly, that we could bury the pipe at 3 m, 4 m, or 5 m deep and that it would be safe within the risk criteria set for the project.

The predictive models and the development of a sound design basis for pipelines is, in my view, still several years away. I take heart, though. Drew Allan (this volume) made a suitable distinction between collision and damage. His risk model dealt with the term collision which was simply geometric intersection of a pipe at a specific burial depth by a keel with a specific draught. That is certainly not, in my view, the equivalent to pipeline damage. From the engineering standpoint, that is an area in which further work needs to be done before rational criteria can be developed.

On the timing aspect, I believe that progress in this area can be accelerated by trying to conduct less work in isolation. It is gratifying to see projects like the DIGS experiment which is proposed for this summer coming together with what appears to be a very good multidisciplinary team.[1] Given that the appropriate levels of funding can be achieved, I think that project in itself will probably provide more data than we have collected in other areas over the last two or three years.

Long-Term Needs

Lastly, my own thoughts on needs. One of the important requirements is a long-term commitment of research funds. My ideas have mirrored closely what the ESRF is proposing to do: supporting repetitive mapping and getting into process modelling, which can be anything from seabed interaction to flux simulation and grounding simulations. But finally and most important, when all this work is complete, we have to verify the interaction so that we feel more confident about the application.

Another area that would help the engineers would be to have a better visual impression of what some of the underwater features look like. We know what fathometer and sidescan features look like, and that the records of each have their limitations. We know that water clarity is always a problem in photography. However, I think that there is a possibility that photo documentation of features using suspended camera arrays would help to get a better visual picture. The systems have been used in places like Lake Erie and the Merimac and have been described in the National Geographic Magazine, for instance.

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[1]The Dynamics of Iceberg Grounding and Scouring (DIGS) experiment successfully observed the seabed effects of ice scour processes and measured iceberg motion during ice-seabed interaction events. The experiment took place during August 1985 on Makkovik Bank, Labrador.

Lastly, I cannot fail to mention here that co-operation between industry and government in research is essential to continuing the progress that has been made.

In closing, I'd like to say thank you to the people who organized the workshop. I have certainly enjoyed it and feel very pleased that I was able to be here at their invitation.

Vaughn Barrie, C-CORE

I will make a few comments from the data collector's perspective.

There has certainly been large changes in the knowledge base and our understanding of ice and iceberg scour since the Montebello workshop three years ago. If the proponents of DIGS had gone to Montebello, I think that we would have been shown the door. I know that in the last few years, our ideas on the maximum scour depths/frequencies in the Hibernia area have changed drastically by orders of magnitude based on the development of models and data collection.

There are still a lot of problems with the quality of the data and further problems in understanding what the data are really telling us. This applies particularly to acoustic systems. I am not suggesting that the records we have collected have to be rerun, but I think we have to go back to some of the earlier records and reinterpret them in light of present-day understanding of the acoustic techniques. This need is particularly important in the area of depth measurement and in actual detection of features. One question is: Are we detecting everything? Although we have used a variety of systems we could be missing a lot of information. Bob Marcellus (this volume) also mentioned this problem.

Returning to the DIGS program, from the general feeling of this meeting concerning modelling and in particular iceberg interaction with the seabed, the essential word is dynamic. It is a dynamic environment and it is the dynamics we have to look at. We need the six degrees of freedom to improve our models and to bring them closer to real data. We hope that experiments like DIGS will provide the relevant data.

Another area of interest that is becoming more of a concern is the problem of scour infilling. One problem here is in determining the infill rate at the time of the scour. Do we get an immediate infill of substantial quantity depending on the environment? None of our geophysical techniques for scour-depth measurement seem capable of detecting that initial infill. Then there is the problem of infill over time which is very important in determining at what frequency repetitive mapping should take place.

One of the other areas that deserves mention is the actual failure of the seabed. There has not been much discussion on that topic here. Nevertheless, the question remains: How does the seabed fail? An understanding of failure mechanisms will certainly help in the design of subsea facilities. As a geologist and scientist not involved in that area, I feel I would like to have more input from the geotechnical community.

Finally, I would like to re-iterate what Drew Allan said concerning the convergence of the models of ice-keel statistics and ice-scour statistics. These data have to be brought closer together. We also need to accommodate the very long scours in the ice-scour data bases. Thank you.

Steve Blasco, Atlantic Geoscience Centre

As far as the Beaufort Sea is concerned, the big issue is uncertainty and somehow we have to reduce that uncertainty. I'm confident that it will be reduced and improved, but if, and only if, we continue to acquire data at the same rate at which we are acquiring it now. Secondly, we must acquire good data. I don't think it is widely known here but we have worked with a data set 12 years-old from the Beaufort Sea that was not originally collected for ice scour research. It was collected for site-specific surveys and for other purposes. We've had to accommodate the problem of different paper feed rates and other variances to use that data to the best advantage. We now realise that it is worth the cost of paying for extra ship time to collect good data, basically because of the greater information it contains. We did not realise that before, and are only just understanding that aspect now. For example, I think this repetitive mapping project cost $800,000 and marked the first occasion on which that level of effort into ice scour research had been expanded to collecting the basic data. I am quite confident that we are going to increase our data rate and shall, in future, be collecting better data and obtaining better measurements. I like the idea of pursuing several methodologies because I think that they will eventually converge. With the better data and the resulting convergence, we are going to reduce the uncertainty problem and solve the issue.

I agree with Bob Marcellus (this volume) that the scour depth problem might be somewhere between 4.5 and 10 m. We'll be able to give you an answer in five years but I don't know whether you are going to like it.

Roger Pilkington, Gulf Canada Resources Inc.

Bill Roggensack asked: Will we have enough data by 1988? I do not think that this is the question. The point is that we will be told by our superiors that a pipeline is to be laid and we are asked how deep it must be. In reality, we never have enough data with which to give an answer. We never had enough data to build Tarsiut in the first place, but it was built and it stood. The same thing applies to all these structures, at least the first time they are attempted. Of course, we have to include a large safety factor and then it is up to management as to whether it is worth the economic sacrifices.

We must also remember that three years ago we had basically no methodology for handling the scour data. We were collecting all these scour data and did not know what to do with it. It is only in the last three years that we've really understood what to do with the information.

Considering some of the different aspects of this work: I think, we need a better general understanding of what scouring is all about, such as the mechanics of scouring, the sedimentation, and infill. I feel that the models that we have developed for calculating return periods are appropriate. As was pointed out earlier, we need to review data quality and we need much more data to input into the models. I am very excited by the data base that was set up last summer in the Beaufort Sea. The only problem is that by 1988, we shall only have three years worth of data in some areas so we shall be using only three years worth of data to predict a 1,000 year return period. We will have to supplement it with other methods and information.

We shall, of course, need to refine the models. We need to look at infilling as Terry Tucker (Weeks et al. this volume) is doing and I think we also need to separate out multi-year and first-year features, and extreme ice features if we can identify those in the scour information. We have to establish whether or not multi-year features have higher values in the tail of the scour distribution curve than would be predicted from the first-year features which are more numerous.

We need to look at the importance of these refinements using the type of sensitivity analyses that Det norske Veritas (Nessim, this volume) are doing. We need to find, in fact, the important parameters to look at.

The physical models are extremely valuable for a general understanding of the mechanism of scouring. More important, they will assist us in extrapolating to real values the results we are getting from data. There again we need to validate the models using as much data as possible.

We should look into errors. A relevant question is: What size of error in pipeline burial depth do we have at this point and how much do we have to spend to reduce the errors?

Finally, I would like to compliment the organizing group for putting this workshop together in short order.

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APPENDIX A

WORKSHOP ATTENDEES and ADDRESSES

Allan, Drew
Petro Canada
Box 2844
Calgary, Alberta
T2P 3ES

Aust, Horst
BGR Germany
P.O. 510153
D3000 Hanover 51
Stillweg 2 Germany

Barnes, Peter
US Geol. Survey
355 Middlefield Rd. MS999
Menlo Park
California, USA 94025

Barnett, Martin
DIAND-ESRF
10 Wellington St.,
Hull, Quebec
K1A 0H4

Barrie, Vaughn
C-CORE
Memorial University
St. John's, Nfld.
A1B 3X5

Bea, Bob
PMB Engineering
#400, 500 Sansome St.
San Francisco
California, USA 94111

Blasco, Steve
Bedford Inst. of Oceanography
P.O. Box 1006
Dartmouth, N.S
B2Y 4A2

Bobby, Walter
Nfld. Petroleum Direct.
Box 4750 - Atlantic Place
St. John's, Nfld.
A1C 5T7

Carrie, Judith
Artic Inst. of N. America
Univ. of Calgary
Calgary, Alberta
T2N 1N4

Chari, T.R.
Engineering Dept.
Memorial University
St. John's, Nfld.
A1B 3X5

Comfort, George
Arctec Ltd.
#16 6325-11th Ave SE
Calgary, Alberta
T2H 2L6

D'Apollonia, Steve
Bedford Institute of Oceano.
P.O. Box 1006
Dartmouth, N.S.
B2Y 4A2

Day, Terry
Day and Associates
Box 2045 Stn. M
Halifax, N.S.

DeJong, Jan
Husky
Box 6525 Stn. N
Calgary, Alberta
T2P 3G7

Dickens, David
Dickens Associates
3732 West Broadway
Vancouver, B.C.

Dowse, Brian
Hardy/Fugro
221-18th St. SE
Calgary, Alberta
T2E 6J5

Elverhoi, Anders
Norwegian Polar Res. Inst.
432 Silver Valley Rd. NW
Calgary, Alberta
T3B 4A8

Fernandes, Mario
Gulf Canada Resources
401 - 9th Ave SW
Calgary, Alberta
T2P 2H7

Frederking, Bob
NRC-Geotech Eng. Section
Div. of Bldg. Research
Ottawa, Ontario
K1A 0B6

Gaskill, Herb
Dept. of Mathematics
Memorial University
St. John's, Nfld.
A1B 3X5

Gillespie, Randy T.
Geonautics Ltd.
Box 8833
St. John's, Nfld.
A1B 3T2

Goodwin, Ross
Arctic Inst. NA
University Calgary
Calgary, Alberta
T2N 1N4

Graham, Bruce
Arctec Ltd.
#16 6325-11th Ave SE
Calgary, Alberta

Graham, Chris
Gulf Canada Resources
401 - 9th Avenue SE
Calgary, Alberta
T2P 2H7

Grass, Jim
Ontario Hydro
700 University Avenue
Toronto, Ontario
M5G 1X6

Herring, I.
Bow Valley
6610 Stn. D
Calgary, Alberta
T2P 3R2

Hnatiuk, John
Gulf Canada Resources
401-9th Avenue SW
Calgary, Alberta
T2P 2H7

Hodgson, Bud
Geonautics Ltd.
Box 8833
St. John's, Nfld.
A1B 3T2

Hotzel, Stu
Petro Canada
2928-16th Street NE
Calgary, Alberta
T2E 7K7

James, David
Esso Resources
339 50th Avenue SW
Calgary, Alberta
T2G 2B3

Josenhans, Heiner
Bedford Inst. of Oceanography
Box 1006
Dartmouth, N.S.
B2Y 4A2

Lanin, Glenn
R.J. Brown
2010 North Loop West
Houston, Texas
77018

Lea, Brian
Dobrocky Seatech
9865 W. Saanich Road
Sidney, B.C.
V8L 4M7

Lever, Jim
C-CORE
Memorial University
St. John's, Nfld.
A1B 3X5

Lewis, Mike
Bedford Inst. of Oceanography
Box 1006
Dartmouth, N.S.
B2Y 4A2

Lien, Reidar
Reidar Lien A/S
Ovre Flatusv, 10
7079 Flatos
Norway

Livingstone, Bill
Gulf Resources
401-9th Avenue SW
Calgary, Alberta
T2P 2H7

Loken, Olav
COGLA-ESRF
355 River Rd.
Ottawa, Ontario
K1A 0E4

Lussenburg, J.
Gulf Canada Resources
401 9th Ave. SW
Calgary, Alberta
T2P 2H7

Marcellus, Bob
Can Marine Engineering
#608 604-1st St SW
Calgary, Alberta
T2P 1M7

McGonigal, Dave
Gulf Canada Resources
401 9th Avenue SW
Calgary, Alberta
T2P 2H7

McKeehan, Dave
INTEC Eng.
Ste 105-16801 Greenspoint Pk.
Houston, Texas, USA 77060

Miller, John
Petro Canada
2928-16th St. NE
Calgary, Alberta
T2E 7K7

Moran, Kate
Bedford Institute of Oceano.
Box 1006
Dartmouth, N.S.
B2Y 4A2

Morrison, Tom
Can Marine Engineering
#608 604-1st St., SW
Calgary, Alberta
T2P 1M1

Myers, Rick
Dome Petroleum
Box 200
Calgary, Alberta
T2P 3H7

Nelson, Cathy
Esso Resources
237 -4th Avenue SW
Calgary, Alberta
T2P 0H6

Nessim, Maher
Det Norske Veritas
#1110-10201 Southport Plaza
Calgary, Alberta
T2W 4X9

Ng, Keith
Husky
Box 6525 Stn. D.
Calgary, Alberta
T2P 3G7

Olynyk, Harry
Geoterrex Ltd.
Ste 107A-9865W Saanich Rd.,
RR2 Sidney, B.C.
B8L 3S1

Parrott, Russell
Bedford Inst. of Oceanography
Box 1006
Dartmouth, N.S.
B2Y 4A2

Piepgrass, Read
Gulf Canada Resources
401 - 9th Ave SW
Calgary, Alberta
T2P 2H7

Pilkington, Roger
Gulf Canada Resources
401 - 9th Ave SW
Calgary, Alberta
T2P 2H7

Quinn, Rick
Geoterrex Ltd.
9865 W. Saanich Road
Pat Bay, B.C.
V8L 3S1

Reasbeck, John
Gulf Canada Resources
401 - 9th Ave SW
Calgary, Alberta
T2P 2H7

Roggensack, Bill
EBA Engineering Ltd.
14535-118th Ave
Edmonton, Alberta
T5L 2N7

Ruffman, Alan
Geomarine Assoc.
Box 41 Stn. M
Halifax, N.S.
B3J 2L4

Schoenthaler, Lorne
Mobil Oil Canada
Box 62, Atlantic Place
St. John's, Nfld.
A1C 6C9

Shearer, Jim
Shearer Consult
26 First Avenue
Ottawa, Ontario
K1S 2G2

Simpkin, Peter
IKB Technologies
Box 297
Topsail, Nfld.
AOA 2YO

Smandych, Al
Bow Valley
6610 Stn. D
Calgary, Alberta
T2P 3R2

Stirbys, Tony
Gulf Canada Resources
401 9th Ave SW
Calgary, Alberta
T2P 2H7

Todd, Brian.
Dept. of Geology
Dalhousie University
Halifax, N.S.
B3H 3J5

Tucker, Terry
CRREL
US ARMY Corps
Hanover
New. Hamp. USA 03755

Van Ieperen, Martin
Pan Arctic Oil
815-8th Ave SW
Calgary, Alberta
T2P 3P2

Westergard, Howard
Canterra
Box 1051
Calgary, Alberta
T2P 3J6

Wood, Peter
COGLA-ESRF
355 River Rd.,
Ottawa, Ontario
K1A 0E4

Woodworth-Lynas, Chris
C-CORE
Memorial University
St. John's, Nfld.
A1B 3X5

Wright, Brian
Gulf Resources
401 - 9th Ave SW
Calgary, Alberta
T2P 2H7