107 An Experiment to
Monitor Four Iceberg
Scours on the Grand Banks
of Newfoundland

Canada

ENVIRONMENTAL STUDIES RESEARCH FUNDS

REPORT NO. 107

December 1991

AN EXPERIMENT TO MONITOR FOUR ICEBERG SCOURS

ON THE

GRAND BANKS OF NEWFOUNDLAND

Susan H. Davidson[1], William T. Collins[2] and Peter G. Simpkin[3]

[1]Sea Science
1844 West 12th Avenue
Vancouver, British Columbia

[2]The Seabed Group Incorporated
451 Kenmount Road
St. John's, Newfoundland

[3]IKB Technologies Incorporated
451 Kenmount Road
St. John's, Newfoundland

The correct citation for this report is:

Davidson, S.H., W.T. Collins and P.G. Simpkin. 1991. An experiment to monitor four iceberg scours on the Grand Banks of Newfoundland. Environmental Studies Research Funds Report No. 107. Ottawa. 110 p.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

SUMMARY

Numerous surveys of the eastern Canadian continental shelves have indicated the presence of distinctive seabed features formed as a result of icebergs impacting the seabed. As these iceberg scours age, the original shape and dimensions may be modified as a result of naturally occurring seabed processes.

The main seabed processes leading to degradation of iceberg scours include regional depositional processes, repetitive iceberg scouring, localized sediment transport processes, and biophysical processes in which benthic organisms alter the nature of the sea floor.

To assess the risk that iceberg scouring of the sea floor presents to seabed structures, estimates of both the longevity of scour features and the degree to which the original scour dimensions have changed with scour aging are required.

This report presents an experimental program designed to monitor the rates of change in dimension of the scours at four study sites and to obtain sufficient hydrodynamic and sedimentary data to allow the measured rates of change of scour dimension to be extrapolated to unmonitored sites. The four scours include Scour 95, located about 70 km to the north-northwest of the Hibernia P-15 discovery well; the Texaco 89-01 scour, about 48 km to the east of Hibernia; the Husky 88-01 scour found a further 10 km to the east near the Whiterose E-09 well site; and Bowers Pit, found 11 km to the east-southeast of Hibernia.

The survey history and a summary of the physical characteristics for each of the four scours are presented together with a discussion of the effectiveness of the previous surveys. The proposed experimental program is a combination of remotely-collected data and in situ measurements together with additional measurements required to extrapolate the observed degradation rates to other unmonitored sites.

<u>RÉSUMÉ</u>

De nombreuses études portant sur les plates-formes continentales de l'est du Canada ont révélé que le lit de la mer présente des caractéristiques particulières par suite du décapage dû aux icebergs. À mesure que ces zones décapées par les icebergs vieillissent, leurs formes et leurs dimensions d'origine peuvent être modifiées par des processus naturels propres au fond marin.

Parmi les principaux processus naturels se traduisant par l'érosion de ces zones affouillées, mentionnons la sédimentation régionale, le décapage à répétition par des icebergs, les processus locaux de transport des sédiments et les processus biophysiques où des organismes benthiques transforment eux-mêmes le lit océanique.

Pour évaluer les risques pour les structures du décapage par les icebergs du fond marin, il faut à la fois estimer combien de temps les zones décapées demeurent inaltérées et dans quelle mesure leur taille initiale a changé au cours des ans.

Ce rapport traite d'un programme expérimental destiné à surveiller les taux de changement des dimensions des zones décapées dans quatre lieux d'étude et à recueillir des données hydrodynamiques et sédimentaires suffisantes pour calculer par extrapolation des modifications survenues dans des sites non surveillés. Quatre zones ont été retenues, à savoir la zone de décapage 95, située à environ 70 km au nord-nord-ouest du puits de découverte Hibernia P-15; la zone de décapage Texaco 89-01, à environ 48 km à l'est du champ Hibernia; la zone de décapage Husky 88-01, à 10 km plus à l'est, près du puits Whiterose E-09; et Bowers Pit, à 11 km à l'est-sud-est du champ Hibernia.

On examine les études antérieures et on fournit un résumé des caractéristiques physiques pour chacune des quatre zones de décapage ainsi qu'une analyse des résultats des études réalisées dans le passé. Le programme expérimental proposé combine des données recueillies à distance et des mesures in situ, ainsi que des mesures supplémentaires nécessaires pour calculer, par extrapolation, les taux de dégradation dans d'autres lieux non surveillés.

1. INTRODUCTION

Numerous surveys of the eastern Canadian continental shelves have indicated the presence of distinctive seabed features formed as a result of icebergs impacting the seabed (e.g., Fader and King 1981; Lewis and Barrie 1981). These features range in shape from roughly circular or elliptical depressions in the seabed (pits) to shallow furrows which may be many kilometres in length. Both pit and furrow scour features are often bordered by raised berms composed of the seabed material displaced during the iceberg grounding and scouring process.

Iceberg scours have been found to occur over wide areas of the shelf and include both modern and relict populations, with modern scour marks generally limited to water depths of less than 200 m (Lewis and Barrie 1981; d'Apollonia and Lewis 1985). In recent years, several iceberg grounding events have been observed directly, creating the opportunity to study scour features of known age.

As iceberg scours age, the original shape and dimensions may be modified as a result of naturally occurring seabed processes. Typically, the scour trough or pit infills with sediment while the scour berm is broken down and berm sediments are dispersed. Although the scour may eventually be obliterated completely from the sea floor, scour features may, in certain environments, become relatively stable and persist over long time periods. Relict scours have been identified in areas such as the west coast of British Columbia (Luternauer and Murray 1983) and the Scotian Shelf (King 1980; Hutchins et

1

al. 1976), where icebergs have not been present for several thousand years.

The main seabed processes leading to degradation of iceberg scours include regional depositional processes, repetitive iceberg scouring, localized sediment transport processes and biophysical processes in which benthic organisms alter the nature of the sea floor. With the exception of repetitive iceberg scouring and certain biomechanical effects, these seabed processes all involve transport of bottom sediments. Transport processes are highly dependent upon the near-bed current climate, the type of seabed sediments and the nature of the local benthic biota in the area where the scour occurred. These factors will be discussed in further sections of this report.

To assess the risk that iceberg scouring of the sea floor presents to seabed structures, estimates of both the longevity of scour features and the degree to which the original scour dimensions have changed with scour aging are required (Lewis 1977; Weeks et al. 1985; Lanan et al. 1986). For this purpose, four iceberg scours on the Grand Banks of Newfoundland have been identified as sites for study of scour degradation rates and processes. These features are shown on Figure 2, together with the regional surficial geology of the study area. Three scours are of recent and known age, with the oldest of the three features formed in 1983. The age of the fourth feature is unknown, although Barrie et al. (1986) consider it to be measurable in tens of years.

The three iceberg scours of known age include Scour 95, located about 70 km to the north-northwest of the Hibernia P-15 discovery well in about 95 m of water; the Texaco 89-01
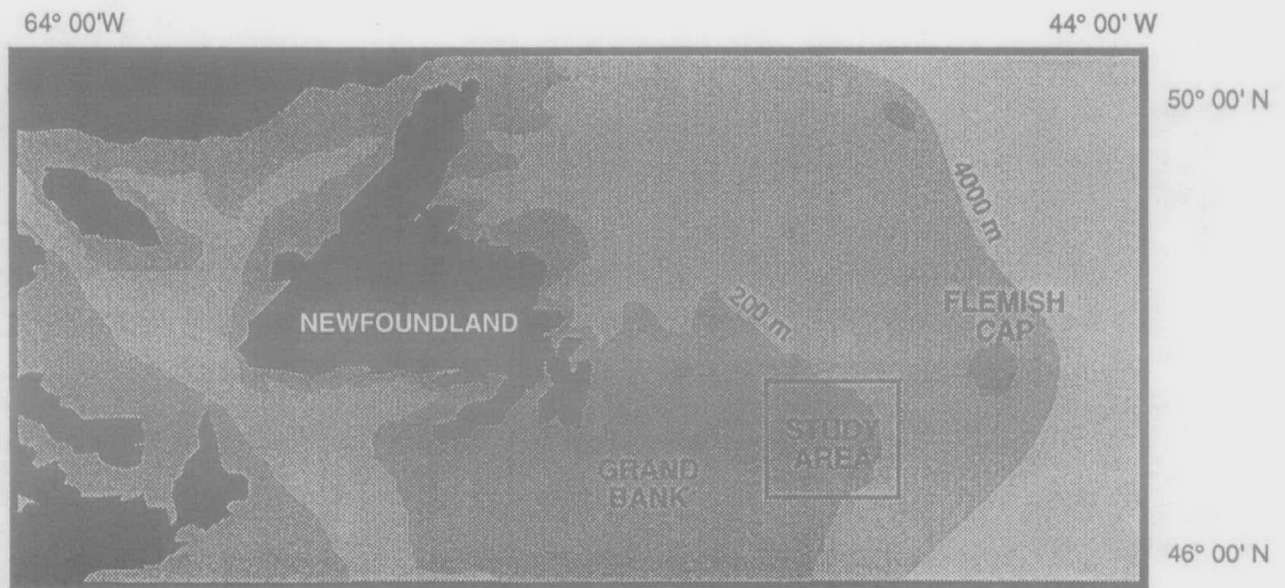
Figure 1. Location of the study area on the Grand Banks of Newfoundland.
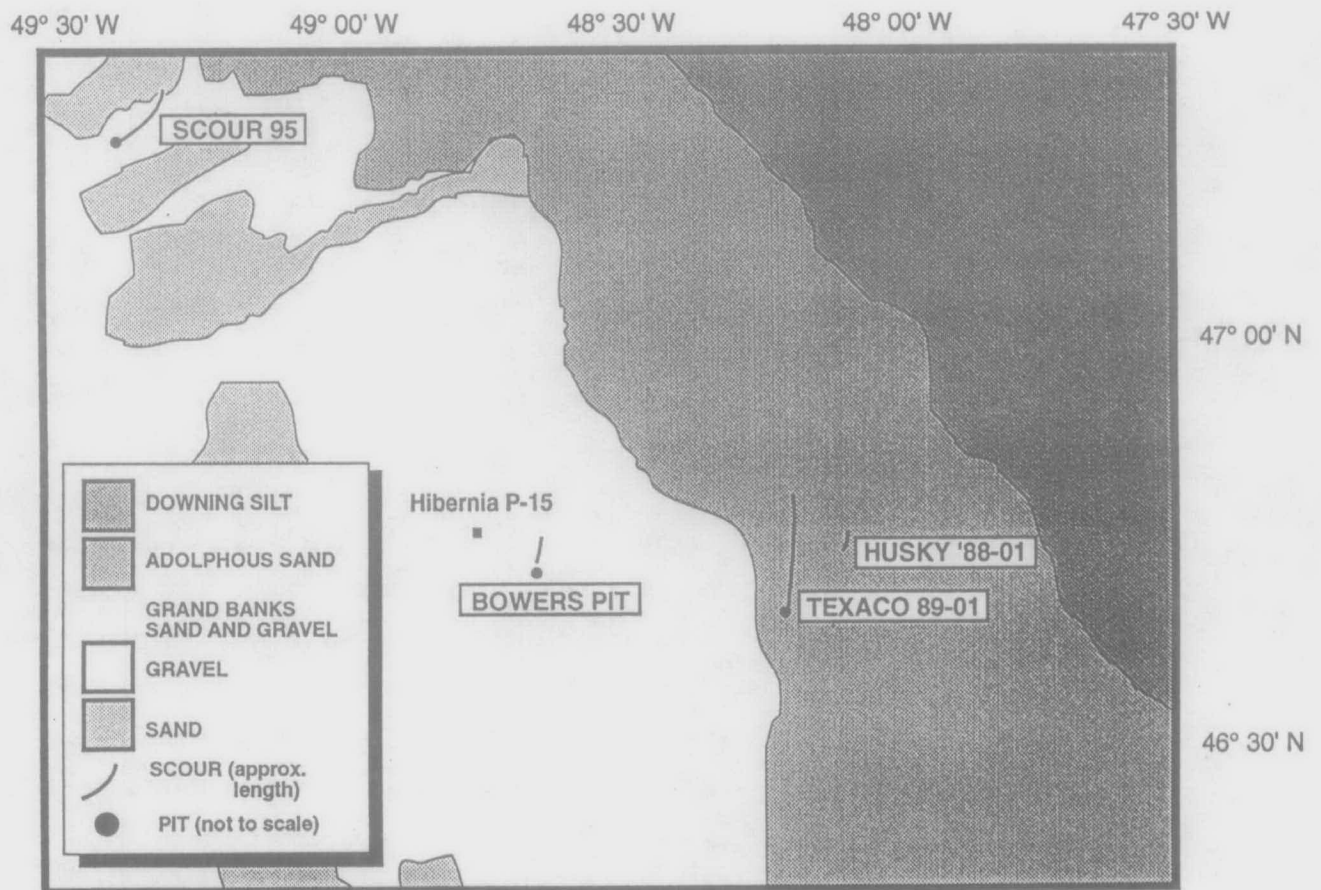
Figure 2. Surficial geology in the study area and location of the four study iceberg scours.

scour, about 48 km to the east of Hibernia in 110 m of water; and the Husky 88-01 scour found a further 10 km to the east near the Whiterose E-09 well site in 125 m of water. The older feature, Bowers Pit, is found 11 km east-southeast of Hibernia in about 90 m of water. Although the commonly adopted names of these scours are somewhat misleading, all except the Husky 88-01 scour consist of both a linear or curvilinear furrow and a terminal pit at one end of the furrow. No terminal pit is associated with the Husky 88-01 scour.

This report presents an experimental program designed with two primary objectives: to monitor the rates of change in dimension of the scours at the four study sites and to obtain sufficient hydrodynamic and sedimentary data to allow the measured rates of change of scour dimension to be extrapolated to unmonitored sites. As prerequisites to the design of a study program, existing survey data for the four sites were compiled, tabulated in terms of equipment used and survey methods, and evaluated for effectiveness in both describing the local geologic conditions at the survey sites and measuring the physical dimensions of the scours. In addition, the major seabed processes leading to scour degradation have been identified for each site and three typical scour environments have been defined.

Section 2 of this report describes the main seabed processes leading to iceberg scour degradation in the Grand Banks region. The regional surficial geology, physical oceanography, and sediment transport processes active in the study area are reviewed in section 3. The survey history and physical characteristics for each of the four scours are described in section 4, followed by a discussion of the

4

effectiveness of the previous surveys in section 5. The proposed experiment is described in section 6, including cost estimates of such a program at industry rates. Technical details concerning geophysical survey methods are contained in Appendix 1 with specifications for the recommended survey equipment in Appendix 2.

2. PROCESSES LEADING TO ICEBERG SCOUR DEGRADATION

The experimental program presented in section 6 of this report has been designed to meet two primary objectives: to monitor the rates of change in dimension of the scours at the four study sites and to obtain sufficient additional data to allow measured rates of dimensional change to be extrapolated to unmonitored scour sites. Both of these objectives require an understanding of seabed processes leading to scour degradation at each of the scours. This section contains a summary of the main processes leading to iceberg scour degradation on the Grand Banks of Newfoundland.

Degradation of iceberg scours occurs through natural seabed processes leading to berm erosion and infilling of the scour trough or pit. Depending on the scour environment, degradation may proceed until the scour feature is completely obliterated or until a relatively stable form, resistant to further degradation, is reached.

Scour degradation may occur over a variety of time scales ranging from short-term processes, active during and immediately after the scouring event when the presence of the iceberg modifies the local hydrodynamic forces on the seabed, to long-term processes occurring on geologic time scales. This project focuses on scour degradation processes which occur after the scouring event, when the iceberg no longer modifies the local hydrodynamics, and on time scales short enough such that oceanographic and geologic climates remain relatively stable.

Previous studies (Davidson et al. 1988; Hodgson et al. 1988) have identified and described the main processes leading to scourι degradation. These processes include regional depositional processes such as ice and iceberg rafting, the effects of repetitive iceberg scouring, local sediment transport and associated bedform migration, and biophysical processes, in which bioturbation leads to breakdown of sediment structures and subsequent erosion of the scours.

REGIONAL SEDIMENT DEPOSITION

In depositional environments, seabed features tend to be gradually obliterated as sediment is preferentially deposited in depressions in the seabed rather than over seabed protrusions. However, the eastern Canadian continental shelves represent a sediment-starved margin which is considered to be erosional rather than depositional (Parrott et al. 1989). Any net sedimentation is usually local in nature and results primarily from reworking of existing surficial sediments through bioturbation, sediment transport and iceberg scouring, with the only input of new sediment to the shelf areas attributed to ice and iceberg rafting.

REPETITIVE ICEBERG SCOURING

In areas where icebergs frequently ground and scour the seabed, the probability is high that some new scours will

cross or overtop existing, older scours, leading to degradation and perhaps even obliteration of older scour features. Estimates for Saglek Bank (Lewis et al. in review) indicate that, under present conditions, 78% of the bank top area will be disturbed by iceberg scouring over a 1000-year period. The relative importance of this scour degradation mechanism can be determined through the repetitive mapping process, however the results, at best, will be qualitative.

LOCAL SEDIMENT TRANSPORT

In areas of active sediment transport, iceberg scours can be readily degraded even though the surrounding seabed undergoes no net erosion or deposition. The transport of sediment is driven by the near-bed currents, both unidirectional and oscillatory, with the amount of material transported depending on the hydrodynamic regime, the type of sediment and the sea floor roughness characteristics. The relative magnitudes and frequencies of sediment transport events at the four study sites are discussed in section 3.

The presence of iceberg scours alters the local flow conditions from those over the surrounding sea floor and may also expose underlying sediment facies with different transport characteristics. Since seabed erosion or accretion in mobile bed environments arises from spatial gradients in transport rates, seabed features such as scours can induce local erosion or deposition.

8

Non-cohesive sediments can be transported either as bedload or as suspended load. As seabed stresses (i.e., bottom currents) increase over no-sediment-motion conditions, sediment is first transported as bedload. As seabed stresses increase past the threshold level for sediment suspension, the primary mode of transport shifts to suspended load. The distance an individual sediment grain is transported before returning to the sea floor is generally much greater in the suspended-load transport mode.

Bedload transport is often the most common mode of sediment movement on continental shelves, particularly for coarse sands and gravels, since a significant increase in seabed stresses is required to suspend these sediments in the water column once the threshold for sediment movement has been exceeded. Bedforms are often found on the sea floor in areas of active bedload sediment transport. The rate of migration of bedforms is directly linked to sediment transport processes and in some cases can serve as an accurate indicator of the magnitude and direction of sediment movement.

Conversely, fine, non-cohesive sediments such as fine sands and silts can be relatively easily suspended into the water column once the threshold for sediment motion has been exceeded. For these sediments, suspended-load transport is likely to be the most common mode of sediment movement. Bedforms are usually absent from such areas. The relative effectiveness of bedload and suspended-load transport modes in degradation of seabed features such as iceberg scour marks is unknown at the present time.

In non-cohesive sediments with sufficient gravel- and cobble-sized material, active sediment transport may lead to

9

the formation of an armour layer or surficial pavement. The coarse surficial layer acts to protect the seabed from further erosion and preserves bottom features from degradation in all but extreme storm conditions. This process may be active in the areas interpreted as surficial gravel lag in the Hibernia region, where iceberg scours appear to be preserved for long periods.

Cohesive sediments on the Grand Banks of Newfoundland appear to be sufficiently compacted to require strong bottom currents in order for sediment transport to occur, except where bioturbation has led to disaggregation of the bottom sediment into loose, fine material. The disaggregated material is fine enough to be transported away by the near-bed currents, leading to erosion of the scour features, particularly the blocky berm structures evident in Bowers Pit and perhaps in the Husky 88-01 scour.

BIOPHYSICAL EFFECTS

Biological recolonization of the seabed after a scouring event occurs on a variety of time scales, with mobile epifauna (e.g., brittle stars, sea urchins, crustaceans and bottom-dwelling fish) able to invade a new scour within hours after formation, whereas slow-growing, long-lived species (e.g., sponges and bryozoans) are secondary colonizers, taking at least six years to become re-established in the study area (Pocklington 1987; R. Hooper, Memorial University of Newfoundland, personal communication). The distribution of benthic organisms also depends on the character and permanence

10

of the sea floor. Stable substrates such as rocks and boulders are required for attachment and growth of encrusting epifauna such as sponges, bryozoans, anenomes and brachiopods, whereas sand substrates, particularly in areas of active transport, are inhabited by more mobile epifauna (molluscs, crustaceans, fish, etc.) as well as burrowing forms of echinoderms, crustaceans and various annelids (Pocklington 1987).

Benthic organisms contribute to the degradation of iceberg scours and other seabed features through two main processes: direct biomechanical disaggregation of seabed sediments, coupled with suspension and transport of the disaggregated fine material by bottom currents; and alteration of the physical properties of bottom sediments.

The first of these mechanisms appears to be the dominant degradation process for scours occurring in overconsolidated cohesive sediments, particularly with respect to erosion of the scour berms (Hodgson et al. 1988). Bioturbation produces a disaggregated surface veneer of reworked fine material which is then suspended by bottom currents and transported away from the scour. In cohesive sediments, newly formed scour berms tend to contain massive, fractured, angular blocks of compressed sediment. These blocks are covered by a network of hairline cracks. If burrowing organisms use these cracks as colonization sites, weakening of the block structure and further fracturing may also occur.

As well as causing disaggregation of cohesive sediment flocs, benthic organisms can change the physical properties of both cohesive and non-cohesive bottom sediments. In particular, sediment shear strength can be significantly

altered by processes including microbiological activity, mucus film bonding and pelletization of surficial sediments (Rhoads and Boyer 1982). In addition, the roughness of the seabed may be controlled primarily by burrows and mounds associated with benthic biota (Chriss and Caldwell 1984).

3. REGIONAL SETTING

SURFICIAL GEOLOGY

The regional surficial and shallow subsurface geology of northeastern Grand Bank has been reviewed and summarized in map form by Fader et al. (1985), with subsequent revisions by Edward L. King and Associates (1989). The thin surficial sediment cover is underlain by the older sediments of the Banquereau formation in the Hibernia development area (Grant et al. 1986). This formation consists of a sequence of interbedded silts and fine sands with hard, overconsolidated clays ranging to more massive, stiff sands. Deltaic, wedge-shaped bodies locally. The boundary between these sediments and the overlying units is unconformable and may represent the erosional surface of the Late Wisconsinan low sea-level stand (Edward L. King and Associates 1989).

The Quaternary section is generally thin, consisting of glacial till, glaciomarine sediments and reworked sand and gravel deposits formed during a late Quaternary-early Holocene sea-level transgression. Scattered boulders, with locally high concentrations, are thought to be the erosional remnants of glacial deposits (Edward L. King and Associates 1989). The Quaternary section in the study area consists of three main surficial sedimentary units as shown in Figure 2.

The Downing Silt unit occurs over the northeastern portion of the study area, in waters deeper than 110 m. This unit consists of moderately sorted, fine sand with

interspersed shells and gravel, and is less than 5 m thick. Adjacent to the Downing Silt, in water depths from 90 to 110 m, is the Adolphous Sand unit, consisting of a thin veneer less than 1 m thick of clean, fine-grained sand with minor gravel and shells. This deposit is relatively uniform and continuous, although some segregation of fine and coarse sand is present. Bedforms are rare (Edward L. King and Associates 1989). The Husky 88-01 and Texaco 89-01 scours occur in the Adolphous Sand unit.

The third distinctive surficial sedimentary unit in the study area is the Grand Banks Sand and Gravel, occurring in water depths of less than 90 m. This unit consists of a basal lag layer, ranging in size from pebbles to boulders, overlain by coarse- to fine-grained sand with variable gravel. This unit is subdivided into two facies: a) gravel and b) sand, of which the gravel facies represents the reworked basal lag layer. Present- day reworking of the sand facies is evidenced by numerous bedforms (Edward L. King and Associates 1989). The Grand Banks Sand and Gravel unit is generally less than 5 m thick and is discontinuous in some areas (Parrott et al. 1989). Both Scour 95 and Bowers Pit occur in this unit.

PHYSICAL OCEANOGRAPHY

The major physical oceanographic processes contributing to the near-bed current regime on the Grand Banks of Newfoundland have been reviewed in detail by Seaconsult Ltd. (1984) and by Davidson et al. (1988). These physical processes include large-scale circulation features such as the

14

Labrador Current and associated eddies and meanders (Leblond 1982), atmospherically forced motions such as wind-driven currents and inertial oscillations, tides, internal tides, internal waves and surface wind waves. De Margerie and Lank (1986) have found that the study area is not a likely site for the generation of internal tides and internal waves.

The Labrador Current is the primary large-scale circulation feature on the continental shelf of the Canadian east coast (Smith et al. 1937; Petrie and Anderson 1983; Greenberg and Petrie 1988), with three main branches. Of the two offshore branches, one flows southward along the Grand Bank shelf edge slightly to the east of the study area, and the second flows eastward, north of Flemish Cap.

Whereas mean currents in the offshore branches of the Labrador Current are relatively strong, with current speeds reaching 0.60 ms^{-1}, mean currents on Grand Bank are relatively weak (0.02-0.10 ms^{-1}) and are dominated by the variance in current speed (Petrie and Anderson 1983). An analysis of current meter records in the Hibernia area by Petrie and Warnell (1988) indicates that although the mean near-bed current speed is approximately 0.13 ms^{-1}, vector-averaged mean currents are essentially zero in this area. A similar analysis by Barrie and Collins (1989) indicates a net northerly flow in water depths less than 100 m and a consistent southerly flow in deeper waters to the east, closer to the Labrador Current.

Tidal currents in the Hibernia area are weak, with mean maximum near-bed tidal currents of about 0.10 ms^{-1} and extreme values reaching 0.20 ms^{-1}. The predominant direction is east-west, although there is a significant north-south current

15

component as well. Although tidal currents are weak, analysis of one year of data from Hibernia indicates that the tidal band accounts for 51% of the current variance for periods longer than 12 h (Petrie 1982).

A two-dimensional, depth-averaged numerical model for storm-driven currents has been developed and applied to the Grand Banks of Newfoundland by Brian Petrie of the Department of Fisheries and Oceans at the Bedford Institute of Oceanography (BIO). The 1-, 10-, 32- and 100-year return period storms have been used by Amos and Judge (in review) as input to a sediment transport model for the Grand Banks. For the 100-year storm, current velocities reach a maximum oMwabout 0.68 ms^{-1} at Hibernia, decreasing to 0.20 ms^{-1} for the 1-year return period storm event.

The wave climate at Hibernia is dominated by storm waves predominantly from the northwest during the winter months, with peak wave periods in the 12- to 14-s range and significant wave heights exceeding 8 m (Neu 1982; Walker 1984). Winter storm waves from the southwest and west often have peak wave periods from 14 to 16 s, although waves from these directions occur more frequently during the summer months. A wave height of 8 m together with a period of 13 s will produce an oscillatory current at the seabed reaching 0.44 ms^{-1} in 90 m of water. The extreme storms described by Amos and Judge (in review) have maximum wave-induced bottom velocities, based on the significant wave height and a water depth of 90 m, ranging from 0.34 ms^{-1} for the 1-year storm event to 1.39 ms^{-1} for the 100-year storm event.

Although surface waves are almost always present in the Hibernia region (wave heights exceed 1.5 m about 80% of the

16

time (Neu, 1982)), wave-induced currents do not always penetrate to the seabed. The depth of penetration increases with the wave period, with periods of 10.7 and 12.9 s required to generate bottom currents in 90 and 130 m water depths, respectively. Neu (1976) has shown that the largest wave periods are not generally associated with the largest waves, but often with moderate swell ranging from 1 to 4 m in height. However, statistics are not available concerning the joint probabilities of wave heights and periods.

In the absence of joint probability statistics, a relationship developed by Mobil Oil Canada Ltd. (1985) can be used to estimate peak period (T_p) based on significant wave height (H_s):

$$T_p = 5.1686\ H_s^{0.449}$$

Using this relationship, we can estimate that a wave period of 10.7 s corresponds to a significant wave height of 5.1 m and a wave period of 12.9 s corresponds to a height of 7.7 m. A wave height of 5.1 m is exceeded at Hibernia about 9% of the time and a height of 7.1 m is exceeded 1% of the time (Neu 1982). Thus, although the oscillatory currents generated by surface waves are significant, they are relatively infrequent components of the bottom current field.

In summary, the near-bed current climate in the study region is generally quiescent most of the time, with combined mean and tidal flow components reaching 0.10 to 0.15 ms^{-1} on a routine basis and 0.20 to 0.25 ms^{-1} during extreme tides. The direction of these currents is variable; in water depths of less than 100 m, currents may be strongest to the west or northwest, and to the east or southeast in deeper waters

closer to the Labrador Current. During significant storm events (most likely to occur during the winter months), both storm-driven, unidirectional currents and wave-induced, oscillatory currents will dominate the near-bed current field.

SEDIMENT TRANSPORT

As discussed in sections 1 and 2, the majority of the seabed processes leading to degradation of iceberg scours involve the transport of bottom sediments. Transport processes, in turn, are highly dependent on the near-bed current climate and the nature of the seabed in the study area, both summarized in the previous sub-sections of this section.

The potential for transport of bottom sediments in the study region has been previously analysed by Barrie et al. (1984), Barrie and Collins (1989) and Amos and Judge (in review). Barrie et al. (1984) have found, based on indirect evidence such as seabed morphology and lithofacies development, that net sediment movement occurs towards the south-southeast and parallel to the isobaths.

Barrie and Collins (1989) have investigated the frequency of bedload sediment transport in the Hibernia region through an examination of the threshold of sediment movement, with unidirectional and oscillatory flow components considered separately. Bedload transport due to the unidirectional flow component was found to be rare, occurring less than 2% of the time and only during the winter months. Conversely, sediment

18

movement due to the oscillatory, wave-induced current component was found to occur more than 30% of the time between November and March in 70 m water depth, and about 10% of the time in 90 m. The combined effects of unidirectional and oscillatory current components on flow within the bottom boundary layer and resulting sediment movement were not considered.

Amos and Judge (in review) have used a two-dimensional numerical model to estimate the rates and directions of storm-driven sediment transport on the Grand Banks of Newfoundland and the Scotian Shelf. The 1-, 10-, 32- and 100-year return period storms were modelled, with the combined effects of storm-driven unidirectional currents and surface waves considered in the near-bed current climate. Tidal currents and the effects of the Labrador Current were not included, and a constant sediment grain diameter of 0.35 mm was used to reduce the complexity of the modelling exercise. The significant wave height, H_s, was used to characterize the wave field. Additional transport calculations were performed for the Hibernia development site.

The model results indicate a general sediment movement to the east on northeastern Grand Banks for all modelled storms. Sediment movement was found to be limited to water depths of less than 100 m for the 1-year return period storm event, extending to depths of 200 m for both the 32- and 100-year storm events. The rate of sediment transport at the Hibernia site was found to be three orders of magnitude larger for the 100-year storm event than for the 1-year storm event.

A more detailed analysis of sediment transport for the Hibernia site considered the effects of varying sediment grain

size on sediment mobility. Figure 3 shows the peak rate of sediment transport at Hibernia for each of the four modelled storms for a range of sediment grain diameters. Amos and Judge (in review) found that the near-bed currents during the peak of the 100-year storm event were capable of transporting sediments up to 40 mm in diameter, whereas the 1-year storm event could transport materials up to 2 mm in diameter.

Although useful in characterizing the temporal variations in sediment movement for the study region, these previous studies yield few insights into the differences in sediment mobility and transport rates between the four study scour sites. A brief analysis of the relative magnitudes and frequencies of sediment transport events at the four sites was conducted as part of this project to provide qualitative background information for the design of an experimental monitoring program. The following analyses assume a flat seabed at each site and should not be used as accurate estimates of scour degradation rates at the study sites.

Sediment transport calculations for the four scour sites were based on the regional physical oceanographic and sedimentologic data summarized in the previous sub-sections. The following transport calculations include the combined effects of unidirectional and oscillatory current components on flow within the bottom boundary layer (Davidson and Amos 1985), where the unidirectional flow component includes the mean circulation, tidal currents and storm-driven currents. Wave height data have been obtained from Walker (1984) for monthly sea states and from Amos and Judge (in review) for extreme storm events.
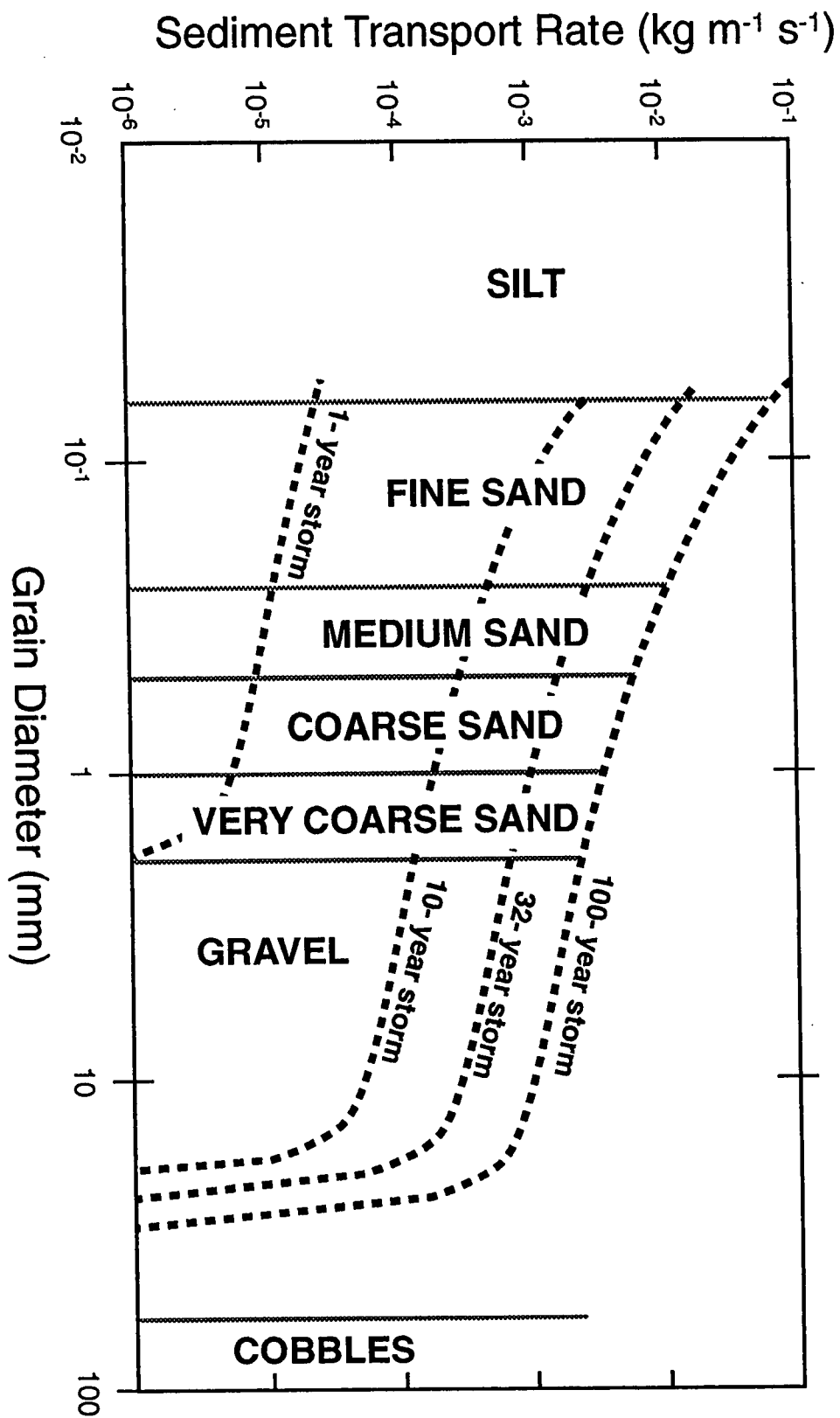
Figure 3. The effect of grainsize on the peak sediment transport rate at Hibernia during the 1-, 10-, 32- and 100-year storm events (after Amos and Judge, in review).

In general, the sandy sediments throughout the study region are relatively stable and undergo reworking only during major storm events, when wave-induced bottom velocities reach significant levels. The following transport analyses were based on the 1-year return period storm for each month, i.e., the January storm represents the average conditions for the largest storm occurring each year during that month. Based on the work of Huntley and Hazen (1988), the wave climate for each individual storm event was characterized by $H_{1/100}$, defined as the average height of the highest 1% of the waves during the storm. Wave periods were based on the relationship developed by Mobil Oil Canada Ltd. (1985) described previously in this section.

Figure 4 shows the sediment transport rates for sandy sediments at all four scour sites, for the monthly 1-year return period storms as well as for the 10- and 100-year return period storms. The transport rates shown in Figure 4 are intended to provide qualitative comparisons between the four scour sites and should not be compared quantitatively with the transport rates shown in Figure 3, since the sediment transport rates calculated for the Hibernia site by Amos and Judge (in review) use a different set of input conditions than those used in the present calculations.

Figure 4 shows that no transport of sand occurs at any of the four sites during the months of May through August; this indicates that a storm with a return period greater than one year is required to initiate sediment movement during the summer months. Conversely, transport of sandy sediments occurs at all sites during the months of October through March, indicating that a storm with a return period of less than one year may also initiate sediment movement during the winter
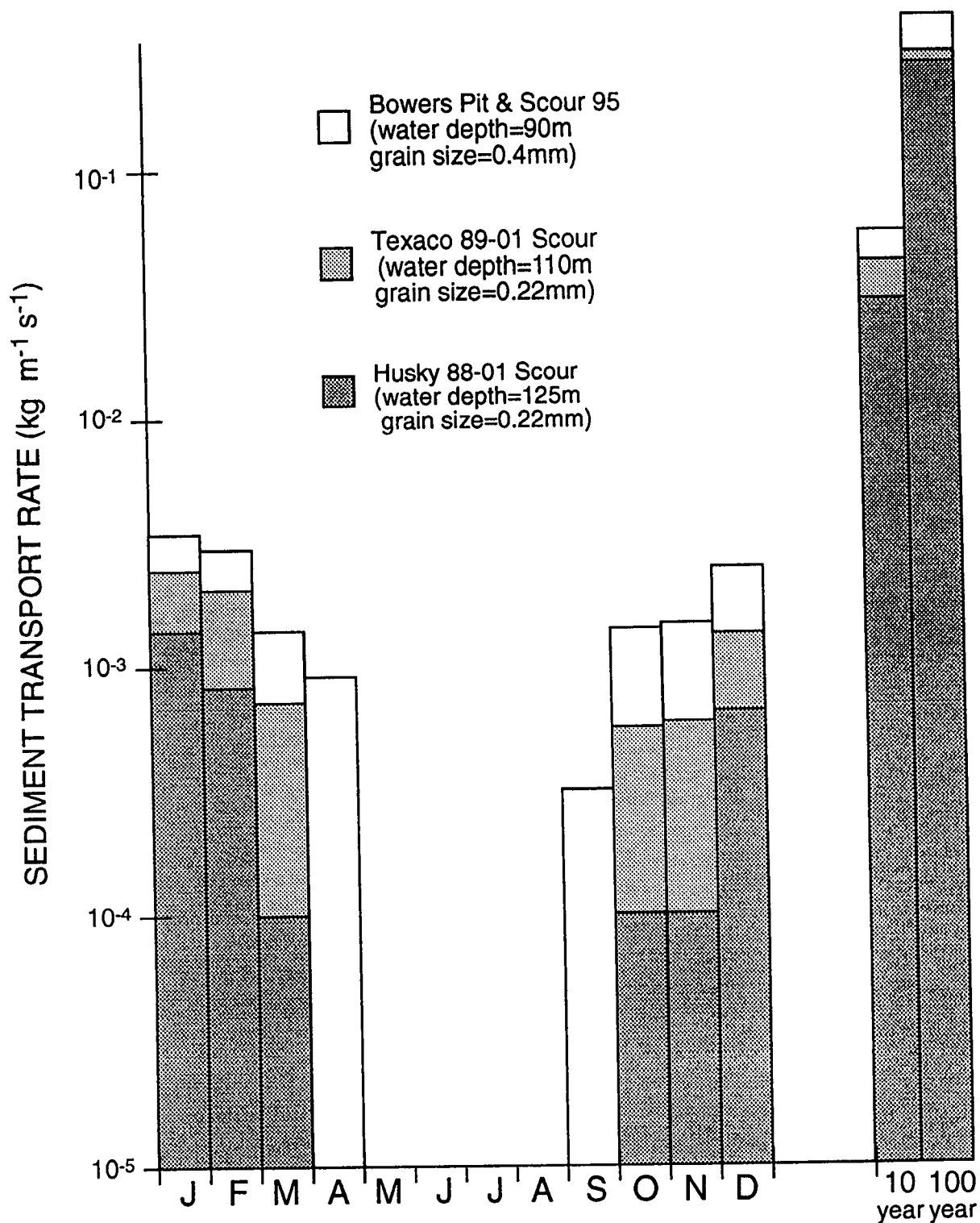
Figure 4. Sediment transport rates for sandy sediments at the four sites for the 1-year return period storm for each month, and the 10- and 100-year return period storms.

months. During the months of April and September only the shallower water sites of Bowers Pit and Scour 95 exhibit sediment transport.

Of the four study sites, the Husky 88-01 scour is located in the deepest water and is thus the furthest removed from the effects of surface waves and storm-induced bottom currents. The sandy sediments in this area are relatively fine, with a mean grain size of only 0.22 mm. Significant sediment motion in the vicinity of the Husky scour occurs during 1-year return period storms for the months of October through March, with the greatest transport occurring during the January storm event and no transport between the months of April and September. Transport rates during the 10- and 100-year storm events are two and three orders of magnitude, respectively, greater than the transport rates during the monthly storm events.

The fine sands near the Husky scour are likely to be transported mainly as suspended load rather than as bedload, since the threshold stress for sediment suspension is only slightly higher than the corresponding minimum stress for initiation of bedload transport. The general lack of bedforms observed in this area (Woodworth-Lynas 1989) may indicate the dominance of suspended load transport processes rather than a lack of seabed mobility.

Sediments at the Texaco 89-01 site are similar to those near the Husky scour, with the same mean grain size of 0.22 mm. The Texaco scour is in about 110 m of water, roughly 15 m shallower than the Husky 88-01 scour. With this difference in water depth, the same storm event will create larger bottom currents at the Texaco site than at the Husky

24

site. This is reflected in the greater sediment transport rates at the Texaco scour, as shown in Figure 4.

Sediment transport leading to scour degradation at the Texaco 89-01 scour site will occur mostly during the winter months, particularly from December through February. Again, extreme storm events will be a major factor in obliteration of scour features and sediment will be moved primarily by suspended load transport.

Scour 95 occurs in water depths ranging from roughly 90 to 100 m, and appears to cut through three main types of seabed sediments: surficial sands, sands overlying cohesive materials of the Banquereau formation, and sands with a gravel lag layer. Sediment transport rates and frequency of seabed disturbance have been examined for both the sandy sediments and the gravel lag layer. The cohesive materials exposed at the seabed during the scouring process are fine enough such that, if completely deflocculated, they can be transported in suspension by tidal currents alone. These sedimentary environments and the corresponding scour characteristics will be discussed further in section 4.

Bowers Pit and its associated scour also occur in about 90 m of water and have been interpreted to cut through the same three sedimentary environments as Scour 95. Both the surficial sediments and the hydrodynamic environment near Bowers Pit resemble conditions at the Scour 95 site, so the frequency and magnitude of sediment transport events will be similar for both locations.

The sandy sediments in the vicinity of Scour 95 and Bowers Pit are somewhat coarser than those at the deeper Husky

25

and Texaco scour sites, with an average grain size of about 0.4 mm. However, wave-induced bottom currents are stronger at these sites, resulting in a net increase in sediment transport rates compared to the deeper sites.

Again, transport of the sandy bottom sediments occurs mainly in the months from September to April, with rare transport events during the summer months. The coarser sandy sediments near Scour 95 and Bowers Pit are transported mostly as bedload rather than as suspended load; this is reflected in the pervasiveness of bedforms on the seabed in these regions (Mitten 1988). Suspended load transport is likely to occur only during storms with a return period greater than one year.

The gravel lag layer present at both the Scour 95 and Bowers Pit scour sites ranges in size from 5 to 10 mm, with an average clast diameter of about 8 mm. The gravel material is coarse enough such that the lag layer will be disturbed only during extreme storm events. Preliminary calculations indicate that the near-bed currents during the 1-year storm event may be sufficient to dislodge the gravel lag for short periods of time; however, biophysical effects such as mucus film bonding by surface biota may effectively strengthen the surficial lag into a pavement-like material which is rarely dislodged.

4. DESCRIPTION OF THE FOUR SCOURS

This section describes both the scour survey programs and the physical characteristics for each of the four scours. The scours will be described in turn, starting with Bowers Pit, the oldest scour, and ending with the youngest of the features, the Texaco 89-01 scour. A general discussion of scour morphology as a function of environment follows the descriptions of the individual scour features. An evaluation of the effectiveness of the previous survey programs is given in section 5.

BOWERS PIT

Survey Chronology

In October 1980, during a joint government-industry-university-sponsored cruise, a circular seabed depression 5.4 m deep and 100 m wide was identified from Huntec Deep Towed Seismic (DTS) sub-bottom profiler data. The feature, located about 11 km east-southeast of the Hibernia P-15 discovery well (Barrie et al. 1986), was crossed only once by the survey lines and was subsequently chosen as a primary target for research into the origin and significance of seabed pits. In October 1984, the pit was the target of extensive study using HMCS Cormorant and the five-person Submersible Diver Lockout SDL-1 (Barrie and Collins 1985). In preparing for the diving operations, the site was surveyed using a Klein 100-kHz side-scan sonar with a 3.5-kHz sub-bottom profiler.

27

Approximately 2.5 km of side-scan sonar data were recorded during the preliminary survey in 1984. The survey consisted of three north-northwest trending, subparallel lines about 200 m apart, with the middle line centred on the pit. An east-southeast trending tie line also ran across the centre of the feature.

Two submersible dives into the pit were completed during the 1984 study. Still and video photography of the pit were taken and six grab samples were obtained. In addition, a graduated rod designed to measure sediment infill (depth-of-disturbance rod) was erected in the centre of the pit (Collins et al. 1987). A 100-kHz transponder was also placed near the edge of the feature to facilitate future site relocation.

HMCS Cormorant and the SDL-1 returned to the Bowers pit area in August 1985. An EG&G 100-kHz side-scan sonar was used to locate the pit. One submersible dive was completed during this survey. Pit morphology and the associated sediments appeared unchanged from the 1984 investigations (Collins and Clark 1986). The depth-of-disturbance rod indicated that there had been 3 to 4 mm of fine sediment infill at the pit bottom.

In the fall of 1985, two attempts by the submersible Pisces IV to dive at the pit site were unsuccessful because of poor weather conditions. However, 100-kHz Klein side-scan sonar data were collected during two visits to the pit site, providing detailed, large-scale information on pit features (Fader and Miller 1986).

Another detailed survey of the pit was completed during the CSS Hudson cruise 86-018 in July 1986. About 35 km of

survey line were completed using a Klein 100-kHz side-scan sonar, a BIO 70-kHz side-scan sonar and a Huntec DTS sub-bottom profiling system. The survey was run in a star pattern centred on the pit (Parrott and Lewis 1986). An IKU grab sampler collected a sample from the area but it is uncertain whether the sample was located in the pit. Bottom photographs were also taken in the vicinity of the feature. Two piston cores and a remotely-operated-vehicle (ROV) transect were unsuccessful due to high winds and currents.

In August 1988, the MV Balder Challenger, using a motion-compensated Failing 1500 drill rig, completed two boreholes at the pit site. The first borehole sampled inside the pit to a depth of 86 m below the sea floor (Newfoundland Geosciences Ltd. 1988). The second borehole sampled to a depth of 15.5 m outside the pit, providing information on the undisturbed sediments. Also in August 1988, the geotechnical drillship MV Pholas was used as a platform to push a cone penetrometer into the pit to a depth of 90 m below the sea floor.

Physical Characteristics

The Bowers Pit and scour have been described by numerous authors including Collins and Clark (1986), Barrie et al. (1986) and Clark and Landva (1988). The surrounding sea floor averages 87 m in water depth. A reduced scale drawing of Bowers Pit and scour is given in Figure 5. The surficial sediments in the vicinity of Bowers Pit and scour consist of the gravel facies of the Grand Banks Sand and Gravel unit (Figure 2). These surficial sediments have been locally interpreted to consist of gravelly sand or sandy gravel (Barrie et al. 1986) with gravel occurring in areas as an
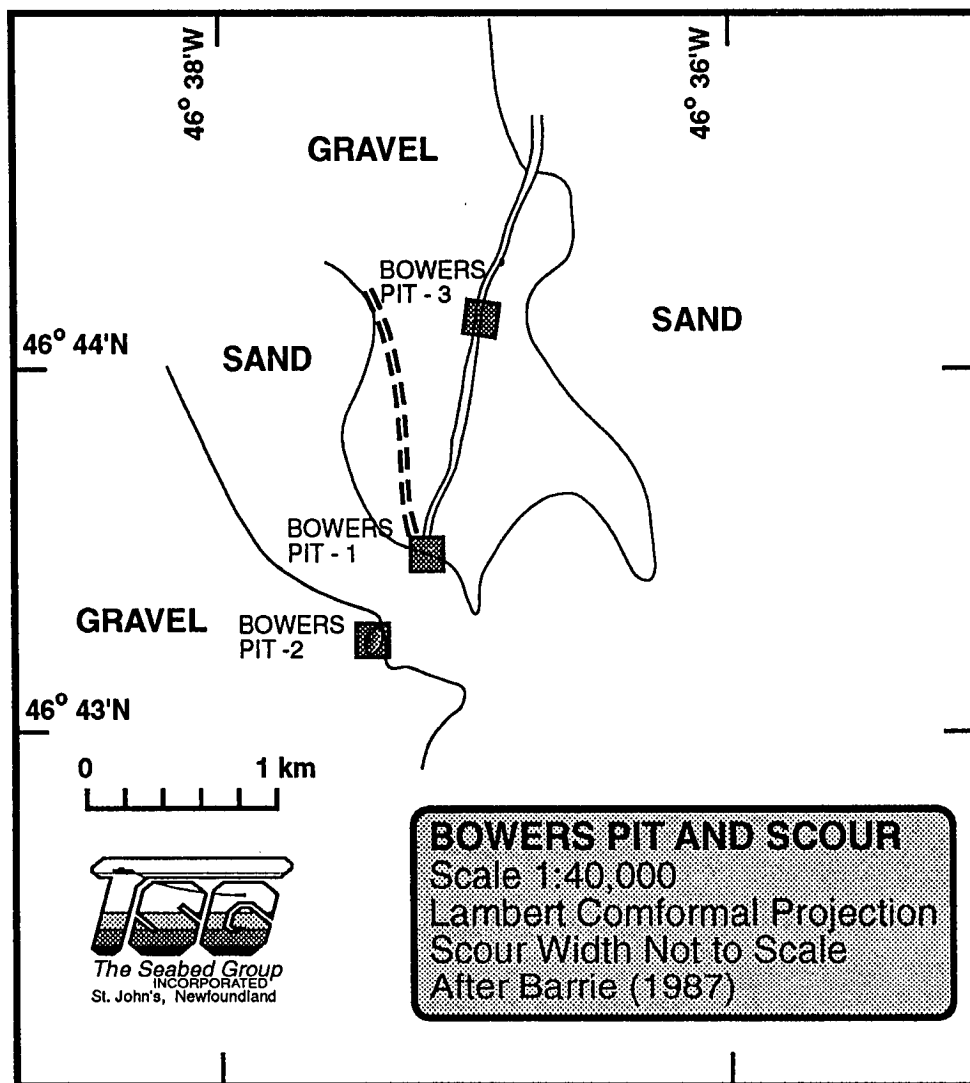
Figure 5. Reduced scale drawing of Bowers Pit and scour.

armour layer over the sand. Bowers Pit and most of the associated scour are in areas interpreted as lag gravel. Figure 6 shows the local surficial geology in the Bowers Pit area.

The Quaternary surficial sediments shown in Figure 6 are less than 1 m thick and lie unconformably over the Banquereau formation (Grant et al. 1986). The latter sediments consist of interbedded silts, fine sands and overconsolidated clays.

Barrie et al. (1986) describe the pit as having an amphitheatre-like shape with a shallow-sloping entrance ramp, two side walls, and a steep back wall. The pit is about 125 m long and 45 m wide, with the long axis oriented to the north-northwest. Direct submersible measurements have shown the pit floor to be 10 m below the surrounding sea floor at the deepest point. A schematic plan view of the pit is shown in Figure 7.

A berm surrounds the pit on all sides with the exception of the entrance ramp to the north. Side-wall berms are up to 2 m higher then the surrounding seabed and are composed of gravel and sand with large boulders at the leading edges. The back-wall berm consists of a discontinuous series of isolated mounds up to 2.5 m high and 3.0 m wide; sediment composition ranges from blocks of overconsolidated cohesive material, through gravel to boulders (Barrie et al. 1986).

The pit walls range in slope from less than 10° at the entrance ramp, through an average of 20° at the side walls, to a maximum of 25° at the back wall. Bioturbated silt and clay sediments outcrop on the walls through a thin veneer of gravel and sand with occasional boulders (Barrie et al. 1986).

31

Legend:
- Iceberg scour
- Sand
- Gravel
- 98 — Contour (m)

Scour associated with Bowers Pit

Bowers Pit

N

46° 44' N
46° 43' N

98
98

88   90   92   94   96

48° 39' W   48° 38' W   48° 37' W   48° 36' W
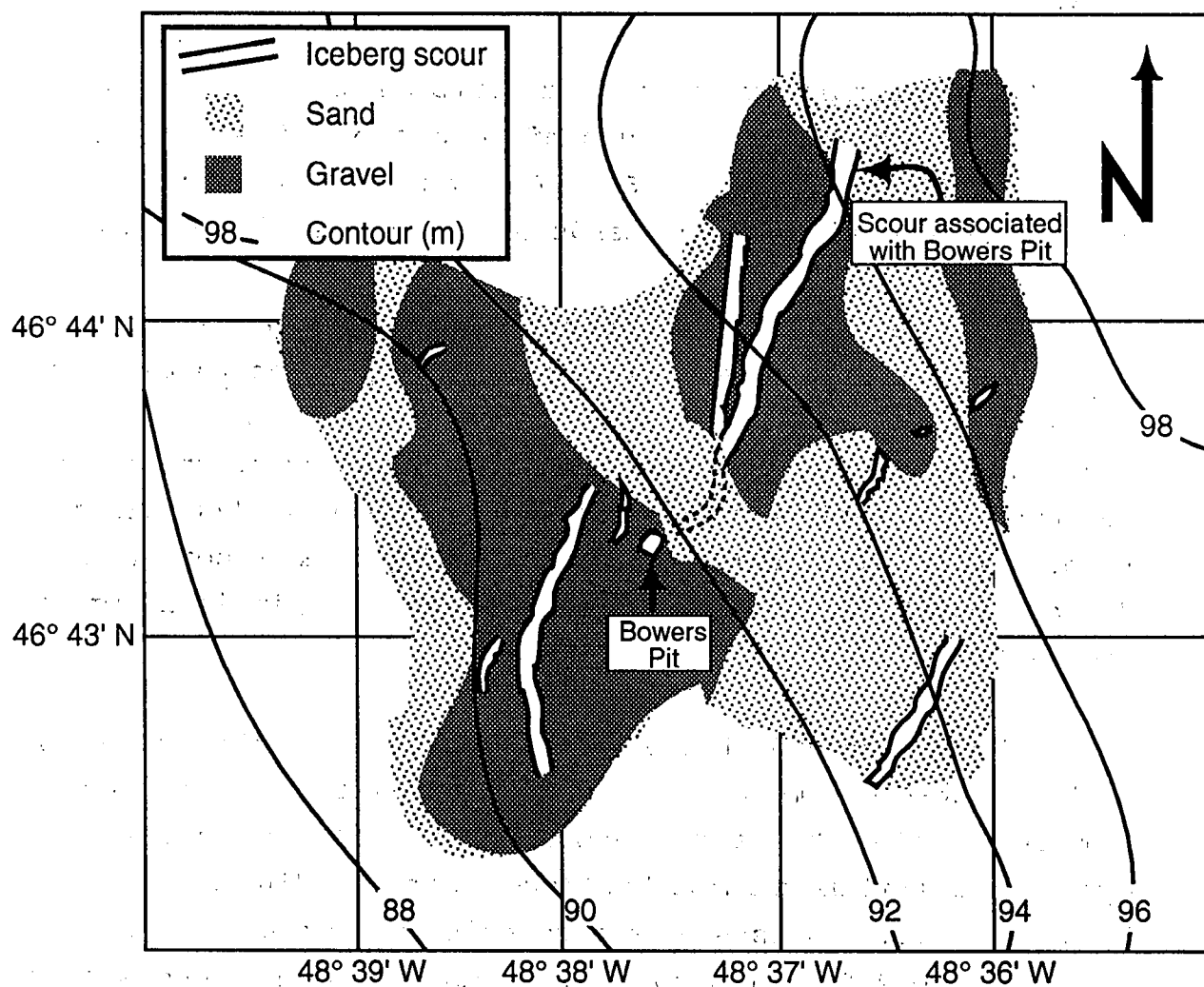
Figure 6. Surficial geology in the Bowers Pit region.

LEGEND

- Back-wall Berm
- Side-wall Berm
- Boulders
- Pit Floor
- Outcropping Silt and Clay beds
- Scallop Bed

Entrance Ramp

N

0   50
meters
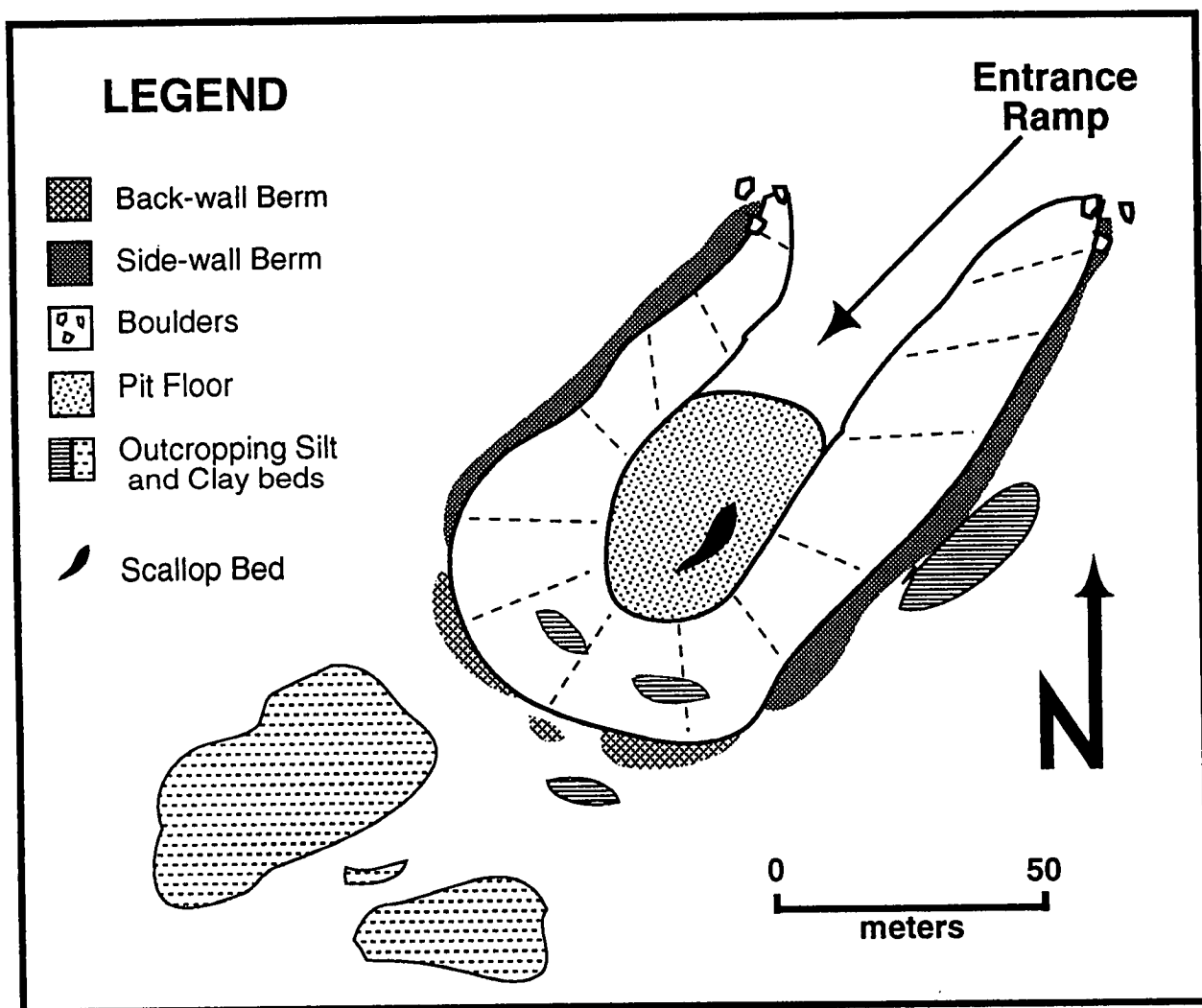
Figure 7. Schematic plan view of Bowers Pit (after Barrie et al. 1986).

The floor of the pit measures about 40 m by 25 m and consists of medium to fine sand with a crescent-shaped scallop bed slightly to the east of the centre. Scattered boulders are also present on the pit floor as are wave-induced ripple marks 2 to 3 cm in amplitude and 30 cm in wavelength. Low-relief, linear gravel troughs approximately 50 cm in width, 15 cm deep and 1.5 m apart are found on the entrance ramp to the pit (Barrie et al. 1986).

The scour furrow leading into Bowers Pit was first detected by the CSS <u>Hudson</u> cruise in July 1986. This survey documented a furrow about 100 m wide and over 3 km long, terminating in Bowers Pit. The depth of the scour trough averages 1.5 m below the surrounding sea floor.

The scour is first detected in sandy sediments, before passing into an area interpreted as lag gravel. The scour appears to have degraded in the sandy sediments, with only portions of the berm visible on the side-scan sonar records. Where the berm is visible, it appears to consist of blocks of sediment of the form generally associated with cohesive sediments, indicating that the iceberg keel cut through the surficial sediments during the scouring process and disturbed the underlying sediments of the Banquereau formation. The scour is relatively well-defined in areas interpreted as lag gravel, where the berms are large and appear to lack a blocky structure, although striations or chatter marks in the scour trough may indicate some penetration of the scour through to the underlying cohesive sediments (Barrie 1987).

SCOUR 95

Survey Chronology

During March of 1983, an iceberg grounding was observed
during drilling operations on northeastern Grand Bank (Parrott
and Lewis 1986). The drilling operators, Mobil Oil Canada
Ltd., initiated a side-scan sonar survey around the iceberg
(assigned the name Berg 95) to determine if it was indeed
grounded. The area near the grounded iceberg was also
investigated to identify and describe any associated scours.
Scour 95 was surveyed again by the drilling operator in the
fall of 1983.

This scour was resurveyed during a cruise of the CSS
Hudson (cruise 83-033, Vilks 1984) later in the fall of 1983.
The equipment used included the BIO 70-kHz and Klein 100-kHz
side-scan sonar systems, the Huntec DTS sub-bottom profiling
system and the towed camera sled BRUTIV (bottom referencing
underwater towed instrument vehicle). The Huntec system
included an acoustic reflectivity module and a single-channel,
airgun reflection seismic system. The survey lines crossed
the scour feature seven times, twice at right angles and five
times at an oblique angle. The 1983 survey covered over 90%
of Scour 95, in addition to identifying several other scours
of unknown age.

A similar suite of equipment was used in a 1986 survey
(cruise 86-018) and three of the 1983 lines were re-run in an
effort to document any changes in the character of the
observed scours. Many additional survey lines were run, both
subparallel to the axis of Scour 95 and crossing Scour 95 at

oblique angles, covering 100% of the recent scour. One line crossed Scour 95 at a right angle. Detailed surveys of the furrow and its termination led to the discovery of a pit at the end of the scour.

Physical Characteristics

Scour 95 is an iceberg-created feature on northeastern Grand Bank. The scour generally trends from north to south and traverses the seabed in an upslope direction at water depths varying between 100 and 90 m. Scour 95 is interpreted to be 6.8 km long and ranges in width from 25 to 50 m, as shown in Figure 8.

Scour 95 is incised into the Grand Banks Sand and Gravel surficial sedimentary unit shown in Figure 2. More specifically, the scour has been interpreted as traversing through intervals of rippled sand, gravel and gravelly sand (Mitten 1988). The surficial unit is generally less than 1.5 m thick and overlies older sediments of the Banquereau formation unconformably.

Starting from the northern and deepest end of the scour, the first 1.4 km of the scour is oriented in a southeasterly direction and traverses through intervals of gravel and sand with sand waves. The scour width in this area is about 45 m. Where the iceberg cut through sands, the scour berms show low relief and appear to spill out onto the surrounding seabed in plumes. The berm morphology suggests that the scour did not cut into the underlying cohesive sediments. After about 2 km the scour continues to traverse through sand but changes to a southwesterly direction.

49° 18'W   49° 16'W   49° 14'W

47° 18'N

0   1   2 km

The Seabed Group
INCORPORATED
St. John's, Newfoundland

G

G

Sand Waves

S

G

SCOUR 95 - 3

Sand Waves

S

G

G

S

SCOUR 95 - 1

G

S - Sand
G - Gravel

S

G

G

47° 16'N

G

Pit

Poor
Data

SCOUR 95
Scale 1:50,000
Lambert Conformal Projection
Scour Width Not to Scale
Dashed Segments inferred
Based on BIO 70 kHz Sidescan
Sonar Compilation by J. Mitten

SCOUR 95 - 2

47° 14'N
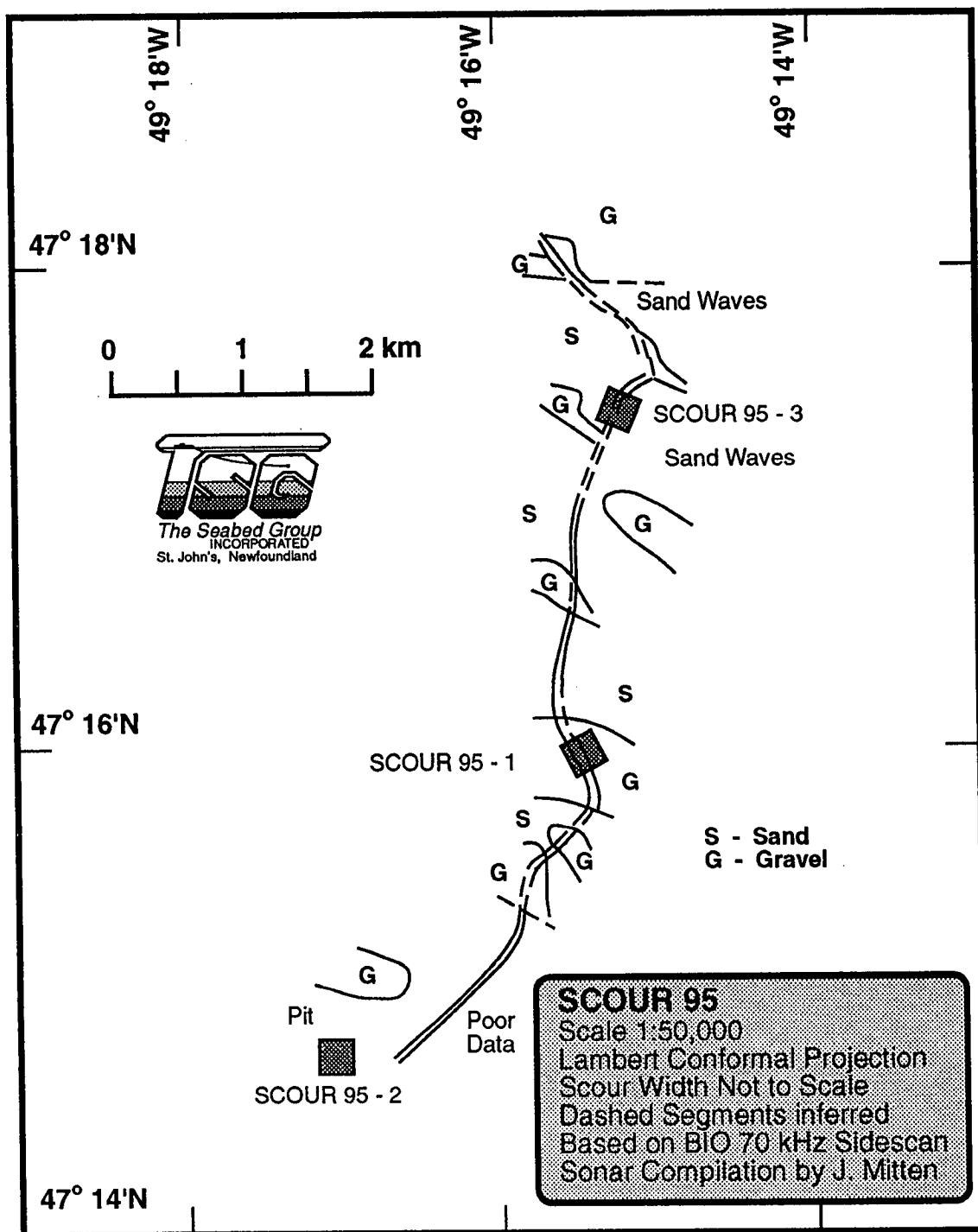
Figure 8. Reduced scale drawing of Scour 95.

Over the next 3.6 km, the scour has a sinuous form and the width ranges from 30 to 45 m. In the places where the iceberg traversed narrow gravel bands it appears to have pushed the gravel onto the scour berms, leaving only sand behind in the scour trough. This effect is particularly evident at the change in direction mentioned above and suggests that the gravel may be only a thin cover over the sand.

The scour then turns slightly westward, traversing 800 m through sand with wide bands of gravel. At one point along the path, where the scour crosses a gravel ridge, the iceberg appears to have lifted nearly clear of the seabed. The scour is 35 m wide at this point. The scour berm in this section has low relief and the scour trough exhibits small, subparallel and semi-continuous ridges.

Along the final 2.5 km, the scour is incised into sand, producing a very low berm. At this point the iceberg probably lifted off, drifted, rolled and impacted the seabed, producing a pit at the terminal end of the scour. The pit is about 90 m in diameter, 1.2 m deep and is encircled by berms up to 3 m in height (Parrott and Lewis 1986).

HUSKY 88-01

Survey Chronology

An iceberg scouring and grounding event near the Husky Whiterose E-09 well-site has been interpreted to have occurred

sometime between 9 and 13 April 1988 (Banke 1988). A seabed survey was completed in early July 1988, using a Klein 100-kHz side-scan sonar system modified to provide an expanded side-scan record presented on an EPC 3200 recorder. The BRUTIV camera sled with a stereo photographic camera system was used to collect seabed photographs, although no photographs were obtained of the recent scour feature. A clam-shell grab sampler was used to collect seabed samples.

In mid-September of 1988, during a cruise of the MV Needler (cruise 88-108), a Klein 100-kHz side-scan sonar, the BIO 70-kHz side-scan sonar, and a combined Huntec DTS shallow-seismic profiler and BIO 70-kHz side-scan sonar system were used. The entire scour is visible on the side-scan records with the Klein system providing the best data. The BIO 70-kHz side-scan sonar system was adequate to define the direction of the scour but resolved very little of the berm and trough morphology. The scour was not resolved on the Huntec DTS records.

Physical Characteristics

The 1988 Husky scour is located near the Husky Whiterose E-09 well-site on the northeastern margin of Grand Bank. The curvilinear, M-shaped scour is about 1.2 km in length and is found in water depths of 122 to 124 m (Figure 9). The surficial geology in the area consists of medium to fine sand with occasional gravel. Bottom photographs indicate an absence of current-generated bedforms (Woodworth-Lynas 1989).

Woodworth-Lynas (1989) and Banke (1988) have interpreted the first point of iceberg contact with the sea floor to be at

48° 04'W

48° 00'W

47° 56'W

46° 53'N

Scour "A"
(older)

0   1   2   3 km

Scour "B"
(older)

The Seabed Group
INCORPORATED
St. John's, Newfoundland

46° 51'N

Husky Scour   Pit

HUSKY - 1

HUSKY - 4

HUSKY - 2

1988 HUSKY SCOUR
Scale 1:60,000
Lambert Conformal Projection
Scour Width Not to Scale
After Banke (1988)

HUSKY - 3

46° 49'N
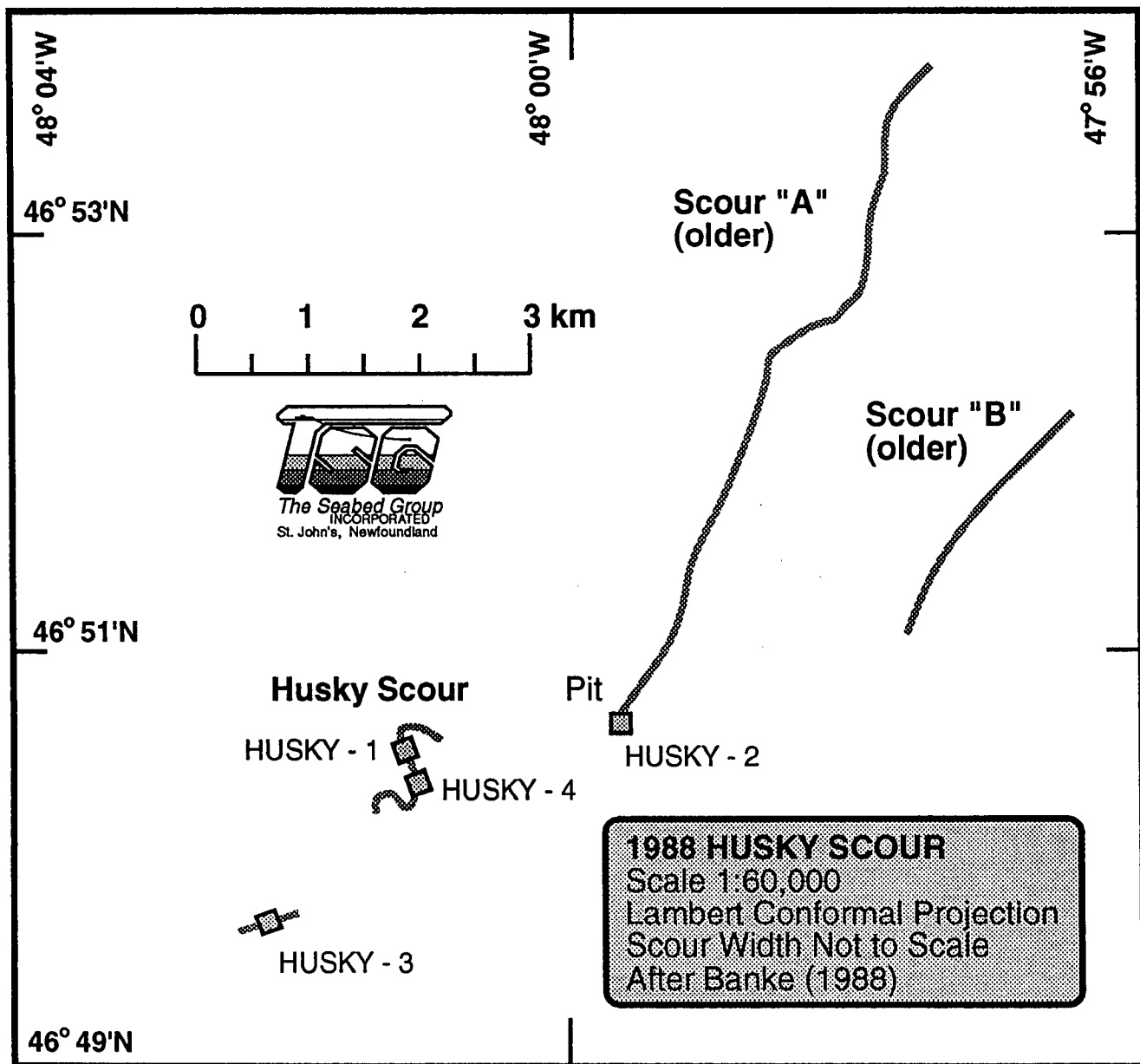
Figure 9. Reduced scale drawing of the Husky 88-01 scour.

the northeast end of the scour, where the scour width is about 5 m and scour depth is negligible. Scour width increases and distinct scour berms develop about 200 m from the point of initial iceberg touchdown, reflecting increasing penetration of the iceberg keel into the seabed. Scour width stabilizes at about 15 m and scour depth at about 0.5 m after a further 200 m.

The berms of this scour generally show irregular crests of low relief and lack the blocky structures characteristic of fresh scours in cohesive sediments (Woodworth-Lynas 1989). One linear feature parallel to the trough in the middle portion of the scour track is followed by a blocky region in the scour trough; these features may indicate some disruption of the underlying cohesive sediments. Circular features in the scour trough together with symmetrical waviness of the berm crests have been attributed to oscillations of the grounded iceberg (Woodworth-Lynas 1989). No terminal pit is associated with this scour.

TEXACO 89-01

Survey Chronology

A large iceberg was observed drifting southward near the Texaco Springdale M-29 well-site early in 1989. This iceberg grounded in 110 m of water where it remained for 45 days, drifting free on 24 April 1989.

A seabed survey along part of the recorded iceberg trajectory was conducted in May 1989 by the Atlantic Geoscience Centre (Fader 1989), during a cruise of the CSS Dawson (Dawson 89-06). The BIO 70-kHz side-scan sonar was used with both a conventional wet-paper recorder and an EPC three-channel graphic recorder in a scale-corrected format. A Klein 100-kHz side-scan sonar equipped with an altimeter was used with a three-channel wet-paper recorder to provide sonar images of higher resolution. As well, high-resolution seismic reflection data and echo-sounder data were collected to provide information on subsurface geology and the depths of iceberg scour features (Parrott et al. 1989).

Less than 75% of the Texaco 89-01 scour was covered during this survey. Of that coverage, about 25% was achieved with adequate resolution to document the features in detail.

Physical Characteristics

The Texaco 89-01 scour is located near the Springdale M-29 well-site on northeastern Grand Bank, in about 110 m of water. The scour is at least 14 km in length and terminates in a large pit (Figure 10). A large grab sample obtained near the iceberg pit showed the undisturbed seabed to consist of a thin layer of medium-grained, well-sorted sand over a subsurface layer of silty sand or sandy silt (Parrott et al. 1989). Edward L. King and Associates (1989) have interpreted the surficial sediments in this region to consist of clean, fine-grained sand with minor gravel and shells.

The geophysical survey began about 14 km north of the grounding site and followed the recorded trajectory of the
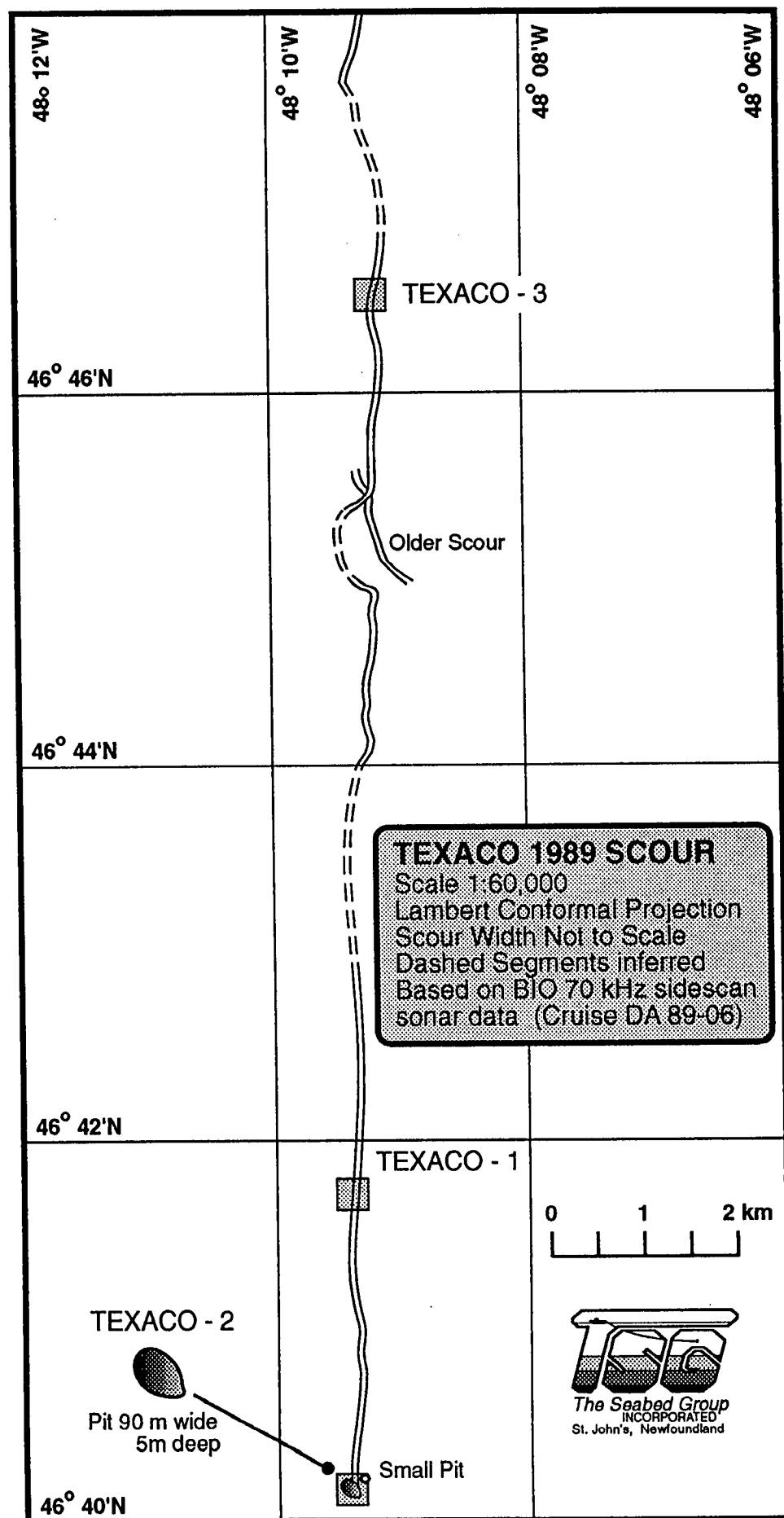
Figure 10. Reduced scale drawing of the Texaco 89-01 scour.

iceberg southwards. The initial touchdown point was beyond the range of the survey. Where first detected by the survey, the scour is less than 1 m deep and 15 m wide. The scour width increases to a maximum of 80 m and crosses an older scour of similar width about 4.3 km south of the start of the survey. At this point, an area exhibiting high reflectivity, interpreted as gravel, appears in the scour trough.

The iceberg scour terminates in a large pit, about 90 m in width and 5 m below the original seabed. The pit appears to be surrounded on all sides by continuous berms rising from 1 to 3 m above the undisturbed seabed. A smaller pit-like feature, roughly 40 m in width with irregular berms, occurs about 70 m to the northeast of the large pit.

The Klein 100-kHz side-scan sonar data revealed linear ridges parallel to the iceberg track in the scour trough and a complex structure of internal ridges in the interior of the terminal pit, parallel to the exterior berm (Parrott et al. 1989).

ICEBERG SCOUR ENVIRONMENTS

As discussed in section 2, the main processes leading to degradation of seabed features on the continental shelves of eastern Canada include regional sediment deposition, repetitive iceberg scouring, local sediment transport and biophysical processes. On northeastern Grand Bank, regional sediment deposition is negligible and is not considered an important factor in the obliteration of seabed features.

Repetitive iceberg scouring may be an important mechanism contributing to scour degradation, however, its relative importance is unknown at the present time.

The relative importance of local sediment transport and biophysical processes in the degradation of iceberg scours will depend on the particular scour environment, where each scour environment is distinguished by a unique set of hydrodynamic, sedimentary and biological characteristics. Three main scour environments covering the range of conditions encountered by the four scours will be described in this section.

Previous studies (Davidson et al. 1988; Hodgson et al. 1988) have found that the general morphology of new scours depends on the type of sediments into which the iceberg penetrates. The communities of benthic organisms present at a particular site and the intensity of sediment transport events also depend on the characteristics of the bottom substrate, although the near-bed current climate plays an important role as well. The following scour environments have therefore been classified primarily in terms of sediment type, with secondary divisions based on the local hydrodynamic climate.

The three scour environments identified for the purposes of this project are: surficial sand (may include some gravel), cohesive sediments, and gravel lag or surficial pavement. These environments have been identified primarily through interpretation of geophysical and side-scan sonar records, calibrated where possible by bottom grab samples and visual observations. However, it should be noted that some degree of uncertainty is associated with the determination of sediment

45

type from side-scan records, as exemplified by the ambiguity between rippled sands and gravelly sediments (J.V. Barrie, personal communication, Geological Survey of Canada, 1990). Table 1 shows the distribution of scour environments for the four study sites.

TABLE 1

Distribution of scour environments in the study areas

	Bowers Pit	Scour 95	Husky 88-01	Texaco 89-01
Surficial Sand	■	■	■	■
Cohesive Sediments	■		■	
Gravel lag or pavement	■		■	

Surficial Sand

The Texaco 89-01 and Husky 88-01 scours, in addition to major portions of Scour 95, have been interpreted to occur mainly in sandy sediments. Both the Texaco and Husky features were surveyed relatively soon after formation, giving some information on the characteristics of new scours in sandy

sediments.   Unfortunately, visual confirmation of the
interpreted scour features was not available for either site.
The surveys of Scour 95 provide information on the
characteristics of a somewhat degraded feature in this
environment.

New scours in sandy sediments appear to have distinct
berms, although the morphology of these berms varies
considerably.   Woodworth-Lynas (1989) describes portions of
the Husky 88-01 scour berms as confused and indistinct;
however, he suggests that this area represents the location of
the stationary grounded iceberg.   Conversely, the pit
associated with the Texaco 89-01 scour has well-developed
berms surrounding the pit on all sides and rising up to 3 m
above the original sea floor (Parrott et al. 1989).   In the
areas where Scour 95 cuts through sands, the scour berms,
representing the morphology of a somewhat degraded feature,
have been interpreted as having low relief, with berm
sediments dispersed in plumes over the surrounding sea floor.

Side-scan sonar data for the Texaco 89-01 scour indicate
linear ridges in the scour trough parallel to the iceberg
track.   Linear features in scour troughs have been attributed
to boulders and other large debris embedded in the keel of a
scouring iceberg (Woodworth-Lynas 1989) or to irregularities
in the iceberg keel itself (Parrott et al. 1989).   Linear
features appear to be absent from older scours in sandy
sediments, probably indicating seabed reworking by local
sediment transport processes.   It is expected that these
linear features would be degraded relatively rapidly, perhaps
within a year of scour formation.

47

Although both local sediment transport and biophysical processes contribute to the degradation of scours in sandy sediments, it is expected that sediment transport processes are the major factor leading to scour obliteration. The influence of benthic biota will be limited to small-scale sediment dispersion around individual organisms and to changes in the sediment shear strength.

Sediment transport can either as bedload or as suspended-load transport. In areas of fine silty sands, suspended-load transport is likely to be the dominant transport mode, whereas bedload transport is likely to be dominant in medium to coarse sands and gravels. The relative efficiency of these two transport modes in the degradation of bottom features is unknown.

The rate of degradation of scours in sandy sediments will depend to a large extent on water depth. Scours in deeper waters are more protected from the effects of storms and surface waves; as discussed in section 2, sediment transport events are less frequent and less intense than in shallower waters. For similar sediment grain sizes, scours in deeper water depths will be preserved for a longer period of time.

Included in this scour environment are features occurring in sandy gravels or gravelly sands (Bowers Pit and scour), where the gravel content of the surficial sediments is too low for an armour layer or surficial pavement to develop. The degradation rate for scours in these coarser sediments will be somewhat slower than for features in fine- and medium-grained sands in similar water depths.

48

Cohesive Sediments

Sediments of the Banquereau formation underly the surficial sediments in the Hibernia area. The Banquereau unit consists of interbedded silts and fine sands with hard, overconsolidated clays ranging to more massive sands (Edward L. King and Associates 1989). As the surficial Quaternary section is generally quite thin, some of the iceberg scours have cut through to the underlying Banquereau sediments. For the purposes of this project, the Banquereau sediments are differentiated from the overlying surficial sand unit only when the fines content is sufficiently high to cause the sediment to act in a cohesive manner. In particular, areas of Bowers Pit, the scour leading into Bowers Pit and the mid-section of the Husky 88-01 scour show evidence of disruption of the cohesive sediments underlying the surficial sand unit.

New scours in cohesive sediments are characterized by blocky berm structures and linear features in the scour trough. The cohesive sediments are thought to be extruded in a plastic manner from beneath the scouring iceberg, forming berms composed of large fractured blocks of sediment with near-vertical surfaces exceeding the angle of stability for non-cohesive sediments (Hodgson et al. 1988). Linear features in the scour trough resemble those described for sandy sediments.

Older scours in cohesive sediments tend to have much more rounded berm profiles, reflecting breakdown of the blocky structures. The sediment blocks degrade through a combination of biophysical processes and sediment transport. Bioturbation can cause berm degradation at two scales: large-scale fracturing of cohesive sediment blocks into smaller blocks,

leading to a more rounded berm profile, and small-scale deflocculation of cohesive sediment flocs into smaller particles which can be suspended into the water column and transported away by the ambient tidal currents. In addition, bedload transport of the surrounding surficial sands may lead to infilling of the scour troughs with sandy sediments.

Gravel Lag or Pavement

Large sections of both the scour leading into Bowers Pit and Scour 95 cut through sediments interpreted as sand with a surficial lag layer or pavement. The coarse surficial layer ranges in size from gravel to cobbles with occasional concentrations of boulders.

The scouring event will disturb the surficial layer of coarse sediments, exposing finer sandy sediments at the seabed/water interface. The gravel material previously armouring the seabed will be mixed with the underlying sands and perhaps will be incorporated preferentially into the scour berms rather than into the scour troughs. New scours will probably resemble those described for the surficial sand environment.

Initially, scour degradation will occur mainly as a result of sediment transport processes. Berm sediments will be dispersed into the scour trough and onto the surrounding seabed. Trough infilling may be limited by a lack of sediment supply from the surrounding armoured seabed. As degradation proceeds, an armour layer may redevelop, protecting the scour berms from further degradation except during extreme storm events.

5. SURVEY METHODS

Many survey techniques have been developed to investigate
the surface and shallow subsurface geology of continental
shelves throughout the world, primarily as a result of
interest in offshore oil and gas reserves. Table 2 lists the
equipment available for use in such surveys, with the
particular equipment and survey techniques used to study the
four scours summarized in Table 3.

This section contains a review of the survey techniques
and equipment previously employed in the study of the four
scours. The purpose of this review is to evaluate the
effectiveness of these techniques both in characterizing the
surficial geology and sedimentary processes at the scour sites
and in providing quantitative information on rates of change
in dimension of the scour features. The survey techniques
have been subdivided into five categories: seismic profiling
techniques, side-scan sonar surveys, visual techniques,
sediment sampling, and sediment accumulation/erosion
measurements. Details of individual surveys are contained in
Appendix 1.

SEISMIC PROFILING

The reflection seismic technique uses the principle that
sound propagates in a medium outward from the source until it
is acted on by physical changes within that medium. The
physical changes are invariably associated with changes in the

TABLE 2

List of seabed monitoring techniques and available equipment

REMOTE MEASUREMENTS	DIRECT MEASUREMENTS

Geophysical techniques

Side-scan sonar
    BIO 70-kHz
    Klein 100-kHz
    Klein 50-kHz
    Klein 3-channel
    EG&G dual-frequency
    ORE 100-kHz
    sector scanning sonar

Seismic profiling
    Huntec DTS internal
    Huntec DTS external
    Huntec DTS sparker
    NSRF sparker
    airgun 10"
    airgun 40"
    12-kHz sub-bottom
    3.5-kHz sub-bottom

Echo-sounder

Special presentation techniques
    Seismic profiling
        reconfigured EPC
        ARM or C-ARM
        bottom-aligned
    Side-scan sonar
        slant range correction
        expanded display

Visual techniques

Camera systems
    BRUTIV (still and video)
    ROV
    BROWSER system
    bottom tripod camera

Submersible observations

Seabed sampling

Core sampling
    gravity
    piston
    rotary
    vibracore
    geotechnical borehole
    box core
    submersible core

Grab sampling
    IKU
    Shipek
    Van Veen
    submersible grab

Sediment concentrations

Direct Sampling

Acoustic measurements

Optical measurements

**Sediment
accumulation/erosion**

Depth-of-disturbance rods

Sediment traps
    suspended load traps
    bedload traps

**Sediment transport
processes**

Tracer experiments
    radioactive
    non-radioactive

TABLE 3

Equipment and techniques used previously at the
four study scour sites

	Bowers Pit	Scour 95	Husky 88-01	Texaco 89-01
Sidescan sonar				
BIO 70-kHz	•	•	•	
Klein 100-kHz	•	•	•	
Klein 3-channel	•	•		•
EG&G dual-frequency	•			
ORE 100-kHz		•		
Seismic profiling				
Huntec DTS internal	•	•	•	•
Huntec DTS external		•	•	•
airgun 10"	•	•		•
airgun 40"	•	•		
12-kHz sub-bottom	•			
Echo-sounder	•			
Special presentation				
reconfigured EPC			•	
Visual techniques				
BRUTIV	•	•		
submersible observations	•			
Core sampling				
geotechnical borehole	•	•		
Grab sampling				
IKU	•			
Van Veen		•	•	
submersible grab	•			
Sediment accumulation				
depth-of-disturbance rods	•			

acoustic characteristics of the material such as acoustic impedance (a product of sound speed and bulk density) and are often manifest as boundaries between the different materials. At a boundary, the acoustic energy that forms the wave front will be subject to redirection; some of the energy will continue into the "new" medium, in about the same direction as the incident wave front, whereas a certain percentage will be reflected back towards the source. It is this reflected energy that is detected at some point in space in the vicinity of the original source and used to produce the scaled "seismic sections". These seismic sections or profiles, when obtained continuously and regularly along a transect, form the graphic display (output) of the reflection seismic technique.

The prime requirements for seismic profiling are, therefore, the sound source, the medium, the target boundaries and the receiving system, all integrated within a certain geometric framework.

The characteristics of source and receiver, together with their geometric arrangement, directly control the quality of the seismic profiles relating to a particular geologic setting. Also, the nature of the target boundaries themselves affect the characteristics of the resulting display. The problem in obtaining the most useful geomorphic information about the seabed is to select a source and receiver and then to operate the combination in the most appropriate manner with the optimum geometric configuration. This optimization is not trivial in that quite often conflicts will arise that will force certain compromises to be implemented.

The classic compromise is between seabed penetration and resolution, in which the need for low frequencies to minimize

acoustic absorption conflicts with the short pulses (high frequencies) required for high definition of seabed features. This conflict results in a compromise between target depth and resolution potential in the shallower sediments.

The most common method of addressing this problem is to use a number of different profiling systems and design each system for particular target zones. The Huntec Deep Tow Seismic (DTS) system, for instance, is designed for high resolution profiling of reflectors to depths of 100 m beneath the sea floor in continental shelf areas.

The Huntec DTS system produces a high fidelity (repeatable) impulse with the wide spectral characteristics necessary for high definition profiling. The wide source bandwidth gives the Huntec DTS the theoretical capabilities to resolve layered targets to an accuracy of 20 cm. The deep tow capability offers several advantages in that the source and the receivers can be positioned in an acoustically quiet environment removed from the effects of ship, wave and sea surface noise. Compared to surface towed systems, system motion is much reduced and operation in more severe weather conditions is possible. As well, a deep-towed system can be operated closer to the seabed, resulting in a reduced aperture, or footprint of the sound impinging on the sea floor, and giving better spatial resolution of targets in the horizontal direction.

Certain broadband seismic receiving systems, as well as seismic sources, have an effective aperture due to their directional characteristics. The overall system performance is, therefore, a function of both source and receiving apertures. However, another conflict exists with commonly

55

used, eel-type receiving arrays due to the near-field limits.
If used too close to a target, bandwidth reduction will take
place, resulting in reduced resolution (smearing) in both
vertical and horizontal directions.

The importance of aperture size depends strongly on the
type of target geology. For flat-lying and smooth topography
where the surface roughness of the layers or the boundaries
between layers is less than the dimensions represented by the
effective length of the pulse of the incident sound, a large
aperture can be tolerated as most of the acoustic energy is
specularly reflected. In other words, the acoustic boundaries
act as plane reflectors. However, if a boundary or surface is
relatively rough or undulating, then it does not act simply as
a plane reflector, but rather as a scattering target or as an
assembly of smaller scattering centres. The effect of this
scattering process is that the seafloor and deeper boundaries
within the seabed appear diffuse rather than as distinct
boundaries on the seismic sections. This effect is
exacerbated by increasing the distance between the source and
target or when inhomogeneities within the geological structure
approach the dimensions represented by the acoustic pulse.

Such is the case with the sediments that make up the
seabed in the vicinity of the iceberg scours addressed in this
project. The surficial sediments overlying the undulating
surface of the Banquereau sediments are very thin, varying in
thickness from zero to several tens of metres. Thus, the
rough nature of the boundary forms a diffuse target which will
scatter sound energy rather than act as a plane surface
reflector.

56

An acoustic profile collected with a wide aperture, high-resolution seismic profiling system is not likely to exhibit a well-defined boundary between the surface of the older sediments and the overlying Quaternary sediments, except where the boundary is reasonably flat for a considerable distance (100 m). The effects of this distributed target on the resulting seismic section are exacerbated by the fact that the echo produced is interpreted as a coarse sand or gravel lag layer which is not very different acoustically from the underlying materials.

SIDE-SCAN SONAR

Side-scan sonar systems were originally developed to acquire plan-view images of the surface of the seabed through the use of a broad-angle acoustic beam. In normal use, a pair of transducers together with a receiving system are mounted in a towed fish. Images of the sea floor are obtained parallel to the path of the tow-fish, covering a swath extending from beneath the fish out to some predetermined width on each side of the tow path.

Side-scan sonar systems use relatively high frequency sound pulses, ranging from 10 to 500 kHz depending on the particular system. In general, higher frequencies provide greater resolution of sea floor features at the expense of the width of the sea floor swath covered by the survey line. For example, a 100-kHz side-scan system can resolve bottom features on the order of 1.0 m in size, whereas a 500-kHz system has a resolution of less than 0.5 m. Typical total

57

swath widths are greater than 750 m for the 70-kHz system, 500 m for the 100-kHz system, and on the order of 100 m for the 500-kHz system.

Images of the sea floor are created from the signals returning to the receiver as reflections from the sea floor. The returning acoustic pulses are presented as light to dark images on paper records, with the degree of darkening of the paper a function of the amount of energy reflected from the sea floor back to the acoustic receiver mounted on the tow-fish.

The reflectivity of the sea floor is influenced by the sediment type and by any roughness elements on the seabed. Roughness elements may consist of relatively large-scale features, such as shipwrecks or iceberg scour marks, as well as smaller-scale bedforms and individual boulders or cobbles. Large objects such as boulders and larger bedforms, in addition to providing a highly reflective surface, also produce an acoustic shadow in the lee of the feature which appears as a white area on the recording paper. These seabed reflections combine to provide an oblique plan view of the morphology and texture of the sea floor.

Several factors must be considered when interpreting and comparing side-scan sonar records: scale distortions, thermocline effects, sources of seabed reflectivity, and relative position of the survey path with respect to the seabed feature of interest. Scale distortions include those in both slant range and aspect ratio. Slant range distortions arise from the difference in the length of the sound travel path from the inside to the outside of the swath and result in a compression of the side-scan record close to the centre-

line, with a relative expansion at the outer edges. Aspect ratio distortions result when the cross-track scale differs from the along-track scale. The cross-track scale is a function of the sonar system whereas the along-track scale depends on the ship speed. These scale distortions may be corrected through appropriate data processing.

The presence of a distinct thermocline below the level of the tow-fish will produce interference at the outer limits of the swath. This interference arises from differences in water density and thus the speed of sound propagation above and below the thermocline, together with the associated sound wave refraction processes. Thermocline interference can be minimized by towing the fish below the thermocline level where possible.

The relative darkness of the resulting side-scan sonar records indicates the reflectivity of the seabed; reflectivity varies with sediment type and seabed roughness characteristics. However, in some cases different seabed conditions can lead to similar reflectivity values. For example, a bidirectional rippled sand field may produce the same degree and type of energy reflection as a gravel or cobble surface, leading to problems in record interpretation. When repetitive surveys of the same feature are conducted, changes in the relative angle of the survey track to the axis of the scour may also introduce apparent, rather than real, changes in scour morphology and create further difficulties in record interpretation.

In terms of iceberg scour features, side-scan sonar surveys indicate the seabed sediment type and provide some quantitative information on the dimensions of the scour. The

width and length of the scour can be resolved relatively simply from side-scan records, but the scour relief is difficult to ascertain from what are essentially plan-view images of the seabed. Some estimates of berm height and furrow depth can be calculated based on the width of the shadow zone and the relative position of the tow-fish; more quantitative information is available from points where the survey track crosses the scour. Repetitive side-scan surveys provide information on large-scale morphological changes in seabed features but lack the resolution necessary to accurately quantify the rate of degradation of scour features.

Three types of side-scan sonar systems have been used in the previous surveys of the study scour sites: the BIO 70-kHz side-scan system, a Klein model 531T 100-kHz side-scan sonar with a third channel for display of the altimeter echo, and an EG&G model 260 side-scan system with dual frequency (100 kHz and 500 kHz) capabilities.

As summarized in Appendix 1, each of the side-scan sonar surveys has suffered to some degree from scale distortions. The different cross-track and along-track scales used in these surveys exacerbate the problem of presenting the data in the form of 1:1 scaled mosaics or composites. As well, all survey data are presented at different scales, hampering inter-survey comparisons. Slant-range correction is also required if good mosaics are to be produced, unless the tow-fish is very close to the sea floor (within 5 m).

The BIO 70-kHz side-scan provided good regional data but did not have the resolution to accurately resolve the seabed changes that may have taken place between return visits to the scour sites. The Klein 100-kHz side-scan sonar had the

capability to resolve more subtle changes in the seabed but was limited by operational constraints such as ship's speed and tow-fish height above the sea floor.

Although a 500-kHz side-scan sonar system was not used in any of the surveys, it has the capability to resolve seabed features smaller than 0.5 m. This level of seabed resolution should be adequate to resolve gross changes in scour morphology.

To maximize the usefulness of data from the side-scan sonar system, the repetitive mapping survey must be completed using the same settings for the following survey parameters: tow-fish height from bottom, ship speed and survey track orientation. Such uniformity can best be accomplished by using a towed remotely operated vehicle (ROV) with an attached side-scan sonar system. The survey grid should be designed with uniformly spaced survey lines, with lines running both parallel and perpendicular to the axis of the scour.

VISUAL

The BRUTIV (bottom referencing underwater towed instrument vehicle) system has been deployed as a camera and video sled on Bowers Pit, Scour 95 and in the vicinity of the Husky 88-01 scour. BRUTIV is usually towed 3 m above the sea floor (Parrott and Lewis 1986), with real-time video fed directly to the survey vessel. Photographs are processed after recovery of the vehicle. Although stereo photographs of

the sea floor were obtained in the vicinity of the Husky 88-01 scour, no photographs were obtained of the scour itself.

The BRUTIV surveys in the Scour 95 and Bowers Pit areas provided photographic records of the types of surficial sediments, the relative roughness of the sea floor, the characteristics of bottom bedforms and the nature of the sea-floor biota. The stereo photographic capabilities provide quantitative information on the relief of bottom features. However, repetitive surveys of a specific feature or area are difficult without a towed-body positioning system. In addition, for large-scale relief features the photographic process may lack the capability to resolve feature dimensions quantitatively, particularly when the scale of the feature exceeds the viewing field of individual photographs.

SEDIMENT SAMPLING

Numerous seabed sampling devices have been used at the four scour sites. Van Veen and Shipek samplers obtain a relatively small sample of the uppermost 10 to 15 cm of the surficial seabed material. Large sampling devices, such as the IKU grab sampler used in the Scour 95 area and the clam shell grab used at the Husky 88-01 site, obtain larger samples with greater penetration into the seabed. At best, it is possible to obtain relatively undisturbed samples of the uppermost 20 cm of the seabed using one of the larger devices.

The use of free-fall coring devices in the study area is limited by the relatively hard nature of the seabed sediments.

Submersible rotary coring equipment has not been successful in this area, again because of difficulty in penetrating the relatively hard seabed sediments. Vibrocoring has been successful in sand but problems in core recovery are encountered in gravel areas and in overconsolidated sediments.

Two boreholes were completed at the Bowers Pit site by a surface-mounted drill rig aboard the MV Balder Challenger, with one borehole inside the pit and the second located outside. Coring was successful to a depth of 80 m inside the pit and to a depth of 15 m outside the pit. Samples were obtained at regular intervals although the recovery of samples in the upper 2 to 3 m was limited by seabed disturbance. Samples are in the process of being analysed for geotechnical properties.

SEDIMENT ACCUMULATION/EROSION MEASUREMENTS

A depth-of-disturbance (DOD) rod was deployed in the centre region of Bowers Pit in October of 1984 and revisited in August 1985. This rod consisted of a graduated steel shaft 1 m long. A flat ring was placed around the shaft and connected to an indicator arm 30 cm in length. The rod was inserted into the seabed using a hydraulic wrench mounted on the SDL-1. At the time of deployment, the flat ring rested on the surface of the seabed.

Net seabed erosion or sediment accumulation can be observed directly on the graduated rod. Where bedload sediment motion predominates, the position of the flat ring

will reflect the bottom of the mobile sediment layer, i.e., the limiting depth to which sediment disturbance has occurred since rod placement.   The lowest seabed level will be a distance above this point corresponding to the thickness of the mobile layer.   Where suspended load transport predominates, the position of the flat ring will directly reflect the lowest level of the seabed surface since rod placement.

6. EXPERIMENT DESIGN

The experimental program outlined in this chapter is designed to characterize and quantify the rate of change in dimensions of the four iceberg scours, and to provide data to be used in extrapolating observed sediment processes and scour degradation rates to other study sites. Three types of data are required to achieve these goals: regional, remotely sensed data; localized measurements of degradation rates in the various scour environments; and site-specific hydrodynamic, biologic and sedimentologic data needed to extrapolate measured degradation rates to other, unmonitored, study sites. The recommended experimental program has been divided into modules which correspond to these three types of data.

Remotely sensed seabed monitoring techniques, as listed in Table 2, include geophysical survey methods in addition to bottom photographic techniques. These monitoring techniques are considered remote in that information about the seabed is inferred rather than measured directly. Typically, geophysical surveys are used to characterize the surface and subsurface sedimentary environments on a regional basis, with both calibration information and site-specific details obtained through visual survey methods and actual bottom samples.

Previous geophysical surveys of the four scour sites have been discussed in the technical methodology section of this report, where several problems endemic to side-scan sonar and seismic profiling surveys have been highlighted with recommendations made for improvement in survey techniques and resultant data quality. Geophysical techniques are useful in

65

providing qualitative information on a regional basis, but these survey methods cannot accurately quantify changes in dimensions of seabed features.

Although unable to accurately measure small changes in seabed features, side-scan sonar and seismic profiling surveys do provide a picture of the sedimentary characteristics and active sedimentary processes in a given area, as well as indicating the frequency of occurrence of iceberg scours. Repetitive seismic mapping of the study areas will provide information on large-scale changes in seabed characteristics, such as development of a surficial lag layer and changes in the direction of bedform orientation. Repetitive mapping can also be used to determine the relative importance of repetitive iceberg scouring as a scour degradation mechanism. However, the existing survey lines are not adequate, in terms of both quality of data presentation and quantity of seabed coverage, to provide a baseline data set for comparison with future surveys. The geophysical survey module described in the next sub-section includes recommended procedures for both baseline and repetitive surveys.

In measuring dimensional changes in seabed features, an error of at least 0.5 m is generally associated with geophysical survey methods. Rates of change in scour dimensions may be only centimetres per year (i.e., Bowers Pit infilling of approximately 4 mm in about one year) and thus would not be revealed by geophysical techniques. Localized measurements of dimensional changes, using in situ instrumentation rather than remotely sensed techniques, are required to measure the expected small dimensional changes. In addition to resolving small changes in scour dimensions, in situ instrumentation must be tailored to each separate scour

66

environment. The sub-section on in situ instrumentation describes recommended equipment for all scour environments encountered at the study sites.

The first two modules of the proposed experimental program should provide accurate measurements of the scour degradation rates at the four study scour sites. However, these measurements cannot be extended to unmonitored scour sites without some understanding of the relative magnitudes of the various scour degradation processes and their respective driving forces. Whereas an experiment designed to collect only direct measurements of rates of dimensional change of scours will provide some useful insights into scour degradation, it is recommended that additional data be collected to serve as a basis for the future modelling of degradation processes.

Although the contribution of repetitive iceberg scouring to scour degradation can be assessed through repetitive seismic mapping at each site of interest, the importance of the remaining degradation processes depends on the driving forces at each site. For example, the rate of scour trough infilling caused by local sediment transport is driven by the near-bed currents and depends on the nature of the seabed sediments. Similarly, the rate of berm degradation from biophysical processes will vary with the benthic biota and perhaps the near-bed hydrodynamic climate. To extend the measured scour degradation rates to other sites of interest, individual degradation processes must be identified, quantified and related to the driving forces at each site. The third module of the proposed experimental program is designed to collect the supplemental data required to extend measured degradation rates to other sites of interest.

REMOTELY SENSED DATA

As discussed above, remotely sensed data include both geophysical survey data and photographic records of the seabed. Remotely sensed data can be subdivided into regional data and site-specific data, with the former covering the entire scour and the latter focusing on the in situ monitoring sites.

It is recommended for this study that the Huntec DTS system be used in a combined system with a 100-kHz side-scan sonar as the primary equipment for regional geophysical characterization. Specifications for both the Huntec DTS and the 100-kHz side-scan systems are contained in Appendix 2 of this report. These data will resolve gross changes in scour morphology in addition to defining general sea floor topography, seabed features and sediment types.

Survey lines should be run in a rectangular grid pattern, with lines both parallel and perpendicular to the main axis of the scour. Spacing of survey lines should be roughly 250 m in order to give 180% coverage of the scour with some overlap between survey lines. A minimum of two lines is required in the scour-parallel direction and adequate line extensions should be added at each end of each line. Where the scour is sinuous, sufficient scour-parallel lines should be added to cover the scour completely at a line spacing of 250 m. Short cross lines should be 250 m apart over areas of particular interest but could be further apart elsewhere.

Echo-soundings, corrected to the hydrographic chart datum of lowest normal tide, should also be collected in conjunction

with the regional surveys. A 70-kHz side-scan sonar system could also be deployed at the same time to give wider swath coverage of the scour and surrounding seabed. Water temperature and salinity profiles should be collected daily during the surveys to provide information on the position of the pycnocline and sound velocity within the water column.

For characterization of the in situ monitoring sites, it is recommended that a towed ROV equipped with a 500-kHz side-scan sonar, a 3.5-kHz sub-bottom profiler or narrow-beam echo-sounder and a stereo camera unit be used in a close-grid survey. The ROV must have directional capabilities and a towed-body positioning system including real-time video, so that the position of the tow-fish with respect to both the survey vessel and the sea floor can be calculated accurately. A ROV similar to the Focus 300, distributed by MacArtney ApS, is recommended. Specifications for the ROV system are given in Appendix 2.

For each monitoring site, a rectangular grid pattern should be used with survey lines at 400-m intervals. A single ROV line should also be run along the entire length of the scour by using the steering capabilities of the ROV.

IN SITU MEASUREMENTS

The in situ measurement program is designed to obtain detailed measurements of the rates of change in scour dimensions at specific monitoring sites, primarily through the use of bottom-founded equipment. The choice of monitoring

sites will be discussed prior to the description of the in situ monitoring equipment.

Monitoring Sites

The monitoring sites have been chosen to encompass a range of environmental factors affecting scour degradation rates. The main environmental factors influencing degradation rates have been identified previously as water depth, scour environment and type of feature (i.e., pit or furrow).

The four scours of concern to this project occur in three water depth ranges, encounter three types of scour environments and include both scour furrows and pits. To complete a basic investigation of the relative influence of scour environment, water depth and the type of scour feature on the rate of scour degradation, it would be necessary to instrument at least 18 sites. These 18 sites would represent one pit and one furrow in each of three water depths and three scour environments. Ideally, more than one pit and furrow would be monitored in each of the combinations of water depth and scour environment.

However, the choice of appropriate sites is limited by the combination of environmental factors actually present at the four scour sites. For example, cohesive sediments have not been identified at the Texaco 89-01 site in the middle depth range and a pit appears to be absent from the Husky 88-01 site in the deepest water. As well, the furrow monitoring sites should be chosen in relatively straight sections of the scour so that areas of strong velocity gradients in the along-scour direction are avoided. Although curves and direction

changes in the scour track may affect degradation rates, it is suggested that the relative importance of such changes be examined qualitatively through the regional remotely sensed monitoring program.

The proposed monitoring sites have been chosen to represent the variety of environmental conditions covered by the four scours. The sites have been divided into first and second priority to provide some guidance in selecting sites when the availability of equipment or ship time is limited. The eight first-priority sites include a scour pit and a scour furrow at each of the study sites, while the five second-priority sites represent additional scour furrow sites. The monitoring sites shown in Figures 5, 8, 9 and 10 are marked as general areas rather than as specific sites to allow the exact monitoring sites to be chosen based on the visual information obtained in the remote surveys.

First-priority Sites

Husky-1. Located in the mid-section of the Husky 88-01 scour furrow, between the two main curves of the M-shaped scour, this site represents a scour furrow in the deepest water range and in sandy sediments. The blocky-appearing region in the scour trough should be avoided and the monitoring site located in a relatively straight, uniform section of scour if possible. Unfortunately, the scour in this region is relatively short and variable and may, on closer investigation, prove too confused for a suitable monitoring site. If no suitable site is identified during the preliminary site investigations, it is recommended that site Husky-3 be substituted for this site.

Husky-2. This site is the terminal pit of the older feature, Scour "A", identified during previous surveys. Although the age of this feature is unknown, monitoring of this site would

provide information on degradation rates for a pit-type feature in sandy sediments in roughly 125 m of water.

Texaco-1. Located on a straight section of the scour furrow in about 110 m of water, this site is in the middle depth range of the scours of concern to this project. The sediments in this area consist of fine- to medium-grained sands and the scour feature appears to be well-developed in this region.

Texaco-2. The terminal pit at the Texaco 89-01 scour site occurs in about 110 m of water, in a region where seabed sediments consist of a thin layer of medium sand over a subsurface layer of silty sand or sandy silt.

Bowers Pit-1. This site is located at the transition zone between surficial sandy sediments and the gravel lag area for the scour furrow leading into Bowers Pit. Monitoring of this site will provide important information on the relative rates of scour degradation in these two scour environments. The gravel lag area is the only confirmed region of a scour furrow where the underlying cohesive sediments have been disrupted by the scouring process.

Bowers Pit-2. Bowers Pit is located in the shallowest water depth range of the study sites, where local sediments include boulders, gravels, sands and cohesive materials.

Scour 95-1. This monitoring site is located on a section of the scour furrow where surficial sediments are composed of either gravelly sands or sands with a gravel lag layer. Cohesive sediments appear to be absent from this scour.

Scour 95-2. The terminal pit associated with Scour 95 appears to be incised into sandy sediments.

Second-priority Sites

Husky-3. This site is located on the short touch-down scour portion believed to have been formed after the initial iceberg grounding event. This site represents a scour furrow in the deepest water range and in sandy sediments and is presented either as an alternative or in addition to site Husky-1. If neither of these scour sections provide a suitable site for monitoring of degradation rates, it is recommended that a site be picked on one of the older scours, Scour "A" or Scour "B", also identified during the previous surveys of this scour.

Husky-4. If preliminary surveys indicate that the blocky-appearing region in the mid-section of the scour furrow is composed of cohesive sediments, this site would represent the only location in deeper water where cohesive sediments may have been disrupted by the scouring process.

Texaco-3. Similar to Texaco-2 in that it represents a scour furrow in sandy sediments, this site is separated from the first site by a distance of about 8.0 km. Monitoring of this site will provide useful comparison data and provide some indication of local variability in scour degradation rates.

Bowers Pit-3. Located in about the middle of the gravel lag section of the scour furrow leading into Bowers Pit, this site has been chosen to give more data on the rate of scour degradation in gravel lag areas where the subsurface sediments are cohesive in nature.

Scour 95-3. This monitoring site has been located in the sand-wave portion of Scour 95 to give more data on degradation rates in sandy sediments.

Although this list of monitoring sites appears definitive, it is based on somewhat limited information regarding the nature of the seabed sediments and the morphology of the scour features, particularly for the more recent Texaco and Husky scours. The monitoring sites may have to be adjusted based on the results of the preliminary geophysical survey work.

These thirteen monitoring sites represent the minimum number of monitoring sites required to adequately study the rates of scour degradation under the variety of environmental conditions encountered at the four study scour locations. If additional ship time is available to monitor more sites, it is recommended that additional locations be chosen along straight portions of the scour furrows for each of the four study scours, with precise monitoring locations based on the results of the preliminary survey work.

Monitoring Equipment

Accurate measurements of the rate of degradation of scour features can be obtained only through the use of bottom-founded equipment. The recommended equipment for this task includes an ROV or submersible, equipped with a 500-kHz sector scanning sonar and a stereo camera system adjustable to permit photographs in the vertical plane. If an ROV is used rather than a submersible, a real-time video camera system is required to permit accurate vehicle positioning. Bottom sediment sampling capabilities are also required. Depth-of-disturbance rods are recommended for monitoring sediment accumulation or erosion rates.

The sector scanning sonar is to be used to produce accurate, localized views of the scour morphology. For furrow locations, it is recommended that the sector scanning sonar be deployed in a transect across the scour. It is recommended that 360° scans are completed from positions located to the outside of each scour berm, at the top of each berm crest and from the centre of the scour trough. In scour pits, it is recommended that two perpendicular transects, aligned with the major and minor pit axes, are completed in a similar manner. Suggested instrument locations for scour furrows and pits are shown in Figures 11 and 12, respectively.

Stereo photographs of the scour feature are to be taken in the horizontal plane and the vertical plane. The more conventional horizontal-plane photographs give a plan view of the seabed and should be obtained along the same transects as those used for the sector scanning sonar, with 100% coverage of the transect by stereo pairs.

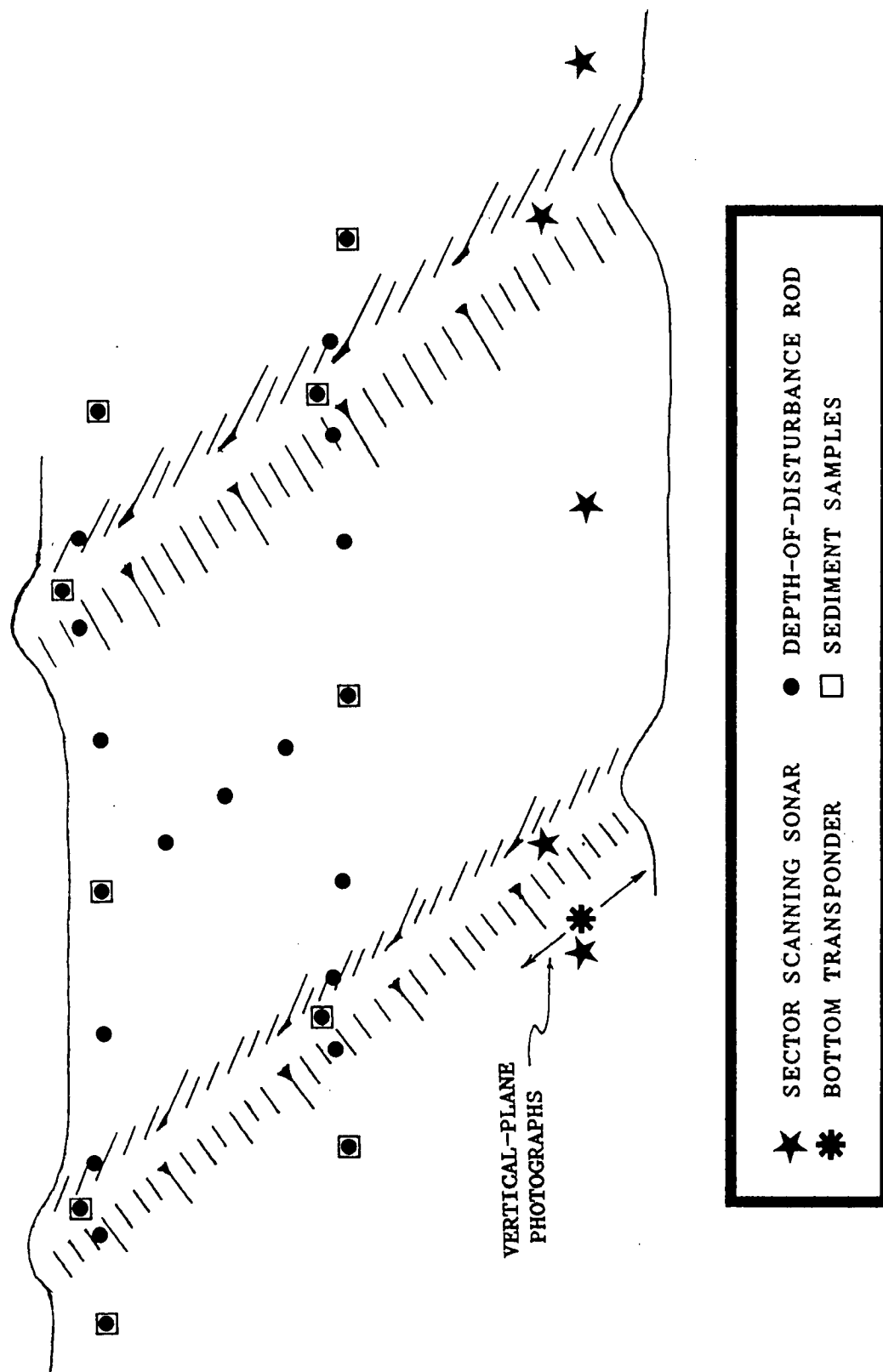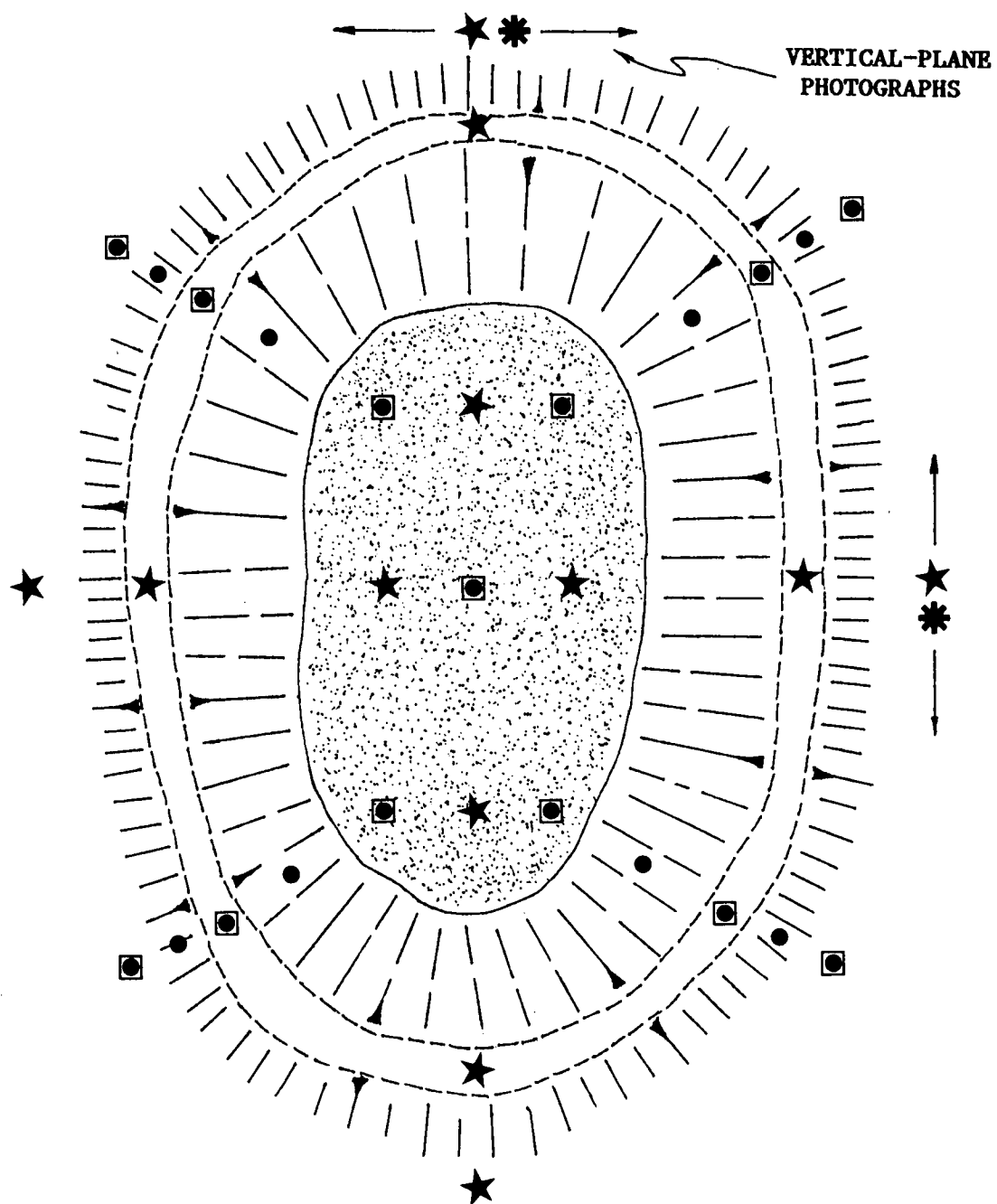Figure 11. Instrument locations for scour furrow monitoring sites.

Legend:

★ SECTOR SCANNING SONAR
★ BOTTOM TRANSPONDER
★ DEPTH-OF-DISTURBANCE ROD
□ SEDIMENT SAMPLES
✱ VERTICAL-PLANE PHOTOGRAPHS

Figure 12. Instrument locations for scour pit monitoring sites.

Vertical-plane photographs will give a detailed view of the degradation of scour berms, particularly when blocky, cohesive berm structures are present. Vertical-plane photographs of the berms are to be obtained along a line parallel to the outer scour berm, centred on and roughly perpendicular to the sector scanning sonar transect line. One line of vertical-plane photographs is recommended for the furrow monitoring sites and two perpendicular lines for the pit monitoring sites. Photographic lines should extend for a minimum distance of 10 m to each side of the sonar transect lines, with 100% coverage of the scour berms in stereo pairs. Suggested vertical-plane photographic survey lines are shown in Figures 11 and 12.

The accurate positioning and relocation of survey lines is crucial to the success of the sector scanning sonar and photographic surveys. This is to be accomplished through the use of accurate shipboard navigation techniques, as outlined in Appendix 2, together with the use of bottom-anchored 100-kHz transponders. Recommended positions for bottom transponders are shown in Figures 11 and 12. As a backup to the bottom-anchored transponders, it is recommended that a passive marking system such as a train wheel with a subsurface float also be used at each in situ monitoring site. However, such a marking system is difficult to position accurately and thus should be deployed a minimum distance of 100 m away from the scour feature of interest.

To provide for maximum repeatability of the survey lines, the equipment used to make measurements must be repositioned with an error of less than 1.0 m. This necessitates the use

of an ROV or manned submersible with accurate positioning capabilities.

Direct measurements of sediment accumulation or erosion may be obtained through the use of depth-of-disturbance (DOD) rods directly implanted in the seabed. However, DOD rods are suitable for use only where any surficial lag layer or pavement is easily penetrated. As discussed in section 5, a DOD rod consists of a graduated steel shaft with a flat ring connected to an indicator arm. These rods monitor both net sediment accumulation or erosion and the depth of the mobile layer.

It is recommended that DOD rods be deployed in an H-shaped pattern at scour furrow monitoring sites, with two scour transect lines and a connecting line down the centre of the scour furrow, as shown in Figure 11. Spacing between rods should not exceed 10 m. The first and last rods in the scour transect lines should be located outside of the scour berms, one rod should be implanted on both the exterior and interior slopes of each berm, one rod at the crest of each berm and a minimum of three rods across the scour trough. The scour transect lines should be about 40 m apart and connected by a line with a minimum of three additional DOD rods down the centre of the scour trough.

The DOD rod sites should be located a minimum distance of 50 m away from the sonar and photographic transect lines in order to minimize site disruption. However, the rods should be deployed close enough to the sonar transects so that bottom conditions are essentially uniform between the two sites. The rods must be deployed and monitored with care since currents induced by the ROV or submersible may significantly bias the

rod readings. The recommended DOD rod arrangement for scour pit monitoring sites is shown in Figure 12.

DOD rods are suitable for monitoring changes in scour dimensions in sediments where a rod can be imbedded in the seabed using a submersible or an ROV and without causing excessive disruption to the seabed. In other areas, such as where scour berms are armoured with pavement-like materials, it may still be possible to monitor part of the scour, such as the trough, using DOD rods. The pattern of DOD rods used at each monitoring site must be adapted based on the local seabed conditions observed during the preliminary survey work.

ADDITIONAL DATA REQUIREMENTS

Extrapolation of the observed scour degradation rates to unmonitored sites requires some quantitative appreciation of the relative magnitudes of the various scour degradation processes and their respective driving forces. This in turn requires additional data on the nature of the seabed sediments, benthic biota and near-bed hydrodynamic conditions. This sub-section contains recommendations for the collection of additional data beyond the basic monitoring of changes in scour dimensions.

Seabed Sampling

Seabed sampling is an integral part of the experimental program. Bottom sediment samples provide calibration

information for the geophysics surveys as well as more detailed information on sediment characteristics affecting sediment transport processes and biological colonization of the seabed. It is recommended that bottom sampling be conducted both on a regional basis as calibration for the regional geophysics program described earlier and on a site-specific basis as part of the in situ monitoring program.

Surficial sediment grain size distributions are required to calibrate the geophysical survey data. Sediment samples should be large enough to include any surficial lag layer or pavement as well as the sediments beneath the surficial material. Sediment samples adequate for this purpose can be obtained using a large sampling device such as the IKU grab sampler (previously used in the Scour 95 area). Small sampling devices, such as the Shipek and Van Veen samplers, cannot obtain an adequate sample in areas of coarser gravel sediments.

It is recommended that a minimum of five grab samples be obtained for each of the four scours. These grab samples should be obtained from the surrounding seabed near the scour and should be distributed along its length. However, care should be taken to avoid the in situ monitoring sites. A locating device should be mounted on the grab sampler to provide the sample location relative to the ship's position. Additional grab samples should be obtained in regions where the geophysics surveys indicate changes in surficial sediment environments.

Sediment samples should also be obtained as part of the in situ monitoring program in order to characterize local variations in sediment properties at the sites where scour

degradation rates are to be measured. It is recommended that sediment samples be obtained using the ROV or manned submersible in conjunction with the implantation of DOD rods. Samples should be obtained from the surrounding seabed, the scour berms and inside the trough or pit. Recommended sampling locations are shown on Figures 11 and 12 for furrow and pit monitoring sites, respectively.

All sediment samples should be analysed for grain size distributions. It is important to analyse the samples in enough detail to differentiate between, for example, fine- and medium-grained sand. It is recommended that grain size distribution curves be presented as percent finer vs. grain size in mm, rather than using the phi-scale more commonly employed by geologists. In addition, the large IKU grab samples should be analysed to determine the infauna present at each sampling site.

Hydrodynamic Measurements

Measurements of near-bed flow velocities are required to quantify sediment transport processes and to relate the hydrodynamic conditions at the monitored sites to unmonitored sites. Two types of near-bed velocity measurements are important: long-term measurements to indicate the range of flow conditions encountered throughout the year and detailed short-term measurements of velocity profiles and shear stresses within the water column.

Long-term measurements are best carried out using an electromagnetic current meter mounted in a tripod-type frame resting on the sea floor. Horizontal flow velocity components

should be measured approximately 1.0 m above the seabed. The current meter should have adequate data sampling capabilities to resolve both mean and oscillatory components of the near-bed flow field. As most of the sediment transport at the scour sites occurs during storm events in the winter months, the current meter should either have adequate data storage capabilities to store one year of data or, alternatively, provisions should be made for changing the data tape at appropriate time intervals. A data collection scheme should be considered in which data are recorded only when flow velocities exceed some minimum value.

Current meters for long-term measurements should be located in the vicinity of the first-priority scour furrow monitoring sites (Husky-1, Texaco-1, Bowers Pit-1 and Scour 95-1). Two current meters should be deployed at each of these sites to collect coincident data in the centre of the scour trough and outside of the scour berm on the surrounding seabed. Current meters should be located in the vicinity of the photographic transect lines.

If the availability of current meters is limited, it is recommended that two meters be deployed at the Bowers Pit-1 site. If only one current meter is available, it should be deployed outside of the scour berm at this site. The Husky-1 or Texaco-1 site should be considered next in priority for long-term current measurements. Long-term measurements at the pit monitoring sites should be considered based on the results of the current measurements at the furrow sites.

Short-term measurements of velocity profiles, together with sediment concentrations within the water column and photographs of the sea floor, should be collected with a

RALPH-type instrument system (Heffler 1984). This type of instrument system combines current meters with bottom photography and sediment concentration measurement systems, with all instruments controlled by a central processing unit with a common data logger. Measurements of this type would be most useful if collected during a winter storm event, however, operational constraints may prohibit instrument deployment during the winter. It is recommended that RALPH be deployed at one site during calmer spring or summer conditions. RALPH should be deployed both inside the scour trough and outside the berm, for a period of about one week in each position. Data collection should be coincident with the long-term current measurements described above. The resulting data should be analysed prior to any additional deployments of this type of instrument system.

SUGGESTED OPERATIONAL SCENARIO

The above experimental program contains tasks to be completed for each scour and for each in situ monitoring site. The tasks for each scour include the Huntec DTS and 100-kHz side-scan sonar surveys, a single towed ROV line, IKU grab samples and deployment of current meters for long-term measurements. Tasks to be completed at each in situ monitoring site include the detailed survey using the towed ROV with 500-kHz side-scan sonar and stereo camera unit, sector scanning sonar transects, stereo photographic transects, implantation of DOD rods and sampling of seabed sediments at the DOD rod sites. In addition, a RALPH-type instrument is to be deployed at one in situ monitoring site.

83

The following operational scenario has been developed assuming that the experimental program will be run completely on one scour at a time; i.e., that all work will be finished on Scour 95, for example, before moving on to the Husky 88-01 scour.

Repeat for each scour:

1) Locate scour feature.

2) Complete Huntec DTS and 100-kHz side-scan sonar surveys of the complete scour.

3) Obtain large grab samples using the IKU grab.

4) For first in situ monitoring site:
   a) Locate site
   b) Deploy ROV equipped with 100-kHz transponder, DOD rods and sediment sampling apparatus
   c) Complete brief site survey, using real-time video capabilities, to locate photographic transects and sites for DOD rod deployment
   d) Deploy 100-kHz transponder
   e) Implant DOD rods
   f) Obtain sediment samples
   g) Recover ROV
   h) Deploy long-term current meters; one in scour trough and one outside scour berm.

5) Repeat steps 4 a through h for remaining in situ monitoring sites.

6) Deploy towed ROV with 500-kHz side-scan sonar system and stereo camera unit; complete surveys of each in situ monitoring site in addition to a single line down the centre of each scour.

7) Recover towed ROV.

8) Repeat for each in situ monitoring site:
   a) Locate site
   b) Deploy ROV with sector scanning sonar and stereo camera unit
   c) Complete sector scanning sonar transect
   d) Complete vertical- and horizontal-plane photographic lines

84

e) Photograph DOD rods with emphasis on
   sediment/rod interface
f) Recover ROV.

If a RALPH-type instrument is to be used, it should be
deployed in conjunction with the long-term current meters in
step 4h and should be recovered after as long a time period as
is feasible.

The above operational scenario describes the recommended
procedures for the first phase of the experimental program.
This phase has been designed to provide good baseline data as
well as to install the necessary monitoring equipment. In
subsequent phases of the experimental program, portions of the
regional surveys should be repeated and the in situ monitoring
sites resurveyed at regular intervals. In particular, steps
2, 6, 7, and 8 should be repeated at regular intervals. In
addition, the current meters must be recovered as necessary to
read and replace the data storage tapes.

It is recommended that the scours be resurveyed and the
in situ monitoring sites revisited approximately one year from
the original survey dates. Since the rates of scour
degradation are expected to be seasonally dependent, it is
important to resurvey the experimental sites at the same time
of year if possible. The frequency of further surveys should
be determined based on the results observed after one year.

ESTIMATED COSTS

The costs associated with undertaking an experimental program such as that outlined above can be subdivided into three main components: vessel charter, lease of geophysical equipment and lease of ROVs. The discussion of these costs is intended to be used as a guide in the preparation of budgetary estimates; costs should be considered as order-of-magnitude estimates only. All costs are given in 1990 dollars.

Vessels

Outside of government agencies, very few vessels are currently maintained in a state of readiness for geophysical operations on the Grand Banks of Newfoundland. One vessel which has periodically operated on the Grand Banks is the MV Arctic Prowler, owned and operated by McElhanney Engineering Surveys Ltd. Although initially commissioned for well-site surveys, this vessel has more recently been involved in pipeline and cable route surveys using both remote- and close-inspection techniques involving small- and medium-sized ROVs. The MV Arctic Prowler is equipped with state-of-the-art navigation systems and handling systems for bottom-operated equipment. Although it lacks a bow thruster, this vessel can be anchored for site work if required. The quoted rate is $6,500 per day, including fuel and operating expenses. When mobilized for full 24-h operation, navigation systems add a further $3,300 per day inclusive of personnel. If the experimental program recommended in this report is to be implemented, it is strongly suggested that the use of a dynamically positioned vessel be investigated.

86

Geophysical Systems

Lease rates for the major components have been obtained from east coast sources. The following rates are for lease on a daily basis; some reduction can be expected for weekly and monthly lease periods.

Huntec DTS system with 100-kHz side-scan	$1,000
Klein 100-kHz side-scan – dual channel	350
ORE 100-kHz side-scan – dual channel	350
3.5-kHz sub-bottom profiler	350

Operators for these systems should be costed at $450 per day.

ROVs

Several ROVs of various sizes are available on the east coast of Canada. Two possible sources are Global Underwater Consultants of Dartmouth, Nova Scotia and Polaris Marine Services Ltd. of St. John's, Newfoundland.

Global Underwater Consultants have a Phantom HD2 ROV which has been used successfully from the <u>Arctic Prowler</u>. This ROV has remote video capabilities and can support a Photo Sea or other still camera system and a sector scanning sonar such as the Mesotech 971. The Phantom HD2 can provide about 45 lbs of downward thrust but is not available with an arm, although one could be fitted. The Phantom HD2 leases for $1,000 per day including operator. The camera and sector scanning sonar systems lease for about $200 per day. A less expensive sonar system, controlled by a PC computer, is available from ROMAR.

Polaris Marine Services Ltd. have three types of ROV available at St. John's. A small inspection device, suitable only for remote observation, can carry remote video, still camera and sonar system. The medium-sized ROV can be fitted with an arm and has the capability of being lowered inside a garage; this system would require substantial modification to insert the DOD rods into the seabed. Both the small- and medium-sized systems would be supplied with two operators for $900 and $1,200 per day, respectively, with an additional preparation fee dependent on the level of customization required.

The third type of ROV available from Polaris Marine Services Ltd. is the Duplus, a third-generation Mantis ROV. This system is possibly the only ROV presently available on the east coast capable of inserting the DOD rods. The Polaris Duplus has powerful manipulators and can be fitted with a carousel to hold the DOD rods and it has been fitted with a stereo camera system in the past. Cost for this unit and its handling gear is about $2,500 per day, including a crew of three.

Consumables

The consumables include the bottom transponders and the DOD rods and can be expected to be about $1,000 per in situ monitoring site.

Mobilization

The expected mobilization time for the recommended experimental program is about two days, with an additional day for demobilization. Assuming two days are required in each direction for transit to and from the study area, a minimum of seven days is required in addition to actual survey time. Extra mobilization time may be required for the larger ROVs to allow for modifications to existing systems.

Survey Duration

No firm estimates of the time required to complete the recommended experimental program can be given because of uncertainties in the amount of bottom time required for the ROV program and the number of in situ monitoring sites per scour. However, a full 24-hour period should be allocated for the remote geophysics program and another 24-hour period for the detailed bottom survey at each in situ monitoring site.

Weather

Only the summer months may give sufficient weather windows to allow for ROV operation. Although geophysical programs have been run year-round in the study area, the winter weather windows may limit operational time to about 20%. For the full experimental program outlined in this section, 4 to 6 weeks of ship time may be necessary to ensure that the major portion of the work on each scour is completed.

REFERENCES

Amos, C.L. and J.T. Judge, in review. Sediment dynamics of eastern Canadian continental shelves. Proceedings of the Canadian Continental Shelf Seabed Symposium, Bedford Institute of Oceanography, October 2-7, 1989.

Banke, E., 1988. Scour survey at Whiterose E-09. Contract report for Husky Oil East Coast Project.

Barrie, J.V., 1987. The origin of Bowers Pit and Scour: a re-evaluation. Contract report to the Geological Survey of Canada, 7 p.

Barrie, J.V., C.F.M. Lewis, G.B. Fader and L.H. King, 1984. Seabed processes on the north-eastern Grand Banks of Newfoundland: modern reworking of relict sediments. Marine Geology, Vol.27, 209-227.

Barrie, J.V. and W.T. Collins, 1985. Preliminary results of investigations into seabed stability in the Hibernia region of the Grand Banks during operations of HMCS Cormorant and SDL-1 submersible. Geological Survey of Canada, Open File Report.

Barrie, J.V., W.T. Collins, J.I. Clark, C.F.M. Lewis and D.R. Parrott, 1986. Submersible observations and origin of an iceberg pit on the Grand Banks of Newfoundland. Current Research, Part A, Geological Survey of Canada, Paper 86-1A, 251-258.

Barrie, J.V. and M.B. Collins, 1989. Sediment transport on the shelf margin of the Grand Banks of Newfoundland. Atlantic Geology, Vol. 25, 173-179.

Chriss, T.M. and D.R. Caldwell, 1984. Universal similarity and the thickness of the viscous boundary layer at the ocean floor. Journal of Geophysical Research, Vol. 89, No. C4, 6403-6414.

Clark, J.I. and J. Landva, 1988. Geotechnical aspects of seabed pits in the Grand Banks area. Canadian Geotechnical Journal, Vol. 25, 448-454.

Collins, W.T. and J.I. Clark, 1986. Submersible investigations into sediment transport and surficial features of the northeast Grand Banks of Newfoundland. Report to the Atlantic Geoscience Centre, Department of Energy, Mines and Resources.

Collins, W.T., D.R. Parrott, J.V. Barrie and B. Imber, 1987. Tools and techniques for manned submersible studies of sediment transport and ice scour on the eastern Canadian continental shelf. Proceedings of the 19th Annual Offshore Technology Conference, Paper OTC 5517, 289-294.

d'Apollonia, S.J. and C.F.M. Lewis, 1985. A numerical model for calculating long term spatial distribution and mean frequency of iceberg grounding events. Ice Scour Workshop, Feb.5-6, 1985, Calgary, Alberta.

Davidson, S.H, J.V. Barrie and S. de Margerie, 1988. Modelling the infilling of seabed depressions. Report to the Atlantic Geoscience Centre, Department of Energy, Mines and Resources.

de Margerie, S. and K. Lank, 1986. Tidal circulation of the Scotian Shelf and Grand Banks. Report to the Atlantic Oceanographic Laboratory, Department of Fisheries and Oceans.

Edward L. King and Associates, 1989. Quaternary Geology of the Hibernia Area of northeast Grand Bank. Report to the Atlantic Geoscience Centre, Geological Survey of Canada, Department of Energy, Mines and Resources.

Fader, G.B.J., 1989. Cruise Report Dawson 89-006. Geological Survey of Canada Internal Report.

Fader, G.B. and L.H. King, 1981. A reconnaissance study of the surficial geology of the Grand Banks of Newfoundland. Current Research, Part A, Geological Survey of Canada, Paper 81-1A, 45-46.

Fader, G.B., C.F.M. Lewis, J.V. Barrie, D.R. Parrott, W.T. Collins, R.O. Miller and S. d'Apollonia, 1985. Quaternary geology of the Hibernia area of northeast Grand Bank, Geological Survey of Canada Map 14968QG.

91

Fader, G.B.J, and R.O. Miller, 1986.   A reconnaissance study of the surficial and shallow bedrock geology of the southeastern Grand Banks of Newfoundland.   Current Research, Part B, Geological Survey of Canada, Paper 86-1B, 591-604.

Grant, A.C., K.D. McAlphine and J.A. Wade, 1986.   The continental margin of eastern Canada: geological framework and petroleum potential. In: Future Petroleum Provinces of the World, AAPG Memoir 40, M.T. Halbouty, ed; 177-205.

Greenberg, D.A. and B.D. Petrie, 1988.   The mean barotropic circulation on the Newfoundland shelf and slope. Journal of Geophysical Research, Vol. 93, No. C12, 15,541-15,550.

Heffler, D.E., 1984.   RALPH - an instrument to monitor seabed sediments. Current Research Part B, Geological Survey of Canada Paper 84-1B, 47-52.

Hodgson, G.J., J.H. Lever, C.M.T. Woodworth-Lynas, and C.F.M. Lewis, 1988.   The Dynamics of Iceberg Grounding and Scouring (DIGS) Experiment and Repetitive Mapping of the Eastern Canadian Continental Shelf. Environmental Studies Research Funds, Report No. 094, Ottawa.

Huntley, D.A. and D.G. Hazen, 1988.   Seabed stresses in combined wave and steady flow conditions on the Nova Scotia continental shelf: field measurements and predictions. Journal of Physical Oceanography, Vol. 18, 347-362.

Hutchins, R.W., D.L. McKeown and L.H. King, 1976.   A deep tow high resolution seismic system for continental shelf mapping. Geoscience Canada, Vol. III, 95-100.

King, L.H., 1980.   Aspects of regional surficial geology related to site investigation requirements - eastern Canadian shelf. In: Offshore Site Investigation, D.A. Ardus, ed., Graham and Trotman, London.

Lanan, G.A., A.W. Niedoroda and W.F. Weeks, 1986.   Ice gouge hazard analysis.   Proceedings of the 18th Offshore Technology Conference, Houston, Texas, 5-8 May 1986, No. OTC 5298.

Leblond, P., 1982. Satellite observations of Labrador Current undulations. Atmosphere-Ocean, Vol. 20, 129-142.

Lewis, C.F.M., 1977. Bottom Scour by Sea Ice in the Southern Beaufort Sea. Beaufort Sea Project, Department of Fisheries and Oceans, Beaufort Sea Technical Report 23.

Lewis, C.F.M. and J.V. Barrie, 1981. Geological evidence of iceberg grounding and related sea floor processes in the Hibernia discovery area of Grand Banks, Newfoundland. Symposium on Production and Transportation Systems for the Hibernia Discovery, Newfoundland Petroleum Directorate, St. John's, Newfoundland, 146-177.

Lewis, C.F.M., H.W. Josenhans, A. Simms, G.V. Sonnichsen and C.M.T. Woodworth-Lynas, in review. The role of seabed disturbance by icebergs in mixing and dispersing sediment on the Labrador Shelf; a high latitude continental margin. Proceedings of the Canadian Continental Shelf Seabed Symposium, Bedford Institute of Oceanography, October 2-7, 1989.

Luternauer, J. and J.W. Murray, 1983. Late Quaternary morphologic development and sedimentation, central British Columbia continental shelf. Geological Survey of Canada Paper 83-21.

Mitten, M.J., 1988. Case histories of iceberg scouring and pitting events on the Grand Banks of Newfoundland. Report submitted to the Atlantic Geoscience Centre, Department of Energy, Mines and Resources.

Mobil Oil Canada Ltd., 1985. Mobil Hibernia Development Studies 1985, wave hindcast study extension. Report submitted by MacLaren Plansearch Ltd. and OceanWeather Inc.

Neu, H.J.A., 1976. Wave climate of the North Atlantic - 1970. Atlantic Oceanographic Laboratory, Bedford Institute of Oceanography, Report Series BI-R-76-10, Dartmouth, Nova Scotia.

Neu, H.J.A., 1982. 11-year deep-water wave climate of Canadian Atlantic waters. Canadian Technical Report of Hydrography and Ocean Sciences No. 13, Department of Fisheries and Oceans.

Newfoundland Geosciences Ltd., 1988. Geological and geotechnical borehole program - Grand Banks of Newfoundland. Report to the Atlantic Geoscience Centre, Department of Energy, Mines and Resources. Project No. G068.

Parrott, D.R. and C.F.M. Lewis, eds., 1986. Cruise Report Hudson 86-018, Grand Banks of Newfoundland and Flemish Pass, July 2 - 14, 1986. Geological Survey of Canada Internal Report.

Parrott, D.R., C.F.M. Lewis, G.V. Sonnichsen, D.C. Mosher, M. Douma, J. Lewis, J. McG. Stewart and D.P. Kimball, 1989. Near-surface seismic reflection studies of the Jeanne d'Arc Basin, northeastern Grand Banks of Newfoundland. Current Research, Part B, Geological Survey of Canada, Paper 89-1B, 67-73.

Petrie, B., 1982. Aspects of the circulation on the Newfoundland continental shelf. Canadian Technical Report of Hydrography and Ocean Sciences, BIO-82-11, Bedford Institute of Oceanography, Dartmouth, Nova Scotia.

Petrie, B. and C. Anderson, 1983. Circulation on the Newfoundland continental shelf. Atmosphere-Ocean, Vol. 21, 207-226.

Petrie, B. and D. Warnell, 1988. Oceanographic and meteorological observations from the Hibernia Region of Newfoundland Grand Banks. Canadian Data Report of Hydrography and Ocean Sciences No. 69, Department of Fisheries and Oceans.

Pocklington, P., 1987. Ageing iceberg scours by studying the dominant recolonizing biogenic elements. Report to the Atlantic Geoscience Centre, Geological Survey of Canada, Department of Energy, Mines and Oceans.

Rhoads, D.C. and L.F. Boyer, 1982. The effects of marine benthos on physical properties of sediments. In: Animal - Sediment Relations, L. McCall and M.J.S. Teresz, eds., Plenum Press, New York, New York.

Seaconsult Ltd., 1984. Oceanographic information for the eastern Canadian offshore: adequacy for exploratory drilling. Report to the Royal Commission on the Ocean Ranger Marine Disaster.

Smith, E.H., F.M. Soule and O. Mosby, 1937. The Marion and General Greene expeditions to Davis Strait and Labrador Sea. U.S. Coast Guard Bulletin 19, U.S. Department of Transport, Groton, Connecticut.

Vilks, G., (ed.), 1984.   Report of Cruise No. 83033, CSS
       Hudson, 28 October - 7 November.   Geological Survey of
       Canada Internal Report.

Walker, R.E., 1984. Wave statistics for the North Atlantic -
       1970 to 1982. Canadian Data Report of Hydrography and
       Ocean Sciences No. 16, Department of Fisheries and
       Oceans.

Weeks, W.F., W.B. Tucker III and A.W. Niedoroda, 1985.   A
       preliminary simulation study of sea ice induced gouges in
       the sea floor.   Proceedings of the Arctic Energy
       Technologies Workshop, Morgantown, West Virginia.

Woodworth-Lynas, C.M.T., 1989. Iceberg grounding event at the
       Whiterose wellsite, April 9 - 12th, 1988.   Contract
       report for Husky East Coast Project, C-CORE Contract
       Number 89-C3.

APPENDIX 1

CRUISE REVIEWS

APPENDIX 1

CRUISE REVIEWS

SIDE-SCAN SONAR DATA

Three types of side-scan sonar systems have been used in the previous surveys of the four scour sites. These are the BIO 70-kHz BIO side-scan system, a Klein model 531T side-scan sonar with a third channel for display of the altimeter echo, and an EG&G model 260 side-scan which has dual frequency (100 kHz and 500 kHz) capabilities.

Hudson Cruise 83-003

The BIO 70-kHz system was used initially for target identification and then for the regional setting of Scour 95 on the Hudson cruise 83-033. This system is generally used with a repetition rate of 1 s and produces side-scan sonograms with a total swath width of 1,500 m. On this cruise the sonograms were presented on wet paper 40 cm wide, representing 750 m cross-track and equivalent to a scale of 1:3,750. Along-track scales vary with ship's speed and generally range from 1:6,000 at 4 knots to 1:9,000 at 6 knots.

The Klein 100-kHz three-channel system was also used on the Hudson 83-033 cruise to provide greater detail of the sea floor. This system usually presents a 500 m swath on paper 25 cm wide, giving a cross-track scale of 1:2,000 and an

along-track scale, also a function of ship's speed, of about 1:3,500 at 4 knots.

The field data from both of these systems are not, therefore, scale corrected nor are they slant-range corrected; features which would substantially improve attempts to present the sonograms as mosaics.

Hudson Cruise 86-018

On the Hudson 86-018 cruise, the BIO 70-kHz side-scan was again used with a 1-s firing rate but the sonograms were displayed on a three-channel, dry-paper EPC recorder alongside Huntec DTS data. This presentation is far superior to that used on the earlier cruise. The cross-track scale was about 1:10,000 and the along-track scale 1:8,000, indicating a scale distortion closely approximating the ideal of 1:1.

The three-channel Klein 100-kHz system was operated on this cruise with a total swath width of 300 m, giving a cross-track scale of 1:1,200. The along-track scale was about 1:2,730, indicating a 2:1 distortion. Neither the BIO nor Klein side-scan sonars had slant-range correction on this cruise. The EG&G system was not evaluated in the test area because of insufficient cable length.

Dawson Cruise 89-006

On the Dawson Cruise 89-006, several recorders were used to display the BIO 70-kHz and Klein 100-kHz side-scan sonograms. Various scales were used ranging from 1:15,000 to

1:2,000 for the Klein cross-track scale. Again slant-range correction was not available.

Whiterose E-09 1988 Survey

On the Husky survey of the Whiterose area in 1988, a reconfiguration of a Klein 100-kHz side-scan sonar was undertaken to expand the side-scan sonogram. A modified EPC 3200 recorder was used at a high sweep speed to give a variety of cross-track scales ranging from 1:2,000 to 1:750 with appropriate expansion along-track. This degree of expansion indicates that the controlling influence in side-scan sonograms is the display method and not the basic side-scan system. The amount of detail observed in this sonogram is quite remarkable considering that the side-scan operates at 100-kHz. The sonograms are not slant-range corrected which, in this particular case, is advantageous as the profile of the scours can be seen with greater accuracy than with a surface-mounted echo sounder.

HIGH-RESOLUTION SEISMIC DATA

Hudson Cruise 83-033

The Huntec Deep Tow Boomer system was used on the Hudson 83-033 cruise to define the surficial sediments both in the vicinity of the target scours and on a regional basis.

In the area of Scour 95, seismic sections from both internal and external receiving channels are available with a vertical scale of 1:400 (10 m = 2.5 cm, 250-m sweep) and horizontal scale of approximately 1:6,000. Firing rate appears to have been 750 ms, acoustic reflectivity information is available and tow-fish body motion compensation was in operation (combined pressure and heave mode). The seismic section from the internal hydrophone shows a very well-defined and short sea floor echo with a residual heave component of about 50 cm. Little surface scattering is seen in the reflectivity display; however, the Quaternary boundary is diffuse and not very well defined. The boundary is discernable as a change in the amount of scattering taking place just beneath the sea floor and not as closely-aligned, coherent echoes. In some locations, subsurface echoes within 10 m of the sea floor appear coherent but merge with the background after several tens of metres in lateral distance.

Huntec data from the external hydrophone in the Scour 95 area is not of the same quality as that discussed above. The bottom pulse is much less well-defined, residual heave motion is greater and interference from the sea surface echo can be seen which occasionally masks the area of interest. The lack of a well-defined bottom echo may be caused by the signal filters used during recording, but the other effects are of an operational nature. Little useful information regarding the boundary can be extracted from this record.

In marginal weather conditions, additional real-time heave compensation may reduce the residual tow-fish heave level. Alternatively, bottom flattening may be very useful where the sea floor is flat and even.

Iceberg scours were profiled on three separate occasions during this cruise and three types of Huntec DTS seismic sections (internal hydrophone, external hydrophone, and combined DTS and side-scan sonar) are available from a single equipment system.

The Huntec profiles for the area obtained using the internal hydrophone are very similar in appearance in terms of scales, firing rate, etc., to those obtained during the 83-033 cruise. A little more detail of the near-surface structure is seen, probably because of more appropriate settings of the EPC recorder print controls. Residual heave is present which reduces profile quality.

The Huntec data collected on Day 188 in the Bowers Pit area are again of similar quality to those collected earlier. The consistency and hardness (acoustic) of the material makes the task of differentiating between the top of the older sediments and the thin sediment cover practically impossible. A good section over the pit is seen at 188/1636 near the end of Line 29.

Bowers Pit was also traversed on Day 192. The internal hydrophone data show less residual heave, probably because of improved weather conditions. The appearance of the seismic sections from the Huntec internal hydrophone again suggest a smooth, acoustically hard sea floor. The improved displays also show a reflector between 4 and 5 m beneath the sea floor. Its consistency suggests that it is an artifact of the seismic configuration.

The data obtained with the external hydrophone during the three detailed surveys of scours discussed above appear to have been recorded with a signal filter passband of 300-750 Hz, a range outside the spectrum of the Huntec boomer. The sections are completely devoid of information and an apparent reflector at 50 m near the start of Line 25 (188/1227) is a multiple of the sea floor echo.

The third type of presentation used on this cruise was a three-channel display involving the BIO 70-kHz side-scan and the internal channel of the Huntec DTS. The side-scan is presented with about a 1:1 aspect ratio on a scale of 1:10,000 (both channels using 15 cm of the recorder sweep) with the Huntec display using the remaining 33 cm with a 200-m sweep rate. The graphic quality of both displays is good. The Huntec external hydrophone data is similar in quality to that displayed on the committed recorder and the side-scan image, being scale-corrected, gives a more useful picture of the seabed without loss of detail. This type of dual display, particularly if the profiler and side-scan were integrated in the same towed body, is probably ideal for detailed surveys of this nature. However, the selection of recorder presentation scales, equipment firing parameters and towing geometry to optimize display quality then becomes more important.

Needler Cruise 88-108

On the Needler 88-108 cruise, the BIO side-scan with a scale of about 1:8,000 was again combined with the Huntec internal data for the survey of the Husky 88-01 scour. The display scales are similar to the combined output of the

Hudson 86-018 cruise but the image is less distinct and may have been caused by a recorder stylus problem.

APPENDIX 2

EQUIPMENT SPECIFICATIONS

APPENDIX 2

EQUIPMENT SPECIFICATIONS

HUNTEC DEEP TOW SEISMIC SYSTEM

A) General specifications:

    1)   System must have ARM or C-ARM capability
    2)   Hydrophone should primarily be internal, external will be secondary
    3)   Remote winch for use by Huntec operator
    4)   Effective heave compensation scheme.

B) Operational specifications:

    1)   Fish to be towed 30-40 m above sea floor
    2)   The boomer should fire every 0.25 s
    3)   Power should be set at 200 joules
    4)   Firing should be synchronous with the side-scan system.

C) Display characteristics:

    1)   Use EPC 3200-4600 19" thermal paper recorder
    2)   Along-track scaling same as side-scan sonar system
    3)   Sweep should be 2.5 cm = 10 m
    4)   Additional expanded, bottom-tracked, display sweep should be 5 cm = 10 m
    5)   Delay as necessary to remove water column
    6)   Total depth and heave compensation
    7)   R1, R2 display
    8)   Time-varied gain and band-pass filters must be used
    9)   Annotation showing fix marks every 200 m (based on navigation input)
    10) Recording back-up of both raw and processed data on magnetic tape
    11) Sweep direction must be set according to line heading.

SIDE-SCAN SONAR SYSTEM (100 kHz)

A) General specifications:

  1) The side-scan system should be integrated with the Huntec DTS system
  2) Side-scan sonar system should operate at a frequency of 100 kHz
  3) In a stand-alone system a third channel should be used as a bottom profiler
  4) Remote winch for use by side-scan operator (if not combined with seismic system).

B) Operational specifications:

  1) Range should be set at the 200 m scale
  2) Firing rate should be once every 0.25 s and synchronized with the Huntec system
  3) Fish should be towed 30-40 m above sea floor.

C) Display characteristics:

  1) Recorder should be EPC 3-channel
  2) Port and starboard channels to be set at 1/2 sweep
  3) Third channel to be profiler on the other 1/2 sweep
  4) Display should be slant-range corrected
  5) Display should have a 1:1 aspect ratio at a scale of 1:2,000
  6) Paper speed should be controlled by ship speed
  7) A second EPC recorder should display expanded both cross- and along-track
  8) The second EPC display should not be slant-range corrected
  9) Annotation to show fix marks every 200 m (based on navigation input).

ECHO-SOUNDER (12.5 kHz)

A) General specifications:

  1) Echo-sounder to have expanded presentation.

B) Operational specifications:

    1)   Firing should be synchronous with Huntec and side-scan systems
    2)   Data should be digitized and recorded.

TOWED ROV with 500-kHz SIDE-SCAN SONAR SYSTEM and STEREO CAMERA UNIT

A) General specifications:

    1)   ROV should be used as platform for 500-kHz side-scan sonar and 3.5-kHz sub-bottom profiler or narrow-beam echo-sounder
    2)   ROV should be equipped with a stereo camera unit
    3)   ROV must have directional capabilities and towed body positioning
    4)   Real-time video to allow for accurate positioning of the ROV is required.

B) Operational specifications:

    1)   Side-scan sonar should be set at a firing rate to sonicate a 100 m swath (the firing rate should be about once every 0.0625 s)
    2)   The fish should be set in an auto-altitude mode and be flown at 5 m above the sea floor
    3)   The photographic fire rate should be set to allow as much seabed coverage as possible
    4)   The survey lines should be repeated in the same direction with the fish offset by 25 m.

500-kHz SECTOR SCANNING SONAR SYSTEM

A) General specifications:

    1)   A 500-kHz sector scanning sonar is to be mounted on an ROV or on a manned submersible
    2)   The sonar should have the ability to record in polar mode and sector scan mode
    3)   Data is to be stored on analog or digital tape for presentation on thermal recorder.

B) Operational specifications:

    1)   Transducer must be repositioned at same location and orientation and, in particular, same height from seabed for each survey

    2)   Angle of transducer must be set after sonar unit is on bottom

    3)   Once the angle is fixed, it must be repeated in all subsequent visits to the site

    4)   Sweep direction must be consistent between scans.

C) Display characteristics:

    1)   Video display must be in real time, with a time code, to allow for maximum data quality

    2)   Video data is to be recorded for later playback

    3)   Raw sonar signal must be recorded in analog or digital format to be presented on a thermal recorder

    4)   360° and sector scan data is to be presented as a scaled linear display to allow accurate data comparison.

BOTTOM STEREO CAMERA SYSTEM

A) General specifications:

    1)   An ROV-mounted camera system frame is to be deployed

    2)   The camera should be adjustable to allow for both vertical and horizontal stereo photographs

    3)   Real-time video to allow for accurate positioning of the camera is required.

B) Operational specifications:

    1)   ROV must be positioned at an appropriate distance from berm to illuminate and photograph the berm from the crest to the surface of the surrounding sea floor

    2)   The sector scanning sonar is to be used to position the camera at a fixed distance from the scour berm.

C) Display characteristics:

1) The photographs are to be presented in the form of a mosaic as well as in stereo pairs
2) Mosaic should be scaled equivalent to the sector scanning sonar to allow for accurate comparison.

DEPTH-OF-DISTURBANCE RODS

A) General specifications:

1) Rods should be stainless steel, about 10 mm in diameter and 1.0 m in length
2) Rods to be marked in such a way that they can be read to the nearest 5.0 mm
3) Rods to have identification numbers attached so that number can be read with rod inserted in seabed
4) Rods to have attached sonar reflectors.

B) Operational specifications:

1) Rods to be implanted into seabed to a depth of refusal or maximum of 40 cm
2) Rods to be implanted as near to vertical as possible
3) Rods and surrounding seabed to be photographed soon after implantation, with emphasis on the rod/sediment interface.

SHIPBOARD NAVIGATION

A) General specifications:

1) Accuracy should be industry standard or better than 20 m
2) Position fixes must be at least every 50 m and annotated every 200 m, based on distance down line
3) Lines must have a minimum of 500 m straight run-in and run-out extensions
4) Navigation system must indicate distance along- and off-track to bridge and operators
5) Variations in speed and track error to be minimum industry standard

6) Rigid quality control procedures to be applied such that, if on-line navigation indicates ship is off track by more than 25 m for a significant portion of the line (200 m), then a re-run of the line is enforced
7) Remote display of speed over ground to system operators.