Study of iceberg scour & risk in the Grand Banks region

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FINAL REPORT

STUDY OF ICEBERG SCOUR & RISK IN THE GRAND BANKS REGION

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By

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EXECUTIVE SUMMARY

The discovered recoverable oil reserves on the Grand Banks are estimated to be about 1.6 billion Bbls, with additional potential reserves of about 3 billion Bbls. The estimated Grand Banks gas reserves are 4 Trillion cubic ft. discovered and 5 Tcf potential. Most of the future development scenarios for oil reserves on the Grand Banks include the deployment of wellheads, manifolds and flow lines on the seabed. These systems are being used increasingly in other hydrocarbon producing regions (such as the North Sea) and can bring significant reductions in development costs. In some marginally economic fields, effective use of seabed facilities may tip the balance in favour of development.

On Canada's East Coast, seabed facilities are at risk of contact and potential damage from icebergs. Safe and economic utilization of subsea technologies requires that the risk of damage be reduced to an acceptable level. The aim of the present study was to consolidate and assess our current knowledge base of iceberg scour on the Grand Banks, and establish a risk framework from which intelligent decisions can be made regarding the relative benefits and costs of different protection methods. Critical knowledge gaps, and prioritised recommendations for R&D to address these deficiencies have been provided.

The principal results from the study are summarized below.

Scour (Gouge) Measurement Techniques

- The Grand Banks Scour Catalogue (GBSC) is a compilation of many individual seabed surveys, performed with a variety of different geophysical systems of varying accuracy and resolution.
- The quality and shortcomings of the data are well understood and these have been reviewed.
- Numerous techniques for age dating scours have been proposed, but to date, none have been proven to be reliable and technically feasible.

Iceberg Scour Data

- The Grand Banks Scour Catalogue (GBSC) is an up-to-date compilation of all ice scour data collected in the region since 1979.
- The GBSC contains records of 5720 scour features including 3887 individual scours and 1773 iceberg created pits.
- Scours in sand in water depths less than about 100m are periodically reworked and ultimately destroyed by bottom currents, so scour densities in sand are significantly less than recorded in gravels and other soils.(However, the scour frequencies could be the same).

- Interpreter variability can lead to a minimum of 30% variation in scour density estimates.
- Scour depth data suffer from the limitations of instrument resolution which leads to shallow scours being underestimated and the statistics skewed to the deeper scours. On the other hand the older deeper scours may have preferentially infilled. As well, variability in scour depth across the scour width and length may be important for determining risk to seabed installations.
- Scour lengths are often simply recorded as the length visible in the survey, even though the scour extends beyond. This means that longer scours are often under represented in the database.
- The GBSC has been used to assess scour density (number of scours/square km). This varies from 0 to 30 scours/km^2. It is noted that the highest scour densities are associated with the most recent surveys using modern higher resolution equipment - this suggests scour events were either not visible on the lower resolution data or not interpreted on these earlier surveys.
- In regions where scours are more frequent, (e.g. the Beaufort Sea), repetitive surveys give the best assessment of scour frequency - which is a vital ingredient for risk assessment. On the Grand Banks, the issue of determining scour frequency is a major problem for accurate risk assessment.
- Repetitive surveys have been conducted in a few areas of the Grand Banks e.g. in the North Hibernia region in 1979 and 1990. All but one of these repetitive mapping surveys have detected no new scours over the period covered. In only one survey was one new scour detected in 11 years suggesting a scour frequency of 1.9×10^{-4} /km^2/yr.
- One bounding approach discussed in this report is to assume that all detectable scours occurred over a certain geological time period - the longest being about 12,000 years BP and the shortest being about 2500 years. For the Hibernia region, this yields a lower bound frequency of 8.3×10^{-5} /km^2/year and an upper bound of 4.0×10^{-4} /km^2/year.
- Other methods of establishing scour frequency are based on either scour dating or on a statistical analysis of iceberg fluxes, drift rates and draft distributions.
- The assessment of scour frequency from iceberg flux is an extension of the methodology of assessing collision frequencies with surface piercing platforms. It offers a potentially less uncertain approach to the problem. It also allows a coherent transition from scour frequency to collision frequency with sea floor structures of various heights. This approach has been used in a simple fashion for the Hibernia region and yields about 4×10^{-4}/km^2/year.
- Determining scour frequency from scour density using scour degradation has been reviewed and the effects of water depth and soil type need to be better understood before this approach can be used with any confidence.

- Maximum scour depth in the catalogue is 7m occurring in the 150 - 170m water depth. However, in the 90 - 110m water depth, the maximum depth is 3m with a mean of "measured" scours 0.48m. (Subject to resolution limits of the sensors).
- In the 90 - 110m water depth, maximum and mean widths are 200m and 26m respectively and lengths are 650m (mean) and 9,400m (maximum).
- In general, weak correlations were found to exist between scour characteristics such as depth, width, length, water depth, sediment type, and orientation.

Iceberg Risk to Seabed Facilities

- In reviewing potentially relevant standards (e.g. CSA S471), it was concluded that wellheads should be considered Safety Class 1, since failure could lead to significant hydrocarbon release. In this case, the CSA Standard recommends an annual target safety level of 10^{-5}. The annual target level for a single well or a well cluster installation (including glory holes) is therefore 10^{-5}. Up to about ten entities can be treated individually at the 10^{-5} level. If the number of wells or clusters exceeds ten, it is recommended that the overall safety level be maintained at 10^{-4}, thereby increasing the safety requirement for each installation.
- The risk of iceberg contact with a variety of subsea installations has been considered. Experience suggests they can be classified according to whether they are buried beneath or penetrate above the mudline. In the first instance, only scouring icebergs are of concern, while freely floating icebergs are also of concern in the latter case.
- The annual contact probability from freely floating icebergs can be estimated from average iceberg population (per unit area), average drift speed, and the sum of iceberg keel and structure widths at the point of contact. Annual contact probability is approximately 2×10^{-3} for a 10 m high by 25 m diameter structure in about 100 m of water on the NE Grand Banks. In contrast, the annual probability of contact from scouring icebergs for a structure placed below the mudline is less than 10^{-5}. Contact probability from scouring icebergs depends on the scour frequency and scour dimensions. The advantages of burial below the mudline are significant.
- For scouring icebergs, the risk of contact decreases with increasing burial depth. For holes smaller than the scour width, the probability of contact decreases according to the probability of exceedance for the scour depth distribution. Typically, an order of magnitude reduction in contact probability can be achieved by burial 1 m below the mudline. For large holes, the iceberg may also pitch into the hole thereby increasing the risk of contact. This has been approximated from the excess draft distribution for scouring icebergs derived from a numerical model of the scour process for the NE Grand Banks. The probability of iceberg contact depends on the extent of the structure and the position of the top of the structure relative to the mudline.

- In many cases, the reliability of an installation will be much greater than would be inferred by equating iceberg contact with release of hydrocarbons to the environment. A significant safety margin can be achieved for wellhead installations by considering the effectiveness of automatic shut-off valves in the wellbore.
- Risk of damage to a buried subsea pipeline depends on the scour frequency, scour length, scour depth and pipeline length. Sub-scour soil deformations should also be considered in the risk assessment process. For the NE Grand Banks, the annual probability of iceberg damage for a backfilled pipeline with a cover depth of 1 m is estimated at between 10^{-5} and 10^{-4} per km.
- For offshore pipelines, the state of practice has not reached a full reliability based design. Many codes, including the section of CSA Z662 pertaining to offshore pipelines, require the verification of limit states under the application of the 100 year design environmental load. Since ice scours impart displacements to buried pipelines, design scours are characterized typically in terms of their depth and width. The annual probability of exceedance for scour depth has been estimated for the Hibernia degree square.

Iceberg Scouring Mechanisms

- Scour depth limits due to iceberg strength depend on the geometry of the keel, as well as the ice the soil strengths. A simple analysis shows that an iceberg with a strength of 1MPa can scour to a depth of at least 3m in sand with a 30 degree friction angle. However, the driving force limit from the simulation performed in this study also appears to be about 3m. These considerations suggest that in sands, the scour depth may be limited by either driving force or iceberg keel strength. It should be noted however, that these calculations are very approximate and further refinement is recommended.
- A review of environmental driving forces indicates that current, winds and waves are sufficient to induce scour to the depth levels observed (e.g. to about 2.6m). As well, scour lengths of several kilometers appear to be quite likely and this matches the data.
- The same analysis gives typical results for iceberg heave and pitch during the scouring process. Mean values are quite small e.g. 0.24 degrees pitch and 0.01m heave. However, maximum values are 16.7 degrees pitch and 1.12m heave.
- A separate analysis was conducted to assess the influence of sub-scour soil deformation on a buried pipeline. It is shown that for a scour depth of 1.5m and a typical 914mm pipeline with a cover depth 1m, the peak tensile strain in the pipe is approximately 2% (CSA Standards require verification of strain limits greater than 0.75%). In this case, the cover depth is the clearance between the scour base and the top of the pipe, implying a trench depth of about 3.5m. Required trench depths

depend on scour dimensions, pipeline material, diameter, wall thickness and soil parameters.

Summary & Assessment of R&D Needs

Due to the foresight of the GSC and others, there is a considerable amount iceberg scour data for the Grand Banks. There are some limitations of accuracy due to sensor resolution and interpreter subjectivity and skill, but the data are very important input to risk assessment and the design of seafloor facilities. Although the data give good information on scour density, the extraction of scour frequency, which is the starting point for accurate risk assessment, is not so easy. Because the scouring rate is so low, the use of repetitive scour surveys has, to date, not been able to provide adequate data to reliably assess scouring frequency.

Scour depth data are also important in assessing the risk of buried facilities and is subject to some uncertainties due to instrument resolution limits.

With the data available at this time, and recognizing the uncertainties noted above, the contact frequency with a typical individual sea floor facility is estimated to be in the range 10^{-4} to 10^{-3}. According to the risk philosophy laid out in CSA S471, assuming contact leads to significant oil discharge, then this risk is too high. It is recognized that contact by an iceberg with a structure such as a wellhead does not necessarily lead to an uncontrolled discharge (because of wellbore control valves). Nevertheless, most operators have chosen to reduce this risk by putting the top of such equipment below the mud line. However, because of uncertainties in both scour frequency and scour depths, the risk level as a function of depth of burial is subject to uncertainty.

The incentive to reduce this uncertainty is high because burial schemes such as glory holes are very costly.

Recommendations for Future Work

R&D required to reduce the uncertainties in scour frequency and scour depth can be related to two separate lines of approach. These are either 1) use the scour record, or 2) simulation of scour statistics from iceberg statistics combined with ice/seafloor interaction and limit models. It is recommended that both these approaches be exercised and refined. In fact, when both approaches give similar risk values we might expect that the outcome has some credibility. It should be noted that the second approach is also required to assess risk to structures that protrude above the sea floor.

Recommended R&D thrusts for these approaches are itemized in Tables E.1 and E.2. More detailed discussions of these topics are provided in Section 7 of this report.

Table E.1 R&D to improve methods based on the scour record

Remaining Issue & R&D Thrust	**Priority**
Differentiating between relic and non-relic scours is critical for determining the risk in deep water. It is therefore very important that techniques be developed for determining the *absolute* age of scours.	H
It is believed that sediment type has a significant effect on scour degradation rates, but the magnitude of the effect is not known. To obtain accurate estimates of scour frequency in different sediment types, sediment effects on scour degradation must be determined.	M H
Another approach to obtain scour frequency is repetitive mapping. Repeat mapping over an area previously surveyed 20 or more years ago should be investigated.	M H
Scour density can be a starting point to assess scour frequency. In order to provide consistent scour density/frequency results in shallow water, surficial geology coverage is required to normalize the data according to percentage gravel cover. Such coverage is not available regionally, but could be obtained for selected sites within each bathymetric interval.	M
A number of factors including low resolution sub-bottom profiler data in many of the older surveys do not allow an accurate estimation of the scour depth distribution. A continued effort is recommended to enhance the area covered by high resolution surveys, therefore improving the resulting scour depth distribution.	M
The scour length information in the database probably under-estimates the true length of scours because of difficulties detecting both the start and end points. Length distributions from newer surveys should be compared to those from older surveys with less coverage. Future surveys with 100% coverage are also recommended.	ML
Scour depth documented in the database focuses on the deepest point across the width of a scour. A proper assessment of depth variation from existing and future surveys would help to establish more representative scour depth distributions and variabilities for risk calculations and modeling.	M
There is outstanding work that needs to be conducted on the GBSC. This includes: • Duplicate scours, mapped from two or more different surveys, need to be identified and removed from the database. • The original geophysical data should be re-examined for those surveys that show anomalous scour depth distributions. • The original data should be examined for wellsites in the original Mobil source that appear to have anomalously low scour densities compared to adjacent areas.	MH

Table E.1 R&D to improve methods based on the scour record

Remaining Issue & R&D Thrust	**Priority**
• There are additional regional and wellsite data available in the region which should be incorporated into the GBSC. • All scours recorded on the sidescan for the original Mobil data should be incorporated into the GBSC.	
Through the PRISE program, C-CORE has established a relationship between scour dimensions and the corresponding loads applied to the soil. An investigation of the relationship between the geotechnical properties of the soil and scour dimensions is important for predicting regional differences in the scour depth distribution.	M

Table E2 R&D to improve methods based on simulation of scour statistics from iceberg statistics combined with ice/seafloor interaction and limit models.

Remaining Issue & R&D Thrust	Priority
It is not clear if the general statistics on iceberg draft can be applied to the Grand Banks. Two initiatives are proposed for improving iceberg length and draft statistics on the Grand Banks. 1) Additional iceberg surveys of opportunity during iceberg management operations (and ensuring that the data are placed in suitable database), 2) An investigation of the use of RADARSAT to improve iceberg waterline length statistics for the Grand Banks.	M
This study has developed a preliminary iceberg/seafloor interaction model that accounts for current, wave and wind driving forces, kinetic energy and seafloor strength. The model does not include an ice strength limit. It is recommended that a more comprehensive model be developed which includes an ice strength limit and which can also be used to assess forces on sea floor structures above the mudline.	H
Incorporation of ice strength limits into a scouring model will require an assessment of appropriate ice strengths. It is recommended that a scheme be developed for the ice strength of iceberg keels which is based on previously measured iceberg strength data and other full scale data combined with plausible physics including progressive failure	H

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1.0 INTRODUCTION

1.1 Objectives

To assess the state of knowledge and experience relating to iceberg scours and their effects on Grand Banks Hydrocarbon Development.

- To identify deficiencies in knowledge of regional iceberg scour data, scouring mechanisms, risk assessment of damage to facilities & in the design of protection schemes.
- To recommend and prioritise R&D to address these deficiencies (if any).

1.2 Background

The discovered recoverable oil reserves on the Grand Banks are estimated to be about 1.6 billion Bbls, with additional potential reserves of about 3 billion Bbls. Most of the discovered oil is in the four largest reservoirs in the Jeanne d'Arc basin; i.e. Hibernia (700 million Bbls), Terra Nova (350 million Bbls) Hebron (195 million Bbls), Whiterose (180 million Bbls). The latter three fields will be produced using floating production systems requiring sea floor facilities. These are at risk from damage caused by scouring and deep draft icebergs.

The estimated Grand Banks gas reserves are 4 Trillion cubic ft. discovered and 5 Tcf potential. The conventional approach to transporting gas is a sub sea pipeline. However, the risks associated with damage to a pipeline from scouring icebergs need to be understood and managed.

Managing the risks associated with scouring icebergs can potentially add costs to the production of Grand Banks hydrocarbons. Yet it is in the Nation's benefit that these hydrocarbons are cost-competitive, for several reasons:

1) Maximizing development of Grand Banks hydrocarbons creates wealth for Newfoundland and the rest of Canada.
2) The energy intensity of Grand Banks oil production is estimated (Croasdale and Associates, 1999) to be about 10 times less than alternative future Canadian supplies such as oil sands mining. Therefore East Coast oil has inherently lower greenhouse gas emissions per barrel of production. Maximizing East Coast oil production can help Canada achieve its commitments under the Kyoto Agreement.

3) Natural gas will be used in the short term for incremental power generation in order to lower greenhouse gas emissions. Therefore any R&D to bring economic natural gas to market also has the potential benefit of lowering GHGs emitted .

Most of the future development scenarios for oil reserves on the Grand Banks include the deployment of wellheads, manifolds and flow lines on the sea bed. These systems are being used increasingly in other hydrocarbon producing regions (such as the North Sea) and can bring significant reductions in development costs. In some marginally economic fields, effective use of seabed facilities may tip the balance in favour of development.

On Canada's East Coast, seabed facilities are at risk of contact and potential damage from icebergs. Safe and economic utilization of subsea technologies requires that the risk of damage be reduced to an acceptable level. The Hibernia export lines are designed so that the release of hydrocarbons can be minimized, and the equipment is easily repaired or replaced should damage occur. Alternately, equipment can be shielded from icebergs through burial or the installation of protective structures. In this context 'burial' refers to placing the structures such that their upper-most surfaces are below the mudline. The Terra Nova Project is currently placing wellheads in open 'glory holes'. Several smaller oil and gas fields being considered for development (e.g. Ben Nevis, Whiterose, Hebron) may use subsea pipelines from 'satellite' seabed wells and other seabed facilities. A natural gas pipeline is also being considered for the region.

Buried structures are at risk from scouring icebergs. Since scouring is an infrequent occurrence, the risk of contact is significantly lower than for structures projecting above the mudline. The present study aims to consolidate and assess our current knowledge base of iceberg scour and deep draft icebergs on the Grand Banks, and establish a risk framework from which intelligent decisions can be made regarding the relative benefits and costs of different protection methods. The study will also identify knowledge gaps and opportunities for improving sea bed facilities risk assessments and protection schemes.

1.3 Study Area Selection

The Study Area as shown in Figure 2.1 was selected as it includes the most active area of Offshore Petroleum Exploration, Significant Discoveries and Production Licenses within the Jeanne d'Arc sub-basin. The area includes Northeast Grand Banks, Flemish Pass and western portion of the Flemish Cap (45.850°N to 48.830°N and 45.830°W to 50.800°W).

2.0 REVIEW OF SCOUR MEASUREMENT TECHNIQUES

2.1 Overview

Although direct observations have been made on a number of ice scours using manned submersibles (Barrie et al., 1986, Hodgson et al., 1988), regional mapping of ice scours on the Grand Banks has been based primarily on information collected using geophysical techniques (d'Apollonia and Lewis, 1981; Nordco, 1984; Geonautics Limited, 1989; Myers et al., 1995). Regional surveys and site surveys conducted since the late 1970's (Figure 2.1) used a variety sidescan sonars, sub-bottom profilers, and single beam echo sounders as the primary mapping tools. Since the mid-1990's, multibeam echo sounder data has been collected on the Grand Banks by the Geological Survey of Canada, Atlantic.

2.2 Detection Techniques

2.2.1 Sidescan Sonars

Operating Principles

Sonar systems transmit an acoustic pulse through the water column, and receive the subsequent return energy that is reflected off the seafloor. Sidescan sonar systems utilize two side-looking transducers (port and starboard) mounted in a single body which is typically towed behind the survey vessel. The acoustic pulse transmitted by the sidescan sonar transducers has a narrow beam angle in the horizontal plane (along-track direction), typically on the order of 0.5^o to 1.5^o, and a wide beam angle in the vertical plane (across-track direction). Consequently, each transmitted pulse scans a narrow swath of seafloor extending up to several hundred meters to either side of the survey track. The return energy reflected from the seafloor (backscatter) is received by the transducer, transmitted through the tow cable to the sonar processing unit, and typically displayed as grey scale images on a graphic recorder or digitally.

Recording of successive sonar pings along the survey track produces a plan view of the seafloor (i.e. sonogram) that is analogous to a low-angle oblique aerial photograph. Typically, the higher the return sonar energy levels, or backscatter, the darker the grey tone displayed on the sonogram. Variations in the backscatter level occur due to changes in bottom sediment type, seafloor relief, irregularities, or raised relief targets. Experienced interpreters are able to map the surficial sediment distribution and the presence of seafloor features such as ice scours and sediment bedforms from the sonograms.

Ice Scour Detection and Resolution

Ice scours are well-suited to detection by sidescan sonar techniques due to the local disruption of the pre-scour seabed morphology, and the sediment distribution patterns associated with the scouring process. The lateral berms and incisions of recent, or fresh, scours produce linear sonar targets that are readily detected in areas of otherwise uniform bottom morphology. Winnowing of the lateral berms, and infilling of the scour incision, on older degraded scours result in localized changes in the sediment distribution pattern that are also detectable on the sonograms. The ability to detect individual scours is dependent on the size of the scour, the degree of scour degradation, the complexity of the surrounding seafloor geology, the quality of the sidescan sonar data, and the experience of the interpreter.

Scour measurements compiled in the Grand Banks Scour Catalogue (GBSC) were obtained from sonograms collected using BIO (70 kHz), Klein (50 kHz and 100 kHz), ORE (100 kHz), Simrad (120 kHz), and Edgetech (100 kHz) sidescan sonar systems. The frequency, pulse length, and acoustic beam pattern of the transmit pulse are quantifiable factors which affect the resolution capabilities of these sidescan sonar systems (Table 2.1). In general, the higher the sonar frequency, the shorter the pulse length, and narrower the beam angle, the higher the resolution of a particular system. The sidescan range setting and survey speed also affect the resolution of the sidescan system by controlling the along-track distance between successive sonar pings and the across-track scale of the hard copy sonogram. It is important to note that the along-track and across-track resolution listed in Table 2.1 represent the ability to resolve closely spaced target features rather than the absolute size of detectable targets. Under ideal survey conditions, all of the sidescan systems used on the Grand Banks are capable of detecting relatively small seabed disturbances. For example, seafloor marks formed by the otter boards of deep sea bottom trawls, which are typically 1-2 meters wide and tens of centimeters deep, have been detected on sonograms from each of the systems.

Several less quantifiable factors also affect the quality of the sidescan data, and consequently the ability to detect ice scours on the resultant sonograms. These include; the survey towing configuration (particularly the height of the towfish above the seafloor), survey weather conditions (sea state), equipment operation (i.e. tuning), type of recording equipment, and line orientation. Under less than ideal survey conditions, it is not uncommon to observe significant differences on sonograms collected on successive passes of an area using the same system. In some cases, ice scours detected on one pass can not be discerned on a second pass using the same equipment, particularly if the passes were surveyed at different orientations. It is difficult to quantify the performance differences of each of the sidescan systems. Direct comparisons of various system types are available from three sources.

1. The BIO 70 kHz and Klein 100 kHz sidescan systems were operated simultaneously on several GSC, Atlantic surveys used in compiling the GBSC. Sidescan range settings were typically set at 250 meters per channel for the Klein system and 750 meters per channel for the BIO system. The GBSC scour records include code parameters, which identify whether ice scours were observed on only one or both of the sidescan data sets. Of 145 scours measured using the Klein 100 kHz data, 60 features were apparent on both data sets while 85 features were not detected on the corresponding BIO 70 kHz sonograms. A total of 101 scours, which crossed the survey line, were measured using the BIO 70 kHz data. Of these, 97 events were also observed on the Klein sonograms while only 4 scours measured on the BIO sonograms were not detected on the Klein data. In summary, only 41% of the total population of scours measured using the Klein sonograms would have been detected and catalogued if only the BIO data was available. Conversely, within the range settings of the Klein data, 96% of the scours measured using the BIO system would have been catalogued if only the Klein data had been available.

2. Repetitive mapping of the ESRF 4000 series lines conducted in 1990 included both ORE 100 kHz and Klein 50 kHz sidescan data sets (Geonautics Limited, 1991). A total of 280 scours were measured during the data analysis, of which 116 were visible on the Klein sonograms only, 9 were observed on the ORE sonograms only, and 115 were detected on both sidescan data sets. Thus, approximately 41% of the total recorded population were not visible on the ORE data set, while 3% were not visible on the Klein data set.

3. Qualitative comparisons of different sidescan sonar system types involving data collected during separate surveys were conducted at the White Rose and Terra Nova exploration sites (Cumming and Sonnichsen, 1997; Myers and Campbell, 1996). At the Terra Nova site, comparison of BIO 70 kHz and Simrad 120 kHz data sets suggests that most scours were apparent on both data sets with only a small number of features detected on only one type sonogram. At the White Rose site, sonograms from areas of overlapping

coverage surveyed with a Klein 100 kHz system in 1988 and 1990, and with a Simrad 120 kHz system in 1996 were examined to compare the relative ability to detect ice scours. Although quantitative results are not presented, the importance of data quality is identified as a major limitation in scour detection, as scours on poorer quality records are less well defined and thus more likely to be overlooked or misinterpreted.

In general, more scours appear to be discernible on aspect-corrected sonograms collected at relatively low range settings, such as most of the Klein 100 kHz sonograms. Some older sonograms collected using the ORE 100 kHz system are difficult to interpret due to along-track compression ratios of up to 5:1 to 7:1 (Nordco, 1982), and may have a lower confidence of scour detection. In most cases, smaller scours are difficult to detect on sonograms collected at large range settings, such as BIO 70 kHz system with a typical range setting of 750 meters per channel. However, in areas of complex bedforms, some scours are more easily detected on the larger range sonograms of the BIO system (Myers et al., 1995). Regardless of the sidescan system used, the overall data quality of the sonograms is the primary limiting factor for ice scour detection.

Ice Scour Measurement

Scour width, length, and orientation are important scour parameters that are measured from sidescan sonograms. Surficial sediment type, scour plan shape, scour morphology, berm development, and the location of scour end-points are also obtained from the sonograms. Accurate scour depth measurements can not be obtained from sidescan data. Consequently, scour depths are only available for those scours which cross the survey track and are recorded on the accompanying echo sounder or sub-bottom profiles.

Scour width is measured on sonograms as the distance between the lateral berm crests which occur on either side of the scour incision. One average width measurement is typically recorded for each scour or scour segment. The accuracy of scour width measurements is estimated to be on the order of +/- 5 meters. Scour berms are not apparent on sonograms for many severely degraded ice scours, which are only detected as low-reflectivity lineations related to infilling of the scour incision by fine grained sediment. The scour width recorded for these features is expected to be less than that recorded for more recent or fresh scour events.

Scour length is measured on sonograms as the distance between the start and end points of the scour. However, many scours extend beyond the sidescan data coverage on regional survey lines and have recorded lengths which are less than the true length. True scour lengths are easily and accurately measured where 100% seafloor survey coverage exists, such as Wellsite and recent GSCA surveys. The GBSC database includes a code value which indicates whether or not the complete scour was observed on the sonograms.

Scour orientation is calculated by determining the intersection angle between the scour and the ship track recorded on the sonograms and correcting for the survey line orientation. Measurements are typically measured to +/- 1^{o}, although due to variations in the sidescan towfish attitude the accuracy of the resultant orientation measurements for individual scour events may be +/- 10^{o} or more.

Geo-referenced positions for each scour event are determined relative to navigation fix marks printed on the sonograms. For most systems the event marks recorded on the sonograms represent the ship antennae position at the time of the navigation fix. Positioning of scours may be +/- 100 meters or more due to the limitations of positioning systems predating the Global Positioning System and uncertainties in estimating the layback of the sidescan towfish behind the survey vessel. Advances in differential GPS, short baseline acoustic (SBL) positioning systems, and digital acquisition/processing have improved the ability to accurately map and re-map scour events using sidescan sonar systems.

Interpreter Variability

Due to the qualitative nature of sidescan data, there is a certain degree of interpreter variability inherent in ice scour mapping even with the use of experienced interpreters. Variation in the measurement of scour dimensions and, perhaps more importantly, in the number of ice scours detected by different interpreters are both known to exist. The most comprehensive study of interpreter variability was conducted during the construction of the East Coast Scour Database (Geonautics Limited, 1989). A limited comparison of interpreter variability was also conducted during the compilation of the GBSC (Myers et al., 1995). Results of repetitive mapping programs are also available to assess variability in the detection ice scour features (Geonautics Limited, 1991; Myers and Campbell, 1996).

In the Geonautics (1989) program, five experienced interpreters were involved in re-analysing randomly selected sonogram segments to assess interpreter variability in the detection and measurement of ice scours. Results of this study indicate an average interpreter variability of between 10% and 30% for measurements of scour length, width, depth, and orientation. Extreme variability values recorded for each key scour parameter ranged from 35% to 116%. Similarly, the number of scours detected varied by less than

30% for most of the interpreters involved in the study, with an extreme value of 133% for one of the interpreters. Extreme variability is attributed to small sample sizes or different interpretations in areas of complex surficial geology. A more limited interpreter variability study conducted during the compilation of the GBSC involved only two interpreters (Myers et al., 1995). Differences in scour parameter measurements for the GBSC study fall within the limits of variability determined by Geonautics. With respect to scour detection, 73% (54 of 74 total features) of the total number of scours recorded in the GBSC study were identified by both interpreters. The remaining 27% of recorded features were only recorded by one or the other interpreter. Differences in scour detection were most pronounced within an area of complex sediment bedforms.

Repetitive mapping programs conducted at the Hibernia-White Rose region (Geonautics, 1991; ESRF 4000 Series) and at the Terra Nova development site (Myers and Campbell, 1996) included a re-interpretation of the original baseline data sets. The number of scours detected during the re-interpretation studies was more than double that originally recorded at each site; 83 total ice scours versus 40 original scours at the 4000 Series site, and 71 total ice scours compared to 35 scours originally recorded at the Terra Nova site. In both comparisons, it is apparent that the original interpreters conducted a conservative scour interpretation, identifying only very prominent features. This is partly due to the fact that in the original studies, an interpreter only had the choice of including or omitting an indistinct or uncertain feature. During the re-interpretation studies, interpreters recorded a qualitative assessment of scour clarity which allowed for the inclusion of less prominent features which are, nevertheless, considered as possible or probable ice scours. It is expected that significantly lower scour densities will be associated with data sources which did not include a qualitative assessment of scour clarity.

In summary, interpreter variability is an important factor to be considered in assessing the risk to subsea installations presented by ice scouring process. Following the recommendations of Geonautics (1989), end users should allow for a possible variation of 30% in the scour parameter measurements extracted from ice scour databases. Similarly, scour density estimates calculated from the recorded scour population should allow for a minimum 30% variation due to interpreter variability in the detection of scour features.

2.2.2 Profiler Systems

Most scour depth measurements recorded in the GBSC were obtained from deep-tow sub-bottom profiler records. The Huntec DTS system was used on the majority of the regional surveys conducted by the GSC Atlantic. The Huntec DTS deep-tow boomer, the

NSRF V-fin deep-tow sparker, or the ORE 136A deep-tow 3.5 kHz profiler systems were used on most wellsite surveys. Occasionally, where sub-bottom profiler data was not available, scour depths were recorded using echo sounders and hull-mounted 3.5 kHz profilers (Nordco, 1984).

Operating Principles

Geophysical profiling systems, whether echo sounders or sub-bottom profilers, transmit an acoustic pulse through the water column and receive a return echo from the sea floor. Echo sounders transmit a relatively high-frequency narrow-beam pulse (typically 12 kHz to 200 kHz) that is capable of providing a detailed profile of the sea floor but does not penetrate through coarse seafloor sediments to any degree. Sub-bottom profilers typically transmit a broad frequency spectrum (typically 400-10,000 Hz) with sufficient low frequency energy to profile through most near surface sediment cover. The types of profilers used to measure ice scours in the compilation of the GBSC are compared in Table 2.2.

Ice Scour Measurement and Resolution

Scour depth is the most important scour parameter that is measured from profiler records. Where apparent, berm heights and the shape of the scour profile have also been recorded in most cases. In some early scour catalogue programs, apparent scour width measurements were obtained from profiler records. Scour depth is measured as the distance between an interpreted pre-scour (smoothed) seafloor surface and the maximum recorded depth of the scour incision.

The measurement of scour depth from profiler records is dependent on a number of factors, as outlined below.

- The ship track must pass directly across an ice scour in order to profile the scour depth. This condition is met for approximately one-third (1095 of 3269 scours with depth measurements) of the GBSC scours recorded within the study area.

- The ability of the interpreter to correlate between sidescan and profiler records. In the case of very shallow scours, or scours that are superimposed on an irregular seafloor profile, it is not always possible to match a feature observed on sonograms to the profiler record. Correlation is generally not a problem for large or deep scours formed on a smooth seafloor.

- The resolution of the profiling system is an important factor, especially in the recognition and measurement of shallow scours with depths at or near the system resolution. Actual resolution is a function of the theoretical resolution of the system, weather conditions (primarily for hull-mounted profilers), profile display scales, the pre-scour seafloor roughness, and the experience of the interpreter. Approximately 48% of scour depth measurements recorded within the GBSC, have an associated interpreter depth code value which indicates that the scour depth is less than the profile resolution.

- The size of the acoustic footprint, across which the initial seafloor reflection is generated, is an important factor in accurate recording of deep and narrow incisions. If the scour width is significantly less than the acoustic footprint, the deepest part of the scour may not be resolved on the profiler record, and the subsequent scour depth measurement will be less than the true scour depth (Harris and Jollymore, 1974; Barrie et al., 1986, Geonautics Limited, 1989). This may be the case for many deeper water scours, described as steep v-sided features (Nordco, 1982), that were imported into the GBSC from earlier databases.

- Scour infilling is another factor to consider with respect to scour depth measurement distribution, especially in non-cohesive sediment. Some level of scour infilling occurs during, or immediately following, the scouring process (Woodworth-Lynas et al., 1986). Scour incisions may also be modified or infilled over time due to local transport of bottom sediment (Barrie et al., 1986; Hodgson et al., 1988). Scour infill was not measured or detected for any of the scours contained in the GBSC.

2.2.3 Multibeam Sonars

Multibeam sonar technology, capable of providing detailed 3-D images of seafloor bathymetry and acoustic backscatter plots, has been used to map ice scours on the Grand Banks by the Geological Survey of Canada, Atlantic since the mid-1990's (Sonnichsen 1996). At present, the GBSC database includes ice scour data obtained from multibeam data sets collected using the Simrad EM100 and the Simrad EM3000 systems. The earlier EM100 system operates at 95 kHz frequency, with 32 individual 2^o by 3^o beams. The EM3000 system operates at 300 kHz frequency with 127 individual 1.5^o by 1.5^o beams.

Multibeam sonars utilize beam-forming techniques to transmit a fan-shaped array of individual sounding beams which collect detailed bathymetric soundings across a wide swath of seafloor. The width of a multibeam swath is a function of the angle between the outermost sounding beams and the water depth along the survey line. Sounding density is a function of the number of individual beams, the beam spacing, and the water depth. Multibeam systems must include equipment to correct for vessel motion, tide variations, and sound velocity, as well as apply position data to provide a digital file of geo-referenced soundings. Properly processed multibeam data sets are capable of providing a digital terrain model of the seafloor at resolutions of less than a few decimeters (Hughes-Clarke et al., 1994). The commonly used sun-illuminated, shaded-relief images of multibeam data provide a detailed view of seafloor morphology.

Scour Detection and Measurement

Cumming and Sonnichsen (1997) report on a comparison of ice scour detection between sidescan sonar and multibeam data sets collected near the White Rose discovery site on the Grand Banks. Preliminary field observations of the multibeam data revealed a large number of scours, including subtle older features. Subsequent comparison with sidescan records indicated that the EM100 system was not able to resolve very shallow scours with depths of less than 0.5 meters. Scours with depths greater than 0.5 meters were consistently apparent on both the sidescan and multibeam data sets. Occasionally, older subtle scours apparent on the multibeam imagery were not detected on individual sidescan records. The data comparison at the White Rose site indicate that multibeam sonar is a viable technique for scour mapping which should improve over time with increased system resolutions. The advantages and limitations of multibeam sonar versus sidescan sonar for ice scour mapping are listed below.

Multibeam Advantages

- Multibeam data sets can provide an accurate geo-referenced image of the seafloor and scour event. Sidescan acoustic positioning / layback uncertainties and towfish motion may influence the mapped scour position and orientation compared to hull-mounted multibeam systems.

- Scour depth can be measured along the entire length of a scour using multibeam data, thus providing scour depth variation and rise-up information.

- Some subtle scour features detected only on multibeam mosaic image.

Multibeam Limitations

- At present, the major limitation of the multibeam sonars used on the Grand Banks is the inability to resolve scours that are less than 0.5 meters deep. This limitation may be reduced as multibeam system resolutions improve. Sonnichsen (1998) reports a multibeam scour detection limit of 0.4 m scour depth for data collected on the Grand Banks in 1998.

- Depending on the sounding spacing and detail of the post-processing images, it is possible that small, or narrow, scours may be missed.

- Although multibeam systems provide backscatter data, the acoustic morphology of scours is better defined using sidescan systems.

- At present, there is no automated method of measuring scour depth, and scours incorporated into the GBSC do not include scour depth measurements obtained from the multibeam data.

2.3 Time dating or Ageing of Scours

It is necessary to determine the age of an observed scour population in order to convert the scour density observed on sonograms to scour frequency. At present, there is no agreed upon method to accurately determine the age of the scour population on the Grand Banks. Dating techniques used in previous studies include repetitive mapping, geologic constraints, cross-cutting relationships, direct sampling, scour degradation, biological re-colonization, and residency time. Each of these techniques is discussed below with respect to the ice scour population in the present study area.

Geological Constraints

1. Shallow portions of the Grand Banks (less than 110 meters present water depth) were subaerially exposed during a low sea-level stand dated at approximately 15,000 years BP (Fader and King 1981). Any scours formed previously would have been eroded during the low sea-level stand and subsequent marine transgression. The maximum age of the recent scour population observed in water depths of less than 110 meters is estimated at 10-12,000 years B.P. at which time water depths over the bank tops were sufficient to allow the passage of icebergs (Barrie et al., 1984).

2. Lewis and Parrot (1987) correlate the historical presence of icebergs to the abundance

of ice rafted material in sediment cores collected on the northeast Newfoundland Shelf, and suggest that the Grand Banks area is a marginal iceberg zone that experiences intermittent iceberg incursions. They suggest that the recent scour population may relate to an increased iceberg flux in the late Holocene, aided by an intensification of the inner Labrador Current at approximately 2,500 years B.P. (Scott et al. 1984).

Repetitive Mapping

The repetitive mapping technique is based on the collection of two or more sets of sidescan sonar data over a period of one or several years. It has been successfully used in the Beaufort Sea and high Arctic to determine scour impact rates (Barnes and Reimnitz, 1986, Myers et al. 1996a, Blasco et al., 2000). New scours are identified by conducting a detailed examination of the baseline and repetitive sonograms. Any new scour features observed are dated within the time interval between the dates of the baseline and repetitive surveys. Given a significant new scour population size, the resultant scour frequency rates calculated using repetitive mapping can be used to infer the time period over which an observed scour population has accumulated.

Several sets of repetitive mapping coverage are available for the Grand Banks. The most extensive of these are a series of 70 km long lines, referred to as the 4000 Series, that were surveyed between the North Hibernia and Trave-White Rose wellsites in 1979 and 1990 (Geonautics Limited, 1991). Limited repetitive mapping data sets were collected at the Terra Nova site between 1988 and 1994 (Myers and Campbell, 1996), and at the White Rose site between 1988 and 1996 (Cummings and Sonnichsen, 1997). Additional repetitive mapping of some regional lines has also been conducted by the GSC, Atlantic.

Results published to date indicate that scouring rates are very low. Four possible new iceberg-created pits have been identified; two at the 4000 series site and two at the White Rose site. No new linear scour features have been identified in the published literature to date. Considering the 4000 series, at approximately 340 km^2 coverage, if one new scour had occurred over the 11 year repetitive mapping period, the corresponding scour frequency would be 0.00027 $scours/yr/km^2$. At this rate, the observed 4000 series population of 280 scours would have accumulated over a period of approximately 3000 years. This would represent a minimum age estimate, since no new scours were actually detected in the 4000 series repetitive mapping program.

Due to the low rates of scouring on the Grand Banks, it is expected that additional repetitive mapping data may be required to provide better constrained estimates of scour frequency throughout the study area.

Cross-Cutting Scour Relationships

For dense scour populations with numerous superimposed scours, it is possible to determine the relative age of the cross-cutting scours from sonograms. Woodworth-Lynas (1983) sub-divided the scour populations on the densely scoured Labrador Shelf into relative age classes based on cross-cutting scour relationships. However, as a stand alone method, the cross-cutting scour relationship technique can not provide an absolute age for ice scours.

For most areas on the Grand Banks, in water depths less than 110 meters, scour density is too low to sub-divide the scour population into various age classifications based on cross cutting scour relationships. Two populations of cross-cutting scours occur in water depths greater than 110 meters; a dense population of partially buried relict scours displaying a degraded scour morphology, and a sparse population of more recent scours, displaying a relatively fresh scour morphology, which is superimposed on the relict scoured surface in water depths between 110-200 meters.

Scour Degradation/Residency Time

The acoustic character of scours recorded on sonograms can be used to classify scour degradation. Sonograms of recent scours typically show small scale lineations and cross-fractures within the scour incision, and well-defined irregular berm structures. One or more intermediate morphology classes may be discerned during the initial stages of scour degradation, before the small scale features are eventually obliterated and the scour displays an old or severely degraded morphology. Blasco et al. (2000) recognize five scour morphology/age classes on high-resolution sonograms collected off Cornwallis Island in the high arctic. Classification of scours according to the degree of scour degradation does not provide an absolute scour age. Site specific ground truth data is required to assign absolute ages to scours of varying stages of degradation.

Ice scour degradation processes include erosion by bottom currents, sediment infill, biological activity, and cross-cutting by more recent scours. The rate of scour degradation is primarily dependant upon the scoured sediment type, and the hydrodynamic regime in which the scour occurs. In hydrodynamically active areas, newly formed scours in fine-grained non-cohesive sediments may be obliterated in one or two years (Myers et al., 1996b). In moderately active areas, scours formed in gravelly muds off Cornwallis Island display a severely degraded acoustic morphology after approximately 50 years, but may persist as recognizable features on sonograms for several hundred or thousands of years (Blasco et al., 2000). In the hydrodynamically quiet areas along the outer shelf and slope off eastern Canada, relict scours formed during a period of lower sea level and deglaciation approximately 15,000 years B.P. are readily apparent on sonograms (King 1976; Fader and King, 1981; Piper and Periera, 1992).

Detailed studies of scour degradation have not been conducted within the Grand Bank study area, and scour records in the GBSC do not include a description of scour morphology. Scours incorporated into the GBSC since 1992 have a clarity code, which relates to the degree of scour degradation and could be used to estimate the distribution of scour degradation classes. Uniform rates of scour degradation are not expected within the Grand Bank study area due to variation in sediment type and differences in the hydrodynamic regime throughout the region. Storm generated bottom currents are known to periodically rework the surficial sands on the Grand Banks to water depths of approximately 110 meters (Amos and Judge, 1991; Barrie et al., 1984). Consequently, in water depths less than 110 meters, scours formed in sand will be degraded more quickly than those formed in gravels. Scours formed in gravelly sands are also expected to be preferentially preserved due to the formation of a gravel lag veneer. A gravel-cobble lag veneer, formed during the initial degradation period, dramatically slows the degradation process. The acoustic scour morphology of the severely degraded scours remains essentially unchanged for a long time, perhaps hundreds or thousands of years.

Given that scour degradation processes may ultimately obliterate any evidence of an iceberg scour, scour residency time is also an important factor to consider. That is, how long will a scour formed remain as a seafloor feature that is capable of being detected on sonograms. At the Hibernia discovery site, scour densities in areas of lag gravel are 5-30 times greater than those recorded in adjacent sandy bottom (Lewis and Barrie, 1981), despite the fact that the sands form bathymetric highs and thus should be more heavily scoured. Lower scour density in sands compared to gravels is also reported at the South Nautilus, East Flying Foam, and Terra Nova wellsites, and at the GSC (Atlantic) 1994 partial survey of the 4000 series (Sonnichsen, personal communication; Myers and Campbell, 1996b; Synmap Limited, 1996). Thus it appears probable that on the bank tops the scour population recorded on sonograms, especially in areas of mobile sands, represents only a portion of the scours formed since the onset of recent scouring.

Hydrodynamic activity is not sufficient to significantly rework bottom sediments in water depths greater than 110 meters, and scours formed in deeper water are degraded more slowly. A relict and partially buried scour population, interpreted to have formed approximately 15,000 years B.P., is widespread in water depths greater than 110 meters on the Grand Banks and adjacent continental slope. The detection of these relict features on sonograms attests to the low rate of scour degradation, and the potential residency time, for ice scours formed in a hydrodynamically quiet environment.

Direct Sampling

Sediment cores are dated using several methods including; foram assemblages, pollen analysis, and isotope analysis. Palynology has been successful in dating partially infilled scours in deep water off the northeast Newfoundland Shelf region (Mudie, 1986).

Successful scour dating results using direct sampling techniques would require that cores be obtained from scours infilled with a progressive sequence of fine-grained sediments. Some bank-top scours formed in gravel display an apparent sand infill, and may represent possible targets for direct sampling programs. However, it is likely that these sands have been periodically reworked, and may include older shell material from the adjacent seafloor.

An extensive sampling program of scours with varying levels of scour degradation would be required in order to relate direct sampling results to an accumulated scour population. Due to low rates of degradation associated with severely degraded scours, several severely degraded scours would have to be sampled to obtain a statistically reliable age for the oldest observed scours. Any sampling program would also require accurate scour and sampling positions to ensure that cores were obtained from within a scour trough. This is not an easy task due to uncertainties in the mapped position of scours, and difficulties in recognizing scour events at the seafloor.

Direct dating of cores is probably unviable for the shallow water portions of the Grand Banks. In deeper water depths it may be possible to obtain an age for the inferred relict scour population, and any partially infilled scours within the recent scour population.

Biological Re-colonization

The scouring process results in the destruction of the pre-scour benthic community within the scour incision. The rate at which the freshly exposed seafloor is re-colonized by various species may be used to date scours. This method may only be useful for scours that are younger than the complete re-colonization time interval.

Table 2.1 Comparison of Sidescan Sonar Systems

Sidescan System	Frequency (kHz)	Pulse Width (msec)	Beam Width (Degrees)	Range Resolution	Transverse Resolution[1]
Klein	50	0.2	1.5	0.2 m	6.5 m
Klein	100	0.1	1.0	0.1 m	4.4 m
ORE	100	0.1	1.0	0.1 m	4.4 m
BIO	70	1.0	1.5	0.8 m	6.5 m
Simrad	120	0.1	0.75	0.1 m	3.3 m
Edgetech	100	0.1	1.2	0.1 m	5.2 m

[1]Calculated at 250 meter range for all systems.

Table 2.2 Comparison of Profiler Systems

Profiler System	Platform Type	Frequency (kHz)	Beam Width (Degrees)	Footprint Diameter[1]	Vertical Resolution[2]
Echo Sounder[3]	hull-mount	3.5-200	8	7m, 28 m	0.1 m
ORE 3.5	towed body	3.5	55	26m, 104m	0.2 m
Huntec DTS	towed body	0.8-10	11	10m, 39m	0.2 m
NSRF V-Fin	towed body	1-3	N/A	N/A	0.5 m

[1]For source located at 50 and 200 meters above the seafloor.
[2]Theoretical system resolution. GBSC sources incorporate a minimum detectable scour depth of 0.3-0.5 m (Huntec), 0.5 m (ORE 3.5 kHz), or 1.0 m (NSRF V-Fin). The detection limit for scours profiled using hull-mounted systems is variable, depending on the sea state during the survey.
[3]Individual echo sounder types are not identified in the GBSC (beam width and footprint based on survey grade 200 kHz system).

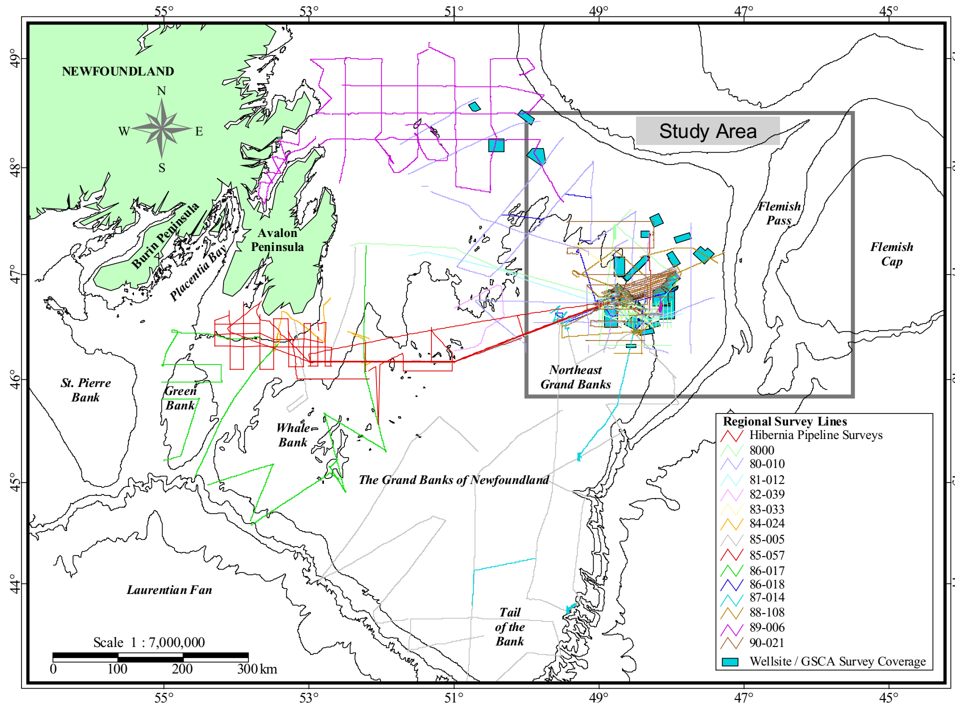


FIGURE 2.1 GBSC1999 Regional Survey Lines, Wellsite / GSCA Multibeam Survey Coverage, and Study Area; Grand Banks.

Canadian Seabed Research Ltd.

3.0 REVIEW OF ICEBERG SCOUR DATA

3.1 Background

The Grand Banks Scour Catalogue (GBSC) is the most complete and up to date record of ice scours detected on the Grand Banks, containing a record of 3887 individual scours and 1733 iceberg-created pits. It was compiled by Canadian Seabed Research Ltd. for the Geological Survey of Canada, Atlantic between 1992 and 1995 (Myers et al.1995), and updated in 1999 (Canadian Seabed Research Ltd., 2000). The GBSC incorporates ice scour data obtained from several sources, including the Mobil Scour database (Nordco 1982 and 1984) and the ESRF 4000 Series repetitive mapping program (Geonautics, 1991).

In contrast to the earlier East Coast Ice Scour database, which provided scour statistics within 2 km line segments (Geonautics, 1989), the GBSC catalogues individual ice scour features. It contains records of 5620 individual scour features, including both linear scours and iceberg-created pits, and includes information on the feature type (i.e. scour or crater/pit), location, and physical dimensions. Approximately 30% of the GBSC records are iceberg-created pits. These are essentially point-source features, formed by the grounding or rolling of icebergs, with an average depth of 3.0 meters. The distribution of iceberg-created pits on the Grand Banks is documented by Davidson and Simms (1997), and is not addressed further in this report.

3.2 Overview of the Grand Banks Scour Catalogue

The scours recorded in the GBSC were identified and measured from various geophysical data sets including; sidescan sonar, sub-bottom profiler, echo sounder, and multibeam (see Section 2). Survey coverage consists of an irregular network of regional lines collected primarily by the Geological Survey of Canada, and site specific well-site surveys collected by industry (Figure 2.1). Individual regional and well-site surveys are listed in Table 3.1 and Table 3.2, respectively. Figures 3.1 and 3.2 illustrate the various sidescan and profiler systems used on the regional surveys within the study area. Wellsite and research grid survey sites are displayed in Figure 3.3.

The greatest concentration of survey data, and consequently the greatest number of recorded scours, is associated with the high level of petroleum exploration within the Jeanne d'Arc sub-basin in water depths of 80-150 meters. The GBSC includes relatively few scours for water depths greater than 150 meters on the northeast Grand Banks, and no scours from the Flemish Pass region.

A complete listing of the current GBSC database fields is presented in Table 3.3. Due to differences in the recording procedures associated with the various data sources used in compiling the GBSC, many of the scour records are incomplete. For example, the original Mobil database (Nordco, 1982) only included scour type, location, and scour depth for features identified on regional survey lines. Each of the sources of ice scour data used to construct the GBSC are reviewed below.

Mobil Ice Scour Catalogue

The Mobil Ice Scour Catalogue represents the first significant ice scour database for the Grand Banks that contained information on individual scour features. It was compiled from various sources including regional lines surveyed by industry and government, and from wellsite survey data. An original database, compiled using data available to 1981 (Nordco, 1982), was augmented with additional wellsite and regional survey data available to 1983 (Nordco, 1984). The regional and wellsite survey coverage used to compile the database are listed in Table 3.1 and Table 3.2, and displayed in Figures 3.1 to 3.3.

There are significant differences in the scour data recorded in the Mobil Ice Scour Catalogue compared to the more recent GBSC sources. These are summarized below.

- In the original compilation, scour depth and scour position were the only parameters recorded from regional survey data. Sidescan sonar records were only used to distinguish between scour and pit features. Consequently only those scours which crossed the survey line, representing a small fraction of the total observed population, were recorded in the original database. For the wellsite surveys, scours observed on both sidescan and profiler records, and pits observed on profiler records, were included in the original database.

    - For the update compilation, all fresh looking scour features observed on both sidescan and sub-bottom data sets were included for the regional survey lines and wellsites. The scour data records from the update study contain most of the scour parameters contained in the GBSC, including; scour type (scour or pit), plan shape, length, width, orientation and scour depth measurements.

    - For the wellsites, survey reports were reviewed and the original geophysical records were analysed as required to obtain the necessary statistical data (Nordco, 1984). However, in some cases, it appears that scour depth, width, and length measurements were obtained from the wellsite survey report.

- Scour clarity was not recorded, and only fresh unmistakable features were entered into the database. The more recent GBSC sources included a scour clarity parameter allowing the inclusion of less distinct features, which were nevertheless considered to be probable scours.

- Scour depths were typically measured to the nearest 0.5 meter for most of the scours recorded from wellsite data, and a considerable portion of the scours recorded from regional survey data.

Post-1983 AGC/GSC (Atlantic) Surveys (1992 GBSC compilation)

For the original 1992 Grand Banks Scour Catalogue compilation, scour measurements were obtained from 9 cruises conducted by the Atlantic Geoscience Centre between 1983 and 1990 (Table 3.1). Most of these surveys included two sidescan systems and the Huntec DTS sub-bottom profiler (Figures 3.1 and 3.2). Details of individual cruises are summarized in Myers et al. (1995).

Scour reduction and digital database compilation for Dawson 89-009 and the ESRF 4000 Series portion of the Dawson 90-021 cruises were conducted by Geonautics, following procedures described by Geonautics Limited (1991). Scour measurements for the remainder of the AGC data sets were reduced by Canadian Seabed Research (Myers et al., 1995), with the exception of six scours at the Hibernia GBS mosaic site (part of Cruise 87-014) which were obtained from a surficial geology map. All scour features observed in water depths less than 110 meters were incorporated into the GBSC. In water depths greater than 110 meters, only those scours which displayed a relatively fresh acoustic morphology were recorded, thus excluding the population of older degraded scours which are interpreted to be relict scours formed at the end of the last glaciation (Fader and King, 1981).

Data reduction techniques and scour parameter measurements were similar for both CSR Ltd. and Geonautics Ltd.. Individual scours were recorded as one or more segments, with each scour segment representing a significant change in at least one scour parameter. Scour length, width, and orientation were measured directly from the sonograms, and subsequently processed for slant-range and ship-speed corrections to obtain true scour dimensions. Scour depth, profile shape, and berm dimensions were measured directly from sub-bottom profiler records. Most of the scour dimensions have an associated data qualifier code, which provides additional information on the particular scour parameter. For example, the length qualifier parameter indicates whether all or only part of a scour was observed on the sonogram. Scour records reduced by Geonautics do not include scour depth qualifier or sediment type information.

In addition to scour dimensions, scour records include information on the geophysical systems, data quality, scour clarity, and sediment type (Table 3.3).

Post-1983 Wellsites (1992 GBSC compilation)

A total of 21 wellsite survey reports released prior to 1993 were reviewed as part of the 1992 GBSC compilation. Nine of the 21 reports contained detailed scour measurements.

Of these, four surveys conducted in water depths less than 110 meters were selected for inclusion into the GBSC (Table 3.2). Survey reports from the deeper water sites did not distinguish between recent and relict scours and were thus not incorporated into the GBSC. All of the scour information for these scours was obtained from the wellsite survey reports. The original geophysical data sets were not examined.

1999 GBSC Update

Scour data reduced from two recent wellsite surveys and three grid surveys conducted by industry and the GSC (Atlantic), respectively, were incorporated into the Grand Banks Scour Catalogue in 1999 (Canadian Seabed Research Ltd., 2000)(Table 3.1 and Table 3.2). For each of these sites, scours were digitized from digital images; digital sidescan mosaics in the case of the wellsite surveys, and digital sidescan and/or bathymetric digital terrain models constructed from multibeam data collected at the GSC (Atlantic) grid sites. Although the data reduction techniques differ for these recent studies compared to previous GBSC sources (i.e. scour locations digitized from geo-referenced image), the primary scour parameter measurements have not changed. At present, scour depth measurements have not been obtained from the multibeam bathymetry data sets.

Possible Duplicate Scours

In areas covered by more than one survey, some scours may have been identified from two or more data sets and entered into the GBSC more than once. The potential for duplicate scours is greatest in areas of overlapping wellsite coverage, or where regional survey lines cross grid or wellsite survey areas. A preliminary examination of the GBSC revealed that approximately 15% of the recorded scours occur within 100 meters of another scour mapped from a different survey data set. While this does not mean that all nearby scours are duplicates, it indicates that the potential for duplicates is significant. All closely spaced scour pairs would need to be examined individually to assess overall scour dimensions, orientation and plan shape to determine whether or not each pair contained a duplicate entry.

3.3 Scour Densities

3.3.1 Methodology and Limitations

The Grand Banks Scour Catalogue was used to calculate scour density (# of scours/km^2) for 1 km^2 grid cells within the study area. The GBSC1999 was simplified prior to the calculation of scour densities. Scour event coverage was created for the study area that excluded craters and scours coded with possible errors.

A complete survey coverage of the GBSC1999 was then created from the following sources; wellsite survey coverage, GSCA multibeam / sidescan survey coverage, and Regional GSCA survey lines (Navbase96). Regional survey lines were buffered according to the sidescan effective swath as stored in Navbase96. The complete GBSC1999 survey coverage was spatially overlain with a 1 km^2 grid coverage of the study area.

The GBSC scour event coverage of the study area was overlain with the combined Survey Coverage / 1 km^2 grid to create an Ice Scour Density Coverage. The primary product of these calculations is the spatial distribution of scour density presented in Figure 3.4. The original Mobil regional survey line scours could not be incorporated into the density calculations, and are presented separately in a scours per line kilometer format in Figure 3.5. Scour densities are dependent on the number of scours detected within a given seabed swath. As described in Section 2, uncertainties in scour detection levels are introduced by interpreter variability, survey instrumentation, and sediment type. Each of these factors are summarized below.

<u>Interpreter Variability</u>

Interpreter variability is a significant factor not only in the measurement of scour dimensions, but in the detection of scour features. Results of the East Coast Scour Database compilation (Geonautics Ltd., 1989), which included the most intensive study of interpreter variability, indicates typical variability in the level of scour detection between 10-30%. Greater variability may be associated with the Mobil Ice Scour Catalogue source, which did not include a scour clarity qualifier, compared to later sources which measured scour clarity. Such a qualifier allowed interpreters in later compilations to include less prominent features which were nonetheless considered as probable scours. Repetitive mapping studies indicate that scour mapping programs which did not include a scour clarity qualifier recorded less than 50% of scours compared to studies which included a scour clarity parameter (Geonautics Ltd., 1991; Myers and Campbell, 1996).

<u>Sediment Type</u>

Sandy sediments are periodically reworked by storm generated bottom currents in water depths of less than 110 meters. Lower scour densities observed in sands compared to gravels indicate that, over time, part of the scour population formed in sands has been degraded beyond the detection levels of the geophysical systems. The rate at which this occurs is water depth dependent, but is not well constrained at present. Normalized scour density calculations, which could account for the lower level of scour preservation in sands, would require a complete surficial sediment coverage such that the percentage of sand versus gravel could be determined. This level of information on the surficial geology is not currently available on a regional level.

<u>Instrumentation Differences</u>

The level of scour detection is dependent, in part, on the type of survey system used to map the scours. Differences between sidescan systems noted in Section 2.0 may be less significant than the differences between sidescan and multibeam bathymetry. The highest scour densities within the study area occur within the repetitive mapping corridor (GSC,A 98-024) established by the GSC (Atlantic) in 1998 (cf. Figure 3.3 and 3.4). The average scour density for this corridor is approximately twice that of adjacent areas in similar water depths. Scours within this corridor were detected using both digital sidescan and multibeam bathymetry, suggesting that the increased density is due in part to higher levels of scour detection associated with the additional multibeam data set.

<u>Scour Age</u>

The age of the observed scour population on the Grand Banks is not well constrained. Minimum and maximum age estimates differ by almost an order of magnitude. The minimum age estimate, proposed by Lewis and Parrot (1987), is associated with the close of the last climatic optimum and a strengthening of the Labrador Current at approximately 2500 year B.P. The maximum age estimate at approximately 12,000 year B.P. corresponds to the time at which sea level had risen sufficiently following the last glaciation to allow the passage of icebergs onto the Grand Banks (Barrie et al., 1984). At present, there is insufficient direct evidence to infer a best estimate within these ranges.

3.3.2 Results

The spatial distribution of scour density within the study area is displayed in Figure 3.4. Scour density values for individual 1 km^2 grid cells range from 0-30 scours/km^2 within the study area. The highest scour densities are associated with recent surveys where scours were identified using digital sidescan mosaics and or multibeam bathymetry DTM’s (cf. Figure 3.3 and 3.4). These include the East Flying Foam wellsite, the GSC (Atlantic) 98-024 baseline corridor survey, and GSC (Atlantic) Cruise 94-021 (Terra Nova and 4000 Series site mosaics). A prominent bathymetric high, with relatively steep east and northeast facing slopes, located at the southwest end of the GSC (Atlantic) repetitive mapping corridor is the most heavily scoured seafloor within the study area. Scour densities in this area range from 15-30 scours/km^2.

Several wellsites from the 1992 Mobil Ice Scour database appear to have very low scour densities compared to adjacent regional coverage and the more recently surveyed wellsites in the vicinity. These include the Nautilus, Hebron, Rankin, Ben Nevis, and West Hibernia wellsites. In contrast, the Tempest North wellsite appears to be more heavily scoured than adjacent areas. Anomalous scour depth measurements are also associated with the Tempest North site (Section 3.4), suggesting that there are problems with the original scour interpretation for this site.

Scour density is highly variable on a local level, possibly related in part to local changes in bathymetry or sediment type. The most pronounced of these local density variations occur within the East Flying foam wellsite (Figure 3.4). The heavily scoured eastern part of the site slopes relatively steeply towards the east and north. In contrast, the lightly scoured western part of the site is comprised of predominantly flat-lying or gently westward sloping seafloor. Although the scour distribution at this site appears to be strongly controlled by seabed slope, it is also possible that many of the scours formed in sands over the shallow water portion of the site (85-90 m water depth) have been degraded beyond recognition by bottom currents.

Mean scour density values within selected bathymetric intervals are presented in Table 3.4. The mean scour density is 0.56 scours/km^2 for the total survey coverage in water depths of less than 110 meters, and 0.86 scours/km^2 for the total coverage in water depths greater than 110 meters. The highest mean density, at 1.2-1.3 scours/ km^2, occurs between 100-150 meters water depth. Lower density in deeper water may be related to a lower number of deep ice keels. The progressively lower mean density values in shallower water are probably due, in large part, to the reworking of scoured sediments by increased levels of hydrodynamic activity which has led to the obliteration of some scours over time, particularly those formed in sands.

3.4 Scour Frequencies

The scour density information described above shows interesting spatial trends, but is not directly applicable to risk studies. To assess the probability of a point, area, or linear feature on the seabed being contacted by a scouring iceberg, scour *frequency* information is needed. Lewis et al. (1986) conducted an excellent review of the state-of-the-art at that time, and relatively little new work has entered the public domain since. There are several techniques that can be used to estimate scour frequency, and these are discussed below. Because there is considerable uncertainty in all of the techniques, it is useful to begin by bounding the problem. This can be accomplished by putting reasonable time constraints on the formation period of the observed scour record. Estimating the age of the accumulated scour population has the largest potential for error (i.e. outweighing interpreter variability, undetected scours, possible duplicate scours, etc.). As described below, probable minimum and maximum estimates of scour age differ by almost an order of magnitude. Scour frequency results presented in Table 3.4 are based on an inferred minimum age estimate of 2500 year B.P..

3.4.1 Upper and Lower Bounds

The recent geologic record for the Grand Banks region indicates that 12,000 to 15,000 years BP the water depth was approximately 110m lower than it is today. That is, all portions of the Grand Banks currently at water depths less than 110m were above sea level 15,000 years BP. Since the water level rise took place rapidly (over a period of about 3,000 years), it seems reasonable to assume that all iceberg scours in water depths less than 110m were created over the past 12,000 years.

If *all* of the scours created in the past 12,000 years still exist, then the average annual scour rate would be the observed scour density divided by 12,000. For example, in an area were the observed scour density is 1/km^2, the lower bound scour frequency would be 8.3×10^{-5} /km^2/year. It must be assumed in this analysis that the scour rate has been constant over the entire period, since we can only calculate a mean value. This is almost certainly not the case, but it is extremely difficult to predict what the temporal variations may have been. In the absence of more information, the average scour rate must suffice.

It is known that in-filling and reworking of the seabed by currents, waves, and to some extent iceberg scouring, has removed some proportion of the scours from the observed record. The extent of this reworking is expected to be highly dependent on water depth, sediment type and scour orientation (Lewis et al., 1986). The estimated rates of in-filling and reworking for the shallow water regions (less than 110m) suggest that on average, scours created in the past 2500 years are still visible. The residence time for a scour might be expected to depend on scour depth, with deeper scours remaining visible for longer periods than shallow scours. Again taking an area where the observed scour density is $1/km^2$, the upper bound scour frequency would be 4.0×10^{-4} $/km^2/year$.

There is a factor of about 5 difference between the upper and lower bound for scour frequency, which demonstrates the uncertainty involved. Attempts to better define the true scour rate are described below. The scour frequency estimates obtained using these techniques are summarized in Table 3.5.

3.4.2 Repetitive Mapping

The most attractive method for determining scours rates is through repetitive surveys of the same area of sea floor. These should be spaced at sufficiently large time intervals to allow a statistically significant number of new scours to be formed. This technique has been used extensively in the Beaufort Sea and has been attempted in the Grand Banks region (Lewis et al., 1986). The usefulness of this method for iceberg scour rates on the Grand Banks is limited by the relatively low scour rates. Lewis et al. (1986) describe a repetitive mapping study in which no new scours could be positively identified on overlapping sonograms taken 6 years apart. They nevertheless use probability theory to make some statement about likely scour rates. Given the area of the overlapping surveys and the interval between surveys, they calculate that there would be a 50% chance of detecting a new scour in the survey area if the scour rate was 1.01×10^{-3} $/km^2/year$. They then proceed to calculate scour rates for a range of detection probabilities (Lewis et al., 1986; Fig.16). For example, they determine that for 99% confidence that no new scours are observed, the scour rate would have to be 6.73×10^{-3} $/km^2/year$.

The Geonautics Limited (1991) data discussed in Section 1.2 show 1 new scour in a $490km^2$ region over an 11year period. This corresponds to a scour frequency of 1.9×10^{-4} $/km^2/year$.

3.4.3 Numerical Modeling of Grounding Rates

d'Apollonia and Lewis (1986) developed a numerical model of iceberg drift, iceberg draft, and sea floor bathymetry to estimate grounding rates. Icebergs were entered into the model at a specific latitude, and allowed to drift southward through a region divided into square grid cells. The number of icebergs grounding in any given cell was the calculated as the fraction of the total iceberg flux through a cell with drafts within a predetermined range (Lewis et al., 1986). The 'grounding draft range' was based on the distribution of water depths in the cell. The model was calibrated with observations of iceberg grounding along the Labrador coast. The modelled scour rate for the Hibernia area was 3.5×10^{-3} /km^2/year. It was assumed that every iceberg that contacted the seabed created a scour.

Petro-Canada used an in-house numerical grounding model called BERGSIM to estimate scour frequencies at Terra Nova. C-CORE (1999) developed a much more sophisticated numerical grounding model and applied it to the entire Grand Banks region. The results of this work are not publicly available.

3.4.4 Scour Degradation Calculations

Lewis et al. (1986) describe methods to estimate the scouring rate from information on scour degradation. Implicit in these calculations is the assumption that the present scour conditions represent an equilibrium condition between scour creation and scour degradation. Based on work by Gaskill (1986), they estimate that the present scour conditions at Hibernia would require a scour rate of about 1.0×10^{-3} /km^2/year.

Amos and Barrie (1985) estimated scour rates in the vicinity of Hibernia at between 5.0×10^{-4} /km^2/year and 6.0×10^{-3} /km^2/year using a similar approach based on ripple migration rates.

3.4.5 Scouring Period Estimates

Lewis et al. (1986) analysed the geologic and sedimentary history of the Grand Banks and inferred that the observed scours were created over the 2,500 years. For the Hibernia area, were observed scour densities are about 1/km^2, this suggests a scour rate of 4.0×10^{-4}/km^2/year. This is essentially the same methodology used to generate the lower bound estimate above.

3.4.6 Iceberg Flux Analysis

An approach not described by Lewis et al. (1986) is to estimate scour rates directly (analytically) from iceberg flux and draft statistics. Jordaan et al. (1999) have calculated the iceberg areal density for the degree square containing Hibernia to be approximately 0.6. If the average residence time in the degree square is 13 days (110km of net southward drift at an average speed of 0.10 m/s), then the average number of icebergs entering the degree square in one year is 365.25 days × 0.6 / 13days ~ 17. Jordaan et al. (1995) found that the iceberg length distribution on the north east Grand Banks can be closely approximately by an exponential distribution with a mean 59m. If draft is related to length by,

$$D = 3.8 \times L^{0.63} \tag{3.1}$$

(Hotzel and Miller, 1983) and we note that water depths range from 80m to 120m through most of the Hibernia degree square, then the proportion of icebergs that have the potential to contact the seabed in the degree square is,

$$\begin{aligned} p(80 \le D \le 120) &= p(126 \le L \le 240) \\ &= (1 - \exp(-126/59)) - (1 - \exp(-240/59)) \\ &= 0.10 \end{aligned}$$

The number of icebergs that have the potential to contact the seabed per year is 17 × 0.10 = 1.7. If all of these icebergs contacted the seabed and scoured once the scour rate would be 1.7 / 8500 = 2.0×10^{-4}/km^2/year. If we assume that only 50% of the icebergs in the 80 to 120m draft range contact the seabed, but those that do each create 4 scours, then the scour rate would be 4.0×10^{-4}/km^2/year.

3.4.7 Discussion of Scour Frequency Estimates

Several elements of Table 3.5 are noteworthy. First, the scour rate estimates from several previous studies are *higher* than the upper bound value calculated in the present study. As mentioned above, the d'Appollonia and Lewis (1986) model calculates iceberg/seabed contact frequency. If it is assumed that all icebergs that contact the seabed create scours, then this is also the scour frequency. Although it seems reasonable to expect that most icebergs that contact the seabed will leave some visible mark, where the soil strength is high and the iceberg's kinetic energy and driving forces are low, the impression may be negligible.

The second notable feature of Table 3.5 is that the lower bound on the scour rate is far smaller than all the other estimates. It seems likely that the visible scours were created over a much shorter period than 12,000 years.

Scour frequencies can be derived from observed scour densities by applying appropriate multipliers to the scour density data. For the Hibernia region where the scour density is approximately 1/km^2, the analyses described above suggest that the scour frequency is approximately 4.0×10^{-4} /km^2/year. The conversion factor (*k*) is therefore 0.0004. This is equivalent to assuming that the observed scours were created over the past 2,500 years, which seems reasonable. It is also in line with estimates based on present iceberg statistics, which adds a degree of confidence to an otherwise uncertain estimate.

Scour frequency values based on the 2500 year B.P. minimum age estimate are presented in Table 3.4. The mean frequency value for the 110-150 meter water depth interval is approximately 0.00052 scours/km^2/yr.

This approach is subject to some error because it is likely that the conversion factors should be functions of sediment type, water depth and perhaps other factors. For example, scours in deep water (which may be deeper to begin with), are likely to be reworked or otherwise degraded at a slower rate than scours in shallow water. If this were true, applying a conversion based on relatively shallow water would tend over-predict the scour rate in deep water. Lewis et al. (1986) note that sediment reworking does occur at depths greater than 110m, but it may be less intense and periodic.

An alternate approach is to relate the conversion factor to water depth. For example, if k_{80} is the conversion factor at a water depth of 80m, then the conversion factor at water depth d could be calculated as,

$$k_d = k_{80} \cdot \frac{80}{d} \tag{3.2}$$

If k_{80} = 0.0004, then k_{120} would be 0.00027. This might still underestimate the water depth effect. If wave particle motions were the sole cause of in-filling and scour degradation then we might expect and exponential decay with depth since deep water wave particle motions decay exponentially with depth. However, this approach might lead to overestimates of the water depth effect for several reasons. First, horizontal water particle motions (which one would expect to control sediment movement) decrease less than exponentially when the wavelength is more than one half the water depth. Second, currents and other bulk water movements can also contribute to scour degradation.

As discussed in Section 1.2, sediment type may be a more important factor in scour degradation than water depth. In theory, the effect of surficial geology on the scour degradation rate could be assessed by looking at the relative proportions sediment types in a region, and the relative proportions of scours in each sediment type. Assuming that within a narrow depth range and geographic region the likelihood of scour formation and depth of scour are independent of sediment type, and that the scour surveys were not biased toward one sediment regime, the ratio of areal densities is equal to the ratio residence times. The assumption of equal likelihood and depth in each sediment is not strictly correct, but could be quantified using soil strength data.

As a preliminary test of this approach, two well-site surveys were selected: East Flying Foam (1996), and Terra Nova (1994). Information from the surveys is given in Table 3.6.

Because of the large number of scours in sand *and* gravel, two different approaches were used. In the first approach the scours in both sand and gravel are omitted, and scour densities are calculated from the number of scours in sand alone, and the number of scours in gravel alone. In the second approach, the scours that traverse both sand and gravel are added to *both* the sand alone and gravel alone numbers. This will give incorrect absolute scour densities since many of the scours are counted twice, but may provide some insight into the relative residence times. The resulting scour densities calculated using the two approaches are given in Table 3.7.

Focusing on the East Flying Foam data, the results seem reasonable with scour density ratios of 1.26 and 1.88 for the two different techniques. Subject to the assumptions listed above, this suggests that the scours in gravel have a residence time (or life expectancy) of 1.26 to 1.88 times those in sand.

The Terra Nova data is more difficult to interpret and clearly indicates the difficulties in performing this type of analysis on relatively small data sets. Using approach 1, the density ratio is over 10 times larger in gravel than in sand (suggesting a residence time in gravel 10 times that in sand). Using approach 2, the gravel to sand density ratio is less than one (0.64), suggesting that scours in sand have a greater residence time than those in gravel. There are numerous possible causes of this anomalous result, but this analysis has not been pursued further in the present report.

More rigorous analyses of this type may help to identify sediment effects. This could include all the significant processes that may influence scour degradation, such as water depth, waves, bottom currents, sediment type, and bioturbation. Given the apparent importance of sediment type on scour residence time, this is considered to be a high priority for any future work. The same conclusion was reached by Davidson and Simms (1997), who analysed iceberg pit data for the entire Grand Banks region. They state that although sediment type plays an important role in the distribution of pits, there is insufficient data for a proper analysis. They also assessed relative important of different factors influencing pit occurrence and found the three most significant parameters (in order of importance) to be,

1. water depth,
2. seabed stress ratio, and
3. iceberg areal density.

The 'seabed stress ratio' was defined as the ratio of shear stress on the seabed (given water depth, near bottom current speed and direction, wave height and period, grain size, and bottom roughness) to the critical stress required to initiate bed-load transport.

3.5 Scour Characteristics

This section discusses the spatial distribution and statistical properties of scour depth, width, length, and orientation. Each of these properties is assessed within the study area, using available information contained in the Grand Banks Scour Catalogue (GBSC). Figures 3.6 through Figure 3.9 illustrate the spatial distribution for each of the parameters. Statistical properties of scour depth, width, and length according to water depth are presented in Table 3.8.

<u>Scour Orientation</u>

In the majority of cases, it is not possible to determine the actual direction of scouring unless a terminal pit is observed. Consequently, scour orientation measurements in the GBSC range from 0-179, by convention, and do not indicate the actual scouring direction. Figure 3.6 illustrates the scour tracks as defined by the scour start and end points. Also included are rose diagrams of scour orientation for water depths greater than and less than 110 meters. The majority of scours in both regions are oriented N-S to NE-SW, with an inferred south to southwest scouring direction, consistent with the flow of the Labrador Current across the region. A smaller number of scours were recorded within each of the remaining 10^o intervals. These may relate in part to tidal or local bathymetric influences.

Scour Depth

Scour depth measurements in the GBSC represent the distance from the pre-scoured seafloor (which is extrapolated from the seafloor outside of the scour berms) to the deepest observed point within the scour incision. Depth measurements are available for 1095 scours within the study area. The scour depth is less than the profiler resolution for approximately 48% of the scours. The profiler system resolution, ranging from 0.3-1.0 m, is recorded in the GBSC for these scours. Consequently, the mean depths presented in Table 3.8 are higher than the true means would be if all scours could be resolved to 0.1 m depths.

There is a significant increase in scour depth between water depths of 130-150 meters. In water depths less than 130 meters mean scour depth is approximately 0.5 meters, while in water depths greater than 150 meters the mean depth exceeds 1.0 meters for each bathymetric interval. The overall increase in scour depth at approximately 140 meters water depth is readily apparent on the scour depth distribution map (Figure 3.7). Sonnichsen (1999) attributes the increase in scour depths in deeper water to the combined effects of larger icebergs, stronger driving forces, and softer and perhaps thicker surficial sediments. The reworking and degradation of scours in water depths less than 110 meters could also account, in part, for the shallower scour depths on the bank tops.

Sonnichsen (1999) also noted a possible bias introduced by the erroneous inclusion of some relict scours as evidenced by the inclusion of scours in water depths exceeding the maximum observed modern iceberg draft of 200 meters (Figure 3.7). Also of concern is the relatively high proportion of deeper scours recorded from Cruise 80-010 in the original Mobil database (cf. Figure 3.1 and Figure 3.7) and an anomalous cluster of deep scour measurements incorporated into the original Mobil database from the Tempest North survey report (cf. Figure 3.3 and Figure 3.7). These may also represent relict scours, or possibly an error in the original measurement technique.

Because the mean, standard deviation and distribution-function for scour depth are among the most important input parameters in studies of scour risk to seabed facilities, an attempt has been made to extract better depth estimates from the GBSC. Taking the 'measured' scour depths and calculating a mean value gives the mean of the scours deep enough for their depth to be resolved. This value is larger than the true mean depth of the observed scours. A better, but still very conservative, estimate of the mean scour depth can be obtained from the scours where the depth was measured, or the depth was set to the minimum sensor resolution. The mean and standard deviation for all scours meeting these criteria are 0.72m and 0.70m respectively. For water depths less than or equal to 110m the mean and standard deviation are 0.50m and 0.40m. For water depths greater than 110m the mean and standard deviation are 0.88m and 0.82m.

Extracting meaningful depth statistics from the database is further complicated by the fact that sensor resolution varied between surveys, and even within individual surveys, as seabed type, weather, and other contributing factors changed. These problems necessitated a non-standard approach to deriving scour depth statistics.

Looking at the information for the sub-bottom profilers, the depth qualifiers, and the maximum scour depth, it is evident that the data can be divided into several groups, each with common properties. The first distinction is that the ship's track must have crossed the scour (the sub-bottom profiler codes beginning with 5). If the ship's track did not cross the scour, then no depth measurement was possible. Scours with the SBP code 50 were not used because no sub-bottom profiler was available, and scours with SBP code 57 were dropped because no depth values were reported.

The depth qualifier codes indicate whether scour depths were measured (DEPTH_Q code 7), obtained from the survey report (code 4), or the recorded depth is simply the minimum resolution of the sensor (codes 1, 3 and 6). This information is summarized in Table 3.9. It is evident that data with a SBP code of 54 all have sensor resolutions of 0.3m. Therefore these data make up the sub-set used to assess scour depths down to 0.3m. Data with SBP codes 51, 54, and 56 all have sensor resolutions of at least 0.5m. Data with codes 51, 52, 54 and 56 have sensor resolutions of 1.0m or better. The total number of scours reported in each of these three groups indicate the number of scours that can definitively be identified as ≤ 0.3m, ≤ 0.5m, and ≤ 1.0m. Using the data from each group separately, and combining them with the measured depth information (DEPTH_Q codes 4 and 7) for the appropriate SBP codes, allows a complete exceedance curve to be determined for each data sub-set. For example, adding the total number of scours with an SBP code of 54 to the number of scours with measured depths ≤ 0.3m (SBP code 54 and DEPTH_Q codes 4 and 7), gives the total number of scours in the first data sub-set with depths ≤ 0.3m. The number of scours with depths ≤ 0.5m, ≤ 1.0m, ≤ 1.5m and so on can be determined in the same way. The probability of exceedance for each depth is then 1 minus the normalized number of scours at each depth.

Similar exceedance curves can be derived for the data with resolutions of 0.5m and 1.0m. The three curves cannot be simply combined. However, if we consider the first point on each curve to be representative of the proportion of scours less than or equal to the corresponding system resolution, then a composite curve can generated. Figure 3.10 shows the exceedance curve for such a composite, where values for scour depths greater than 1.0m have been taken from the curve for resolution of 1.0m.

If the scour depth distribution is exponential, then a fixed relationship exists between the mean depth (μ) and the median depth ($\tilde{\mu}$),

$$\mu = -\frac{\tilde{\mu}}{\ln(0.5)} \tag{3.3}$$

The median depth for combined exceedance curve in Figure 3.10 is approximately 0.27m, which corresponds to an exponential distribution with a mean depth of 0.39m. However, the shape of the curve in Figure 3.10 does not correspond to an exceedance curve produced by a single exponential distribution. It is likely that the observed scour depth distribution is a combination of several exponential depth distributions. More distinct exponential depth distributions may exist at specific water depths, seabed slopes, etc. but there is insufficient information in the database to test this hypothesis.

Restricting the analysis to cases were the water depth is > 110m and water depth is ≤ 110m yields median scour depths of 0.47m and 0.20m respectively (Figure 3.11). The corresponding means scour depths are 0.68m and 0.29m. The exceedance curves in Figure 3.11 also do not correspond to exponential distributions, and are probably hybrids of several depth distributions. Nevertheless, it is interesting to generate a combined exceedance curve for all water depths from the two data subsets. Exponential distributions with means of 0.68m and 0.29m, weighted by the proportion of scours in the database at water depths greater than and less than 110m (the are 1672 scours at d > 110m and 1597 scours at d < 110m) yields the combined exceedance curve shown in Figure 3.12. This gives reasonable fit to the exceedance curve for all scours generated from the database, except for deep scours, where the simulated distribution under-predicts scour frequency.

The depth distribution described above is of course the depth distribution of presently observable scours. This may not be the same as the distribution of scour depths at the time of formation. Gaskill et al. (1985) looked at the effects of in-filling on the mean scour depth, and changes to the form of the initial depth distribution. Their model indicated that equilibrium, observable mean scour depths are only slightly less than the initial mean depth. They suggest a conservation correction factor of the form,

$$\bar{d}_{act} = 1.07 \cdot \bar{d}_{obs} \quad (3.4)$$

where $\bar{d}_{act}$ is the actual initial mean scour depth, and $\bar{d}_{obs}$ is the mean scour depth observed on the present-day seabed. This correction for has *not* been made for the scour depth statistics presented in this study.

Gaskill et al. (1985) also looked at several different initial scour depth distributions and how their form might change through time. They determined that if the initial depth distribution was exponential (as is widely believed), the observed depth distribution will also be exponential. If the initial depth distribution was 'modal', such as a typical Gamma distribution, then the resulting observed distribution could be mistaken for an exponential distribution. That is, the mode disappears and for depth values greater than the mode, the distribution decays in a manner similar to an exponential distribution. However, the portion of the population with depths less than the mode, would be significantly less than predicted by an exponential distribution. Considering this analysis, and theoretical arguments is seems reasonable to conclude (as many others have) that the initial depth distribution of scours in the study area is exponential.

Scour Width

The scour width measurements in the GBSC represent the distance between the lateral berm crests. Scour width shows an overall general increase with increasing water depth. Mean widths increase from 22 m in water depths of 60-90 meters to approximately 34 m in water depths of 150-210 meters water depth. The spatial distribution of scour width illustrates that most of the scours recorded in water depths of less than 100 meters have widths less than 25 meters, while the majority of scours with widths exceeding 50 meters occur in water depths greater than 100 meters (Figure 3.8). There is considerable local variability, and scour widths exceeding 50 meters have been recorded within each 20 m bathymetric interval. The maximum scour width recorded in the database is 200 meters. As for scour depth, a combination of larger icebergs, stronger driving forces and thicker accumulations of softer sediments have been proposed to explain the overall wider scour occurrence in deeper water.

Scour Length

Scour length is difficult to quantify due to the fact that many scours are only partially recorded within the limits of the sidescan swath coverage. Scour length measurements are available for 2986 scours located within the study area. Of these, approximately 41% extend beyond the sidescan data coverage, and have a recorded length which is less than the true length. The mean scour length for 849 complete scours recorded within a wellsite survey area is 861 meters. In contrast, the mean scour length for complete and partial scours recorded on regional lines is 405 meters and 482 meters, respectively. Figure 3.9 displays the spatial distribution of the length parameter for all scours. The vast majority of scours with recorded lengths exceeding 2 km occur within wellsite or survey grids with 100% sidescan coverage.

The mean lengths presented in Table 3.8 include all scours whether or not the entire scour was observed on the sidescan. The mean recorded length ranges between 500-722 meters within each 20 m bathymetric interval. There is no apparent relationship between scour length and water depth.

3.5.1 Parameter Relationships

The relationships between scour characteristics (shown in Appendix A) are derived for subsets of the GBSC. For each parameter, only those observations meeting certain criteria were used. The criteria are listed in Table 3.10. When two parameters are compared, only those scours for which both sets of criteria are met were used. As a result the number of data pairs varies considerably from plot to plot. All of the scour data used in the statistical analyses of scour depth were derived from observations where the scour crossed the ship's track, and depth was measured with one of the following sub-bottom profilers:

- Huntec DTS,
- NSRF or V-fin,
- 3.5kHz profiler,
- Echo sounder, or
- modified Klein SSS

The corresponding SBP codes are: 51, 52, 53, 54 or 56.

Relationships between scour parameters are shown in the plots in Appendix A. These plots include scours at all water depths. The histograms of scour depth and length show a characteristic exponential pattern with large numbers of small values and a few large values. The histogram of scour width shows a modal distribution with a clear peak at between 10m and 20m. The histogram of scour orientation shows a clear trend toward north/south orientations (it is not known which direction the icebergs were moving when the scours were created).

Very few scour parameters are strongly correlated with each other or with environmental conditions. Mean scour length increases at orientations of about 90° (Figure A7), but this strongly influenced by the small number of samples in these bins, as shown by the individual length values.

Mean scour depths are greater in sand and in sand and gravel, than in gravel alone (Figure A8). This *could* be an important finding, but closer investigation reveals the complexities of these relationships and some of the limitations of the data. The mean scour depths in sand are more than 60% greater than in gravel. However, the majority of the scour observations in gravel come from relatively shallow water depths (mean water depth for scours in gravel = 98m, mean water depth for scours in sand = 141m). Since there may be a relationship between scour depth and water depth (see below), the apparent effect of sediment type on scour depth may not be real. This is further complicated because it is not clear from the data if the scour depth/water depth relationship is real, or the result of sensor resolution.

Figure A9 shows that there are fewer shallow scours in deep water, but this may be due to system resolution biases.

Mean scour lengths are slightly greater for north/south orientations than for east/west orientations (Figure A14).

Perhaps the most surprising result from this analysis is the weakness of the relationships. It may be that cross-correlations between several parameters are masking the relationships between individual pairs. This suggests that multivariate statistical techniques might be more informative. Unfortunately, there are only 27 scours in the study area that meet all the criteria outlined in Table 3.10 (ie. the depth, width, length, and orientation were all measured). Multivariate techniques could be used to determine the effects of combinations of environmental parameters and specific scour characteristics, but the number of possible combinations is quite large.

3.5.2 Comparison to Terra Nova

Mean and standard deviations of scour length, width, and depth reported in the Terra Nova Development Plan (1996) are compared to values derived in the present analysis for water depths less than 110m in Table 3.11. The reported water depth range for the Terra Nova data is 80m to 120m. A direct comparison of measured scour depths

(DEPTH_Q = 4 or 7) from the GBSC in water depths 80m to 120m gives a mean depth of 0.54m and standard deviation of 0.30m.

The mean scour depth reported at Terra Nova is 0.6m. Based on the analysis of depths performed here, this value appears to be conservative. If the scour depth distribution is exponential the standard deviation should be the same as the mean. The depth statistics generated from the GBSC (present study) give standard deviations and means that are roughly the same. This supports the use of the exponential function. The fact that the reported Terra Nova standard deviation is smaller than the mean, suggests a modal distribution (eg a Gamma pdf with parameter $\alpha > 1$). It is likely that this form has resulted from an under-representation of shallow scours in the data set used to generate the mean and standard deviation.

The scour length and width statistics are all in close agreement.

Table 3.1 Grand Banks Scour Catalogue (1999); GSC (Atlantic) and Regional Surveys

Survey Name	Survey Year	Equipment Types[1]	Water Depth (m)	Number of Scours	Pits
Mobil Ice Scour Catalogue	*(1982)*				
Hudson 80-010	1980	1, 7	64-236	420	20
AGC/C-CORE '8000 Series'	1980	4, 7	80-160	49	6
Mobil Ice Scour Catalogue (1984 update)					
Baffin 81-012	1981	1, 3, 7	71-118	26	4
Baffin 82-039	1982	3, 7	67-92	3	0
Hudson 83-033	1983	1, 3, 7	83-100	8	2
Hibernia Pipeline	1983	4, 7	69-156	40	177
S. Hibernia Pipeline Route	1980	4, 7	75-160	5	27
Geonautics/d'Apollonia	1982	4, 7	60-190	71	75
Grand Banks Scour Catalogue (1992 compilation)					
Hudson 84-024	1984	1, 3, 7	57-160	48	38
Hudson 85-005	1985	1, 3, 7	49-144	49	6
Pandora II 85-057	1985	3, 10	92-154	41	2
Hudson 86-017	1986	1, 3, 7	72-133	61	32
Hudson 86-018	1986	1, 3, 7	66-163	171	23
Hudson 87-014	1987	1, 3, 7	57-88	31	0
Needler 88-108	1988	1, 3, 7	66-182	325	49
Dawson 89-009	1989	1, 3, 7	85-223	99	77
Dawson 90-021 (ESRF)	1990	2, 4, 7	77-148	244	16
Dawson 90-021 (regional)	1990	2, 4, 7	62-177	194	9
Grand Banks Scour Catalogue (1999 update)					
Hudson 94-021	1994	1, 5, 10	90-105	192	1
CCGS Matthew 96-011	1996	5, 11	119-138	62	31
CCGS Matthew 98-024	1998	5, 7, 11, 12	90-134	669	0

[1]Equipment Types:

Sidescan: 1 (BIO 70 kHz), 2 (Klein 50 kHz), 3 (Klein 100 kHz), 4 (ORE 100 kHz),
5 (Simrad 120 kHz), 6 (Edgetech 100 kHz)

Profiler: 7 (Huntec DTS), 8 (NSRF V-Fin), 9 (ORE 3.5 kHz), 10 (Echosounder)

Multibeam: 11 (EM100), 12 (EM3000)

Table 3.2 Grand Banks Scour Catalogue (1999); Wellsite Surveys

Well-Site Name	Survey Year	Equipment Types[1]	Water Depth (m)	Number of Scours	Pits
Mobil Ice Scour Catalogue (1982)					
Ben Nevis	1979	4, 9	96-102	15	0
Hibernia P-15	1979	4, 9	78-84	3	1
Hibernia North	1979	4, 9	78-86	4	0
Tempest North	1979	4, 10	146-152	89	0
Trave/White Rose	1979	4, 9	115-149	93	0
'4000 Series'	1979	4, 10	80-150	43	0
Cumberland J-87	1980	4, 9	189-235	2	82
Dana North and South	1980	4, 7, 9	202-260	14	158
Hebron	1980	4, 9	83-99	5	0
Nautilus C-92	1980	4, 7, 9	81-98	7	0
Ragnar	1980	4, 7, 9	184-222	3	56
Rankin	1980	4, 7, 9	70-82	16	0
West Hibernia	1980	4, 9	75-84	8	0
White Rose Flank	1981	4, 7	102-119	90	0
Mobil Ice Scour Catalogue (1984)					
Archer Flank	1982	3, 4, 8	114-132	120	94
Bonanza M-71	1982	4, 8	181-211	12	140
Dominion	1982	4, 7	156-166	14	129
Linnet E-63	1982	3, 4, 8	119-204	73	43
Saronac	1982	4, 8	168-204	88	256
Mara	1983	4, 7	80-100	107	10
Titus	1983	4, 7	160-206	6	153
Voyager	1983	4, 7	92-103	6	0
Grand Banks Scour Catalogue (1992)					
North Ben Nevis (Husky)	1984	4, 7	101-104	1	0
North Ben Nevis; Rev-1	1984	4, 7	100-102	17	4
Burin Bonne Bay	1985	4, 7	100-109	6	3
South Brook	1988	3, 8	85-92	16	0
Grand Banks Scour Catalogue (1999 Update)					
East Flying Foam	1996	4, 9, 10	85-114	186	10
South Nautilus	1998	6, 10	80-91	83	9

[1]Equipment Types: See Table 3.1

Table 3.3 Grand Banks Scour Catalogue (1999) Data Fields

FIELD	DATABASE FIELD NAME	DESCRIPTION
1	SCOUR_ID	UNIQUE SCOUR IDENTIFIER
2	SOURCE	DATA SOURCE (TABLE)
3	CRUISE	CRUISE NUMBER OR NAME
4	DAY	JULIAN DAY
5	S_STIME	SCOUR SEGMENT START TIME
6	BATHY	BATHYMETRY – METERS
7	RISEUP	WATER DEPTH VAR. ALONG SCOUR LENGTH
8	TYPE	SCOUR OR CRATER IDENTIFIER
9	PLN_S	PLAN SHAPE
10	SEG	UNIQUE SEGMENT IDENTIFIER
11	SBP	SUB-BOTTOM PROFILER
12	DEPTH	SCOUR DEPTH - METERS
13	DEPTH_Q	SCOUR DEPTH QUALIFIER
14	WIDTH	SCOUR SEGMENT WIDTH - METERS
15	LENGTH	SCOUR SEGMENT. LENGTH - METERS
16	LENGTH_Q	SCOUR END POINT QUALIFIER
17	ORIENT	SCOUR SEGMENT ORIENTATION
18	NORTHING_S	SEGMENT/SCOUR START UTM COORDINATES
19	EASTING_S	SEGMENT/SCOUR START UTM COORDINATES
20	NORTHING_E	SEGMENT/SCOUR END UTM COORDINATES
21	EASTING_E	SEGMENT/SCOUR END UTM COORDINATES
22	BERM_HT1	BERM HEIGHT - METERS
23	BERM_HT2	2ND BERM HEIGHT - METERS
24	PROFL	PROFILE TYPE
25	B_70	B.I.O. 70 kHz
26	K_100	KLEIN 100 kHz
27	O_100	O.R.E. 100 kHz
28	K_50	KLEIN 50 kHz
29	S_120	SIMRAD 120 kHz
30	E_100	EDGETECH 100 kHz
31	EM100	SIMRAD EM100 MULTIBEAM
32	EM3000	SIMRAD EM3000 MULTIBEAM
33	C_AVL	SIDESCAN CHANNELS AVAILABLE
34	RANGE_CHNL	SIDESCAN RANGE PER CHANNEL - METERS
35	EFF_RANGE	SIDESCAN EFFECTIVE RANGE - METERS
36	QUAL	RECORD QUALITY
37	CLAR	SCOUR CLARITY
38	B_DEV	BERM DEVELOPMENT
39	SED	SEDIMENT TYPE
40	REG_SED	REGIONAL SEDIMENT TYPE
41	HEAD	SHIPS HEADING - 08 to 3598
42	NAV_AVAIL	NAVIGATION AVAILABILITY
43	ANLST	ANALYST/INTERPRETER
44	D_ANLSIS	DATE OF ANALYSIS
45	OLD_ID	SOURCE FILES UNIQUE SCOUR ID
46	ERR_FLAG	PROBABLE ERROR OR DUPLICATE SCOUR
47	COMM	COMMENT FIELD

Table 3.4 Grand Banks Scour Catalogue (1999) Ice Scour Density and Frequency; Northeast Grand Banks

3.5.3 Water Depth meters	50 - 60	60 - 70	70 - 80	80 - 90	90 - 100	100 - 110	110 - 150	150-200	> 200
Ice Scour Density									
Area[1] (sq. km)	4	425	1268	727	1031	695	1463	783	456
Mean	0.00	0.01	0.10	0.55	1.17	1.20	1.29	0.41	0.12
Maximum	0.0	1.9	6.0	18.0	27.0	27.0	14.0	6.7	3.9
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Std. Deviation	0.00	0.09	0.49	1.60	2.40	2.23	1.97	0.92	0.45
Estimated Ice Scour Frequency									
Area[1] (sq. km)	4	425	1268	727	1031	695	1463	783	456
Mean	0.00×10^{-3}	0.00×10^{-3}	0.04×10^{-3}	0.22×10^{-3}	0.47×10^{-3}	0.48×10^{-3}	0.52 x 10-3	0.16×10^{-3}	0.05×10^{-3}
Maximum	0.00×10^{-3}	0.76×10^{-3}	2.40×10^{-3}	7.20×10^{-3}	10.80×10^{-3}	10.80×10^{-3}	5.60 x 10-3	2.66×10^{-3}	1.56×10^{-3}
Minimum	0.00×10^{-3}	0.00×10^{-3}	0.00×10^{-3}	0.00×10^{-3}	0.00×10^{-3}	0.00×10^{-3}	0.00 x 10-3	0.00×10^{-3}	0.00×10^{-3}
Std. Deviation	0.00×10^{-3}	0.04×10^{-3}	0.20×10^{-3}	0.64×10^{-3}	0.96×10^{-3}	0.89×10^{-3}	0.79 x 10-3	0.37×10^{-3}	0.18×10^{3}

[1]Survey coverage area within bathymetric interval

Table 3.5 Summary of scour frequency estimates for the on-shelf region of the north-east Grand Banks (typical of the Hibernia site).

Reference	**Method**	**Frequency Estimate**
d'Apollonia and Lewis (1986)	Numerical Modeling	3.5×10^{-3} /km^2/year
Lewis et al. (1986)	Repetitive Mapping	1.0×10^{-3} /km^2/year†
Lewis et al. (1986)	Scour Degradation	1.0×10^{-3} /km^2/year
This study	Upper Bound	4.0×10^{-4} /km^2/year
This study	Iceberg Flux	4.0×10^{-4} /km^2/year
Lewis et al. (1986)	Scouring Period	4.0×10^{-4}/ km^2/year
Geonautics Limited (1991)	Repetitive Mapping	1.9×10^{-4} /km^2/year
This study	Lower Bound	8.3×10^{-5} /km^2/year

† based on 50% probability of detecting new scours (see text).

Table 3.6 Survey and Scour Information for Well-Site Surveys.

	East Flying Foam	**Terra Nova**
Side Scan Sonar	100 kHz ORE	100 kHz Simrad
Bathymetry Range (m)	85 – 115	90 – 98
Area of Sand (km^2)	151.9 (67%)	14.2 (31%)
Area of Gravel (km^2)	73.5 (33%)	30.7 (66%)†
Scours in Sand	41	1
Scours in Gravel	25	22
Scours in Sand and Gravel	131	53

†1.3 km^2 of transitional material (predominantly sand with shelly gravel) containing no scours was omitted from the Terra Nova calculations.

Table 3.7 Results of scour density calculations for East Flying Foam (EFF) and Terra Nova (TN).

	Approach 1		**Approach 2**	
	EFF	**TN**	**EFF**	**TN**
Scour Density in Sand (km^{-2})	0.27	0.07	1.13	3.80
Scour Density in Gravel (km^{-2})	0.34	0.72	2.12	2.44
Density Ratio (Gravel/Sand)	1.26	10.24	1.88	0.64

Table 3.8 Grand Banks Scour Catalogue (1999) Ice Scour Statistics; Northeast Grand Banks

Water Depth (meters)	**62 - 70**	**71 - 90**	**91 - 110**	**111 - 130**	**131 - 150**	**151 - 170**	**171 – 190**	**191 - 210**	**211 – 230**	**231 - 250**	**251 - 257**
Measured Scour Depth (meters)											
N	10	61	138	111	77	21	42	35	15	15	1
Mean	0.63	0.62	0.67	0.62	0.84	2.03	1.41	1.47	1.17	1.29	2.50
Maximum	1.6	5.3	3.0	3.5	3.4	7.0	3.0	4.0	2.5	1.7	2.5
Minimum	0.1	0.1	0.1	0.1	0.2	0.5	0.5	0.5	0.5	0.5	2.5
Std. Deviation	0.4	0.7	0.5	0.5	0.7	1.5	0.6	0.8	0.7	0.3	0.0
All (measured & system resolution) Scour Depth (meters)											
N	16	123	365	275	110	46	72	56	15	15	2
Mean	0.51	0.51	0.48	0.49	0.93	2.28	1.24	1.27	1.17	1.29	1.50
Maximum	1.6	5.3	3.0	3.5	3.5	7.0	3.0	4.0	2.5	1.7	2.5
Minimum	0.1	0.1	0.1	0.1	0.2	0.1	0.5	0.1	0.5	0.5	0.5
Std. Deviation	0.4	0.5	0.3	0.4	0.8	1.5	0.5	0.7	0.7	0.3	1.4
Scour Width (meters)											
N	25	422	1003	705	199	75	62	44	4	6	4
Mean	23	22	26	27	27	34	33	32	48	61	50
Maximum	73	128	200	185	114	125	65	55	60	100	65
Minimum	5	3	1	4	5	7	8	10	20	45	25
Std. Deviation	17	14	19	17	15	20	13	11	19	22	18
Scour Length (meters)											
N	25	423	1125	897	231	89	62	44	4	6	4
Mean	510	576	656	599	633	549	722	684	500	680	413
Maximum	2030	4100	9366	6400	8806	3200	4200	2950	1200	1250	740
Minimum	31	5	5	21	33	96	74	100	170	220	190
Std. Deviation	608	627	867	737	924	568	652	595	474	387	233

Table 3.9 Summary of scour records where the depth measurement was limited by sensor resolution.

SBP	DEPTH_Q	MAX_DEPTH	Number of Scours
51	1	0.3	141
52	1	No data	-
53	1	0.0 or 0.5	32
54	1	0.3	69
56	1	0.3	13
51	3	0.0 or 0.5	86
52	3	0.5 or 1.0	6
53	3	0.5	4
54	3	0.3	1
56	3	No data	-
51	4	No data	-
52	4	0.5	1
53	4	No data	-
54	4	1.0 to 6.0	36
56	4	No data	-
51	6	0.0 or 0.5	46
52	6	0.0, 0.5 or 1.0	113
53	6	0.5	19
54	6	No data	-
56	6	No data	-
51	7	0.1 to 7.0	470
52	7	0.0 to 3.5	14
53	7	0.4 to 1.8	7
54	7	0.3 to 3.0	24
56	7	0.1 to 1.5	10

Table 3.10 Scour Characteristic Criteria.

Scour Characteristic	**GBSC Code**	**Criteria for Use**	**GBSC Code**
Depth	MAX_DEPTH	Scour depth obtained from report	DEPTH_Q = 4
		Scour depth measured	DEPTH_Q = 7
Length	LENGTH	2 endpoints seen or inferred with confidence	LENGTH_Q = 2
		Entire scour seen on regional data	LENGTH_Q = 5
Width	AVG_WIDTH	Scour width recorded	AVG_WIDTH < 99999
Orientation	AVG_ORIENT	Scour orientation recorded	AVG_ORIENT < 9999

Table 3.11 Comparison of scour characteristics from present study (P.S.) and Terra Nova.

	Length (m)		**Width (m)**		**Depth (m)**	
	Mean	**Std.**	**Mean**	**Std.**	**Mean**†	**Std.**
Terra Nova	565	618	25	14	0.60	0.30
P.S. (all)	542	743	26	17	0.72 (0.39)	0.70
P.S. (≤110)	560	714	24	17	0.50 (0.29)	0.40
P.S. (>110)	523	775	28	18	0.88 (0.68)	0.82

†mean depth values in brackets were calculated from exceedance curves as described in text.

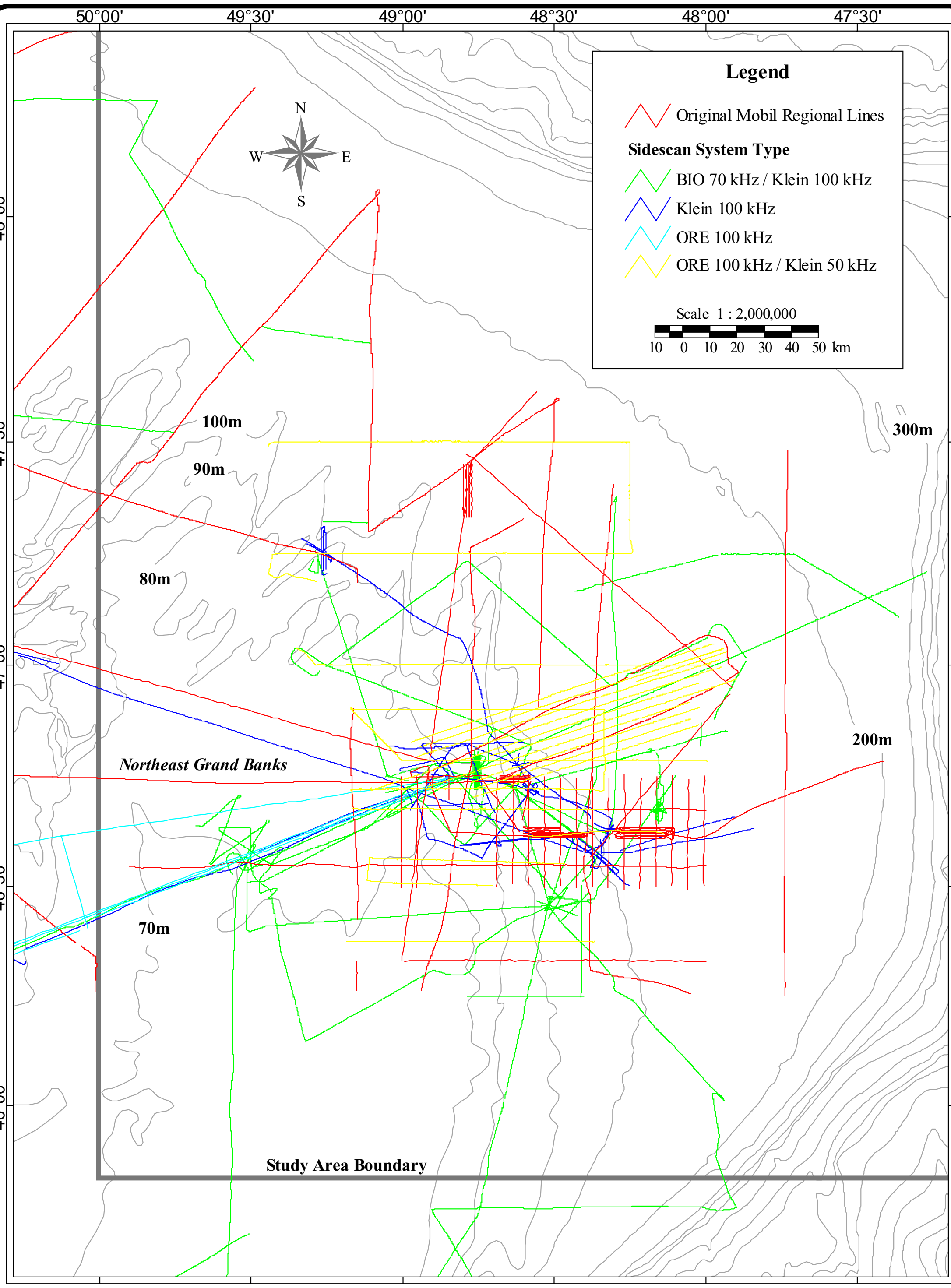


FIGURE 3.1 GBSC1999 Regional Survey Lines According to Sidescan System Type; Northeast Grand Banks.

Canadian Seabed Research Ltd.

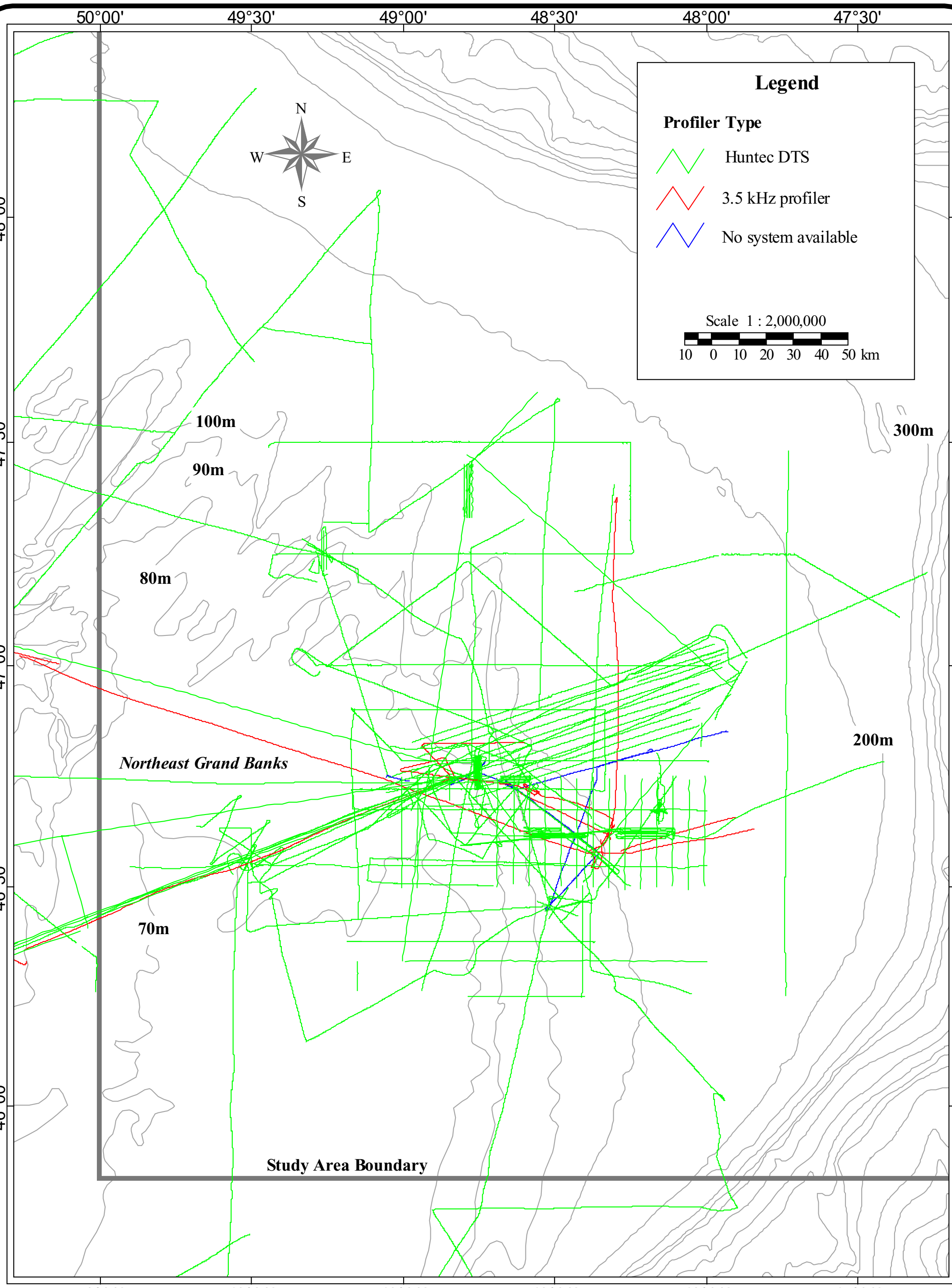


FIGURE 3.2 GBSC1999 Regional Survey Lines According to Profiler Type; Northeast Grand Banks.

Canadian Seabed Research Ltd.

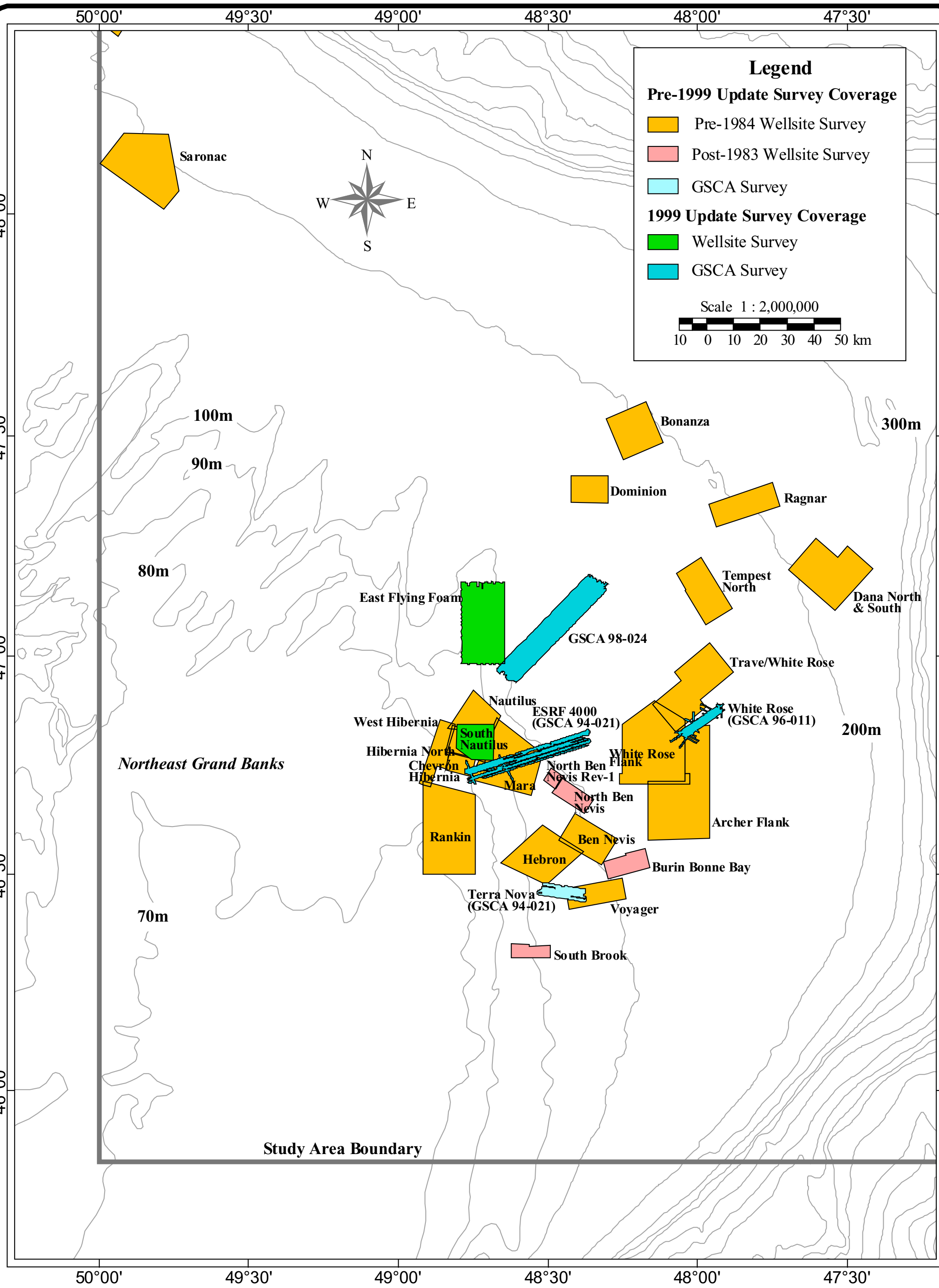


FIGURE 3.3 GBSC1999 Wellsite and GSCA Multibeam Survey Coverage; Northeast Grand Banks.

Canadian Seabed Research Ltd.

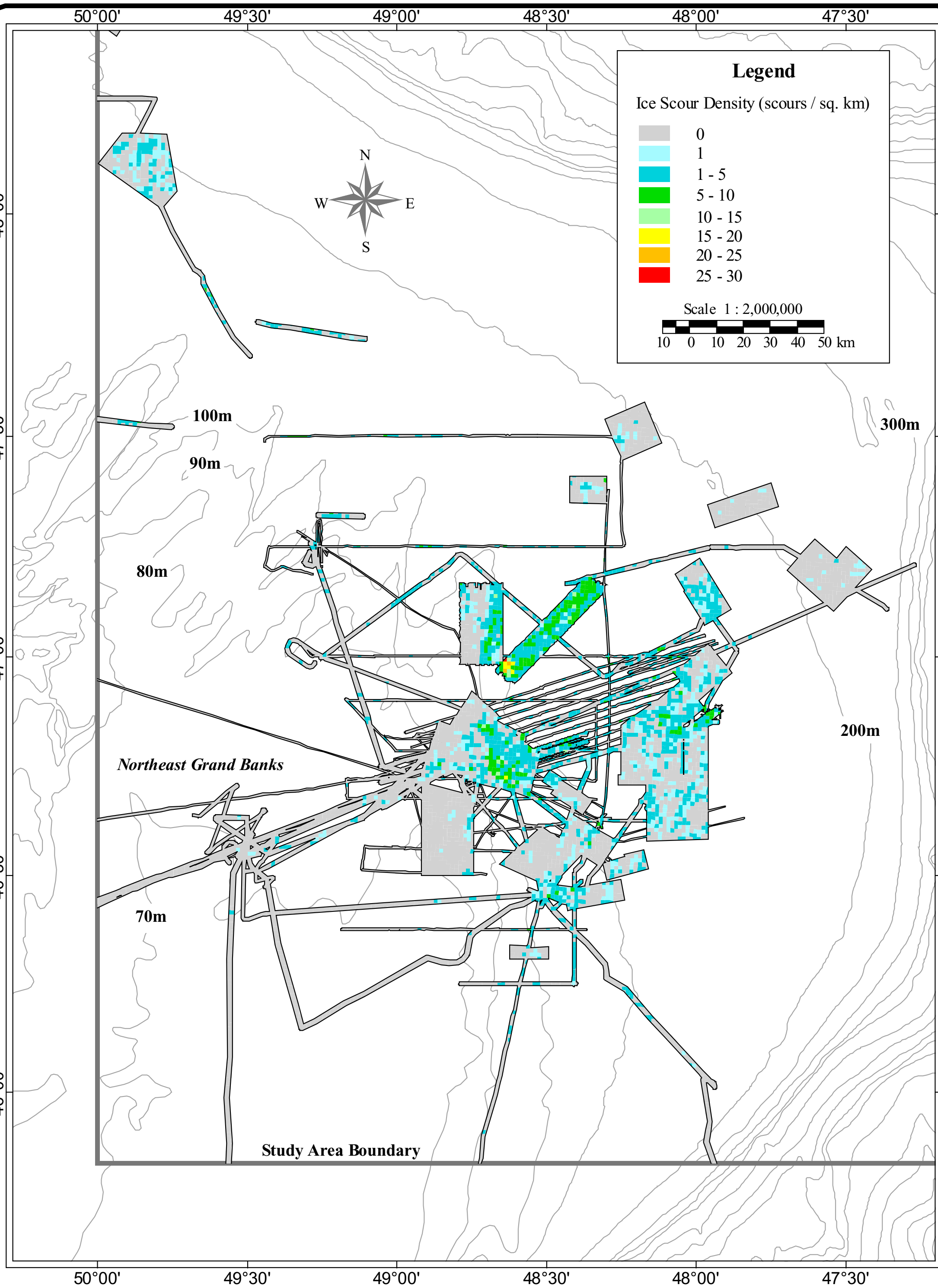


FIGURE 3.4 GBSC1999 Ice Scour Density as calculated for 1 km square grid cells (scours / sq. km); Northeast Grand Banks.

Canadian Seabed Research Ltd.

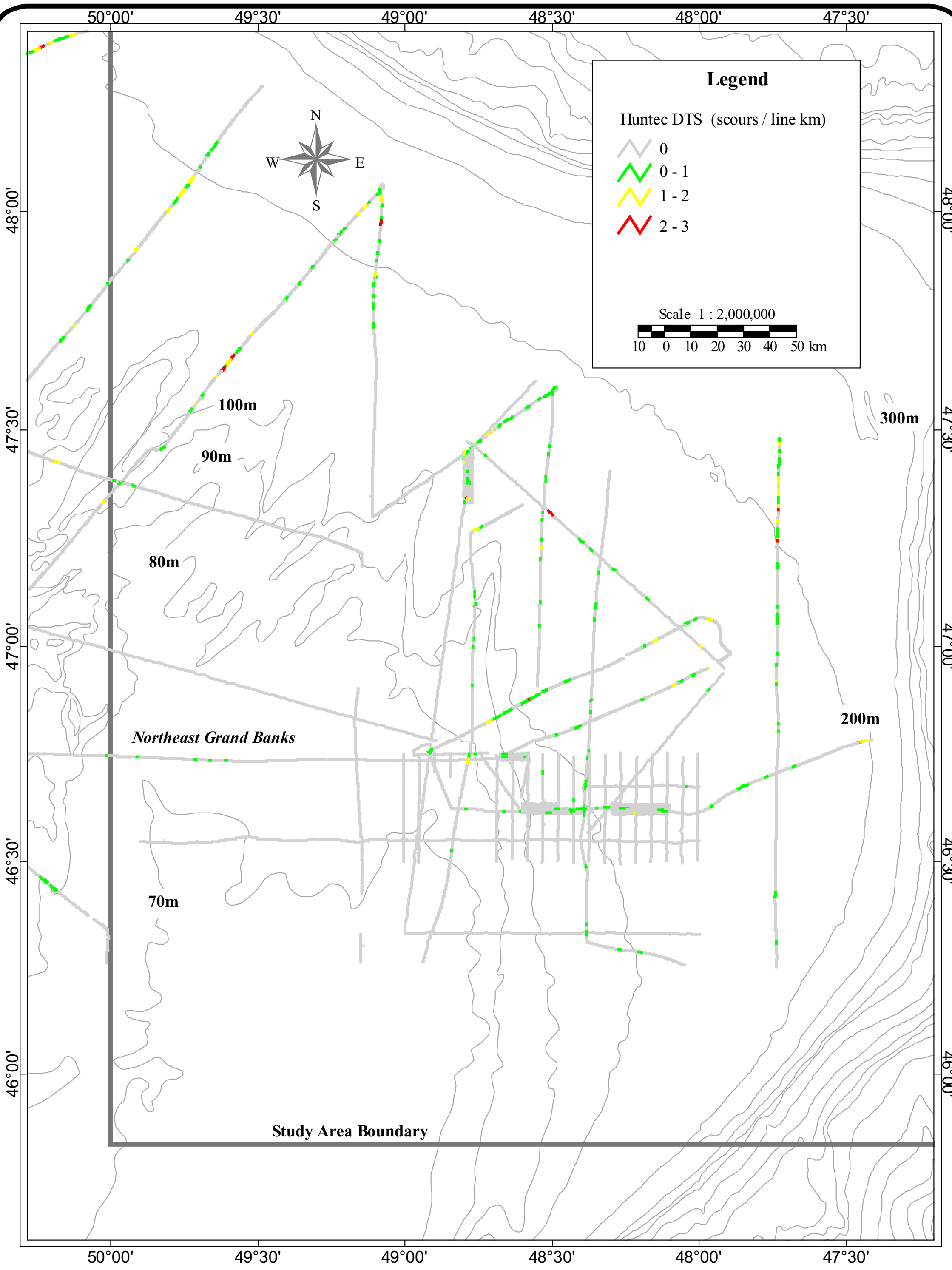


FIGURE 3.5 **Ice Scours per Line Km for Original Mobil Scours Interpreted from Huntec DTS (1982); Northeast Grand Banks.**

Canadian Seabed Research Ltd.

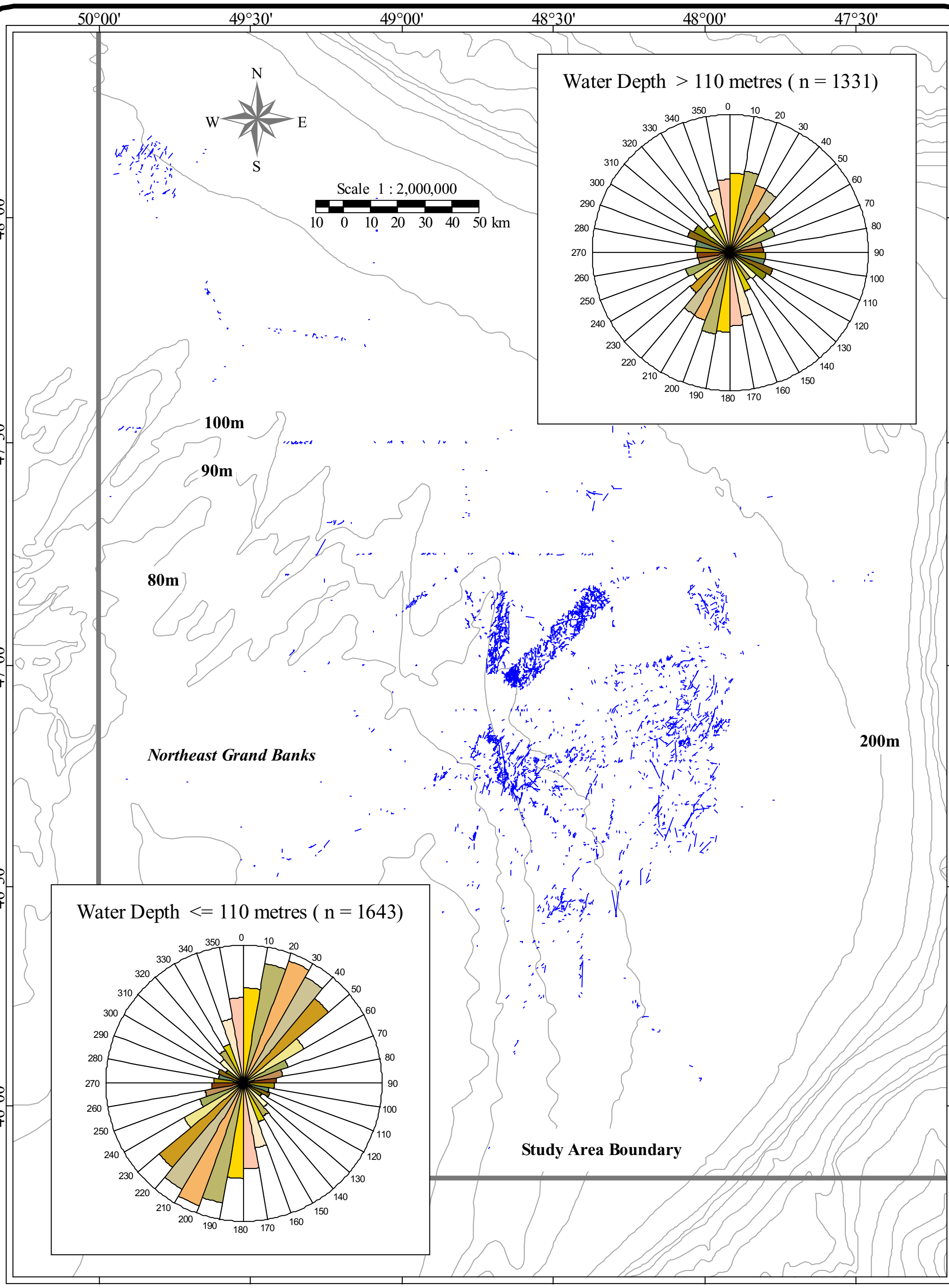


FIGURE 3.6 GBSC1999 Ice Scour Tracks & Rose Diagrams Illustrating Scour Orientation in Water Depth Greater than and Less than 110 metres, Northeast Grand Banks.

Canadian Seabed Research Ltd.

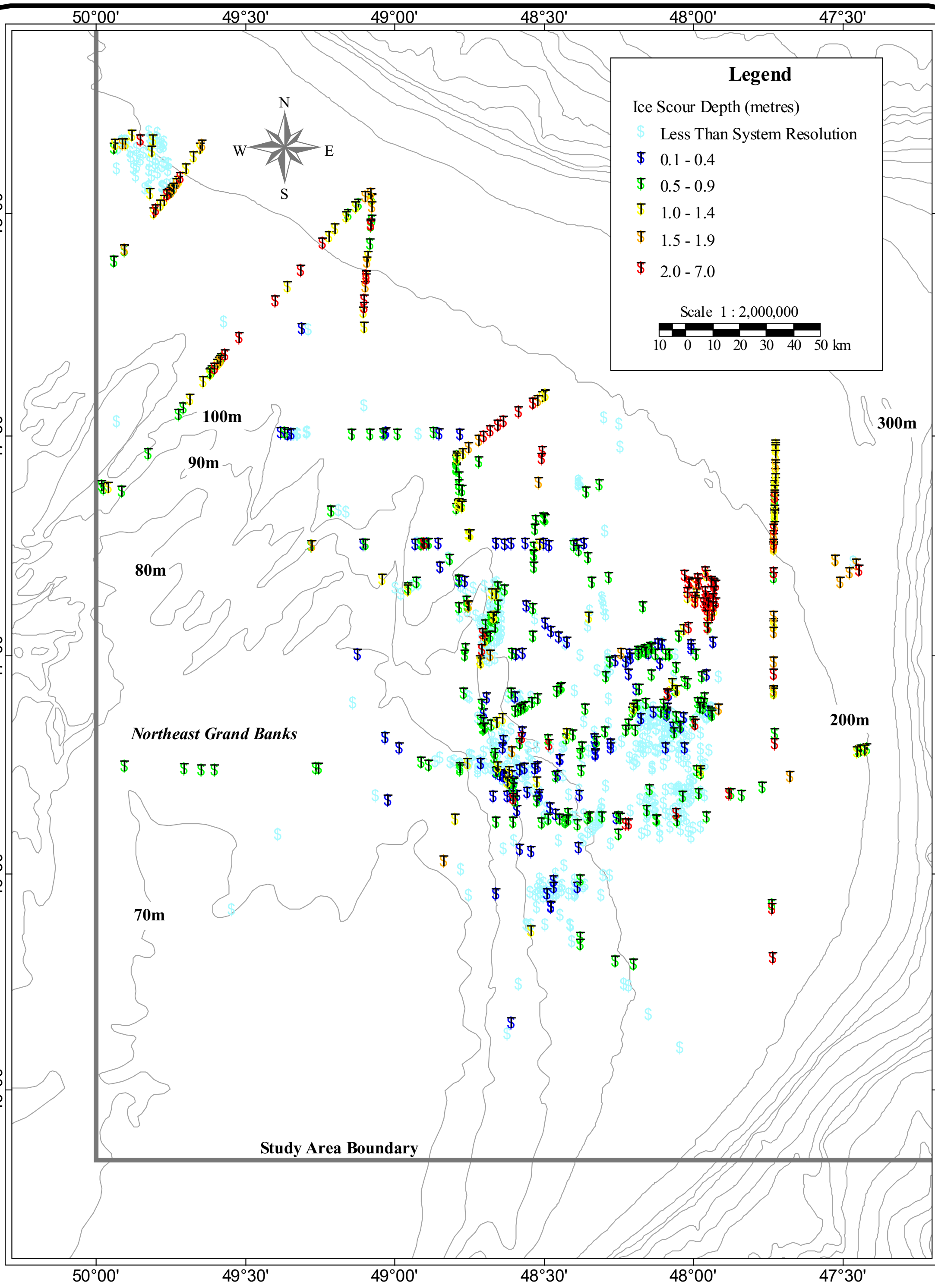


FIGURE 3.7 GBSC1999 Ice Scour Depth Distribution; Northeast Grand Banks.

Canadian Seabed Research Ltd.

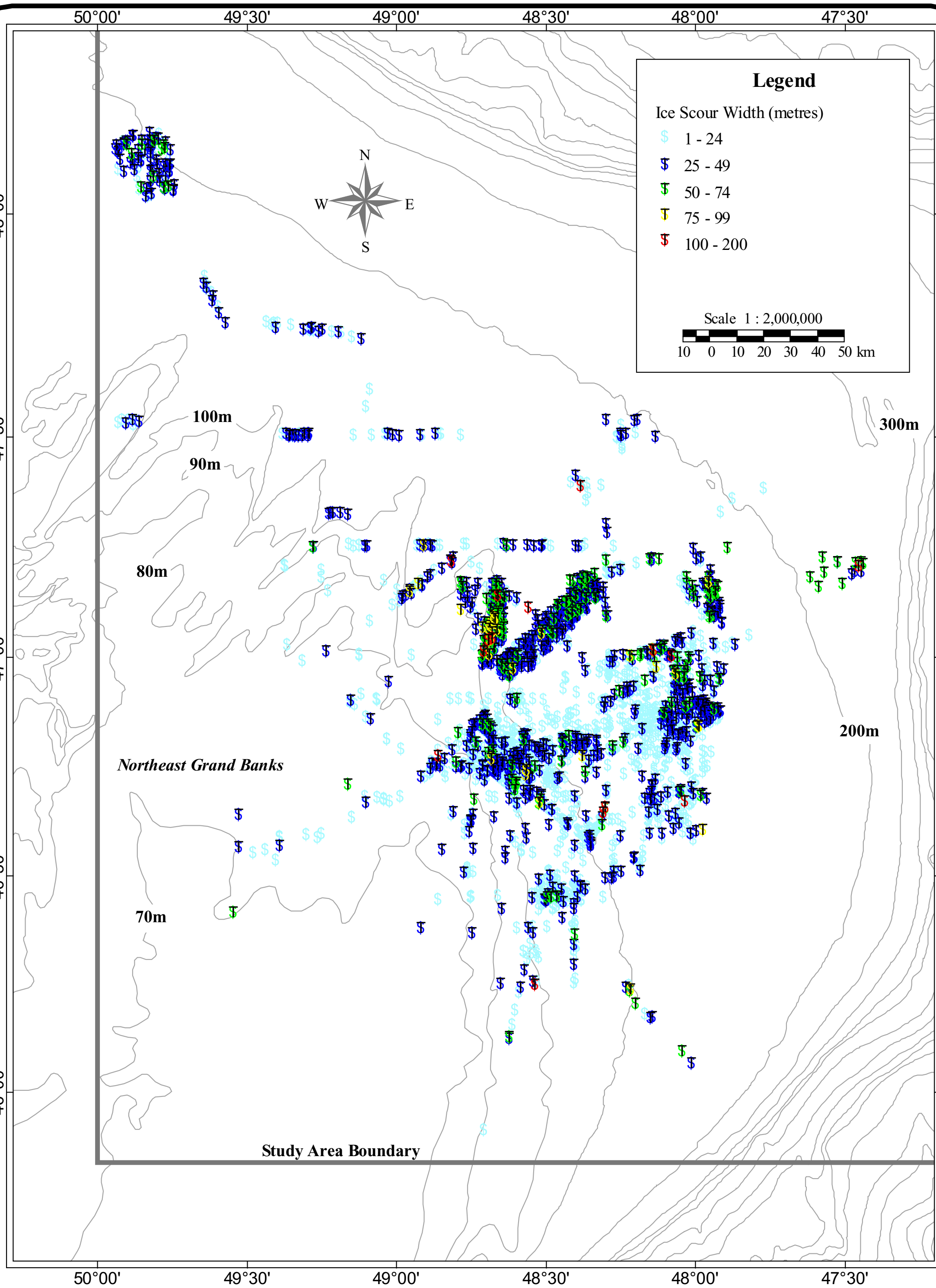


FIGURE 3.8 GBSC1999 Ice Scour Width Distribution; Northeast Grand Banks.

Canadian Seabed Research Ltd.

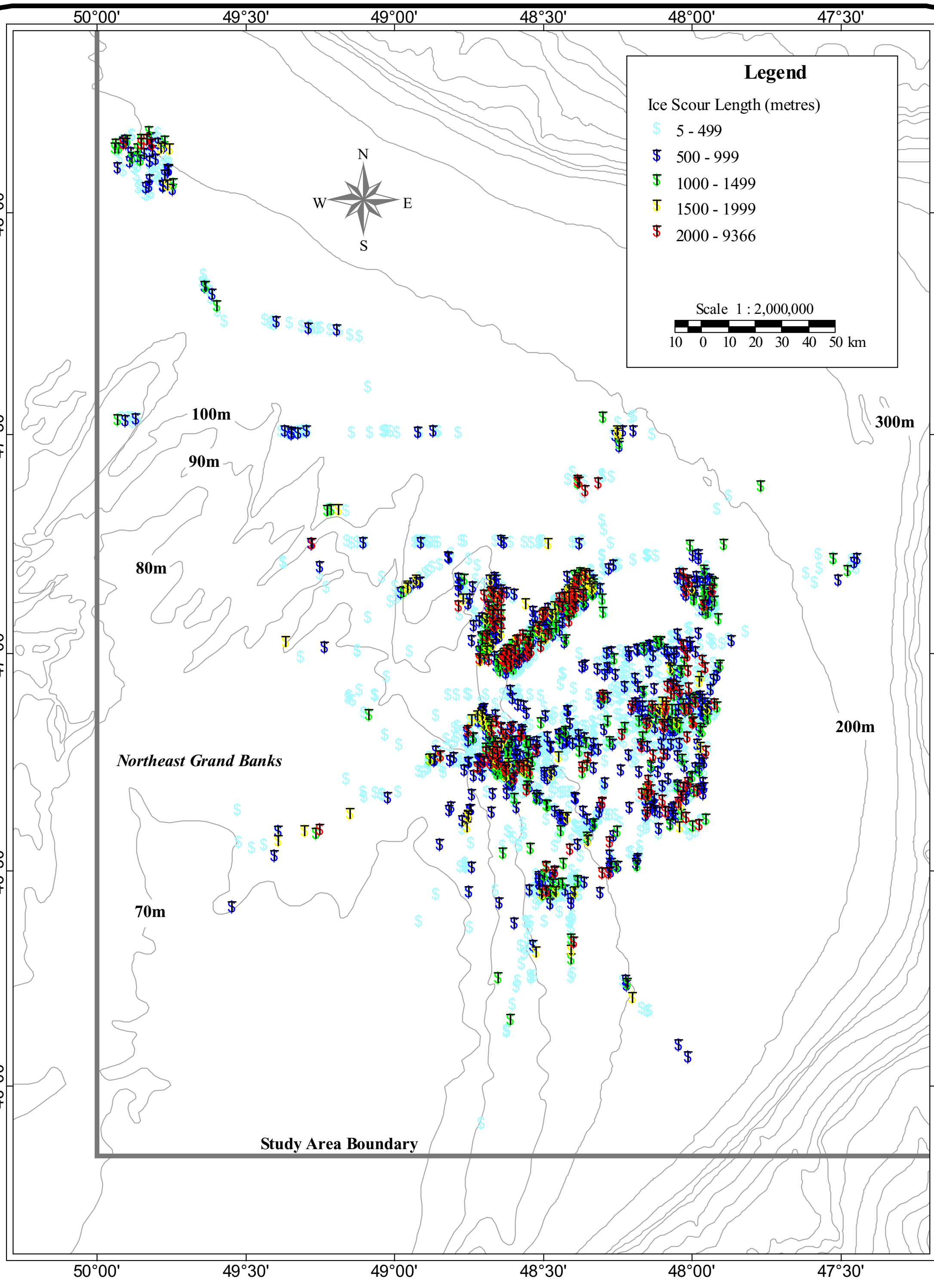


FIGURE 3.9 GBSC1999 Ice Scour Length Distribution; Northeast Grand Banks.

Canadian Seabed Research Ltd.

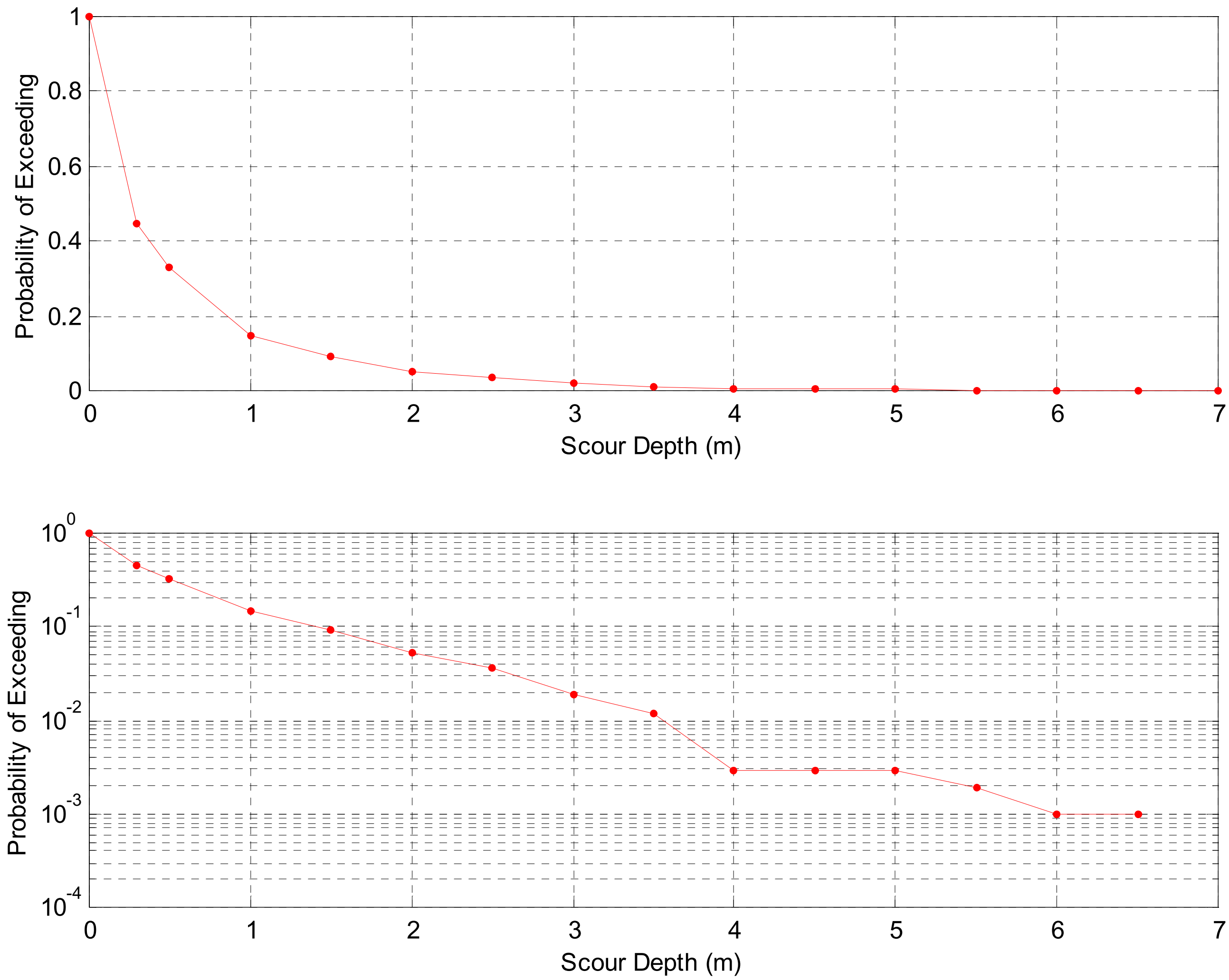


Figure 3.10 Scour depth exceedance curve for all water depths.

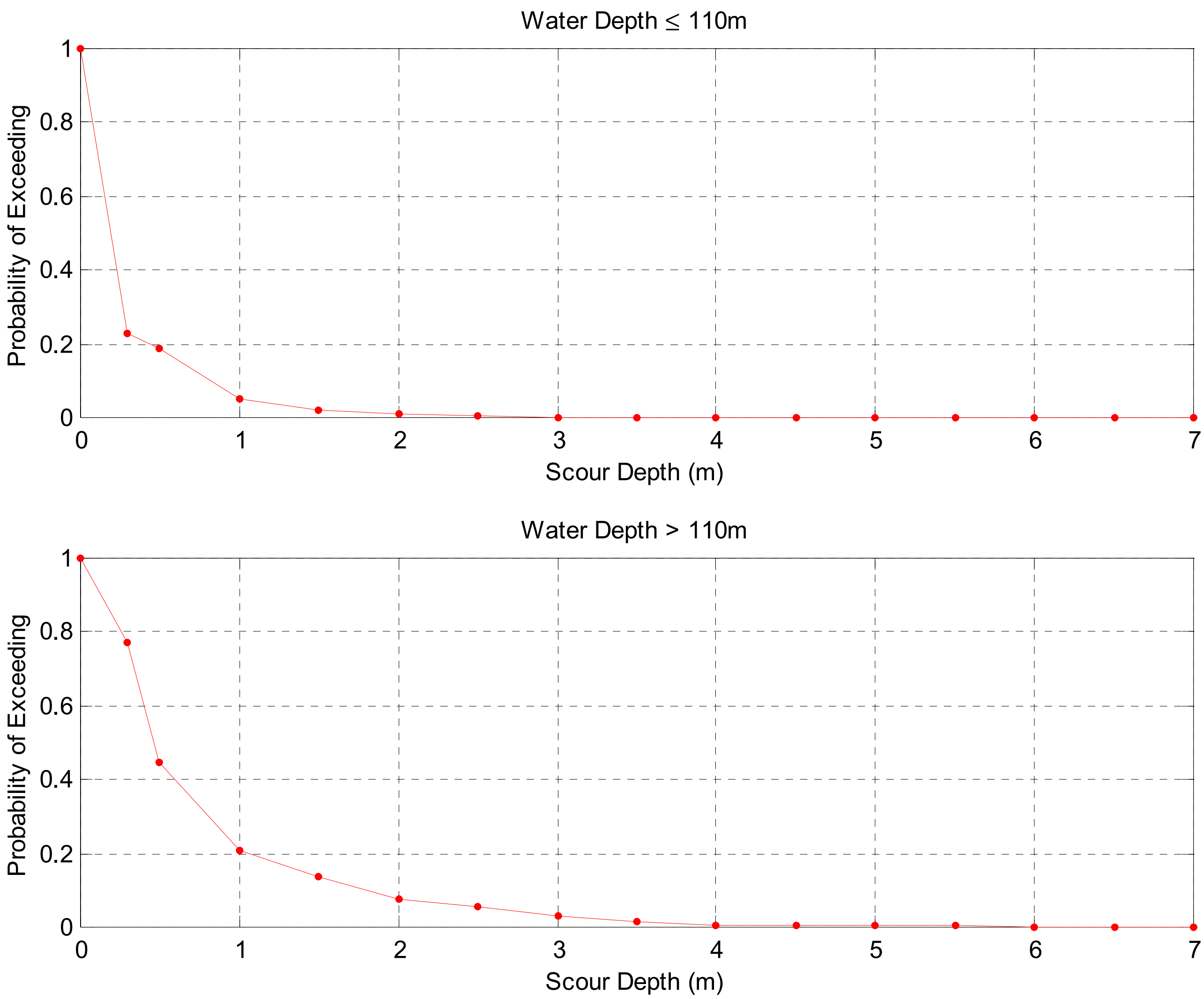


Figure 3.11 Scour depth exceedance curves water depths ≤ 110m (top) and > 110m (bottom).

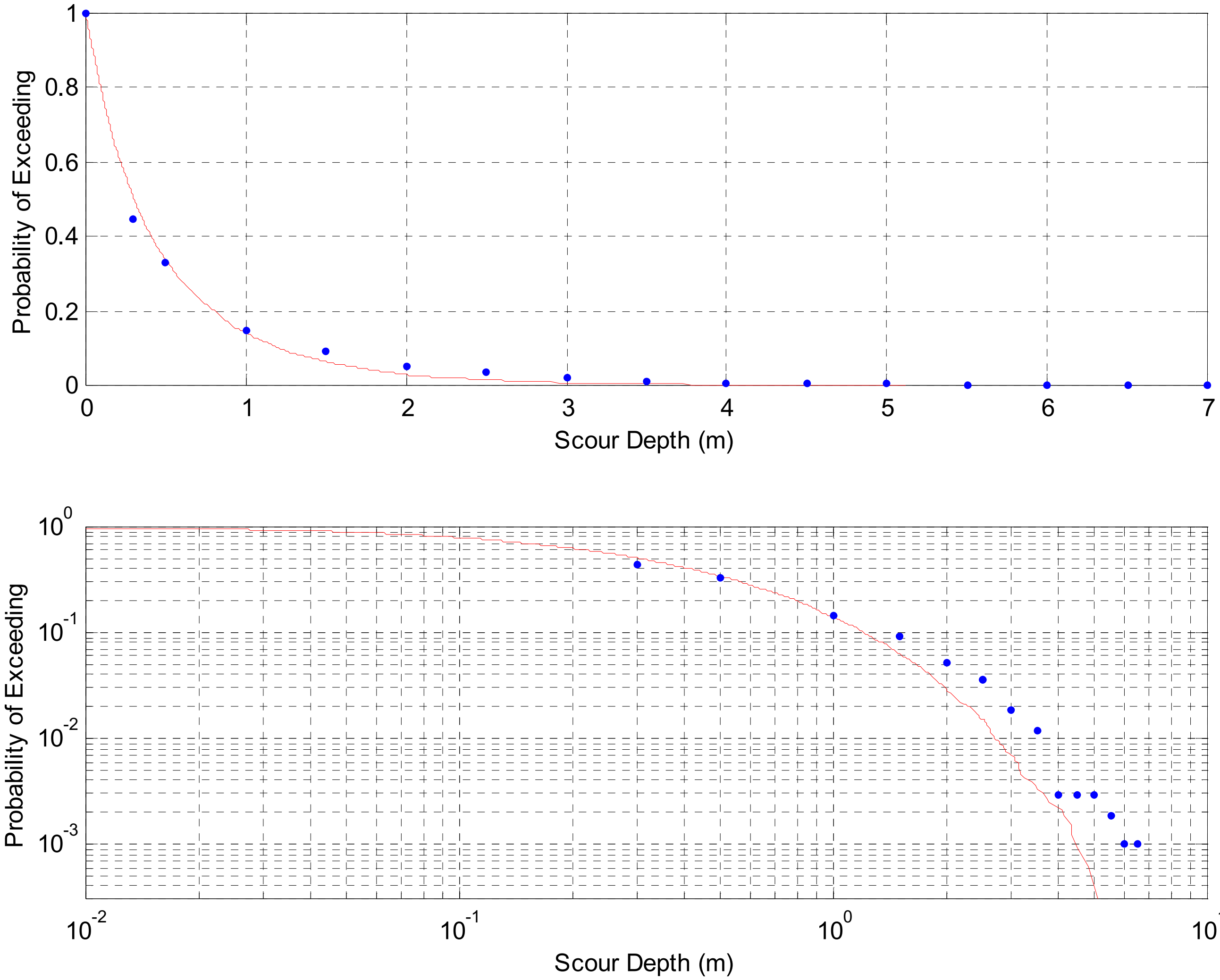


Figure 3.12 Exceedance curve simulated using two exponential distributions (line), and observed scour depth exceedance values (dots).

4.0 ASSESSMENT OF ICEBERG RISK TO SEABED FACILITIES

4.1 Overview

Seabed installations may include subsea production systems (wellheads, manifolds, trees, templates), oil storage facilities, flow lines, pipelines, and protection structures for these facilities.

Assessing risk to such facilities involves two separate issues – icebergs may contact seabed facilities or they may cause damage to them. Risk of contact is relatively easy to determine. Level of damage, however, requires an assessment of structure response mechanisms, iceberg strength, and iceberg behaviour following first contact.

In this section, the various seabed facilities are reviewed with respect to risk from scouring icebergs. Risk estimates are made for the northeast Grand Banks, the main area of interest for oil and gas development. In particular the degree square defined by 46° to 47° N and 48° to 49° W has been used for the risk estimates in the present study.

The various types of seabed facilities have been briefly described in the following sections. The scenarios for contact are identified for each seabed facility according to whether they are placed at or below the mudline. The relevant structure dimensions and characteristics of scouring icebergs are identified for risk analysis. These results are based on the best estimate of the scour rate outlined in chapter 3. In practice, the sensitivity of encounter probability to scour rate should be considered.

The following subsections address encounter probabilities for various subsea protection systems, flow lines and pipeline scenarios and priorities for scour protection in terms of target levels of risk.

4.2 Subsea Production Systems

4.2.1 Description of Systems

Seabed facilities may include subsea production systems such as wellheads, manifolds, Xmas trees, and templates. They may be placed at the mudline, in large open glory holes, in drilled holes, in caissons, or they may be buried.

Unprotected Xmas trees and templates are at risk to freely floating icebergs and scouring icebergs, since the structures are completely above the mudline. The plan dimensions for a vertical Xmas tree are typically less than 5m and heights above the mudline may reach 5m to 7m. Templates used at Terra Nova have varying number of wells (2-5) and have plan dimensions of approximately 12m by 14m with a height of about 8m.

Xmas trees may be placed in drilled holes, which are either cased or uncased. If the hole is uncased, the Xmas tree is placed in the hole with the top of the Xmas tree below the mudline. In this case, only scouring icebergs may contact the Xmas tree. For a cased glory hole the casing may extend above the mudline exposing it to contact from scouring, as well as freely floating icebergs with drafts between the water depth and the top of the structure. Drilled holes of 7-10m diameter are being considered for wellhead protection.

A caisson system has a sacrificial Xmas tree above the seabed and a shearable caisson below the mudline. This system will be affected by both freely floating and scouring icebergs. The Xmas tree and anything above the level of the shearable casing point is sacrificial. The depth of the 'weak link' is determined on the probability of scour to meet risk level requirements, with the critical well head components (and blow out prevention valves) below this depth. Caisson diameters of about 1.5m diameter are being considered for wellhead protection.

Single wells or a template with multiple wells may be placed in a large open hole or glory hole. Structures in these open holes are only affected by scouring icebergs, since the structures would extend above the mudline. The mudline dimensions of glory holes ranges up to 120m at Terra Nova. Glory hole depths depend on the height of the structure placed in the glory hole, since the clearance above the structure is the main consideration. Glory hole depths of 10m have been used at Terra Nova.

4.2.2 Above Mudline Contacts

4.2.2.1 Overview

Iceberg contacts with structures above the mudline may occur from freely floating icebergs with drafts between the water depth and the depth of the top of the structure and from scouring icebergs which make contact with the structure above the mudline. The methodology for estimating the risk of contact for both these scenarios is described in the next two sections.

4.2.2.2 Contact from free floating icebergs

The annual probability of contact for freely floating icebergs with structures extending a distance *'H'* above the mudline may be estimated from

$$\begin{bmatrix} \textit{Annual Contact} \\ \textit{Probability} \\ \textit{(Free Floating Icebergs)} \end{bmatrix} = \rho (W + W_{st}) v T \qquad (4.1)$$

where ρ is the areal density of icebergs (average annual number per unit area) with drafts between d_w (water depth) and d_w-H, W is the effective width of iceberg keel at the top of the structure (i.e. width of keel at depth d_w -H), W_{st} is the effective diameter of the structure, v is the mean iceberg drift speed and T is the time in one year.

Assuming an exponentially distributed iceberg waterline length based on parameters given in Table 4.1, a draft to waterline length relationship was determined from the Mobil Hibernia Development Studies (1981a, 1981b, 1982a, 1982b, 1983a, 1983b, 1984a, 1984b) using a least squares regression to be

$$D = 1.03 \exp (0.70 + 0.78 \ln(L) + \varepsilon_D) \qquad (4.2)$$

where ε_D is a normally distributed random variable with a mean of 0 and standard deviation of 0.24.

The areal density for icebergs in the d_w-H to d_w draft range was calculated by multiplying the areal density for lengths greater than or equal to 16m by a non-detection factor and then by the proportion of these icebergs with drafts between d_w-H and d_w. Iceberg draft was determined from Equation (4.2).

Field measurements of icebergs on the Grand Banks were documented in Mobil Hibernia Development Studies (1984a). These data were obtained using sonar measurements of each iceberg at various positions around the iceberg's circumference and at various depths. Thus, a three-dimensional underwater shape was inferred from the water surface to the iceberg keel. Mean values of iceberg width were computed at each sonar depth for each iceberg in the data set. These widths were plotted against distance above the iceberg keel and then normalised by iceberg draft. A second-order least squares fit of normalised iceberg width (w^*) as a function of normalised height above the keel (z^*) was then made to the bottom 30% of the iceberg data

$$w^* = -9.31\, z^{*2} + 5.30\, z^* + 0.26 \qquad (4.3)$$

For the contact probability estimates made in this section, a water depth of 100m has been assumed. Since the mean waterline length of the Mobil Hibernia Development Studies (1984a) icebergs was 59m, corresponding drafts to 100m would not occur. To ensure correspondence between iceberg shape and scour geometry, the data were scaled to fit the mean scour width and mean scour depth measurements of 24m and 0.5m respectively (assuming the mean scour width was measured at the mudline). The quadratic fit to iceberg keel width data was assumed to pass through the point where $z^* = z/D_i = 0.5/100.5$ and $w^* = w/D_i = 24/100.5$, where z is the distance measured upward from the keel tip (m), w is the iceberg width (m) at a given z and D_i is the iceberg draft (m). This scaling is illustrated in Figure 4.1 in which the original quadratic fit was shifted downward by a constant value to maintain the original shape of the curve.

For the present study, the input values given in Table 4.1 were used for the calculation of contact probability. The annual probability for contacts above the mudline from free floating icebergs is shown in Figure 4.2. In this figure the annual contact probability is plotted against structure diameter for four different structure heights (1, 2, 5 and 10m). This plot shows that the risk of contact increases linearly with structure diameter and with structure height.

4.2.2.3 Contact from scouring icebergs

The annual probability of contact above the mudline from scouring icebergs can be determined from the scour frequency and dimension data, and the structure size as

$$\begin{bmatrix} Annual\ Contact \\ Probability \\ (Scouring\ Icebergs) \end{bmatrix} = P(z) f_{sc} (W_{st} + W) \overline{L}_s \qquad (4.4)$$

where $P(z)$ is the probability of exceedence for a structure buried with its top z m below the mud line (for the case of scouring iceberg for above the mudline contact, $P(z)$ is equal to unity), f_{sc} is the scour rate (number/unit area/year), W_{st} is the structure diameter, W is the iceberg keel width at the top of the structure, and $\overline{L}_s$ is the mean scour length. Refer to Table 4.1 for the value of inputs used for this section.

The results of the model for above the mudline contacts from scouring icebergs are shown in Figure 4.3. In this figure the annual contact probability is plotted against structure diameter for four different structure heights (1, 2, 5 and 10m). The risk of contact increases linearly with structure diameter and with structure height.

4.2.3 Below Mudline Contacts

4.2.3.1 Overview

For risk of contact below the mudline, small and large holes are considered. The distinction between small and large holes has been made since scouring icebergs may actually drop or dip into large open holes. A small hole has been arbitrarily defined to be less than the average scour width. For the present study, the average scour width on the Grand Banks for water depths less than 110m is 24m. Drilled holes for cased and uncased wells would normally be significantly smaller than 24m. Open glory holes would most often be greater than 24 m and would thus be considered to be the large hole scenario.

4.2.3.2 Small diameter hole or structure

For the small diameter structure (diameter less than 24m), the risk of contact to a specific depth below the mudline is determined using equation (4.4) with a value of $P(z)$ determined from a fit to the scour depth data presented in Chapter 3 of this report. If scour depth is exponentially distributed, the probability of exceedence is

$$P(z) = e^{-z/\mu} \qquad (4.5)$$

where z is the depth below the mudline and μ is the mean scour depth.

Contact probabilities resulting from this analysis are presented in Figure 4.4. For some structures, sub-scour soil deformations will be of concern. This issue is addressed in section 5.5.

4.2.3.3 Large open hole or glory hole

For large diameter holes, the risk of contact to a specific depth below the mudline is also determined using equation (4.4), In this case, $P(z)$ is the probability of exceedence for the iceberg keel reaching a depth z in the hole. This is a complex calculation involving the keel offset from the centre of mass and the heave and pitch dynamics of the iceberg. The probability of exceedence $P(z)$ can be estimated from the distribution of excess drafts for scouring icebergs.

Excess draft was computed using the results from the scour model presented in Chapter 5 of this report. Excess draft together with scour depth were calculated as the distance from the mudline at each step in the simulation to the iceberg keel tip in the equilibrium free-floating position. Figure 4.5 presents a comparison of the exceedence probability for excess draft and scour depth derived from each step in the scour simulation model. These data were based on the results of simulation of approximately 60000 icebergs scouring upslope as presented in Chapter 5. The scour depth derived here is based on the assumption that scour depth increases linearly from zero at the beginning of the scour to the maximum at the end of the scour. Though scour depth is not always exactly linear along the scour length, the difference is negligible.

Since scour depths from the model presented in Chapter 5 were, on average, lower than those measured on the Grand Banks, a factor was applied to the exceedance plot for contact with small holes (Figure 4.4). The factor was based on the ratio of modeled excess draft to modeled scour depth for a given exceedance probability. Contact probabilities resulting from this analysis are presented in Figure 4.6.

4.3 Flow Lines and Pipelines

4.3.1 Flow Lines

Small diameter flexible flow lines laid on the seabed (or trenched as at Terra Nova) connect the subsea production system to the FPSO. Export lines from the Hibernia GBS feed the tanker loading facility. Only the seabed portion of flow lines is considered in this sub-task since risk to the risers from free-floating icebergs far exceeds that from scouring icebergs. These lines are generally shorter than pipelines and thus are at a lower risk to damage from scouring icebergs. Flow line lengths at Terra Nova are approximately 2km.

4.3.2 Pipelines

Pipelines proposed for the Grand Banks include oil and gas transmission lines laid on the seabed or trenched to prevent iceberg scour. Typical diameters may reach or exceed 1 m and a concrete coating is used to ensure negative buoyancy.

The main differences between flow lines and pipelines are in the length of the linear feature being considered and their response to soil deformations. Pipelines tend to be considerably longer than flow lines and thus are generally subdivided into smaller segments according to bathymetric features or soil strength. Contact probabilities are computed then for the individual segments, utilizing relevant conditions for each segment and applicable codes then consulted to help recommend safe burial depths.

4.3.3 Method of Analysis

The method presented in this section gives the annual probability of an iceberg scouring to a given depth over a buried linear feature. The method is similar to that outlined in section 4.2.3.2 for computing annual contact probabilities between scouring icebergs and small diameter holes or structures. Rather than using structure diameter, however, the projected length of the linear feature is computed in the direction of movement of the iceberg. The annual probability of an iceberg scouring to a depth *z* over a buried linear feature is then

$$\begin{bmatrix} \text{Annual probability of an} \\ \text{iceberg scouring to a depth} \\ z \text{ over a linear feature} \end{bmatrix} = P(z) f_{sc} (\overline{W} + \langle L_l |\sin(\theta - \phi)| \rangle) \overline{L}_s \qquad (4.6)$$

where $\overline{W}$ is the mean scour width, $P(z)$ is the probability of exceedence for the iceberg keel reaching a depth z below the mudline ($=e^{-z/\mu}$ for exponentially distributed scour depths), μ is the mean scour depth on the northeastern Grand Banks, f_{sc} is the scour rate (number/unit area/year) and $\overline{L}_s$ is the mean scour length. Values of these input parameters are given in Table 4.1.

The term inside angled brackets in equation (4.6) is the mean projected length of the linear feature, where L_l is the length of the linear feature, θ is the iceberg drift angle and ϕ is the linear feature orientation. Since pipelines and flow lines may be oriented at any angle with respect to the scour direction, consideration must be given to how best to determine the mean projected length. Figure 4.7(a) is a distribution of scour orientations on the northeastern Grand Banks, constructed from data provided in Chapter 3. These data are assumed to be representative of iceberg drift directions and are measured positive clockwise from north. A cumulative distribution function (CDF) was constructed (Figure 4.7(b)) from these data. A set of scour orientations was randomly sampled from the CDF and used to compute a set of projected lengths. The orientation angle of the linear feature was assumed to be E-W ($\phi=90°$). The mean value of projected length was then used in the calculation of annual probability of an iceberg scouring to a given depth over a linear feature.

Results of this analysis are presented in Figure 4.8. Examination of this figure reveals that there is a reduction in contact probability when the feature is buried by an amount z below the mudline. The annual probability of scouring to a given depth over a buried linear feature increases linearly with the length of the feature.

Using the analysis outlined in this subsection along and an assessment of sub scour soil deformation, safe burial depths for pipelines and flow lines can be recommended (Figure 4.8). Sub scour soil deformations occur below a scour as a result of stresses induced in the soil through the scouring process. The effect of such sub scour soil movement on a buried pipeline depends on the depth to which the pipeline is buried. More detail is given on this subject in section 5.5.

4.4 Priorities for Scour Protection

4.4.1 Review of Risk Levels

As general background, offshore oil and gas operations contribute only 1.5% of the hydrocarbons entering the marine environment; about 8% comes from natural sources such as seeps. In design decisions, it is necessary to consider both the probabilities and the consequences of the events of importance. Major consequences can result if a subsea blowout occurs, and this is mainly of concern with regard to wellheads and oil storage facilities. Ice scour does not usually lead to serious consequences with regard to human life. With many other facilities, such as flow lines, it is possible to flush these of hydrocarbons so that the risk of pollution is minimized. Some values of target risks are given in Table 4.2, from Wells (1996).

4.4.2 Standards and Codes

A large number of standards and codes were reviewed. These are listed in the reference section—the main source of information—and also in Appendix 1, giving a list of the codes consulted. There is not a large amount of detail given to ice scour. The CSA Z662-99 does refer to sea bottom scour by ice. (sections 11.2.1.2 and 11.2.2.2.1). It is required that loads be determined using established methods, theoretical or based on measurements (C4.6.8). An annual exceedence probability of 10^{-2} per km is given for environmental loads. For iceberg impacts, an exceedence probability of 10^{-4} is specified. The DnV Rules for Submarine Pipeline Systems stipulate that ice scouring and impacts from drifting ice be considered.

The Canadian Standards Association CAN/CSA-S471-92, General Requirements, Design Criteria, the Environment, and Loads, part of the Code for the Design, Construction, and Installation of Fixed Offshore Structures, was reviewed. This Standard sets the safety objectives for the code as a whole. Clause 4.13 states that "when scour, including ice scour, is expected to occur, the depth and lateral extent of scouring shall be evaluated on a site-specific basis and accounted for in the design". There is not any further detail specific to ice scour, but there is substantial guidance on safety issues.

One important aspect is the question of safety classes. These are defined in clause 4.5.2. The Standard defines two safety classes for the verification of the safety of the structure or any of its structural elements:

- Safety Class 1 - failure would result in great risk to life or a high potential for environmental damage, for the loading condition under consideration;

- Safety Class 2 - failure would result in small risk to life and a low potential for environmental damage, for the loading condition under consideration.

Further guidance is provided in the notes provided at the end of the clause:

- If loading hazards can be predicted sufficiently ahead of time to carry out a predefined emergency response plan that ensures personnel safety and environmental protection, then, for that particular loading condition, the structure may be Safety Class 2.
- A safety class may be assigned to the structure as a whole or to its individual structural elements. For example, a structure designated Safety Class 1 as a whole may have certain of its structural elements designated Safety Class 2.

- See Appendix A (of the Standard) for further information on the application of safety classes and on the associated reliability levels assumed in this Standard.

The main target safety level used in the calibration of the CSA code was 10^{-5} per annum, although values as low as 10^{-4} were permitted in the calibration procedure. Figure 4.9 illustrates the situation. In the calibration it was assumed that one of the load cases would dominate, and that it was not necessary to consider all loads as adding a risk of 10^{-5} . To take an example, it is unlikely that scour and wave effects will result in a risk each of exactly 10^{-5} ; usually one might be at this level, with other effects at lower levels of risk. Target safety levels for Safety Class 2 and for serviceability (impaired function) were given as 10^{-3} and 10^{-1} per annum, respectively. Table 4.3 is reproduced here, from Appendix A of the Standard S471 (in which it is labeled as Table A2) because of its relevance.

Various other codes were consulted; a list is given in the Appendix. These contain advice on the design of subsea facilities and wellheads in particular. Risk levels are not given and iceberg scour is not addressed.

4.4.3 Subsea Facilities

There are many components in the subsea facilities that need consideration. These are:

- Wellheads, upon which the tree is installed; they control the rate of flow of liquid and gas from the well. They are generally provided with barriers in the well bore, including possibly a surface-controlled subsurface safety valve. There may also be a shear device, designed to ensure that the tree separates from the tubing if a scouring iceberg interacts with sufficient severity.
- Flow lines/seafloor gathering lines: there are block valves at both ends, and hydrocarbons can be removed. Therefore risk to the environment can be minimized.
- Risers: these will be released by floating production systems. They sink to a certain level, e.g. 40 m, and bergs with drafts greater than this may interact with them. They are flexible so that damage might be minimized on this account; in any event, they can be flushed as in the case of the flow lines.
- Oil storage facilities for subsea production. Here, there is a clear case where severe environmental consequences are possible, and proper structural design is necessary.

As noted earlier, loss of life is not in general a concern in the above discussion; rather it is focussed on pollution issues. Iceberg management programs will also serve to reduce the risk.

With regard to the two levels of safety, represented by the CSA safety classes, in the first safety class (Safety Class 1), failure would result in great risk to life or a high potential for environmental damage, for the loading condition under consideration. For Safety Class 2, failure would result in small risk to life and a low potential for environmental damage, for the loading condition under consideration. Extreme consequences would correspond to subsea blowouts of thousands of m^3 per day for several days, for example. These would correspond to the case, in the present study, where a wellhead was severed, and the well was not secured, for example as a result of an extremely deep scour, or damage to the valves.

As an example of application of the CSA safety rules, suppose that the probability of scour is 10^{-3} per year. Most scours are relatively shallow. A Safety Class 1 event will only occur if the scour is deep and severe enough to damage the valve, which is protected by shear failure devices. The probability of this occurring is multiplied by the value of 10^{-3} already obtained.

4.4.4 Recommendations

It is recommended that the Canadian Standards Association target safety levels and design strategies be followed. Failure of the wellhead resulting from an ice scour should be considered as a Safety Class 1 event. The annual target probability of 10^{-5} would then apply as a risk level. This would apply to

- one isolated single well,
- several wells clustered around a single manifold, or
- several wells placed in a large glory hole.

In a particular development, there will generally be several of these facilities, each with associated probabilities of failure. The probability of a serious consequence increases with the number of the facilities, and it may be advisable to increase the reliability level of the individual entities so as to maintain the probability of a serious (Safety Class 1) consequence at an acceptable level. It is recommended that up to ten facilities be treated individually at the 10^{-5} level. Where the number exceeds 10, it is recommended that the total safety level be maintained at the 10^{-4} level; an individual facility would then have a target level of 10^{-4} divided by the number of facilities. The procedure is consistent with the calibration process used in the CSA, where some risks were accepted at the 10^{-4} level per year.

Other installations, such as flow lines, where the potential damage to the environment is small, could be treated using Safety Class 2 guidelines.

Table 4.1 Input parameters for contact probability analysis

Parameter	Symbol	Value	Source
Mean iceberg waterline length	$\overline{L}_{WL}$	59 m	Jordaan et al. (1995)
Water depth	d_w	100 m	Assumed representative of Grand Banks
Areal Density	ρ	0.6 per deg. square	Jordaan et al. (1996)
Mean iceberg drift speed	v	0.28 m/s	Seaconsult (1988)
Iceberg non-detection factor	μ	1.1	C-CORE (1993)
Scour rate	f_s	4.0×10^{-10} $/m^2/yr$	Chapter 3 results
Structure diameter	W_{st}	Various	Assumed representative of installations
Mean scour length	$\overline{L}_S$	560 m (for water depths less than 110m)	Chapter 3 results

Table 4.2 Risk Values Recommended by Wells (1996)

Employee individual risk	
all process causes	10^{-4} per year
specific process causes	10^{-5} per year
Public individual risk	
all process causes	10^{-5} per year
specific process cause	10^{-6} per year
Risk of major incidents (societal risk)	
near miss from all process causes	10^{-4} per year
accident from all process causes	10^{-5} per year
catastrophic accident from all process causes	10^{-6} per year
accident from specific process causes	10^{-6} per year
catastrophic accident, specific process causes	10^{-7} per year

Table 4.3 Annual exceedence probabilities for specified loads (*CAN/CSA-S471-92, Table A2)*

	Safety Class 1		Safety Class 2	
	Annual Exceedence Probability P_E	Load Factor	Annual Exceedence Probability p_E	Load Factor
Specified loads, E_f based on frequent environmental processes	10^{-2}	1.35	10^{-2}	0.9
Specified loads, E_r based on rare environmental events	10^{-4} to 10^{-3}	1.0	10^{-2}	1.0
Specified accidental loads, *A*	10^{-4} to 10^{-3}	1.0	N/A	N/A

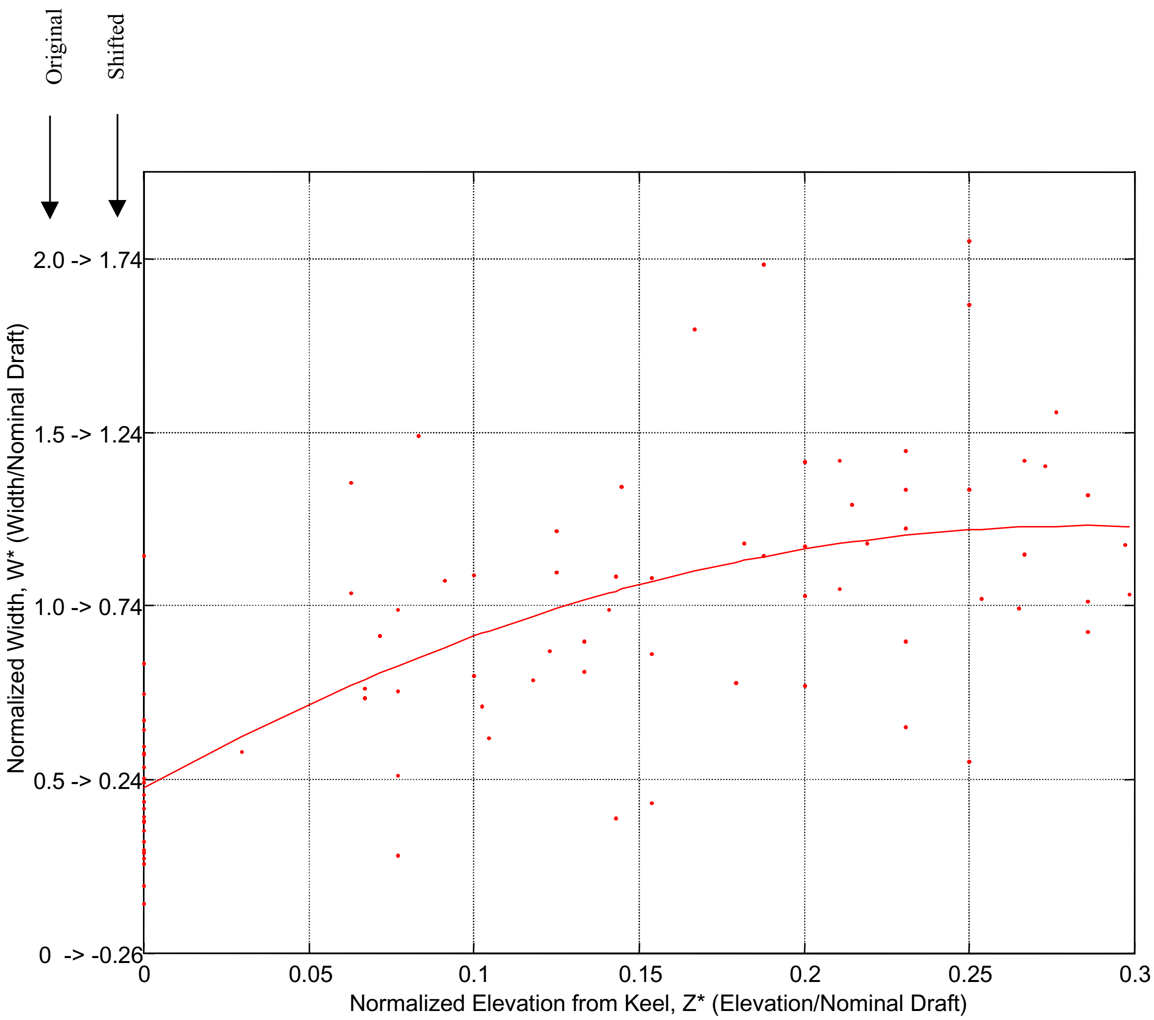


Figure 4.1 Keel shape fit to the Mobil Hibernia Development Studies (1984a) data.

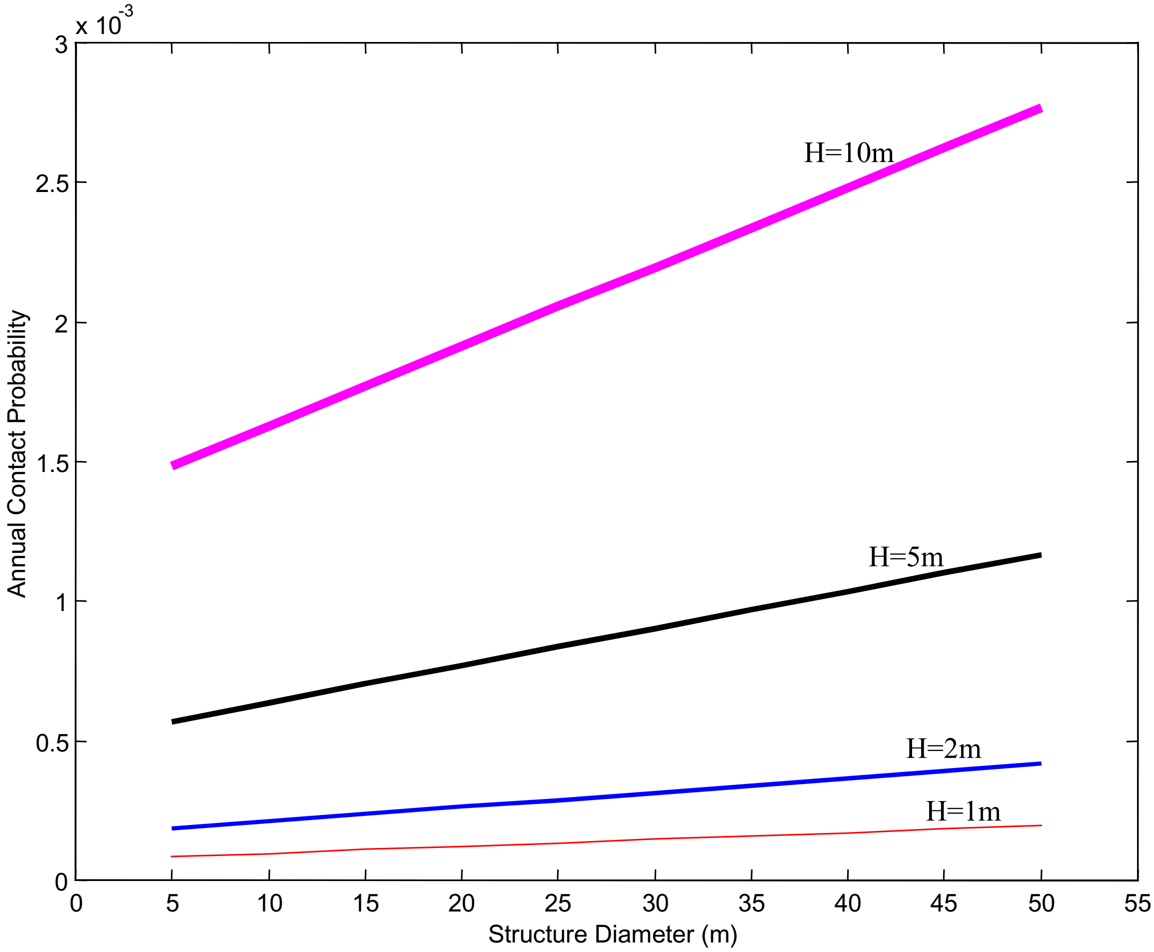


Figure 4.2 Annual Contact Probabilities Calculated for Free-Floating Icebergs and Structures Above the Mudline

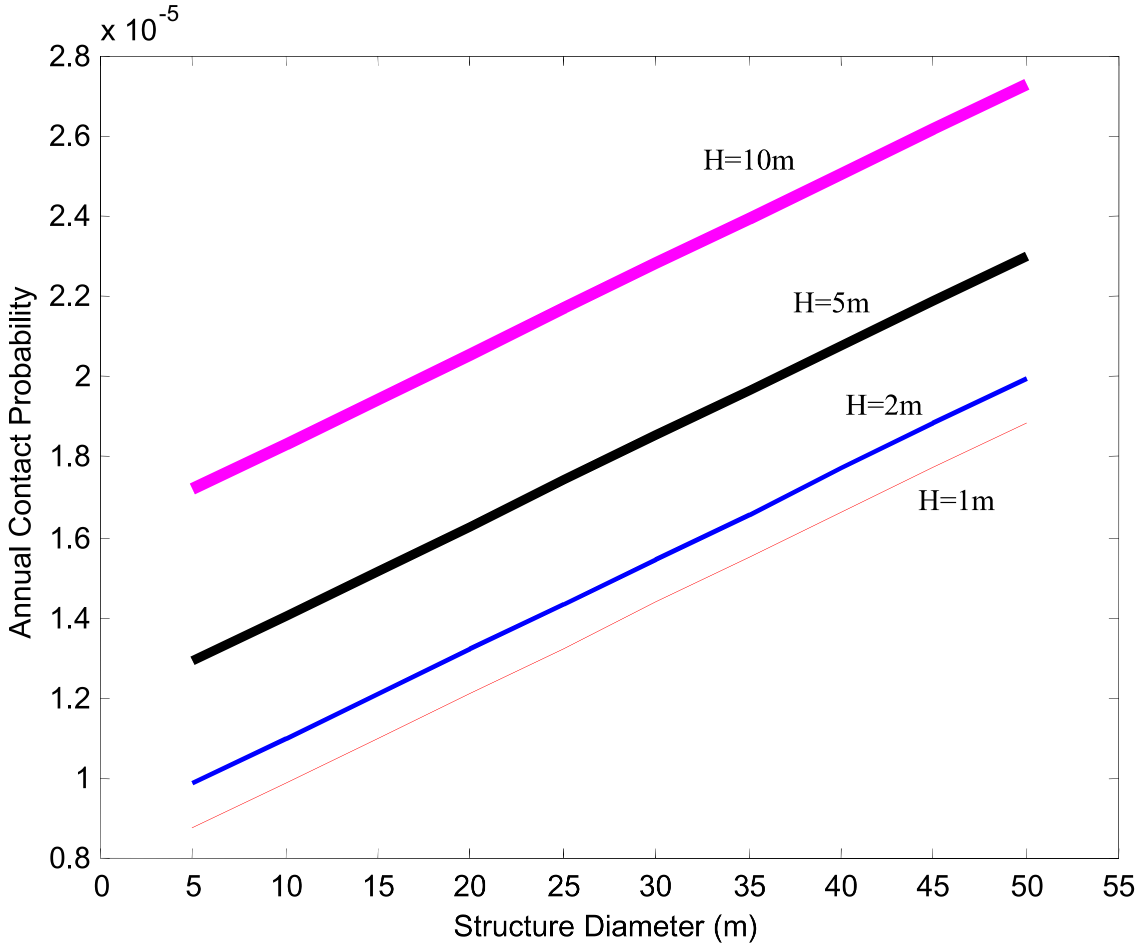


Figure 4.3 Annual Contact Probabilities Calculated for Scouring Icebergs and Structures Above the Mudline

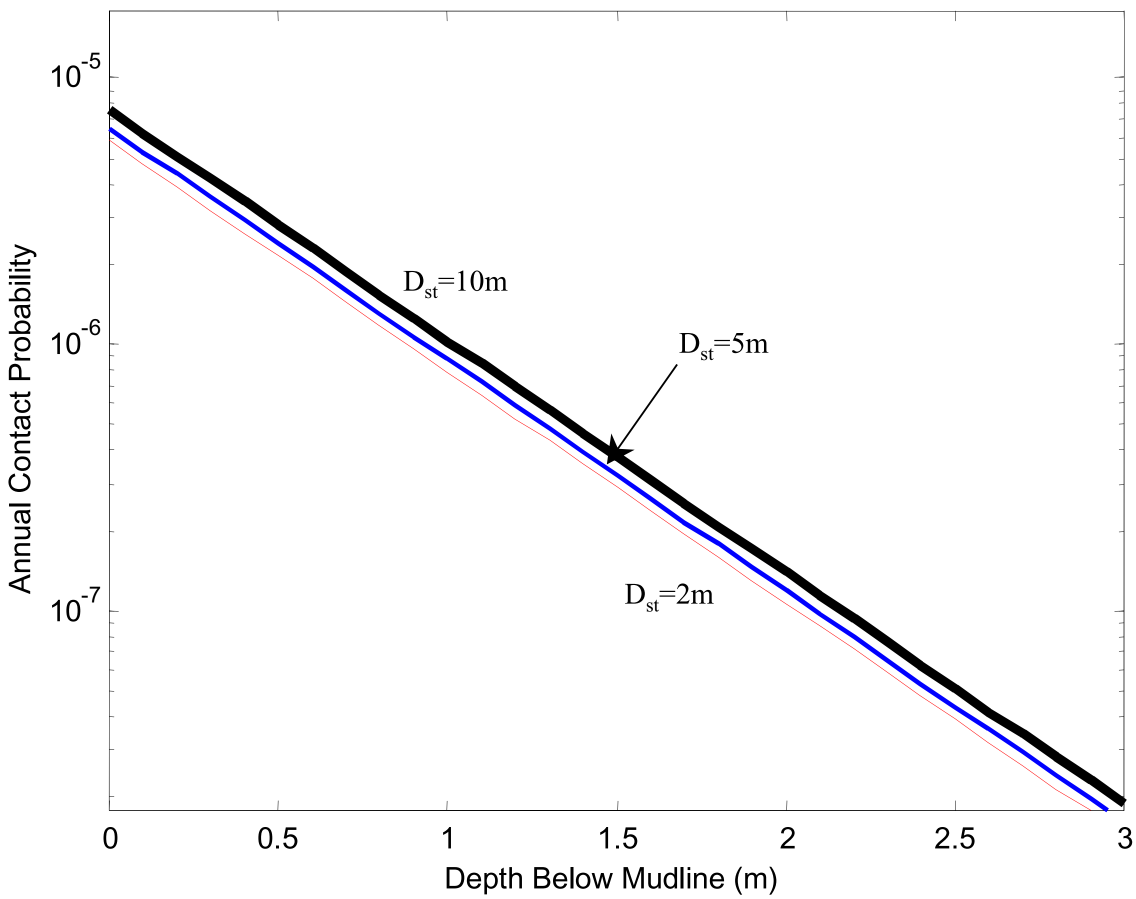


Figure 4.4 Annual Contact Probabilities Calculated for Scouring Icebergs with Small Installations Below the Mudline.

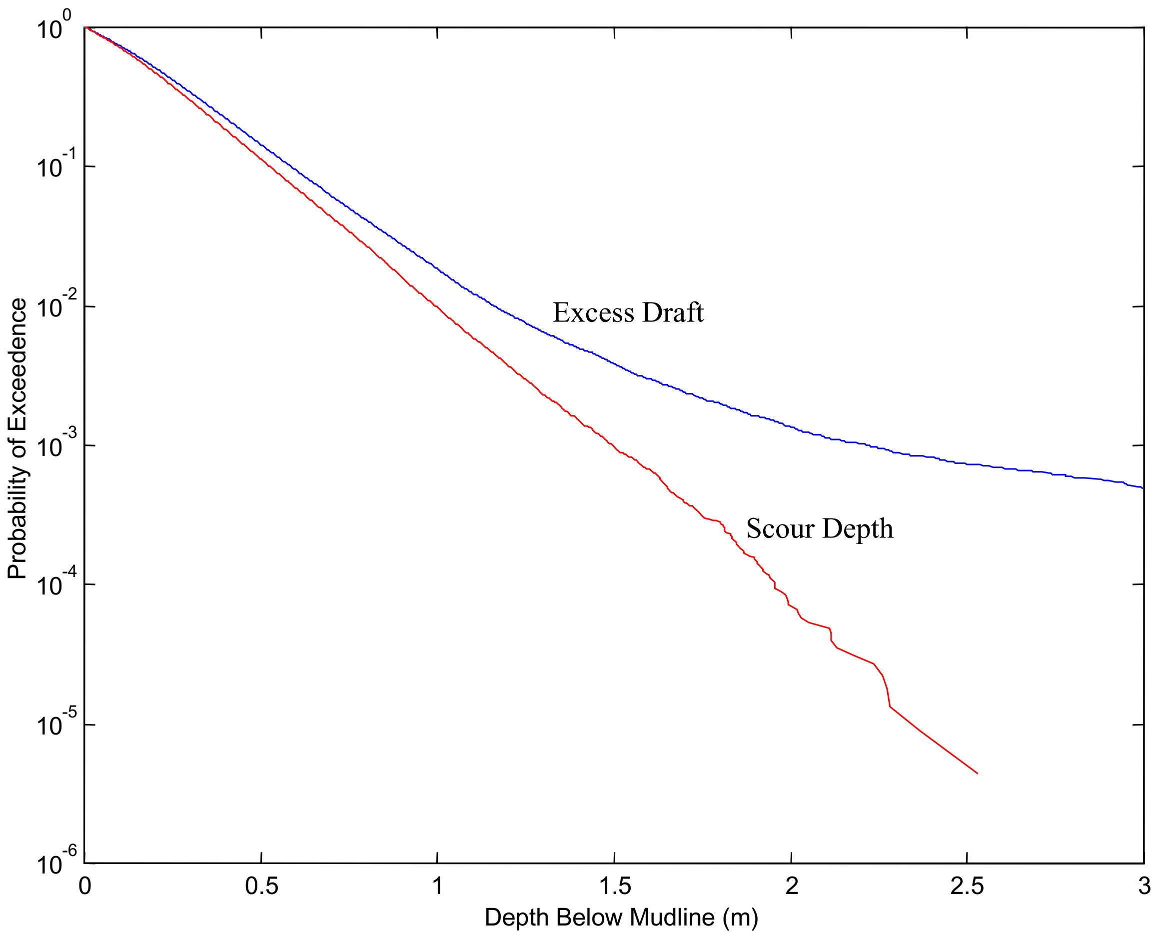


Figure 4.5 Exceedance Probability Comparison for Excess Draft and Scour Depth based on modelled results in Chapter 5.

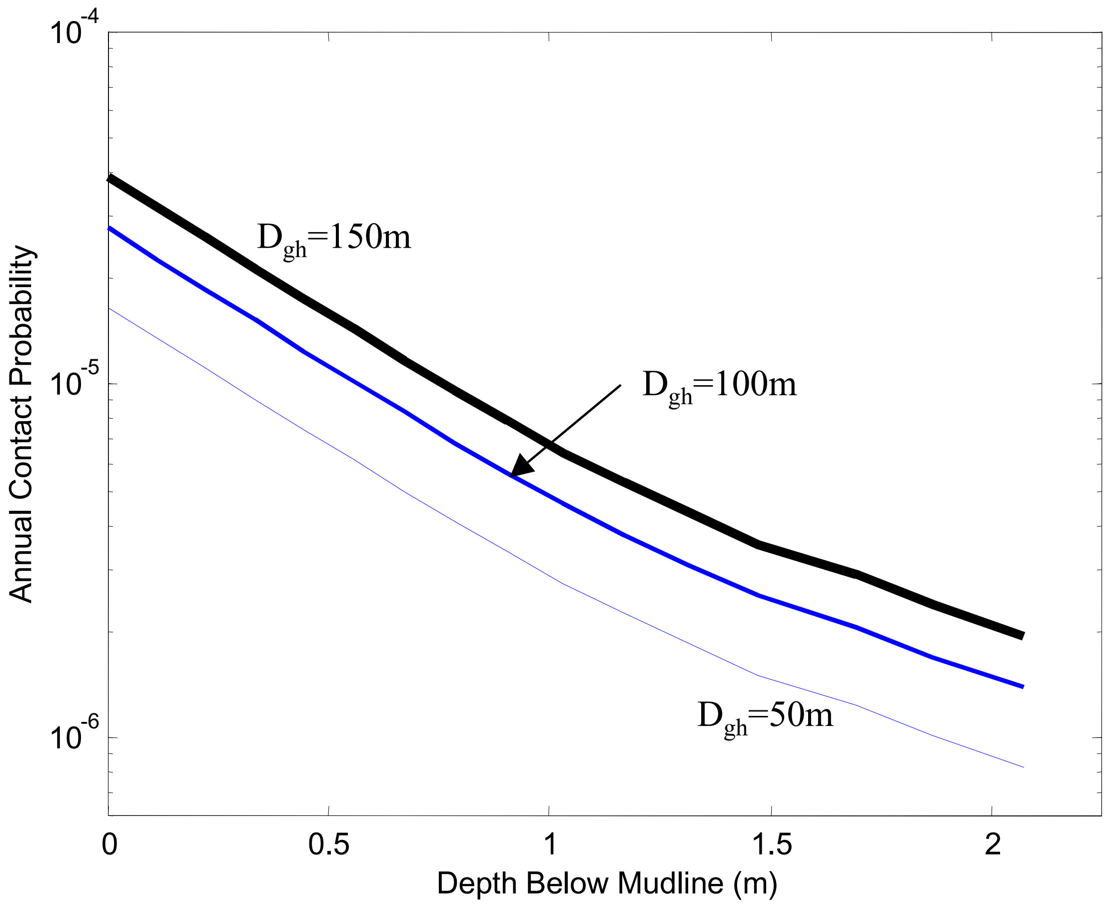


Figure 4.6 Annual Contact Probabilities Calculated for Scouring Icebergs with Structures in Various Sized Large Open Glory Holes

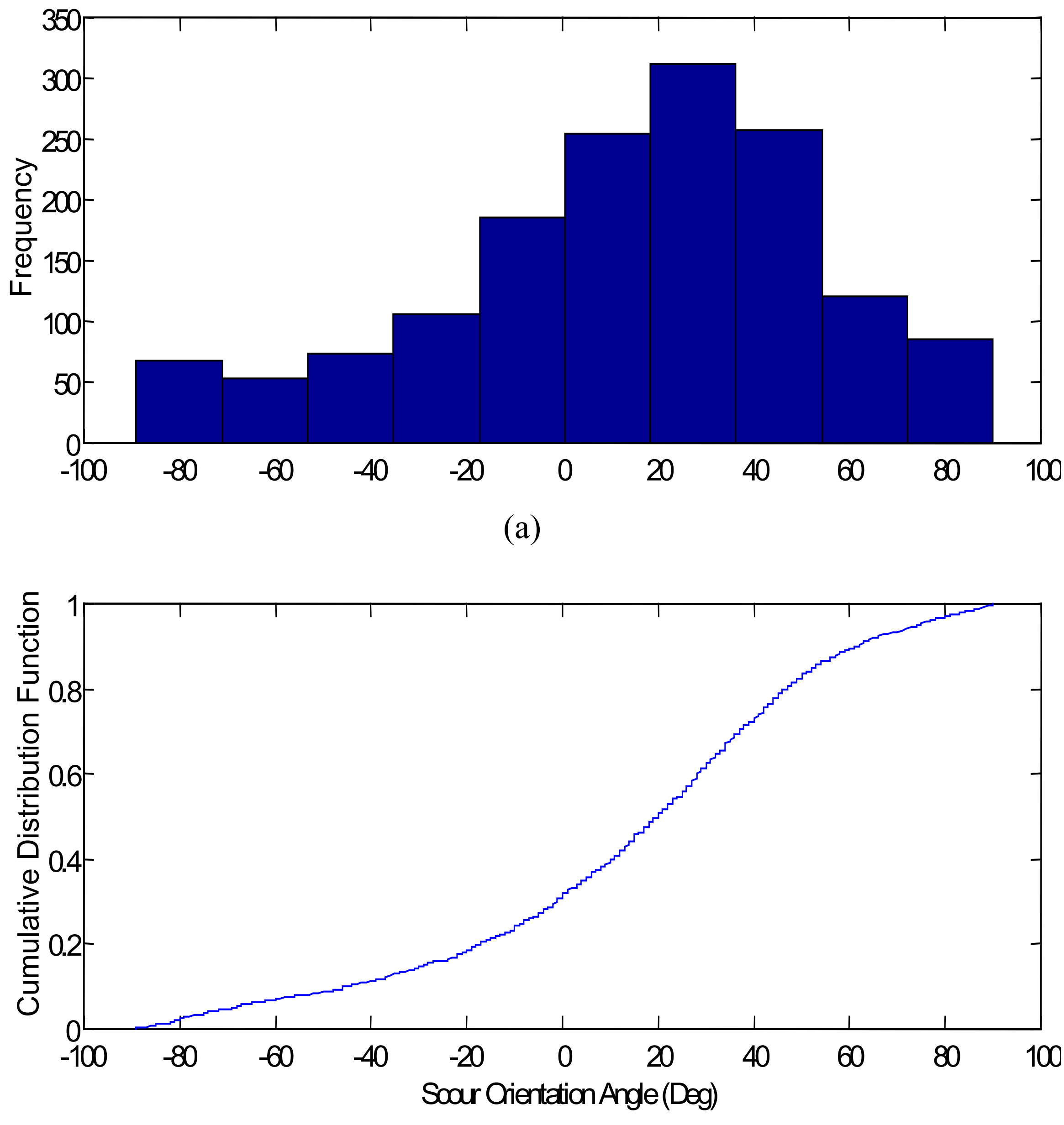


Figure 4.7 Distribution and CDF of Scour Orientations on the Grand Banks in Water Depths Less Than 110m (Measured Positive Clockwise from North).

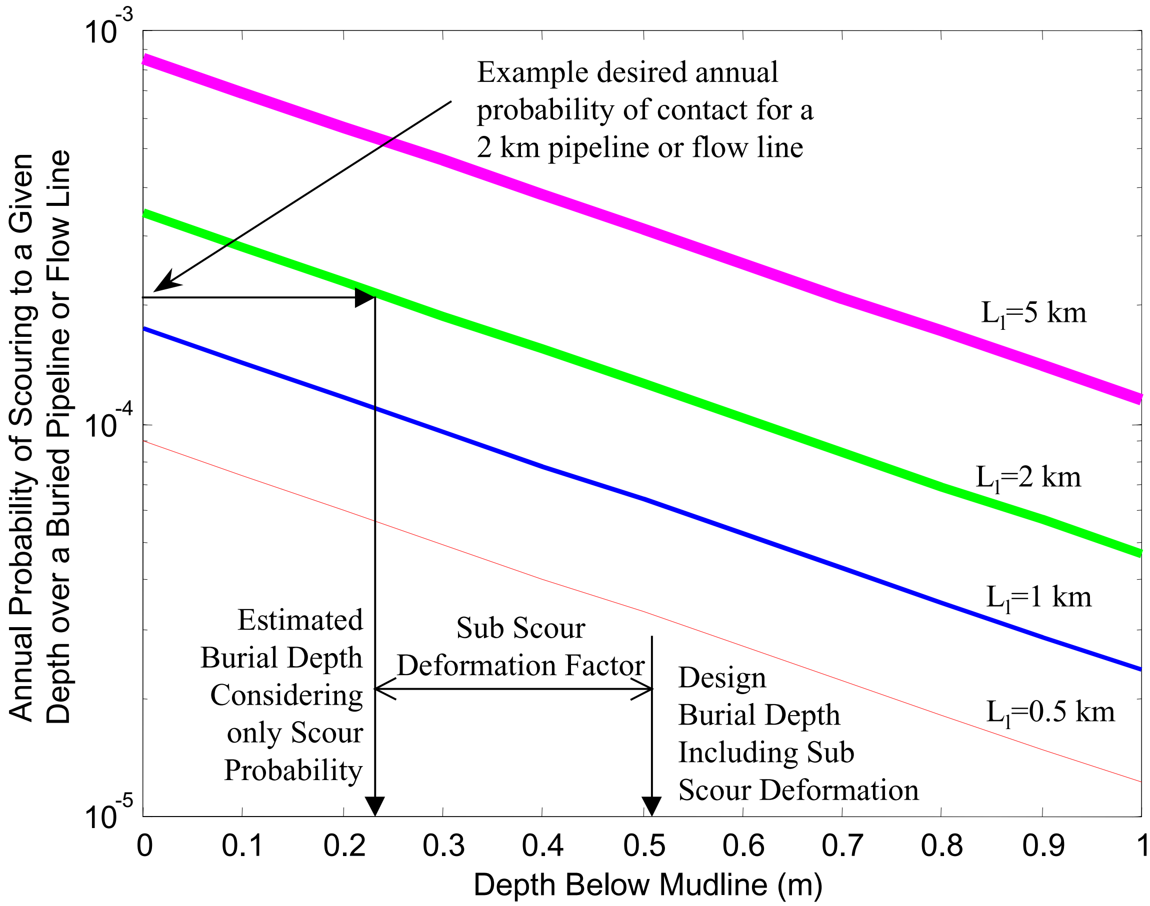


Figure 4.8 Annual probability of an iceberg scouring to a given depth over a buried pipeline or flow line. Figure shows method for determining design burial depth for a 2 km flow line.

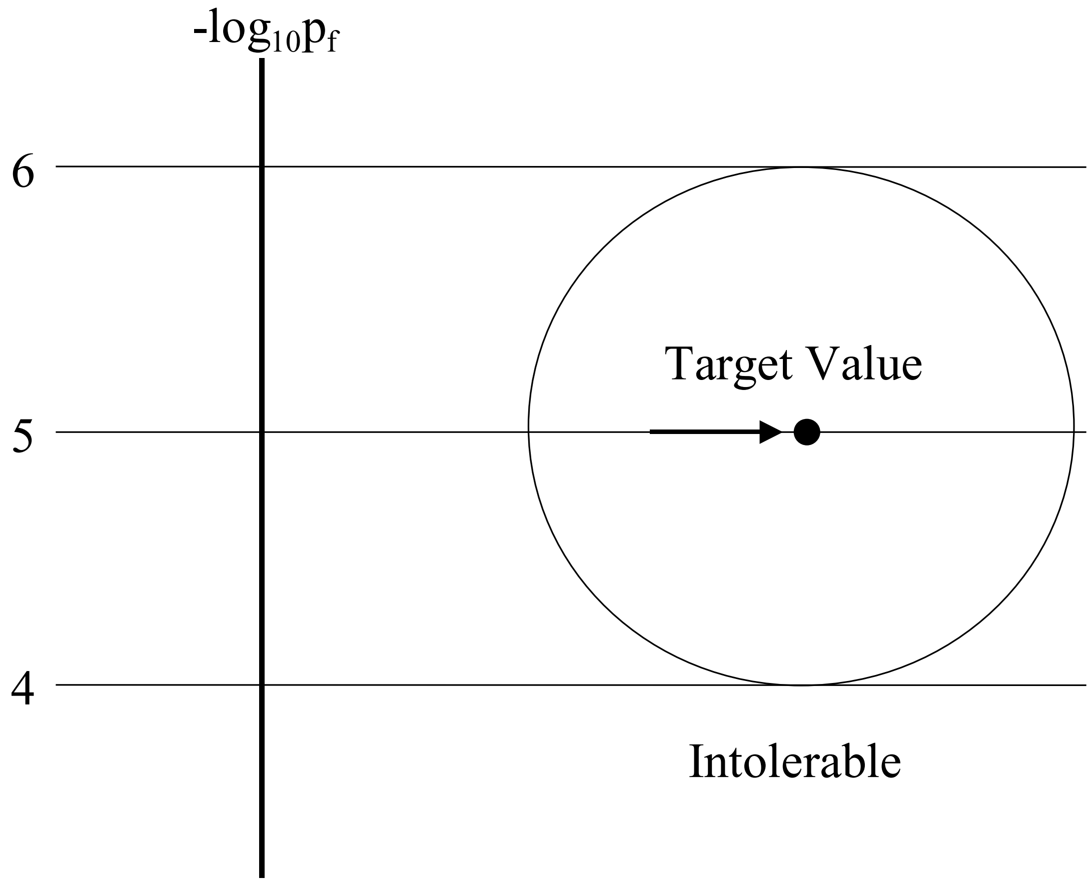


Figure 4.9 Illustration of targets in the CSA code for Safety Class 1

5.0 REVIEW OF ICEBERG SCOURING MECHANISMS

5.1 Overview

The dominant mechanisms governing the penetration of an ice feature into the seabed and the resultant creation of a scour (i.e. scour depression or furrow) are illustrated in Figure 5.1. The plan view is shown in Figure 5.1.a where a three-dimensional rupture surface forms as the ice feature advances and the deformed soil clears to the scour edge. As shown in profile Section A-A′, a dead wedge or zone of relatively stable soil mass develops adjacent to the front face of the keel. During the ice scour event, soil is pushed forward and a frontal mound (i.e. spoil heap or berm) is developed. For steady-state scour processes, a dynamic equilibrium is developed where the "plowed" soil in the failure zone is balanced with creation of the frontal mound and side berms.

The ice scour process can be modeled as a dynamic analysis that considers the ice feature kinetic energy as a state process governed by static equilibrium. Driving force scour models are typically used in conjunction with seabed force models to model the ice scour/soil interaction and predict physical scour characteristics. The main characteristics of several driving force models are summarised in Table 5.1.

5.2 C-CORE Iceberg Scour Model

5.2.1 Overview

A comprehensive model of environmental driving forces, ice scour forces, iceberg characterisation and hydrostatics was developed by McKenna et al. (1999). The analysis was based on a nonlinear iterative solution of the static equilibrium. The environmental driving forces included the effects of wind, wave, tidal current, inertial current and wind-driven Ekman current. This model was applied within a Monte Carlo simulation framework to estimate scour depth distributions. Iceberg geometry and hydrostatic stability were also carefully characterized in this effort.

The present model includes kinetic energy effects as well as environmental driving forces and was built directly on the work of McKenna et al (1999). It allows for determination of scour length and scour depth distributions.

5.2.2 Soil Force model

Under the PRISE program, C-CORE developed an improved model for computing horizontal and vertical soil forces due to scouring ice features (Walter and Phillips, 1998). It is based, in part, on centrifuge experiments conducted at C-CORE. Since details of this model and the data are proprietary in nature, it has not been utilized in the present version of the iceberg scour model.

The scour force model chosen for this work is based on the COGLA model, presented by Been et al (1990). Passive resistance at the front of the scouring ice feature is found using a method modified from that proposed by Sokolovski (1965). Sokolovski's stress field method is a lower bound plasticity solution that assumes two-dimensional plane strain conditions. The Mohr-Coulomb failure criterion is satisfied throughout the soil mass and each point within the mass is in a plastic state. Stresses within the rupture zone are assumed to be in equilibrium with the boundary stresses applied to the soil. The stress distribution is found by satisfying the equations of equilibrium within the failure zone. The Sokolovski approach was modified by Been et al. (1990) to include the formation of dead wedges of soil within the failure zone which are calculated in a similar manner to that described by Hettiaratchi and Reece (1975). The model uses effective strength parameters and assumes drained conditions during scouring. Notable assumptions include:

- Ice keels are wide compared with keel depth - three-dimensional effects are considered to be small and thus are neglected.
- Soil reaction forces are calculated on a unit width basis.
- The program does not compute the normal soil reaction force below the keel, or the sliding resistance on the base of the scour due to the normal force.
- Based on the PRISE work, we believe that the model presented by Been et al. (1990) underestimates soil forces and therefore overestimates scour depth.

5.2.3 Model Framework

The model developed by McKenna et al (1999) was modified to include seabed slope. Solution to the scour problem was made in two steps; a free drift solution, and a solution for upslope scour.

The first step, (free drift solution) was calculated according to McKenna et al (1999). Free drift occurred before icebergs made contact with the seabed and was based on a balance of the environmental driving forces (north-south and east-west directions).

Iceberg velocity and drift angle were varied to balance the forces through a nonlinear minimization scheme, and the resulting values were used to start the upslope scouring iteration routine.

The second step (upslope scouring) began after a free drift solution was found. Once the iceberg made contact with the sloping seabed (Figure 5.3), it was assumed to move a distance Δx in the horizontal plane. The difference between the iceberg draft and water depth at this point provided an initial estimate of the scour depth and therefore the scour forces acting on the iceberg keel. Using the McKenna et al (1999) solution for equilibrium heave and pitch, an estimate of scour depth was made by adjusting the heave and pitch of the iceberg, which in turn reduced the scour depth and associated scour forces. The final solution for iceberg heave and pitch was reached when the hydrostatic forces were in balance with the scour forces.

At this point, the change in the iceberg's potential energy and the work of the scour force was used to determine the remaining kinetic energy.

The change in kinetic energy was solved through a nonlinear minimization procedure to find the iceberg velocity and drift angle for the current increment. If the velocity was positive, the iceberg was again moved by the horizontal increment Δx and the next increment was computed in the same fashion. Otherwise, the iceberg was assumed to have depleted its total kinetic energy and stopped.

Model Assumptions

Assumptions made in constructing the upslope scour model included:

- It was assumed scour always occurred directly upslope. Making this assumption implies that the iceberg always encounters the same slope, regardless of the heading angle change.
- Iceberg length, width, draft and height data from the northeastern Grand Banks were used to determine iceberg dimensions as a function of iceberg length. The data were first transformed to a log-log scale and a linear regression line fit. To remove the bias inherent in this type of fit, a smearing estimate was computed and applied in the fit before the data were transformed back to the linear scale.

Environmental Driving Forces

Environmental driving forces acting on the iceberg include those from wind, wave, tidal current, inertial current and wind-driven Ekman currents. The environmental forces utilized in the model are representative of the northeastern Grand Banks and are based on the work of McKenna et al. (1999).

5.3 Effect of Environmental Driving Forces

5.3.1 Overview

This section presents the sensitivity of iceberg free drift velocity to environmental forces. Four different simulations were run to calculate free-drift velocity. The first assumed environmental forces were comprised of ocean currents alone. The second assumed ocean currents plus waves. The third assumed ocean currents plus wind. The fourth assumed ocean currents plus wind and waves. Sensitivity to wind and current drag coefficients is also presented.

5.3.2 Sensitivity Analysis Results

A summary of the sensitivity analysis of environmental forces on free drift velocity is given in Table 5.3 and is shown in Figures 5.4 to 5.7. These results indicate that while the basic shape of the distributions remains similar, current + wave forces produce higher mean and standard deviations of free drift velocity than current alone and current + wind forces. This suggests that free drift velocity is most sensitive to wave force and least sensitive to current force. While the difference in free drift velocity for icebergs driven by wind and wave forces is small, current force alone produces a significantly lower mean value.

Sensitivity of free drift velocity to wind and current drag coefficients was also examined briefly to determine their effect on the infrequent high free drift velocities reached in certain simulations. A ∀10% change in the value of drag coefficients was applied. Free drift velocity was reduced the most when the wind coefficient was reduced by 10% and the current drag increased by 10%. The effect of this free drift velocity reduction was found to be greater for higher speeds and less for lower speeds but, in all, the reduction was small in comparison to the original free drift velocity magnitude.

5.4 Scour Model Results

Monte Carlo runs of the iceberg scour model were made using representative input distributions of ice, soil, seabed slope and environmental parameters (Table 5.2). A large number of icebergs were simulated (77092). This number was reduced to 58848 by removing the icebergs that did not scour (14441), scours with width less than 5m (3530) and icebergs with a free drift velocity greater than 1.5 m/s (273). Removal of these data is justified since it has been assumed iceberg scour widths less than 5m would be caused by narrow keels that would likely fail before scouring any significant amount. As well, free drift iceberg velocities measured in the field seldom exceed 1.5 m/s.

Resulting distributions of seabed slope and scour depth for scouring icebergs are shown in Figures 5.8 & 5.9 and are summarised in Table 5.4. Distributions and associated exceedance plots of scouring icebergs are shown in Figures 5.10 to 5.12 for iceberg pitch, iceberg heave and scour length. These results are also summarised in Table 5.4. Scatter plots of seabed slope vs. scour length, seabed slope vs. scour depth, free drift velocity vs. scour depth, scour depth vs. scour length and free drift velocity vs. scour length for scouring icebergs are shown in Figures 5.13 to 5.17.

The following observations were made of scouring icebergs:

- In general, higher free drift velocities produced marginally deeper scours
- Scour length generally increased with free drift velocity
- Several scour lengths were very long (close to 100 km) this was the result of nearly flat seabed slopes
- Scours in higher seabed slopes were shorter in length, marginally deeper and occurred less frequently than those in lower seabed slopes
- In general, values of iceberg heave and pitch were quite small

Mean values of scour length and depth from model results compare well with those measured on the Northeastern Grand Banks for water depths less than 110m. A summary of measured scour depths and lengths is given in Table 5.5 which can be compared with model results in Table 5.4. Distributions of measured scour length and scour depth are shown in Figures 5.18 and 5.19.

The mean and standard deviations of measured and simulated scour depth are quite close, while maximum value for measured scours is roughly twice that from the simulations. This can be attributed to the fact that very deep scours on the Grand Banks are generally relict. These scours have not been distinguished from more recent ones in the measured database. Mean values of scour length are also comparable within the same order of magnitude, as are the associated standard deviations. The maximum simulated scour length, however, is considerably longer than the measured maximum value. This may be attributed to model assumptions that do not include iceberg deterioration over time. Based on the comparison of model results with measured data, the model appears to be appropriate for describing iceberg scour on the Northeastern Grand Banks.

5.5 Pipeline Response Analysis

The response of two buried marine pipeline systems, 914mm and 324mm diameter pipe, subject to an ice scour event is investigated by the finite element method. The numerical model considers three components: ice scour/soil response, soil/pipeline interaction and finite element formulation. A brief summary of the numerical modeling procedure is presented and further details are discussed in Kenny et al. (2000).

5.5.1 Finite Element Modeling Procedure

The empirical relationships defining subscour displacements are presented in Nixon et al. (1996) and Woodworth-Lynas et al. (1996). The response functions were derived from analysis of centrifuge modeling tests conducted under the Pressure Ridge Ice Scour Experiment (PRISE). The longitudinal distribution of subscour soil deformation is characterised by a bounded, peak central displacement with a cosine tail distribution as shown in Figure 5.20. The vertical profile (Figure 5.21) exhibits an exponential decay with increasing depth.

The soil/pipeline interaction model is based on ASCE (1984) guidelines for the seismic design of oil and gas pipeline systems. The idealised structural model is illustrated in Figure 5.22. The continuum soil response is approximated by a series of discrete springs. The stiffness terms, k_a and k_h, represent the axial and horizontal displacement components, respectively. The ultimate or yield condition is defined by the ASCE (1984) guidelines.

The finite element analyses were conducted using ABAQUS/Standard version 5.8. The soil/pipeline interaction model (Figure 5.22) was discretised by two-dimensional beam elements (PIPE22) and one-dimensional spring elements (SPRINGA). The finite element model accounted for longitudinal symmetry and the geometric boundary conditions are illustrated in Figure 5.23. The pipeline response is based on Timoshenko beam theory assuming linear elastic, transverse shear behaviour and the constitutive relationship was defined by the Ramberg-Osgood formulation.

The soil response is defined by nonlinear spring elements for the axial and horizontal soil deformation. An idealised bilinear, elastic, perfectly plastic load-deformation relationship was considered. For a given pipeline burial depth, the subscour deformation was determined for a particular scour geometry and soil profile at the neutral axis (i.e. springline) of the buried pipeline. The resultant displacement field was imposed on the horizontal spring elements as an initial displacement boundary condition.

5.5.2 Pipeline Response Analysis

The response analyses considered two pipeline systems, 914mm and 324mm diameter pipe, with equivalent diameter to wall thickness ratio (D/t = 36). Details of the model parameters are summarised in Table 5.6. The internal working pressure was 10MPa was the pipeline grade selected was X65 (CSA, 1998). The pipeline mechanical properties were based on the investigations of Walker and Williams (1995).

A single ice scour event, with a width of 25m and depth of 1.5m, was defined. A granular soil with a friction angle of 40°, representative of conditions on the northeast Grand Banks, was selected for the analysis.

A comparative assessment of the pipeline response was made by considering the same burial depth (i.e. the vertical distance from the seabed to the base of the trench) and an equivalent springline burial depth (i.e. the vertical distance from the seabed to the neutral axis of the pipeline) for the two pipelines. The variation in pipeline cover depths (i.e. vertical distance from the seabed surface to pipe crown) is listed in Table 5.6.

The imposed soil displacement field and computed pipeline response for the 914mm diameter pipeline, with a cover depth of 0.5m, are illustrated in Figure 5.23. The main feature to recognize is the relatively moderated pipeline response, due to the effects of pipe stiffness and curvature response, in comparison with the stepwise character of the imposed subscour displacement.

The peak tensile strain response for the two pipelines as a function of cover depth is illustrated in Figure 5.24(a). The analysis demonstrates that ice/scour/soil pipeline interaction is a nonlinear process. The imposed geotechnical loads on the pipeline are primarily a function of the pipeline diameter, pipe springline and ice scour characteristics (i.e. width, depth). The pipeline response is dependent on the imposed subscour displacement field, geotechnical properties (i.e. strength, load-displacement behaviour) and relative pipeline-soil stiffness. For increasing cover depths, the subscour displacement magnitude decreases and corresponds to a reduction in the peak tensile strain response. In addition, the numerical analysis also indicates the potential for employing small diameter, flexible pipe systems which have negligible bending stiffness but can sustain large axial strains.

Loss of product containment and pipeline integrity due to tensile failure is generally associated with the growth of a small planar defect, in either the pipe body or more likely in a circumferential girth weld. Tensile strain limits are normally established based upon consideration for the potential growth of the largest weld defect that satisfies the weld acceptance criteria. Engineering critical assessment (ECA) methods can be employed to evaluate pipeline integrity based on the adopted welding procedure and establish the tensile strain limit.

In general, satisfying tensile strain limits greater than 2% is considered extremely difficult. Although recognized that field experience has shown pipelines can withstand significant strains, as high as 2.5%, during offshore pipe laying operations, CSA (1999) recommends a tensile strain limit of 0.75% less residual strains in lieu of more detailed analysis.

The peak compressive strain response for the two pipeline systems as a function of cover depth is illustrated in Figure 5.24(b). For combined loading due to internal pressure, external pressure and external displacements, the pipeline should also resist local sectional collapse and global buckling instability. The critical strain (i.e. curvature limit) is a function of pipeline geometry (i.e. diameter, wall thickness, initial pipe out-of-roundness), material properties (i.e. stress-strain response) and applied loads (i.e. axial and transverse geotechnical loads, internal and external pressure). Pipeline stability limits are typically based on empirical and analytical studies. For the analysis conducted, the two pipeline systems satisfy the CSA (1999) requirements as summarized in Table 5.7. The upper bound allowable compressive strain limits considered the 10MPa internal pressure and assumed a water depth of 90m. The lower bound estimate only considered the effects due to pure bending and the collapse reduction factor.

Table 5.1 Summary of Driving Force Model Characteristics.

Model / Reference	Method	Driving Force	Ice Feature
Chari Model Chari (1975)	Energy	Wind current	iceberg idealised rectangular prism added mass constant draught surge motion
FENCO Model FENCO (1975)	Energy	wind current	iceberg idealised rectangular prism added mass constant draught surge motion
	Force	wind wave current	iceberg idealised rectangular prism buoyant righting moment surge and heave motions
COGLA Model Been et al. (1990a)	Energy	wind current	pressure ridge idealised rectangular prism flexural stiffness of ice cover surge, heave and pitch motions
AARI Model Stepanov et al. (1998)	Energy	current tidal current storm surge	hummock field idealised trapezoidal prism drift velocity
C-CORE Model McKenna et al. (1999)	Force	wind wave inertial current tidal current Ekman current	iceberg realistic geometry hydrostatics hydrodynamics added mass surge, heave and pitch motions

Table 5.2 Input Parameter Distributions for Iceberg Scour Simulations.

Parameter	Details	Source
Scour Width (for water depths <110m)	Mean = 24m St. Dev. = 17m	The report Chapter 3
<u>Soil Parameters</u> Friction Angle Cohesion Unit Weight Surcharge	 Mean = 40°, St. Dev. = 2° 0 10 kN/m^3 10 kN per m scour depth	 Assumed Assumed Assumed Assumed
<u>Iceberg Parameters</u> Rake Angle Keel Offset Length Width Draft	 15° Mean = St. Dev. = 7.5m Mean = 155m, St. Dev. = 26m Mean = 124m, St. Dev. = 24m Mean = 97m, St. Dev. = 2m	 Assumed Assumed From regression analysis From regression analysis From regression analysis
Seabed Slope	Mean = 1.83×10^{-3} St. Dev. = 1.54×10^{-3}	Digital bathymetry for Grand Banks region bounded by 48°W, 46°N to 49°W, 48°N (see Figure 5.2)
<u>Environmental Forces</u> Tidal Current Speed Inertial Current Speed Wind Speed Ekman Spiral Current Speed Waves	 Mean = -1.11×10^{-4} m/s (E-W) Mean = 1.2×10^{-5} m/s (N-S) Mean = -9.1×10^{-3} m/s (E-W) Mean = 9.4×10^{-3} (N-S) Mean = 2.8 m/s (E-W) Mean = 3.1 m/s (N-S) 1.49×10^{-2}*(Mean Resultant Wind Speed) Mean = 1.5m, St. Dev. = 0.5m	All values for environmental forces obtained from McKenna et al. (1999)

Table 5.3 Free Drift Velocity Sensitivity to Environmental Forces.

Environmental Force	Mean, V_f (m/s)	Std. Dev, V_f (m/s)	Max, V_f (m/s)	Sample Size
Current	6.7×10^{-2}	4.3×10^{-2}	0.38	20000
Current + Wind	0.21	0.16	1.49	19981
Current + Wave	0.27	0.17	1.48	19969
Current + Wind + Wave	0.36	0.21	1.50	19925

Table 5.4 Summary of Simulation Results for Scouring Icebergs (58848 Icebergs).

Parameter	Mean	Std. Dev.	Max Value
Seabed Slope	2.0×10^{-3}	1.6×10^{-3}	2.15×10^{-2}
Scour Depth (m)	0.44	0.25	2.6
Free Drift Velocity (m/s)	0.34	0.20	1.49
Scour Length (m)	390	917	9.75×10^{4}
Iceberg Pitch (°)	0.24	0.47	16.7
Iceberg Heave (m)	9.8×10^{-3}	1.24×10^{-2}	1.128

Table 5.5 Summary of Measured Scour Data from the Northeastern Grand Banks.

Parameter	Mean	Std. Dev.	Max Value
Scour Depth (m)	0.50	0.40	5.3
Scour Length (m)	600	774	6.49×10^{3}

Table 5.6 Summary of Finite Element Model Parameters for Pipeline Response Analysis.

System		Parameter	Magnitude
Pipeline API 5L X65	Common Parameters	Modelled Length	1000m
		Pressure	10MPa
		Elastic Modulus	205GPa
		Poisson's Ratio	0.3
		Yield Stress	448MPa
		Plastic Yield Offset	1.29
		Hardening Exponent	26.58
	914mm Diameter Pipeline	Outside Diameter	914mm
		Wall Thickness	25.4mm
		Cover Depth	0.5m, 1.0m, 1.5m
	324mm Diameter Pipeline	Outside Diameter	323.9mm
		Wall Thickness	9.525mm
		Cover Depth – Trench Basis	1.1m, 1.6m, 2.1m
		Cover Depth – Springline Basis	1.3m, 1.8m
Granular Soil		Unit Weight	$18kN/m^3$
		Friction Angle	40°
Ice Gouge		Width	25m
		Depth	1.5m

Table 5.7 Calculated Compressive Strain Response and CSA (1999) Pipeline Requirements.

Pipeline System	Peak Compressive Strain	Allowable Compressive Strain (CSA, 1999)	
	FE Model	Internal Pressure (p = 10MPa)	No Internal Pressure
914mm Diameter Pipeline	-0.58%	-1.33%	-1.14%
324mm Diameter Pipeline	-0.27%	-1.39%	-1.22%

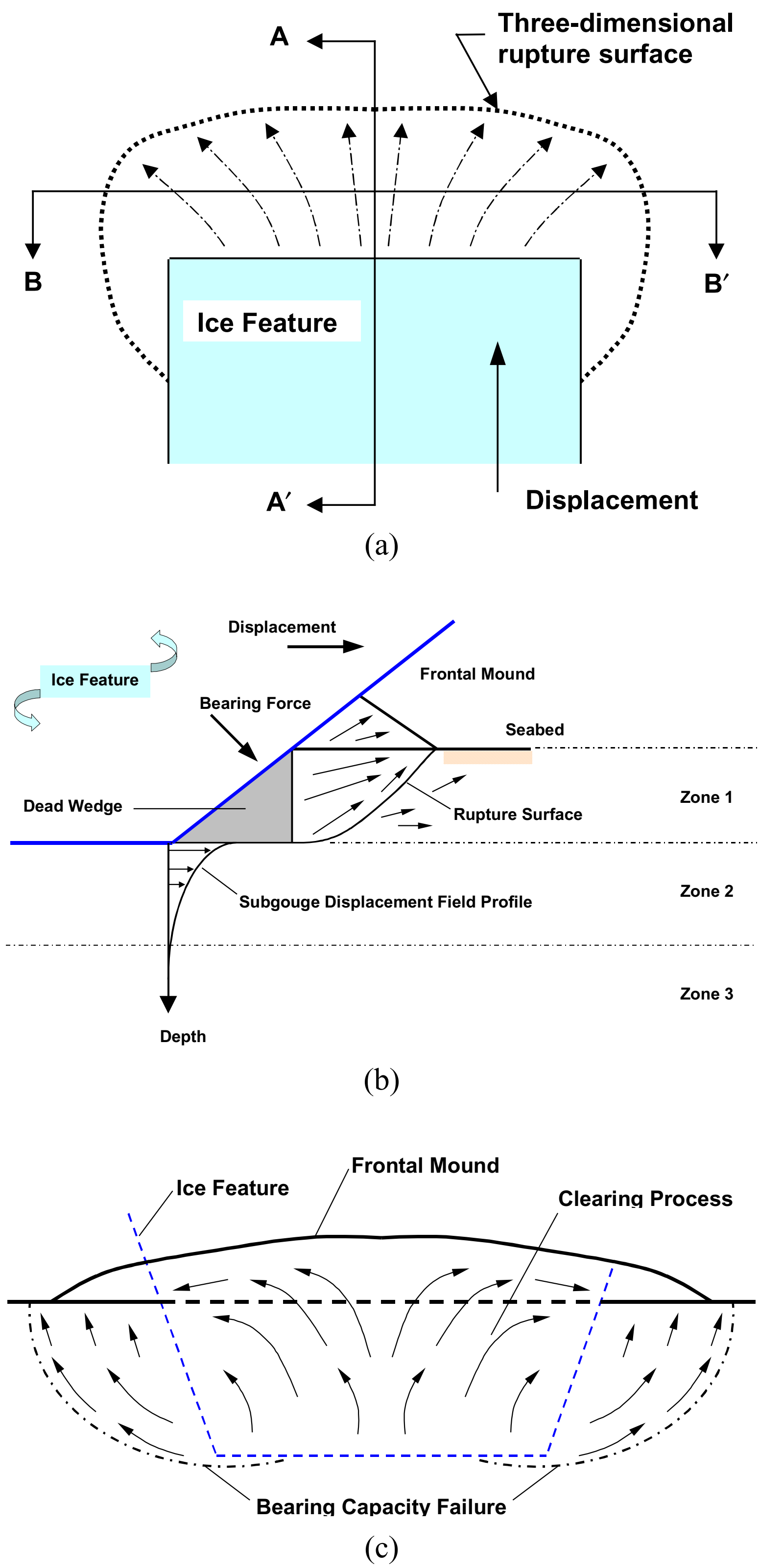


Figure 5.1 Ice gouge mechanisms (a) plan view, (b) section A-A′, (b) section B-B′.

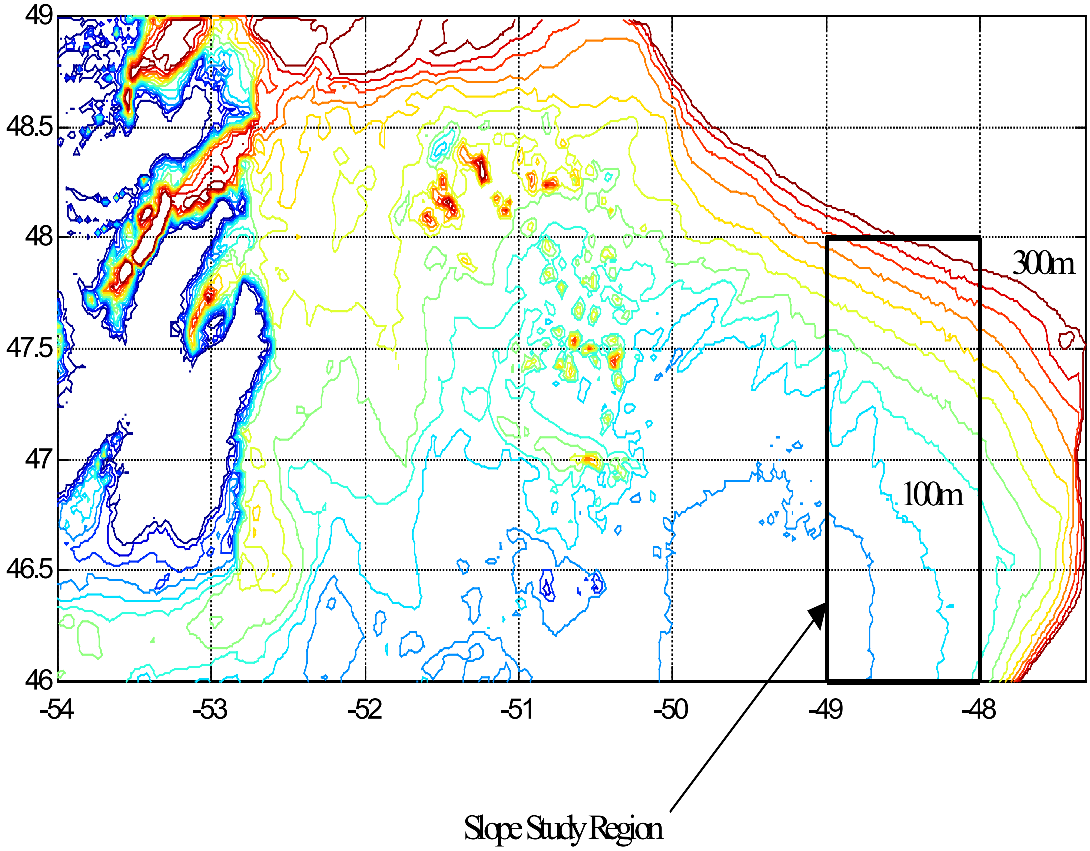


Figure 5.2 Northeastern Grand Banks slope study region.

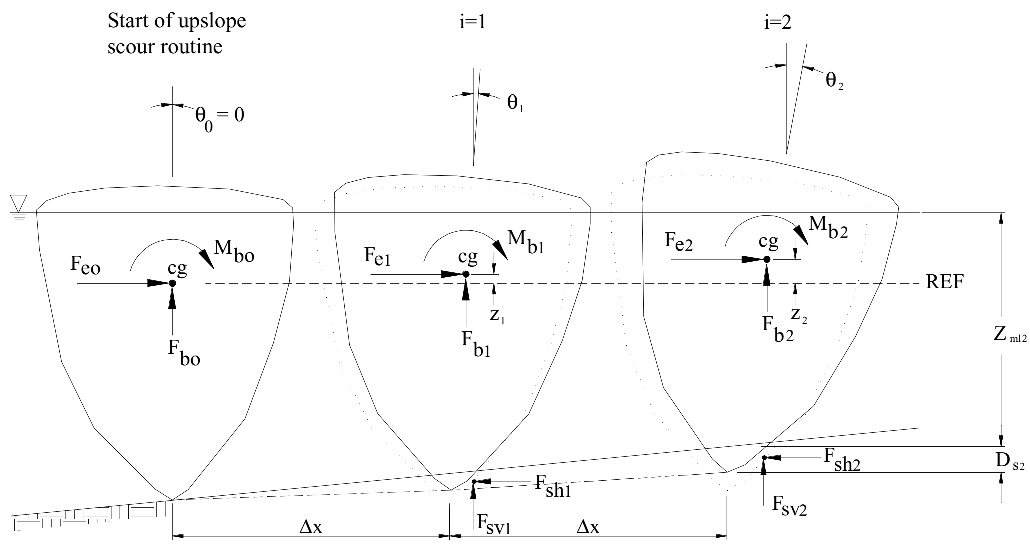


Figure 5.3 Upslope scour model schematic

Where:

θ_i = iceberg pitch at increment i.

i = increment number in upslope scour routine.

Fe_i = environmental force at increment i.

Fb_i = buoyancy force at increment i.

Mb_i = righting moment at increment i.

cg = iceberg centre of gravity.

Δx = increment step size.

z_i = iceberg heave at increment i.

Fsh_i = horizontal scour force at increment i.

Fsv_i = vertical scour force at increment i.

Ds_i = scour depth at increment i.

Zml_i = water depth at increment i.

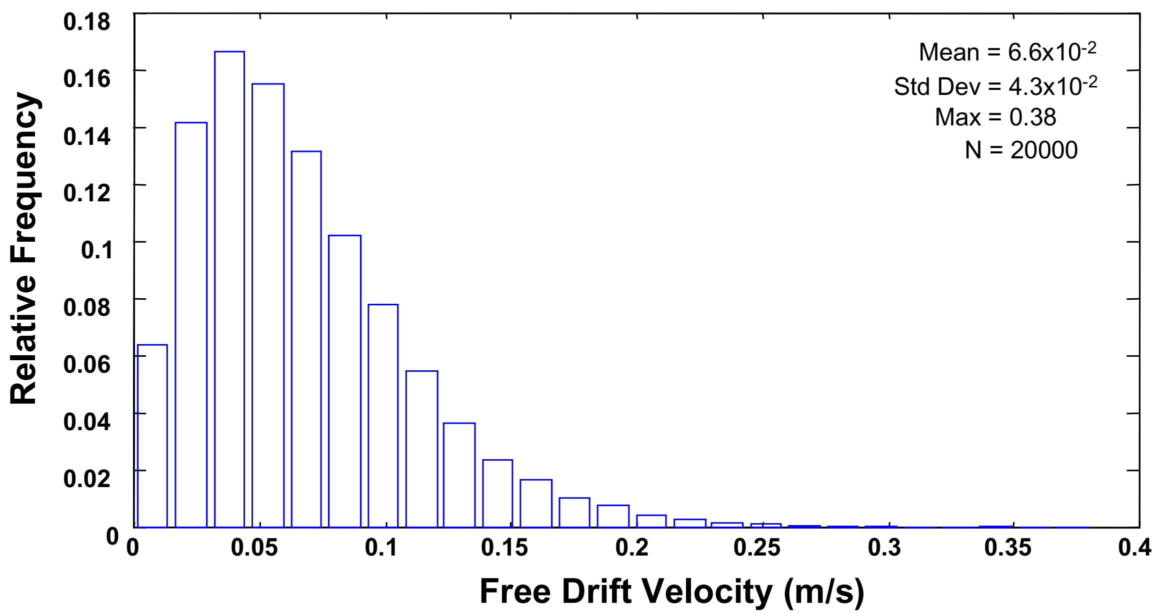


Figure 5.4 Distribution of free drift velocities for icebergs acted on by current forces alone.

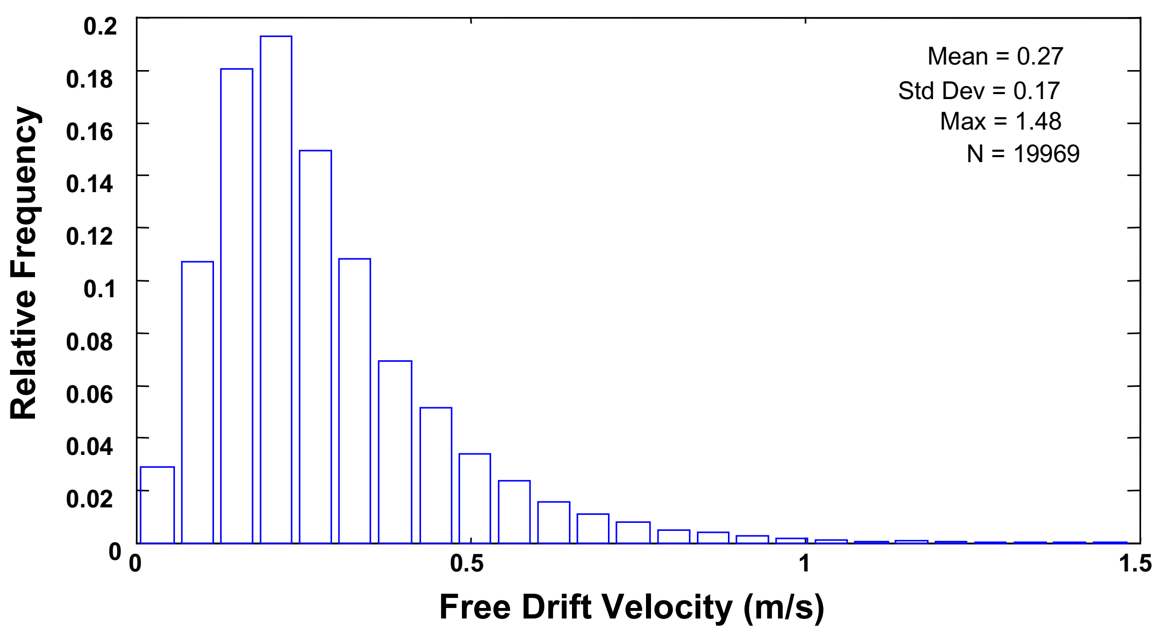


Figure 5.5 Distribution of free drift velocities for icebergs acted on by current and wave forces.

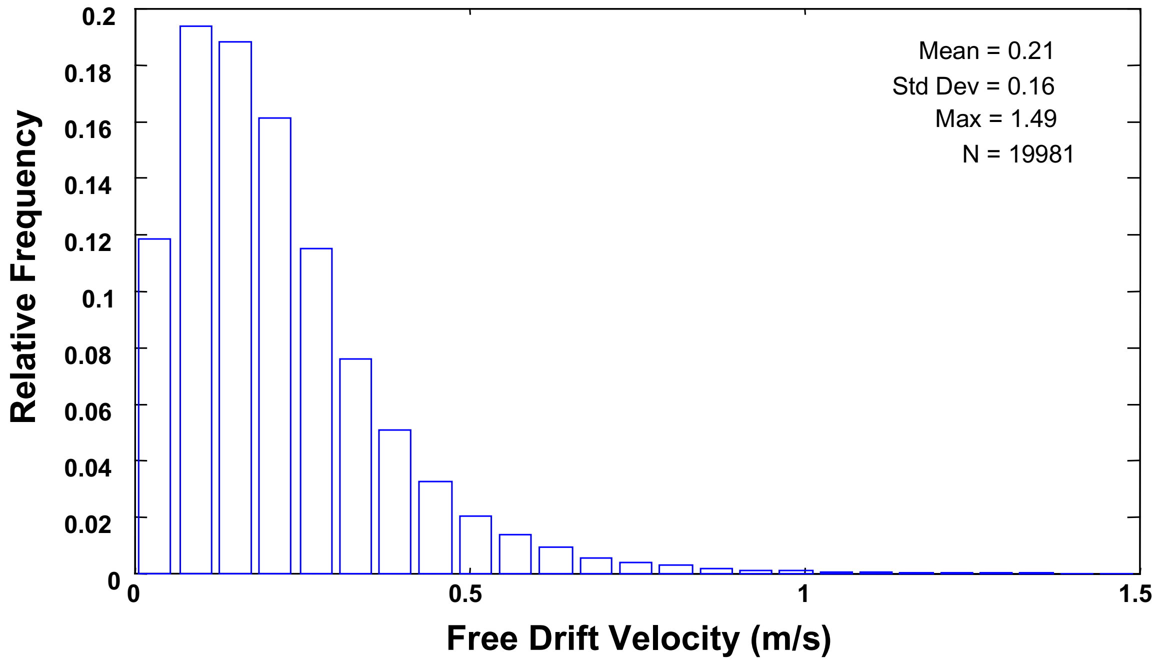


Figure 5.6 Distribution of free drift velocities for icebergs acted on by current and wind forces.

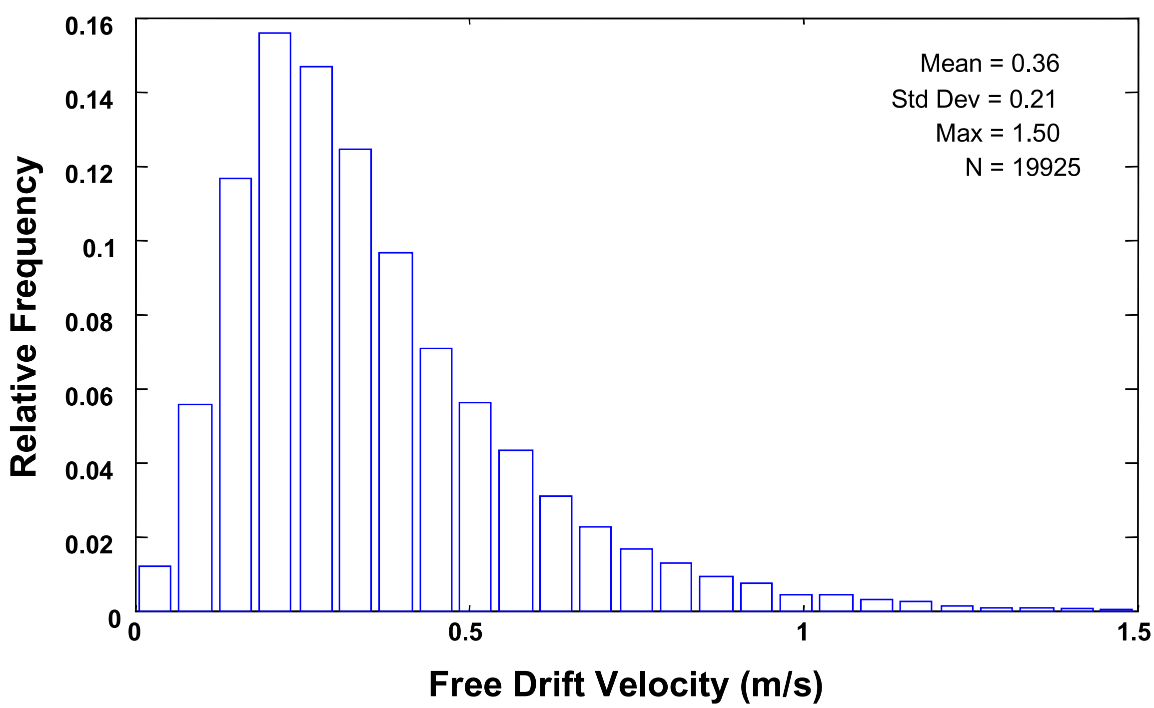


Figure 5.7 Distribution of free drift velocities for icebergs acted on by all environmental forces.

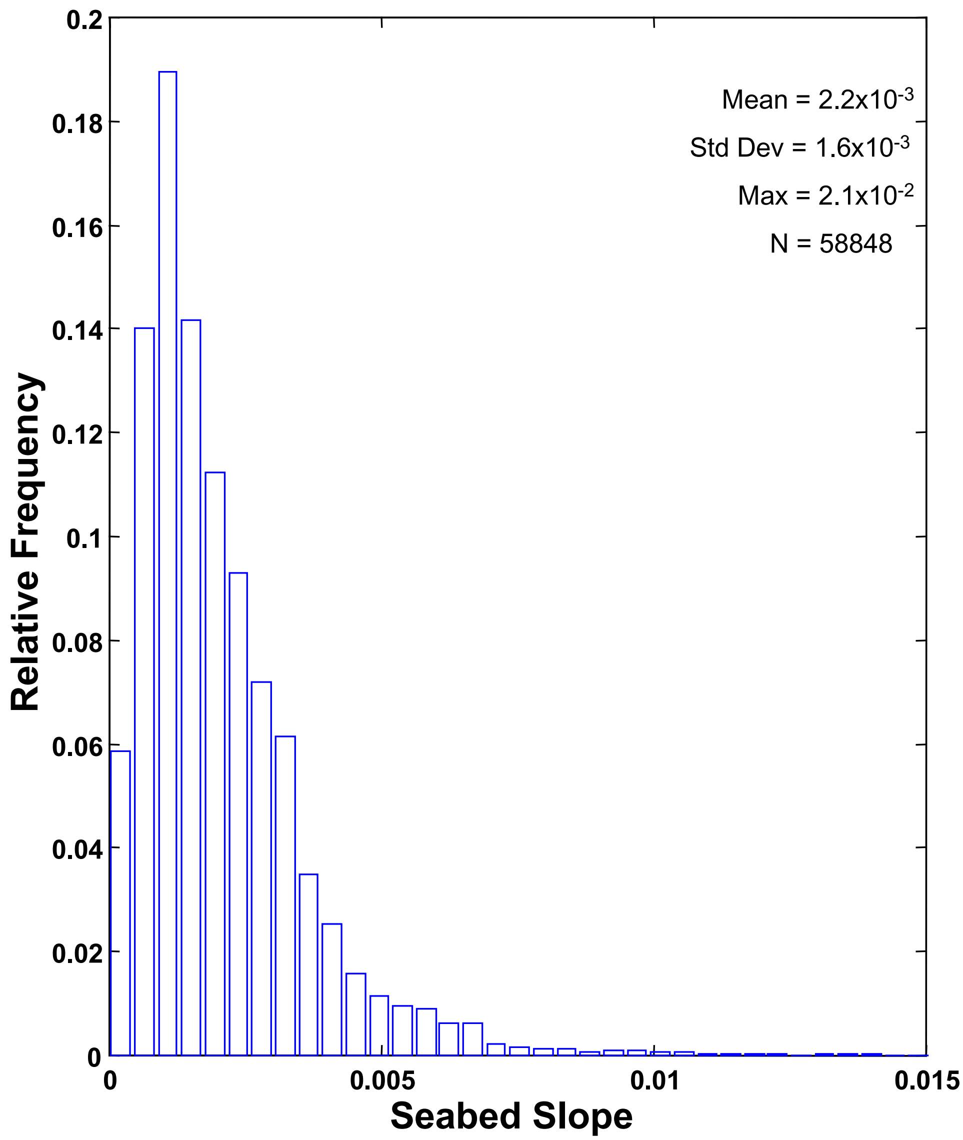


Figure 5.8 Distribution of seabed slopes for scouring icebergs.

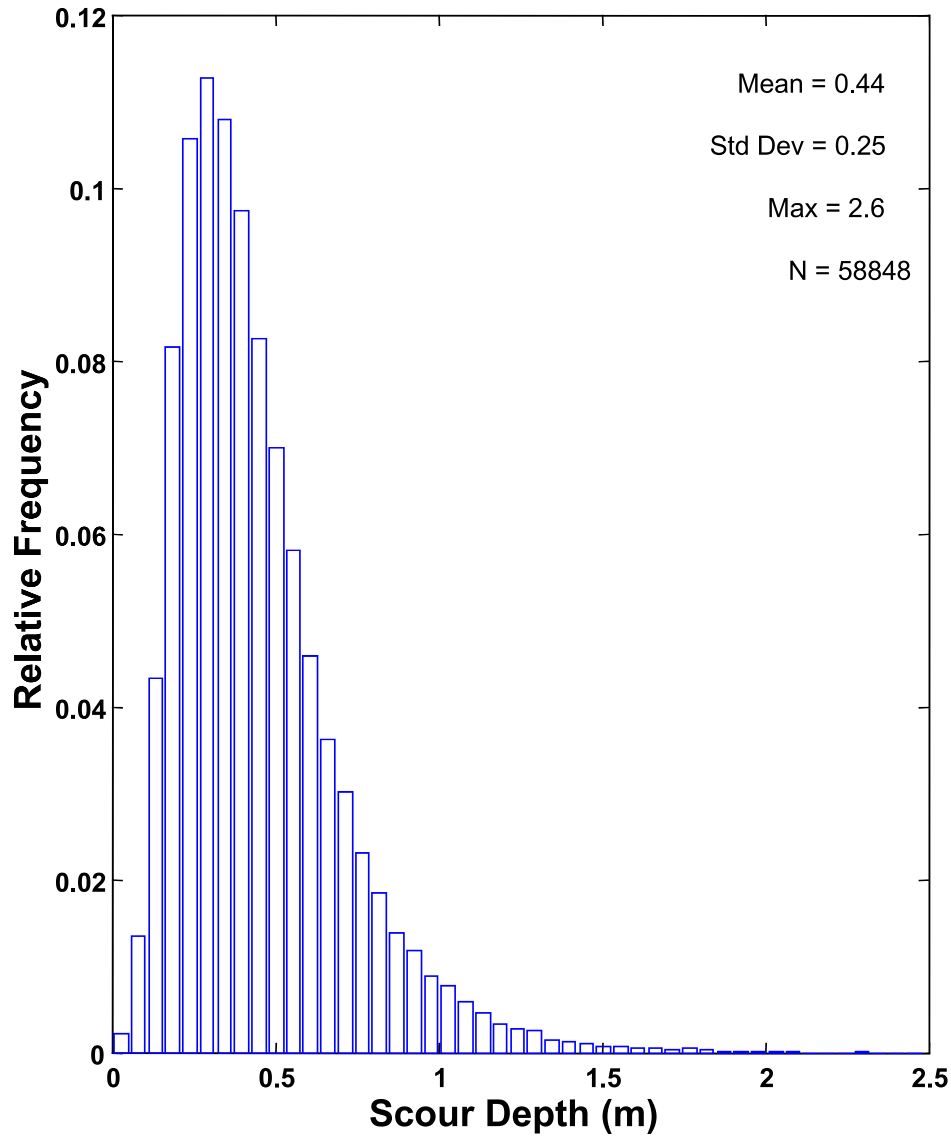


Figure 5.9 Distribution of scour depths for scouring icebergs.

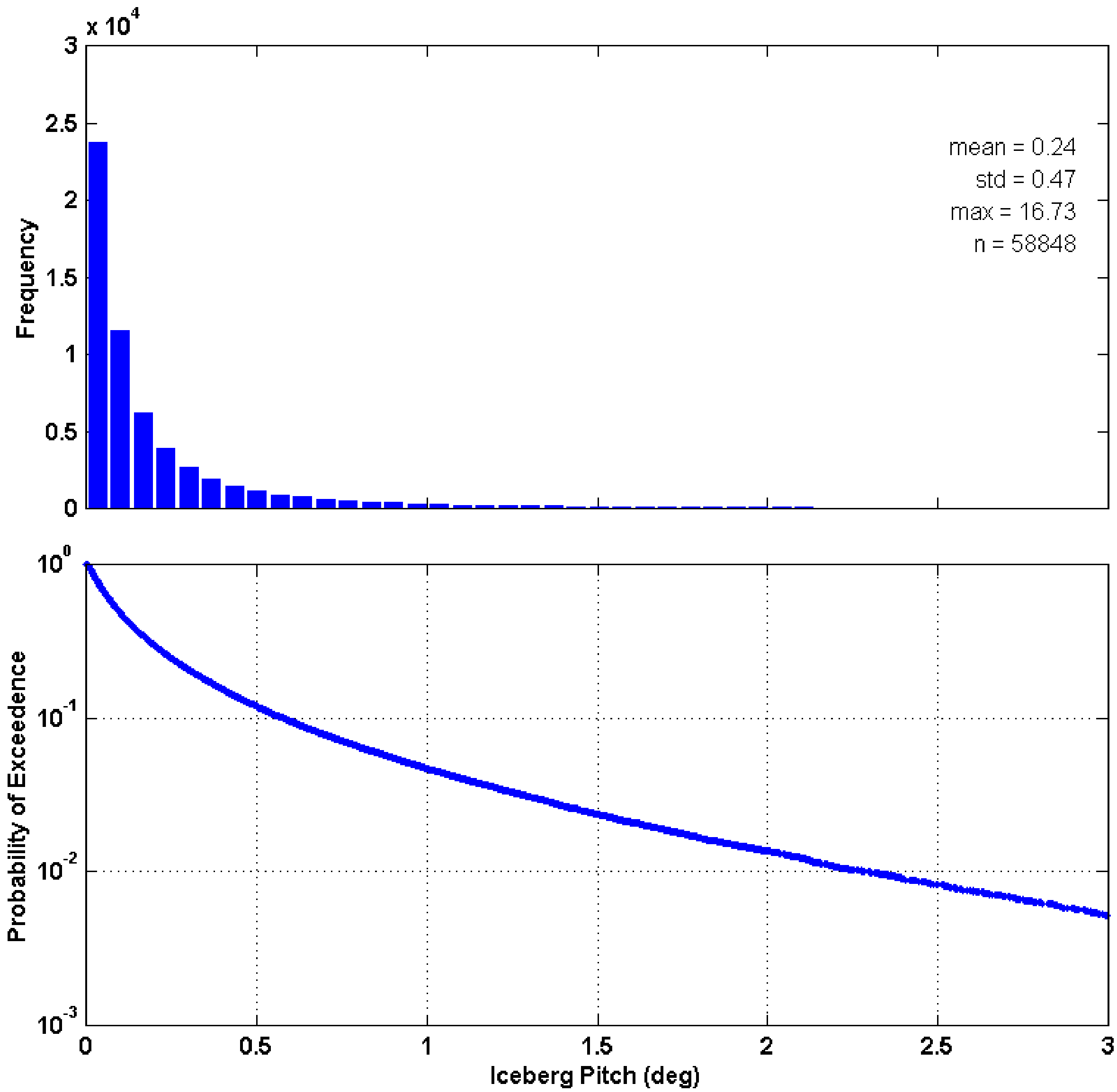


Figure 5.10 Distribution of iceberg pitch and associated probability of exceedence for scouring icebergs from the ice scour model.

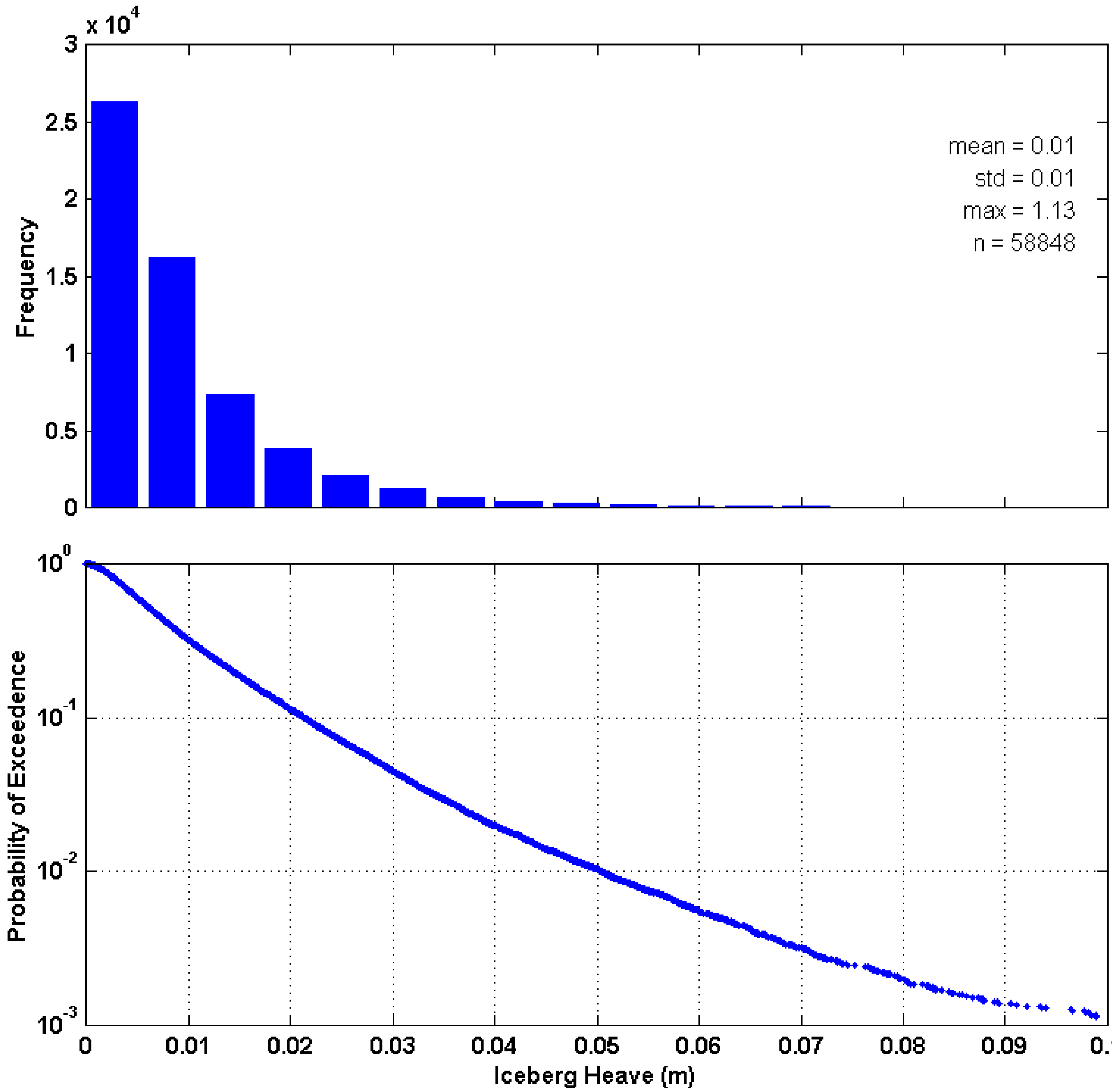


Figure 5.11 Distribution of iceberg heave and associated probability of exceedence for scouring icebergs from the ice scour model.

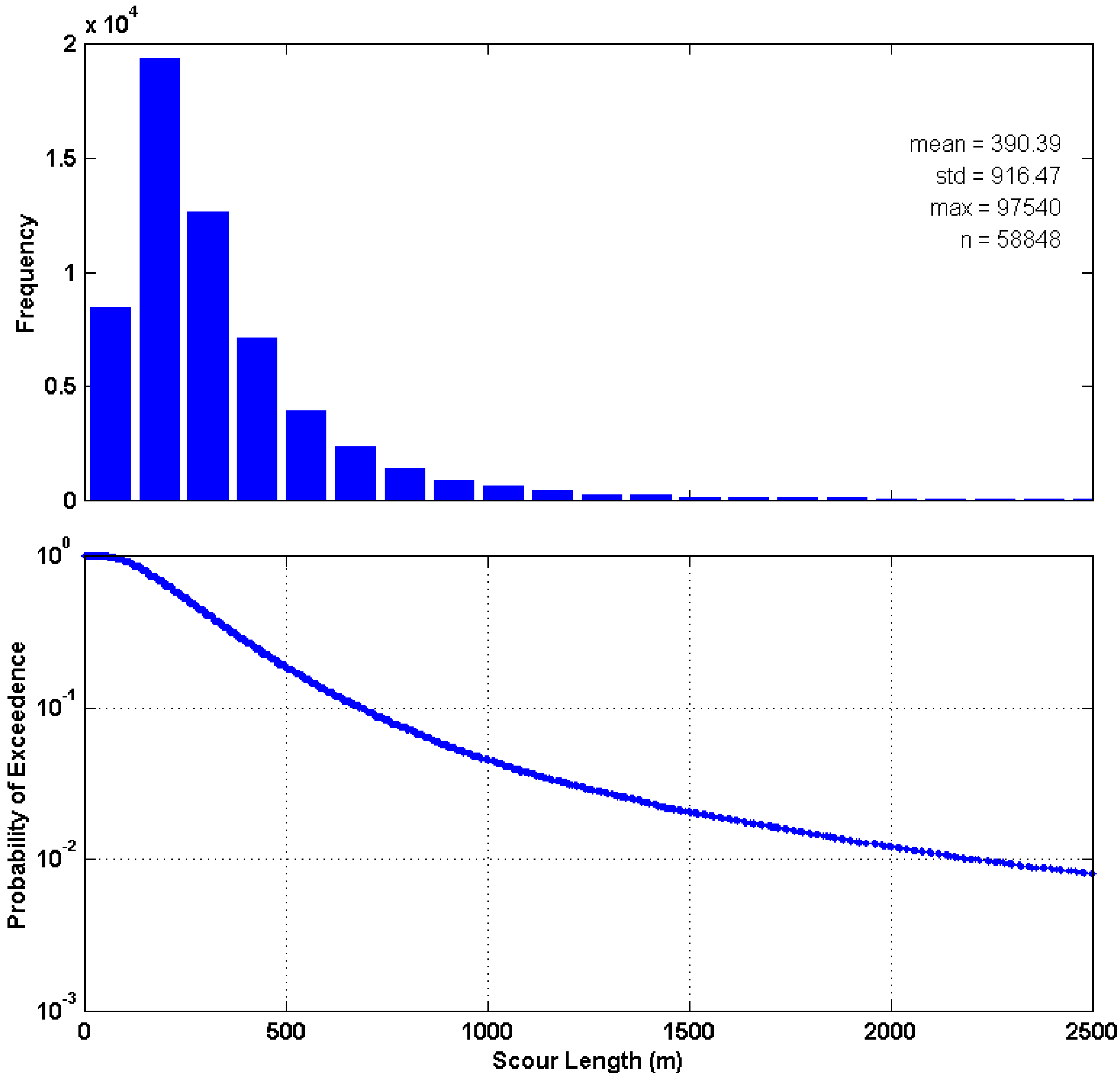


Figure 5.12 Distribution of scour length and associated probability of exceedence for scouring icebergs from the ice scour model.

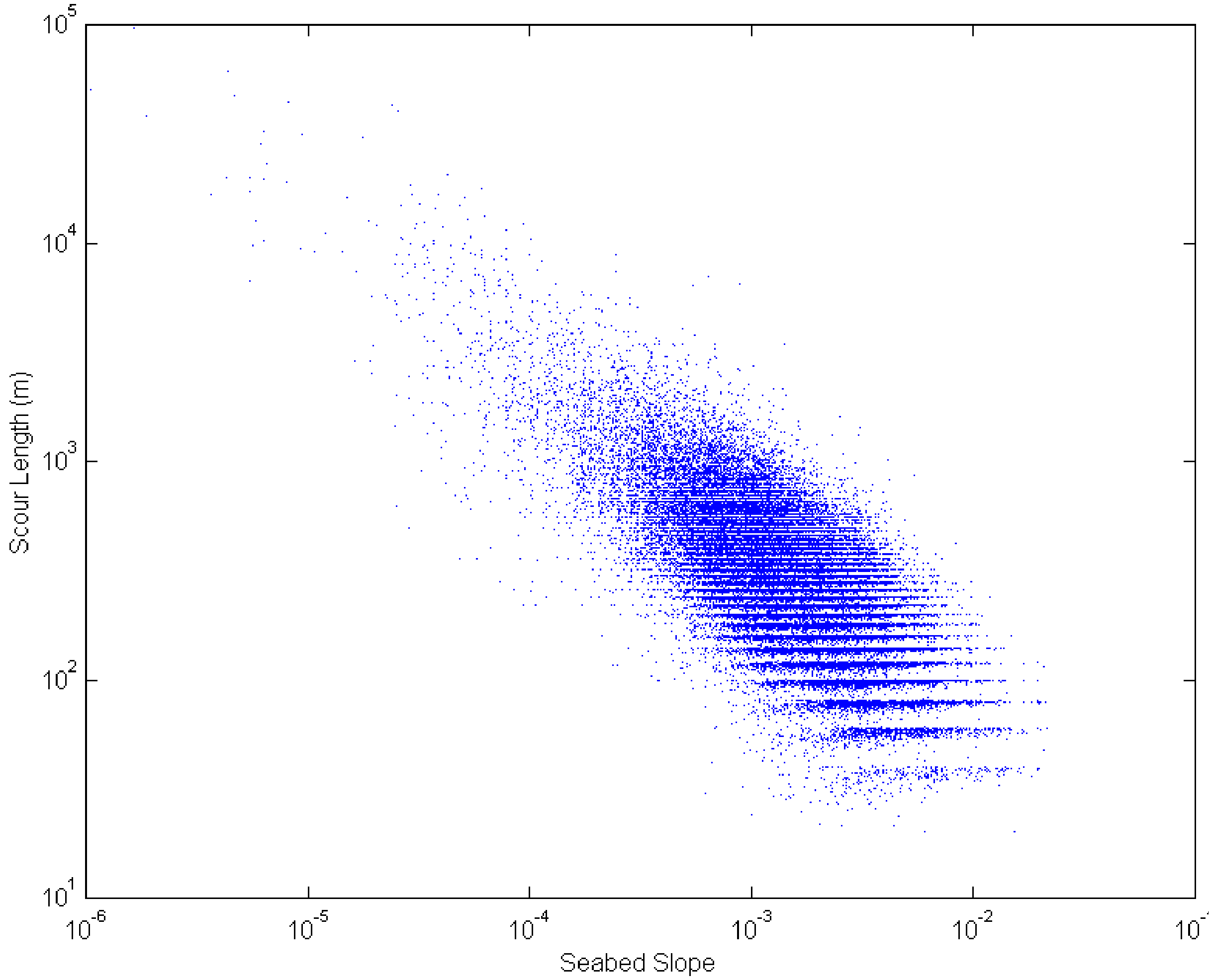


Figure 5.13 Scatter plot of seabed slope vs. scour length for scouring icebergs.

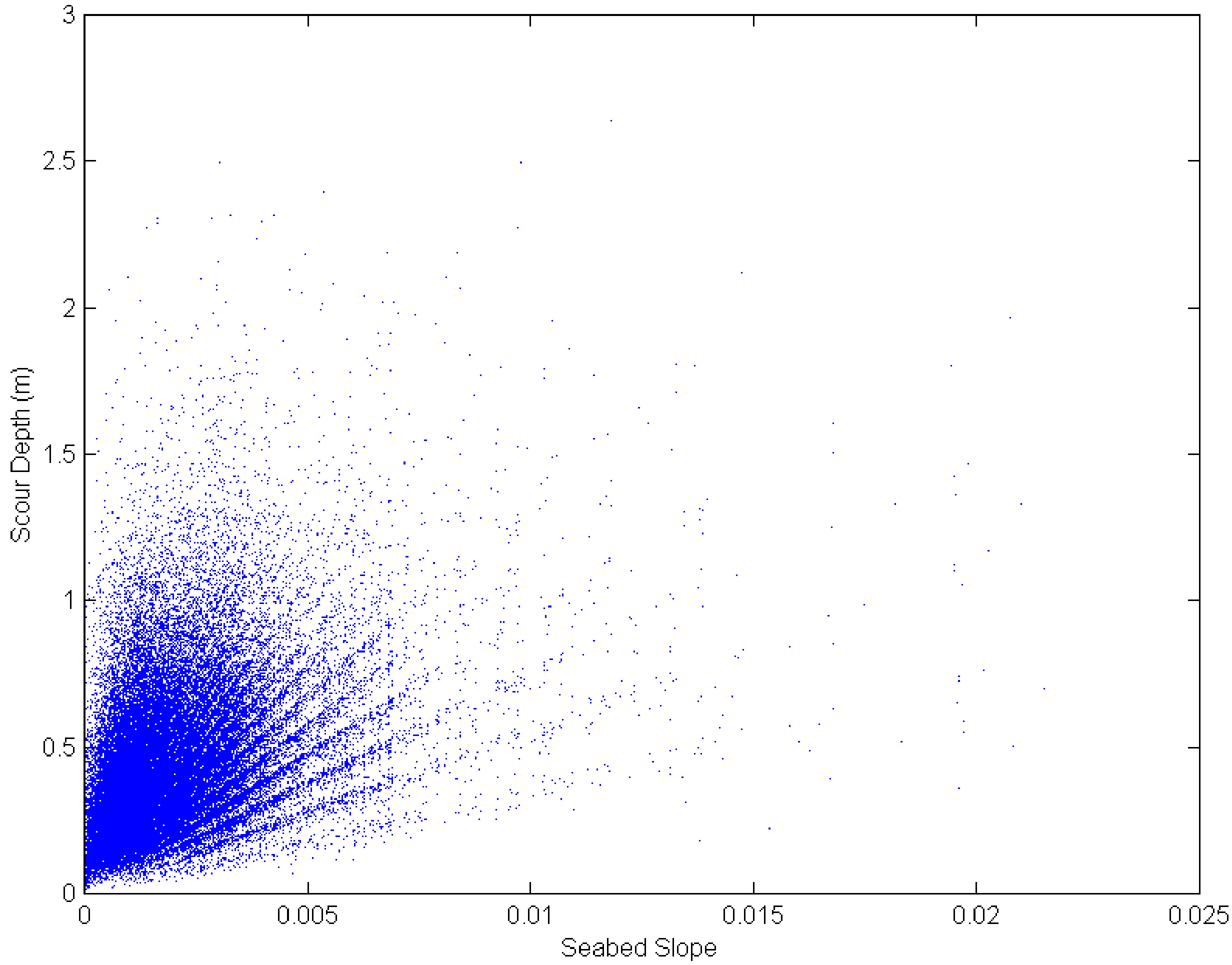


Figure 5.14 Scatter plot of seabed slope vs. scour depth for scouring icebergs.

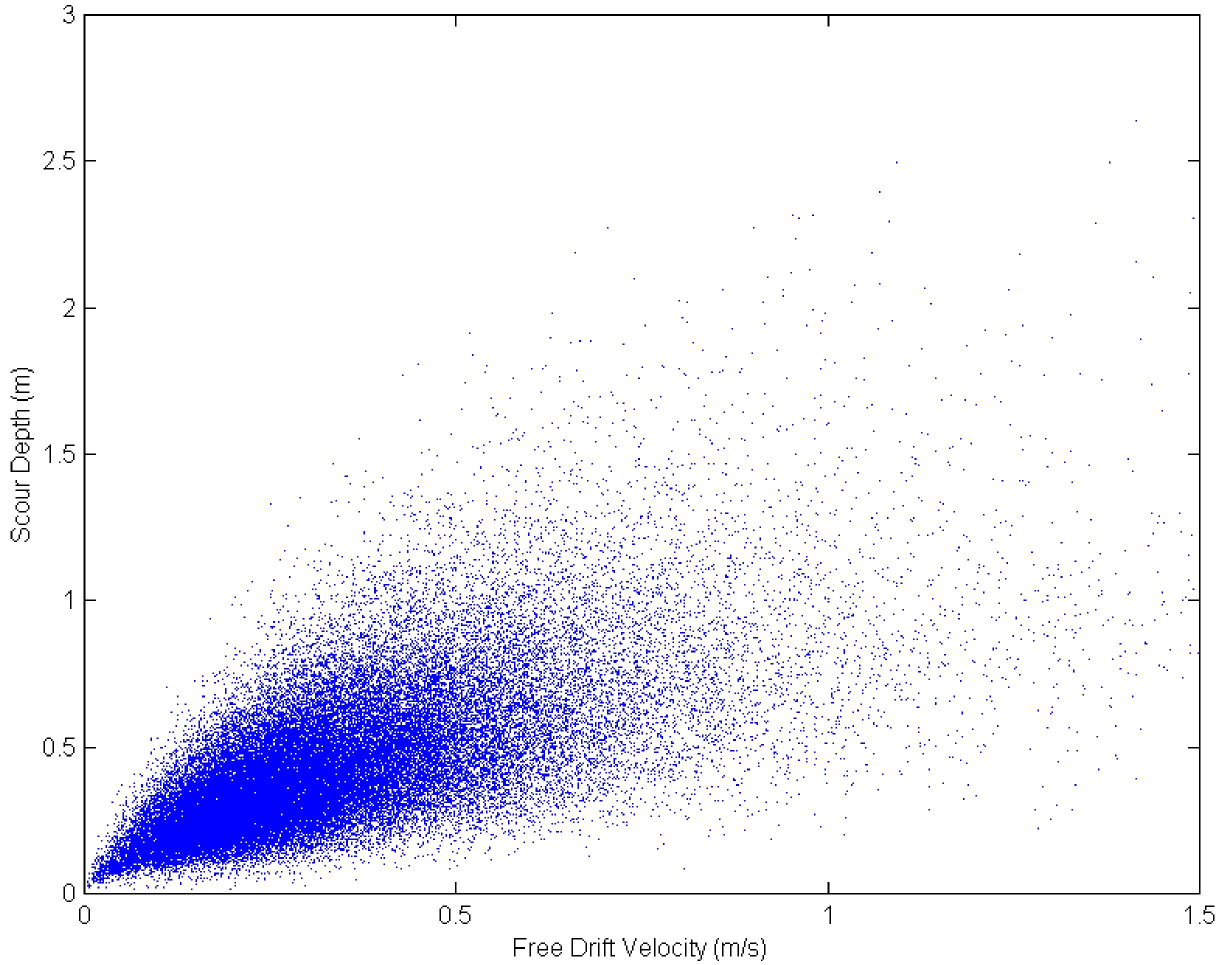


Figure 5.15 Scatter plot of free drift velocity vs. scour depth for scouring icebergs.

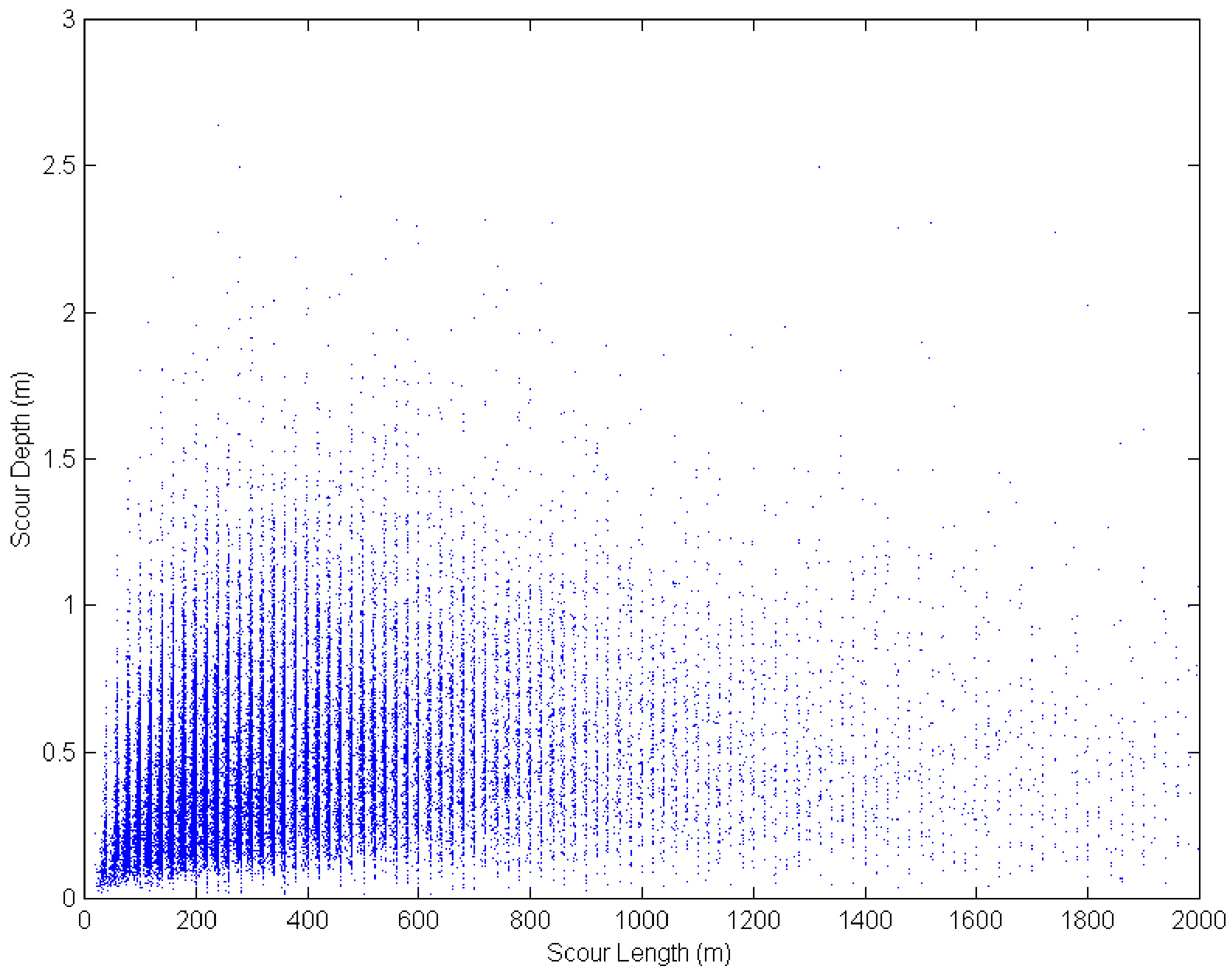


Figure 5.16 Scatter plot of scour length vs. scour depth for scouring icebergs.

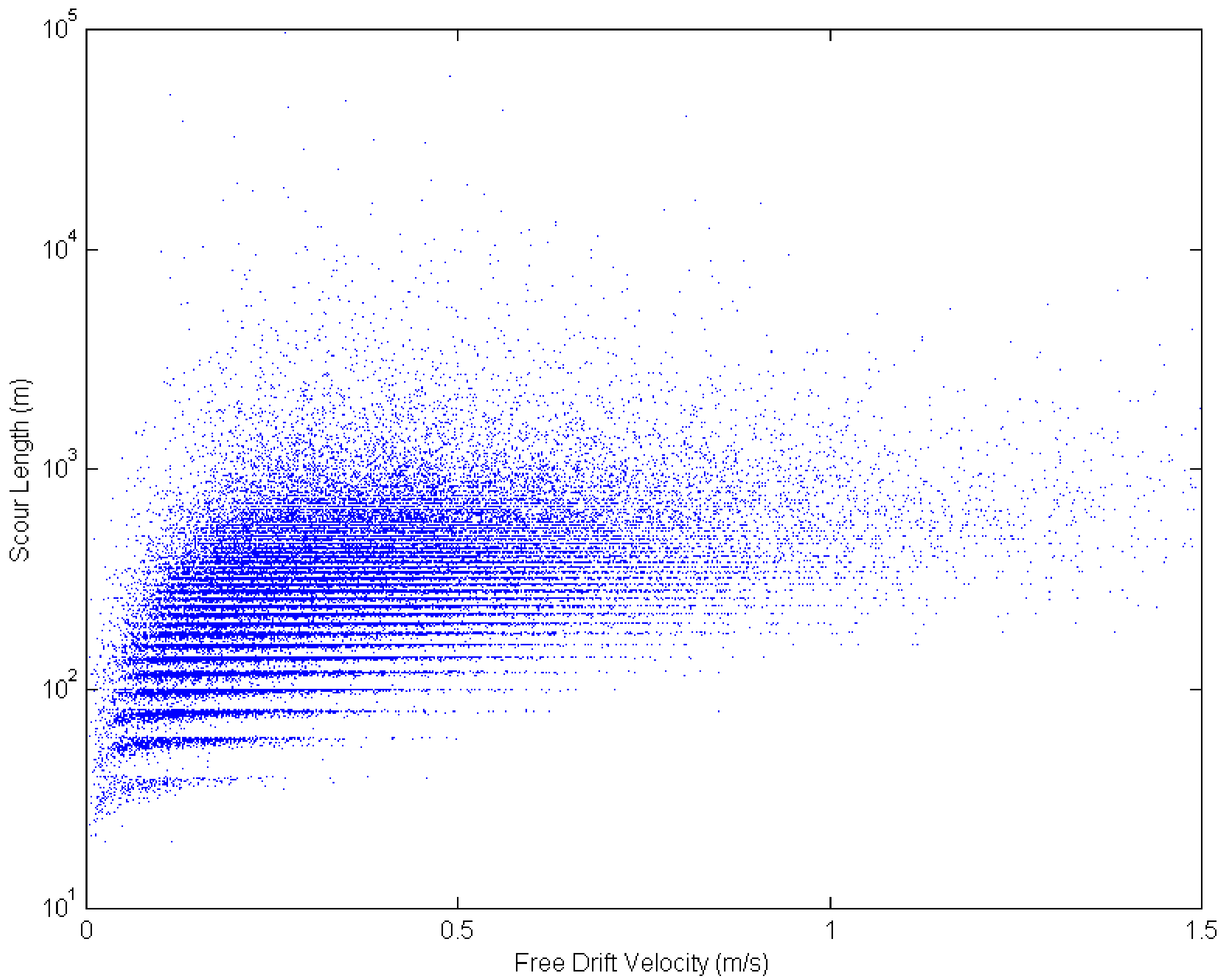


Figure 5.17 Scatter plot of free drift velocity vs. scour length for scouring icebergs.

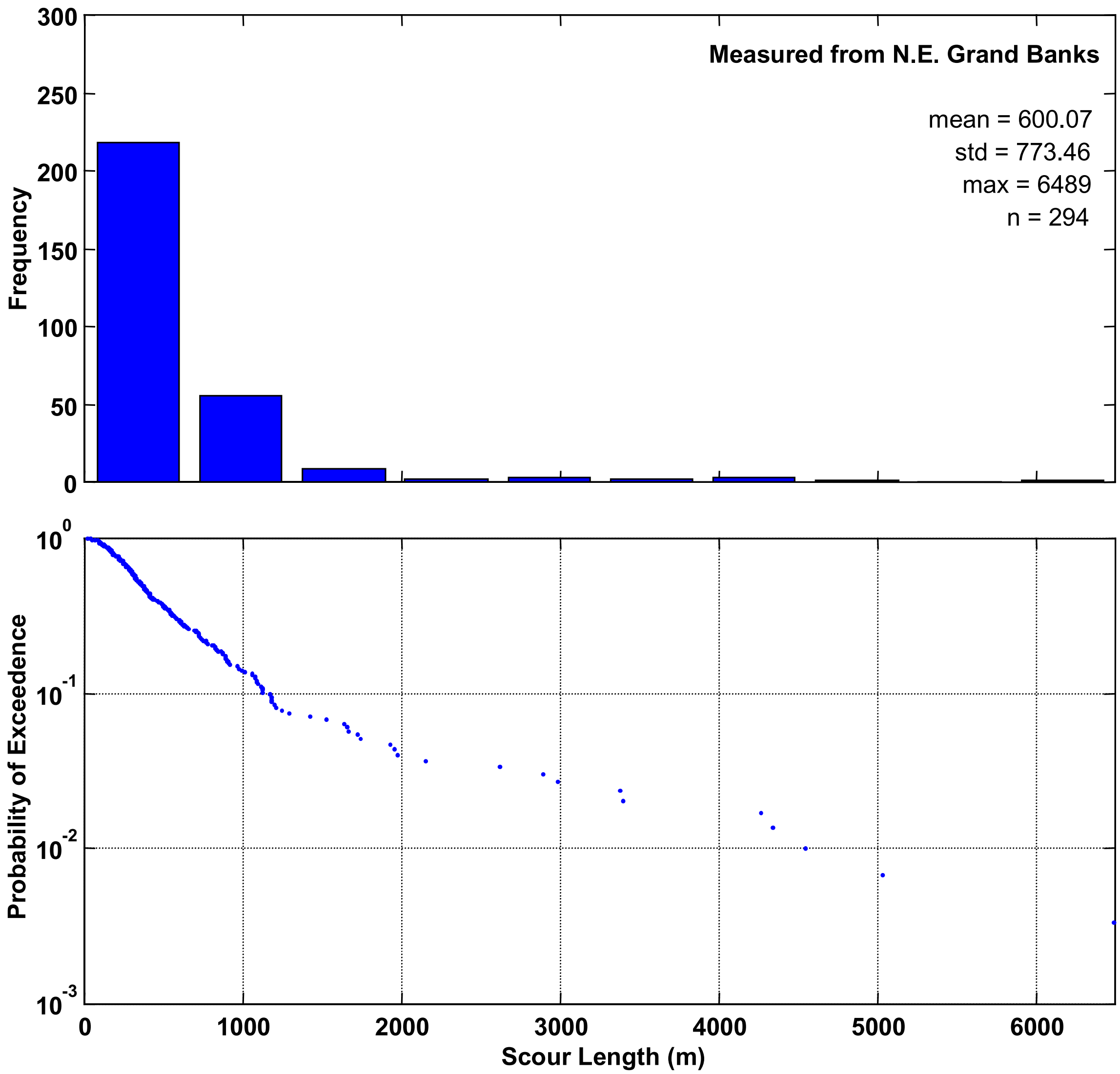


Figure 5.18 Scour length distribution measured on the Northeastern Grand Banks

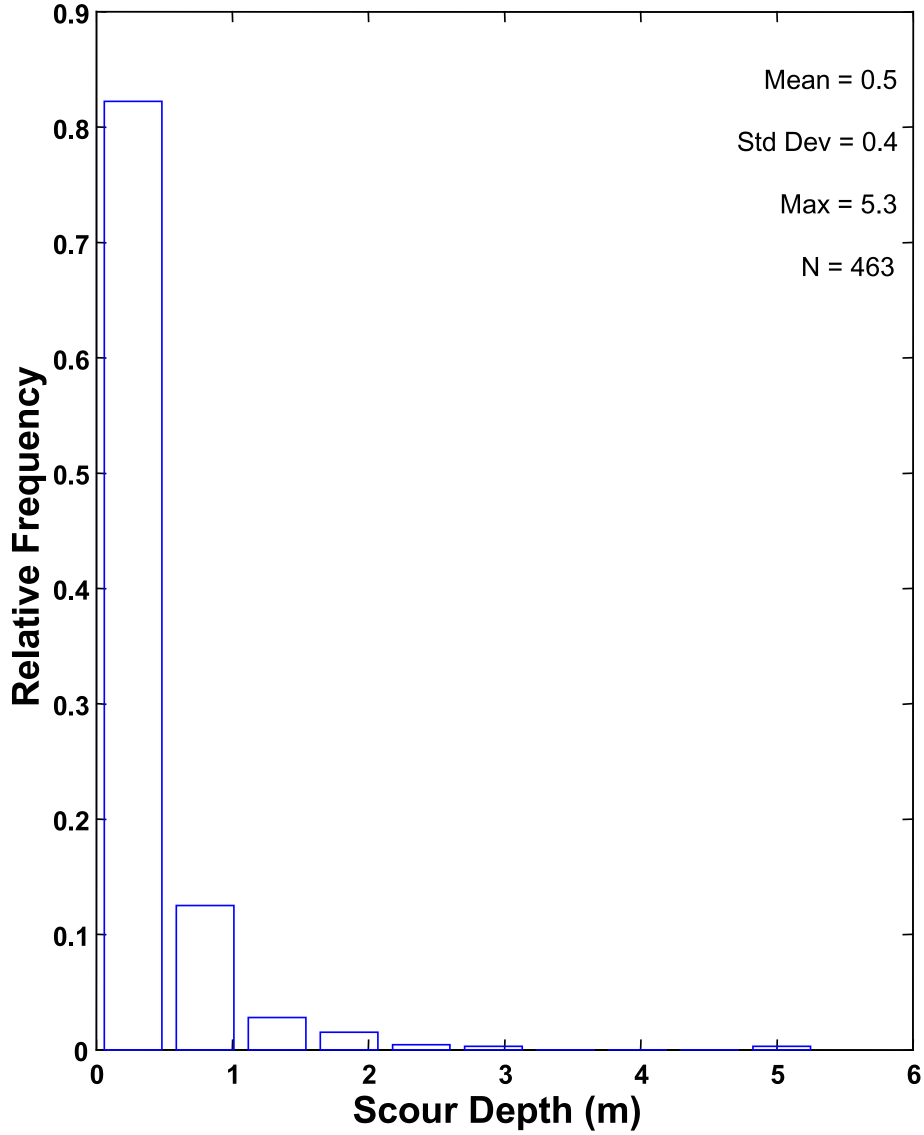


Figure 5.19 Scour depth distribution measured from the Northeast Grand Banks.

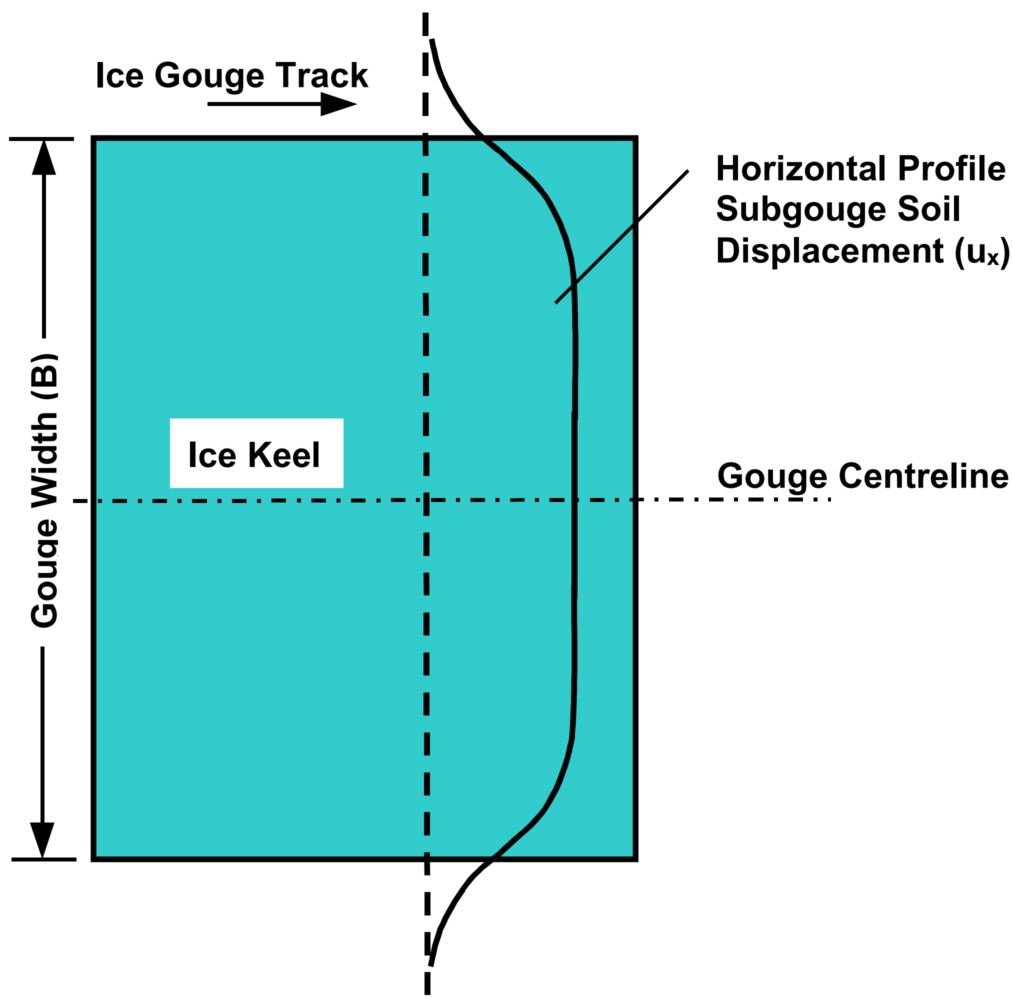


Figure 5.20 Horizontal profile of subgouge displacement field.

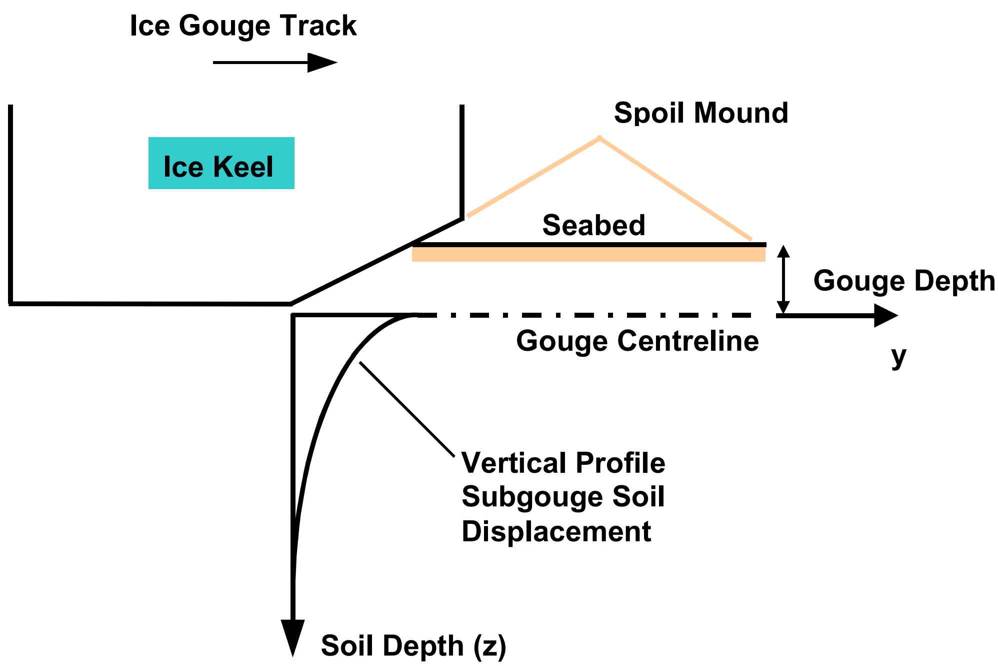
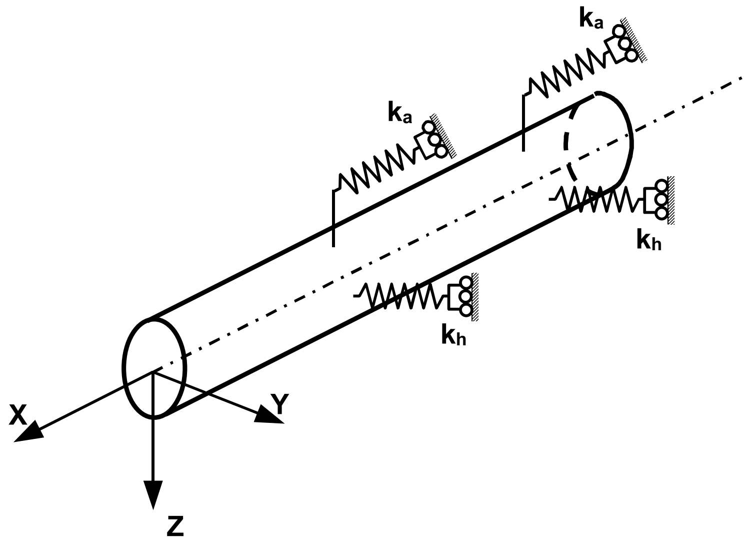
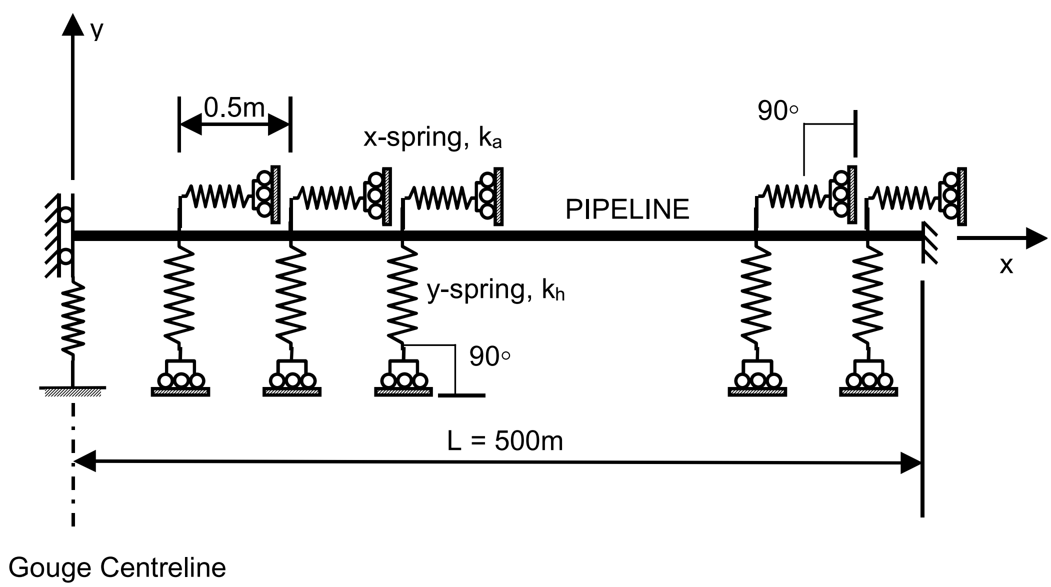


Figure 5.21 Vertical profile of subgouge displacement field.



(a)



(b)

Figure 5.22 (a) Idealised soil/pipeline interaction model
(b) Two-dimensional finite element representation.

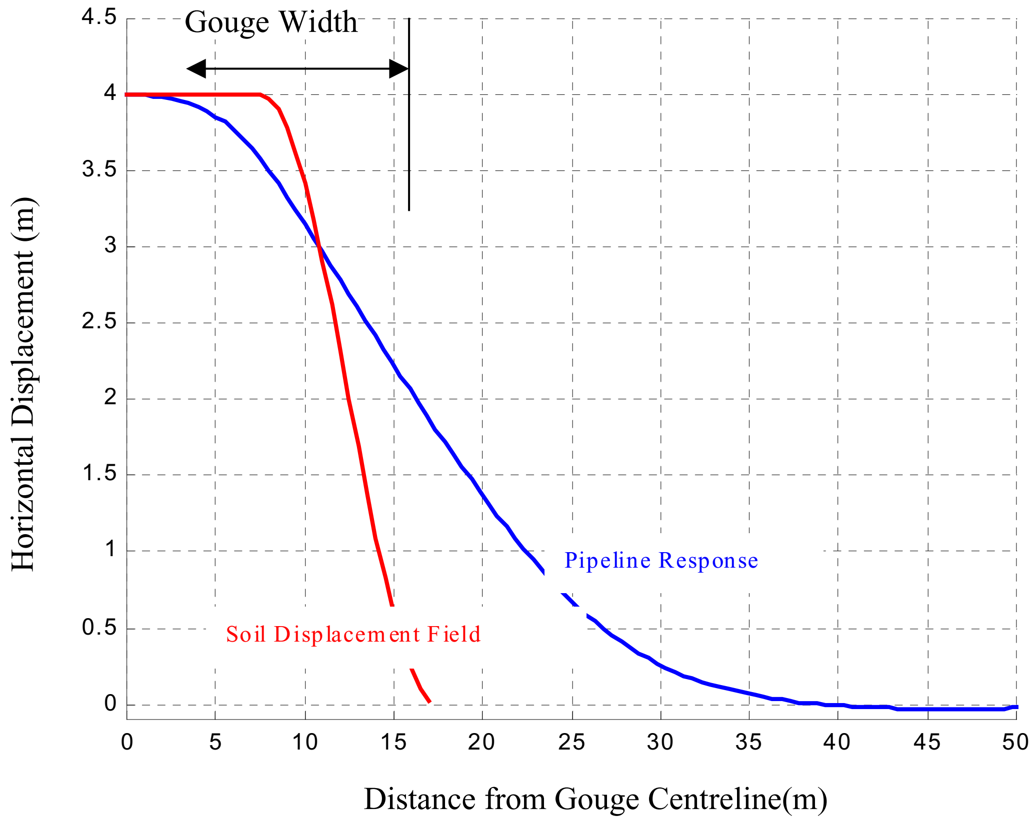
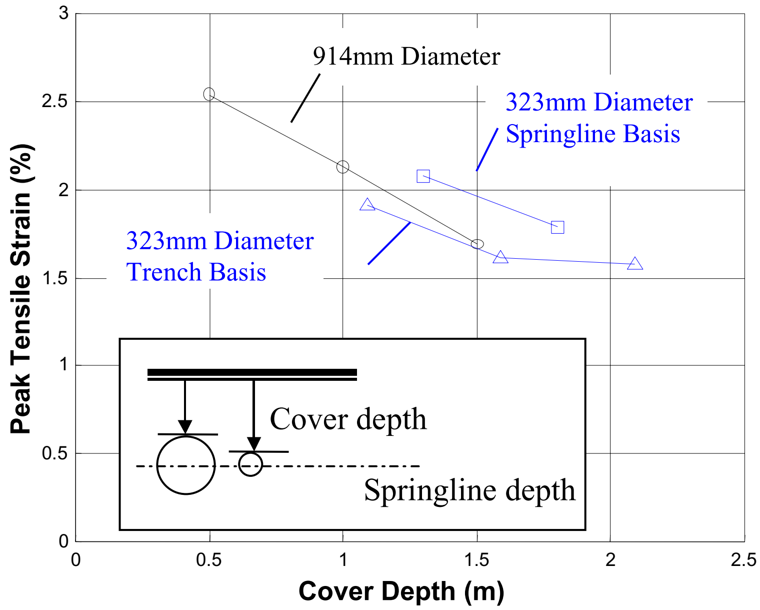
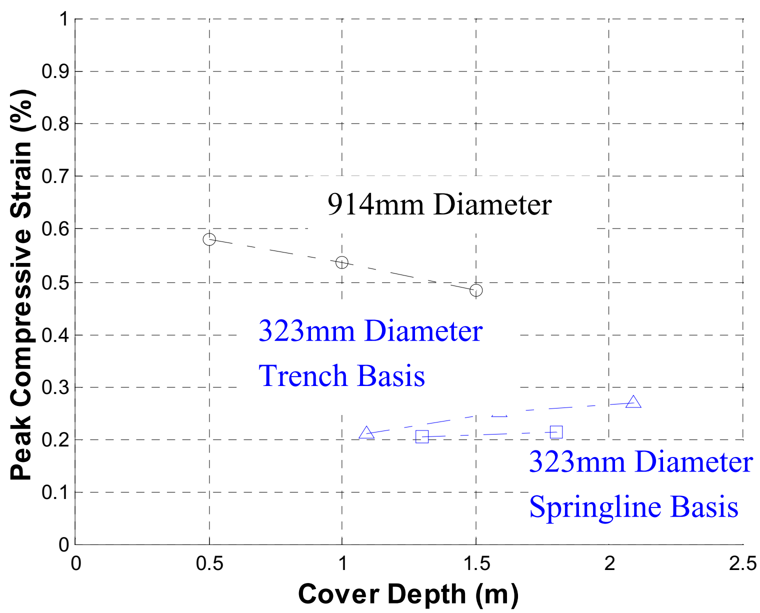


Figure 5.23 Longitudinal distribution of the imposed horizontal subgouge soil displacement field and computed response for the 914mm diameter pipeline at a cover depth of 0.5m.



(a)



(b)

Figure 5.24 (a) Peak tensile strain and
(b) peak compressive strain response for the two pipeline systems as a function of the cover depth.

6.0 Summary and Conclusions

This study has reviewed the data relating to ice scours on the Grand Banks as well as current understanding of the risks to seabed installations from scouring icebergs. In summary:

- The Grand Banks Scour Catalogue (GBSC) is an up-to-date compilation of all ice scour data collected in the region since 1979.
- The GBSC contains records of 5720 scour features including 3887 individual scours and 1773 iceberg created pits. The quality and shortcomings of the data are well understood and these have been reviewed.
- The GBSC has been used to assess scour density (number of scours/square km). This varies from 0 to 30 scours/km^2. It is noted that the highest scour densities are associated with the most recent surveys using modern equipment - this suggests that scours from earlier surveys may have been missed by the interpreter or the scours were not visible on the records from lower resolution sidescan systems.
- As well, scours in sand in water depths less than about 100m are periodically reworked and ultimately destroyed by bottom currents, so scour densities in sand are significantly less than recorded in gravels and other soils.(However, the scour frequencies could be the same)
- It is also noted that interpreter variability can lead to a minimum of 30% variation in scour density estimates.
- Scour depth data suffers from the limitations of instrument resolution which leads to shallow scours being underestimated and the statistics skewed to the deeper scours. On the other hand the older deeper scours may have infilled.
- Scour lengths are recorded as the length visible in a particular survey area, even though the scour may extend beyond the survey coverage. Scour lengths are coded accordingly in the database but longer scours are often under represented.
- Maximum scour depth in the catalogue is 7m occurring in the 150 - 170m water depth. However, in the 90 - 110m water depth, the maximum depth is 3m with a mean of "measured" scours 0.48m. (Subject to resolution limits of the sensors).
- In the 90 - 110m water depth, maximum and mean widths are 200m and 26m respectively and lengths are 650m (mean) and 9,400m (maximum).
- Repetitive surveys have been conducted in a few areas of the Grand Banks e.g. in the North Hibernia region in 1979 and 1990. All but one of these repetitive mapping surveys have detected no new scours over the period covered. In only one survey was one new scour detected in 11 years suggesting a scour frequency of 1.9×10^{-4} / km^2 /yr.

- In regions where scours are more frequent, (e.g. the Beaufort Sea), repetitive surveys give the best assessment of scour frequency - which is a vital ingredient for risk assessment. On the Grand Banks, the issue of determining scour frequency is a major problem for accurate risk assessment.
- One bounding approach discussed in this report is to assume that all detectable scours occurred over a certain geological time period - the longest being about 12,000 years BP and the shortest being about 2500 years. For the Hibernia region, this yields a lower bound frequency of 8.3×10^{-5} /km^2/year and an upper bound of 4.0×10^{-4} /km^2/year.
- Other methods of establishing scour frequency are based on either scour dating or on a statistical analysis of iceberg fluxes, drift rates and draft distributions.
- The assessment of scour frequency from iceberg flux is an extension of the methodology of assessing collision frequencies with surface piercing platforms. This has been reviewed in Chapter 3. It offers a potentially less uncertain approach to the problem. It also allows a coherent transition from scour frequency to collision frequency with sea floor structures of various heights.
- This approach has been used in a simple fashion for the Hibernia region and yields about 4×10^{-4}/km^2/year.
- Determining scour frequency from scour density using scour degradation has been reviewed and the effects of water depth and soil type need to be better understood before this approach can be used with any confidence.
- Scour dating by direct sampling and analysis of pollens and isotopes has been suggested at various times and is reviewed in chapter 2, however, this methods has yet to be successfully applied and proven. In fill rate analysis and biological re-colonization methods appear to have limited application.
- Scour depth is an important parameter in determining the depths of glory holes, pipeline trenches and where to place shear planes in protective caissons. However, scour depths in the data base are subject to a number of uncertainties and deficiencies, e.g. resolution of profilers, lack of depths from multi-beam profilers. As well, variability in scour depth across the scour width and length is important to optimum solutions but is not well known.
- Using data from the GBSC, for water depths of 110m or less, this study yields a mean scour depth of about 0.5 m and a corresponding standard deviation of 0.4 m.
- In reviewing potentially relevant standards (e.g. CSA S471), it was concluded that wellheads should be considered Safety Class 1, since failure could lead to significant hydrocarbon release. In this case, the CSA Standard recommends an annual target safety level of 10^{-5}. The annual target level for a single well or a well cluster installation (including glory holes) is therefore 10^{-5}. Up to about ten entities can be treated individually at the 10^{-5} level. If the number of wells or clusters exceeds ten, it

is recommended that the overall safety level be maintained at 10^{-4}, thereby increasing the safety requirement for each installation.

- The risk of iceberg contact with a variety of subsea installations has been considered. Experience suggests they can be classified according to whether they are buried beneath or penetrate above the mudline. In the first instance, only scouring icebergs are of concern, while freely floating icebergs are also of concern in the latter case.
- The annual contact probability from freely floating icebergs can be estimated from average iceberg population (per unit area), average drift speed, and the sum of iceberg keel and structure widths at the point of contact. Annual contact probability is approximately 2×10^{-3} for a 10 m high by 25 m diameter structure in about 100 m of water on the NE Grand Banks. In contrast, the annual probability of contact from scouring icebergs for a structure placed below the mudline is less than 10^{-5}. Contact probability from scouring icebergs depends on the scour frequency and scour dimensions. The advantages of burial below the mudline are significant.
- For scouring icebergs, the risk of contact decreases with increasing burial depth. For holes smaller than the scour width, the probability of contact decreases according to the probability of exceedance for the scour depth distribution. Typically, an order of magnitude reduction in contact probability can be achieved by burial 1 m below the mudline. For large holes, the iceberg may also pitch into the hole thereby increasing the risk of contact. This has been approximated from the excess draft distribution for scouring icebergs derived from a numerical model of the scour process for the NE Grand Banks. The probability of iceberg contact depends on the extent of the structure and the position of the top of the structure relative to the mudline.
- In many cases, the reliability of an installation will be much greater than would be inferred by equating iceberg contact with release of hydrocarbons to the environment. A significant safety margin can be achieved for wellhead installations by considering the effectiveness of automatic shut-off valves in the wellbore.
- Risk of damage to a buried subsea pipeline depends on the scour frequency, scour length, scour depth and pipeline length. Sub-scour soil deformations should also be considered in the risk assessment process. For the NE Grand Banks, the annual probability of iceberg damage for a backfilled pipeline with a cover depth of 1 m is estimated at between 10^{-5} and 10^{-4} per km.
- For offshore pipelines, the state of practice has not reached a full reliability based design. Many codes, including the section of CSA Z662 pertaining to offshore pipelines, require the verification of limit states under the application of the 100 year design environmental load. Since ice scours impart displacements to buried pipelines, design scours are characterized typically in terms of their depth and width. The annual probability of exceedance for scour depth has been estimated for the Hibernia degree square.

- A separate analysis was conducted to assess the influence of sub-scour soil deformation on a buried pipeline. It is shown that for a scour depth of 1.5m and a typical 914mm pipeline with a cover depth 1m, the peak tensile strain in the pipe is approximately 2% (CSA Standards require verification of strain limits greater than 0.75%). In this case, the cover depth is the clearance between the scour base and the top of the pipe, implying a trench depth of about 3.5m. Required trench depths depend on scour dimensions, pipeline material, diameter, wall thickness and soil parameters.
- A review of environmental driving forces indicates that current, winds and waves are sufficient to induce scour to the depth levels observed (e.g. to about 2.6m). As well, scour lengths of several km appear to be quite likely and this matches the data.
- The same analysis gives typical results for iceberg heave and pitch during the scouring process. Mean values are quite small e.g. 0.24 degrees pitch and 0.01m heave. However, maximum values are 16.7 degrees pitch and 1.12m heave.

Scour depth limits due to iceberg strength obviously depend on the geometry of the keel, as well as the ice the soil strengths. A simple analysis shows that an iceberg with a strength of 1MPa can scour to a depth of at least 3m in sand with a 30 degree friction angle. However, the driving force limit from the simulation performed in this study also appears to be about 3m. These considerations suggest that in sands, the scour depth may be limited by either driving force or iceberg keel strength. It should be noted however, that these calculations are very approximate and further refinement is recommended.

In conclusion, due to the foresight of the GSC and others, there is a considerable amount iceberg scour data for the Grand Banks. There are some limitations of accuracy due to sensor resolution and interpreter subjectivity and skill, but the data are very important input to risk assessment and the design of seafloor facilities. However, although the data give good information on scour density, the extraction of scour frequency, which is the starting point for accurate risk assessment, is not so easy. Because the scouring rate is so low, the use of repetitive scour surveys has, to date, not been able to provide adequate data to reliably assess scouring frequency.

Scour depth data are also important in assessing the risk of buried facilities and is subject to some uncertainties due to instrument resolution limits.

With the data available at this time, and recognizing the uncertainties noted above, the contact frequency with a typical individual sea floor facility is estimated to be typically in the range 10^{-4} to 10^{-3}. According to the risk philosophy laid out in CSA S471, assuming contact leads to significant oil discharge, then this risk is too high. It is recognized that contact by an iceberg with a structure such as a wellhead does not necessarily lead to an uncontrolled discharge (because of wellbore control valves). Nevertheless, most operators have chosen to reduce this risk by putting the top of such equipment below the mud line. However, because of uncertainties in both scour frequency and scour depths, the risk level as a function of depth of burial is subject to uncertainty.

The incentive to reduce this uncertainty is high because burial schemes such as glory holes are very costly.

7.0 RECOMMENDATIONS FOR FUTURE WORK

R&D to reduce the uncertainties in scour frequency and scour depth can be related to two separate lines of approach. These are either 1) use the scour record or 2) simulation of scour statistics from iceberg statistics combined with ice/seafloor interaction and limit models. It is recommended that both these approaches be exercised and refined. In fact, when both approaches give similar risk values we might expect that the outcome has some credibility. Also it should be noted that the second approach is required anyway to assess risk to structures which protrude above the sea floor.

Recommended R&D thrusts for these approaches, with an accompanying summary of rationale are itemized in Tables 7.1 and 7.2.

Table 7.1 R&D to improve methods based on the scour record

Topic Area	**Remaining Issue & R&D Thrust**	**Priority**
Scour dating & Relic scours	There are iceberg scours off the north east Grand Banks in water depths of up to 400m. It is widely believed that these are relic features, created many thousands of years ago when sea levels were much lower and possibly icebergs were much larger. There is an interest exploiting deep-water hydrocarbons and using deep water for hydrocarbon transportation. Although deep water creates some additional challenges, it has the advantage that the scour risk is significantly lower than in shallower water. This means that the costs of protecting facilities from iceberg scour may also be much lower, which could influence the viability of a project. Differentiating between relic and non-relic scours is critical for determining the risk in deep water. Project proponents, investors, regulators, and the public must all be convinced that the scour risk is sufficiently low, and it will be important to prove that the deep water scours are in fact relic. It is therefore very important that techniques be developed for determining the *absolute* age of scours. There are presently no accepted methodologies for absolute dating of scours, and this should be a high priority for future work. An initial scoping of likely methods and probability of success is recommended as a first step. Such a technique, if successful, could also be used to assess scour frequency as an alternate to other methods discussed below	H
Scour degradation	The density of iceberg scours presently visible on the seabed is not directly applicable to risk assessment. Scour frequency is the important parameter, and one of the simplest methods of estimating frequency is by looking at scour degradation rates and using these to convert density to frequency. It is believed that sediment type has a significant effect on scour degradation rates, but the magnitude of the effect is not known. To obtain accurate estimates of scour frequency in different sediment types using this approach, sediment effects on scour degradation must be determined.	M H
Repetitive Mosaics	Another approach to obtain scour frequency is repetitive mapping. Repeat mapping over a survey area previously done over 20 years or so ago should be investigated – noting that it will be essential to separate out the effects of improved resolution of survey methods during this period.	M H
Scour density	Scour density can be a starting point to assess scour frequency. Scours formed in sands in water depths less than 110 metres are periodically	M

Table 7.1 R&D to improve methods based on the scour record

Topic Area	Remaining Issue & R&D Thrust	Priority
	reworked, and ultimately destroyed, by bottom currents. Consequently scour densities observed in sands are significantly less than those recorded in gravels. In order to provide consistent scour density/frequency results in shallow water, surficial geology coverage is required to normalise the data according to percentage gravel cover. Such coverage is not available regionally, but could be obtained for selected sites within each bathymetric interval.	
Scour depth	Scour depth is an important issue when determining iceberg risk to wellheads placed below the mudline, particularly when they are contained in caisson-type systems or placed in small diameter drilled holes. Scour depth is also the most important issue for iceberg risk to buried pipelines. A number of factors including low resolution sub-bottom profiler data in many of the older surveys do not allow an accurate estimation of the scour depth distribution. Scour depths need to be examined from current data collected over portions of the Grand Banks using multi-beam sonar devices. A continued effort is recommended to enhance the area covered by high resolution surveys, therefore improving the resulting scour depth distribution.	M
Scour length	The scour length information in the database probably under-estimates the true length of scours because of difficulties detecting both the start and end points. Length is also an important factor in determining risk from scouring icebergs, and better length information would lead to better estimates of risk. 100% area coverage from multi-beam and/or sidescan surveys offers significant improvements over regional line coverage. This is advantageous for measuring the length of scour marks. Length distributions from newer surveys should be compared to those from older surveys with less coverage. Future surveys with wider coverage are also recommended.	ML
Variability in Scour Depth	Scour depth documented in the database focuses on the deepest point across the width of a scour. Risk to pipelines or buried installations depends on the deepest penetration. However scour modeling depends also on the variation	M

Table 7.1 R&D to improve methods based on the scour record

Topic Area	Remaining Issue & R&D Thrust	Priority
	of the scour depth across the scour A proper assessment of depth variation from existing and future surveys would help to establish more representative scour depth distributions and variabilities for risk calculations and modeling.	
GBSC Data	There is outstanding work which needs to be conducted on the GBSC. This includes • Duplicate scours, mapped from two or more different surveys, need to be identified and removed from the database. There appears to be a number of duplicate scours within the Hibernia area due to the amount of repetitive survey coverage. • Hudson Cruise 80-010 and the Tempest North Wellsite (original Mobil source) appear to have anomalous scour depth distributions. The original geophysical data should be re-examined for these sources. • Some wellsites from the original Mobil source appear to have anomalously low scour densities compared to adjacent areas. If possible, the original data should be examined for these sites. • There are additional regional and wellsite data are available in the region which should be incorporated into the GBSC. • The original Mobil source only included a small portion of the scour population recorded on regional lines (Hudson 80-010 and the 8000 Series surveys). All scours recorded on the sidescan for these surveys should be incorporated into the GBSC.	MH
Soil Bearing Pressures	Through the PRISE program, C-CORE has established a relationship between scour dimensions and the corresponding loads applied to the soil. The geotechnical properties of the soil play a role in this process. An investigation of the relationship between the geotechnical properties of the soil and scour dimensions is important for predicting regional differences in the scour depth distribution. Finally, the calculation of likely soil pressures based on the PRISE model is necessary for making any assessment of ice strength effects (see below).	M

Table 7.2 R&D to improve methods based on simulation of scour statistics from iceberg statistics combined with ice/seafloor interaction and limit models.

Topic Area	**Remaining Issue & R&D Thrust**	**Priority**
Iceberg size and depth distributions	Iceberg draft data is a vital input for risk assessment of structures above the seafloor and simulation of scour statistics. It is not clear if the general statistics on iceberg draft can be applied to the Grand Banks. Two initiatives are proposed 1. Additional iceberg surveys of opportunity during iceberg management operations (also ensuring it is placed in suitable repository) 2. Investigate the use of RADARSAT to improve iceberg waterline length statistics for the Grand Banks	M
Iceberg - seafloor and seafloor structures interaction model	This study has developed a preliminary iceberg/seafloor interaction model which accounts for current, wave and wind driving forces, kinetic energy and seafloor strength. It has been exercised in this study in a limited fashion (e.g. a single keel angle). The model does not include an ice strength limit. It is recommended that a more comprehensive model be developed which includes an ice strength limit and which can also be used to assess forces on sea floor structures above the mudline. The model should then be exercised in both deterministic and probabilistic modes to determine the most influential parameters. It is recommended that the model include other types of ice features such as pressure ridges so that it can also be applied to other ice regions where scours occur. It is suggested that this would be the first part of a phased study which might lead to experimental work to verify parts of the model including a possible ultimate phase of a large scale field test. These latter phases would be examined in Phase 1 as to desirability and feasibility.	H
Ice Strength Limits	Incorporation of ice strength limits into a scouring model will require an assessment of appropriate ice strengths. It is recommended that a scheme be developed for the ice strength of iceberg keels which is based on previously measured iceberg strength data and other full scale data combined with plausible physics including progressive failure. (and which would be capable of integration into it proposed ship/bergy bit	H

Table 7.2 R&D to improve methods based on simulation of scour statistics from iceberg statistics combined with ice/seafloor interaction and limit models.

Topic Area	**Remaining Issue & R&D Thrust**	**Priority**
	impact tests).	

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Appendix A:

Summary of Grand Banks Scour Data

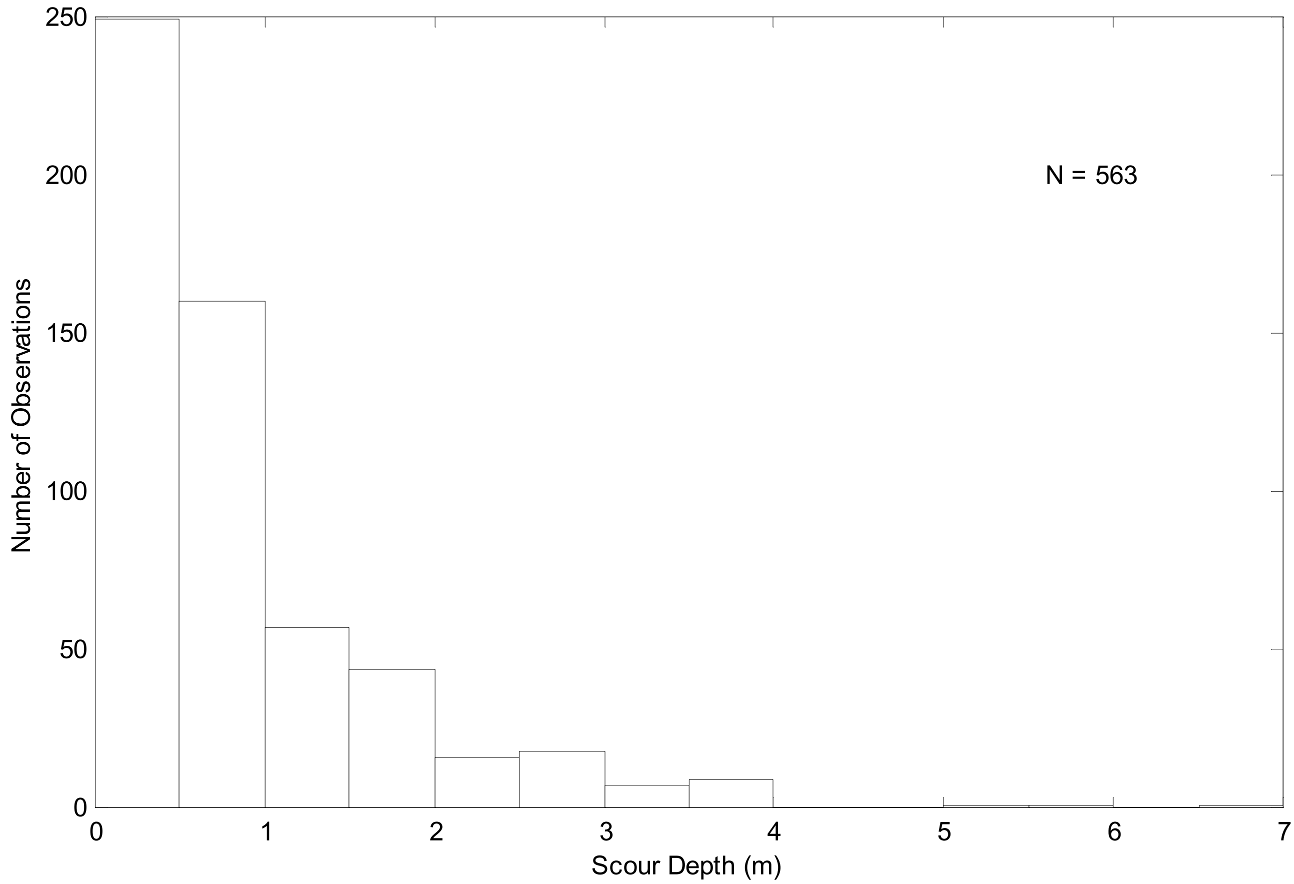

Figure A-1 Histogram of scour depths, all water depths, DEPTH_Q codes 4 and 7.

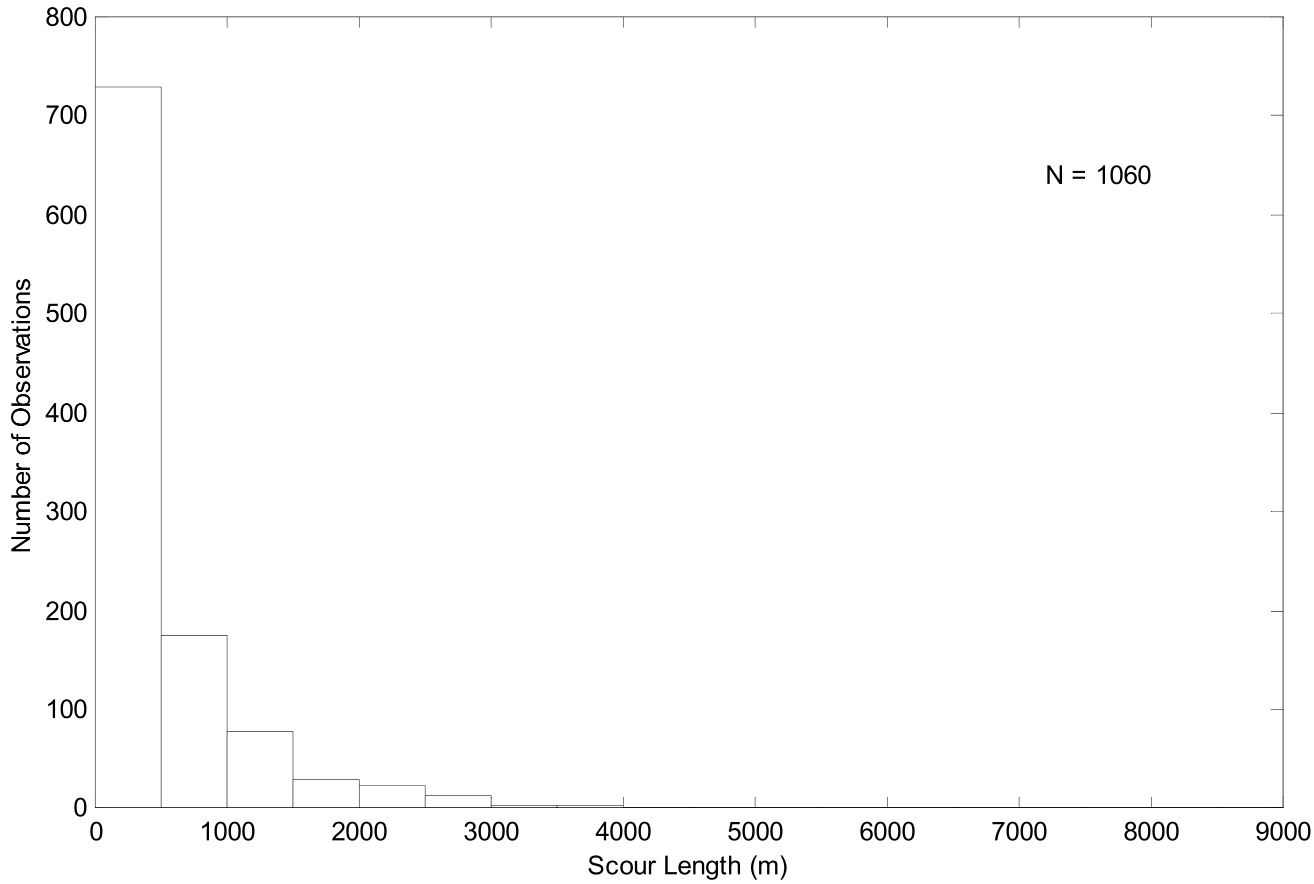

Figure A-2 Histogram of scour length, all water depths, LENGTH_Q codes 2 and 5.

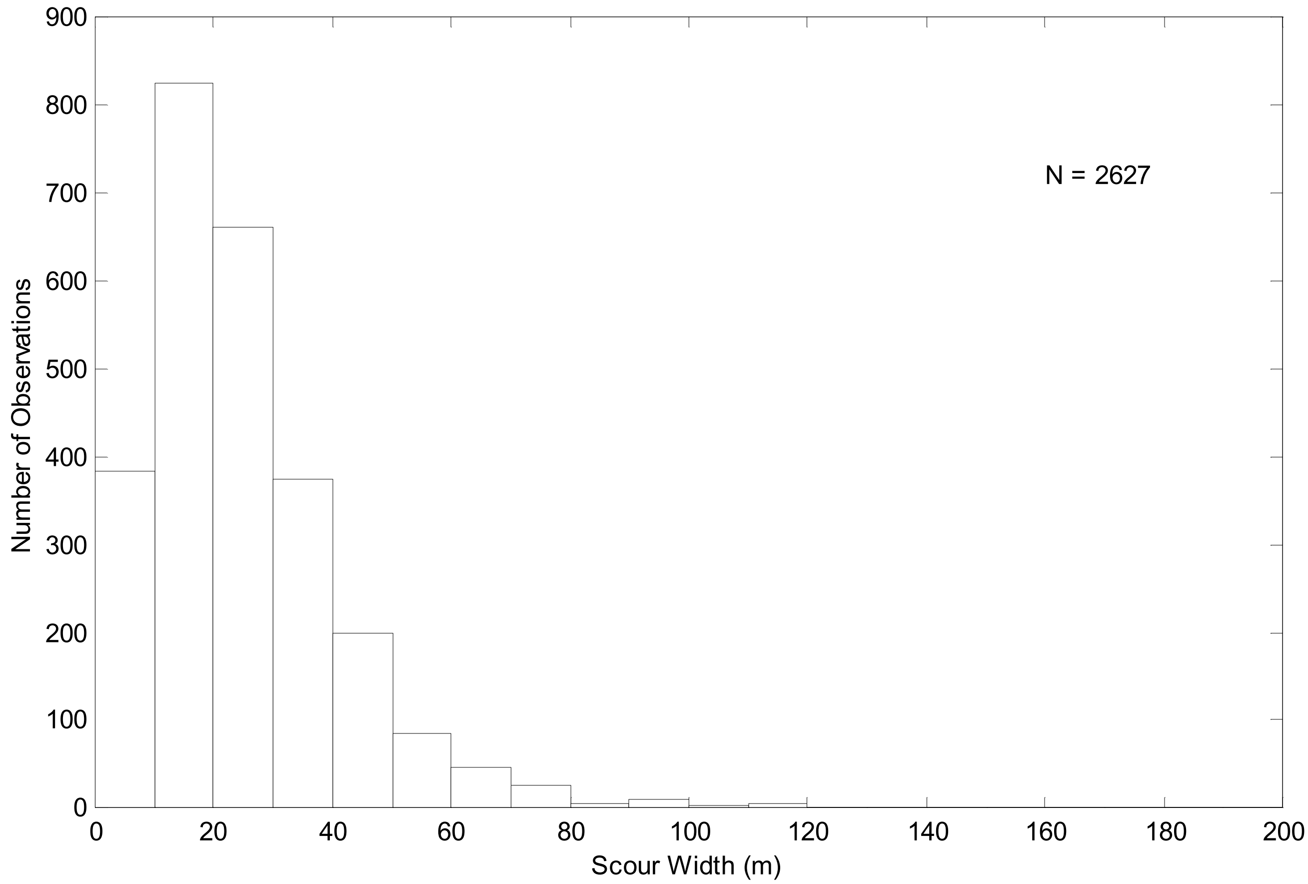

Figure A-3 Histogram of scour width, all water depths, AVG_WIDTH < 99999.

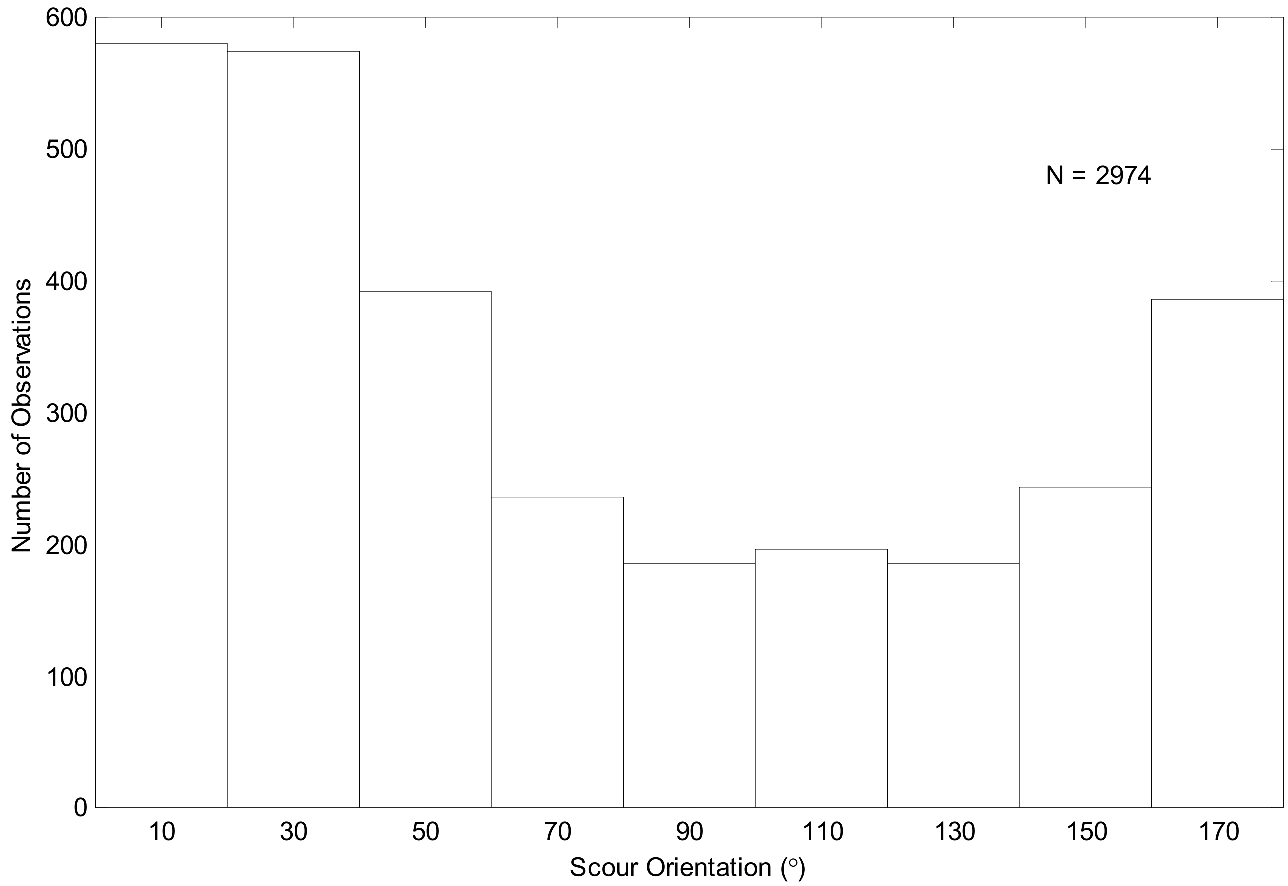

Figure A-4 Histogram of scour orientation, all water depths.

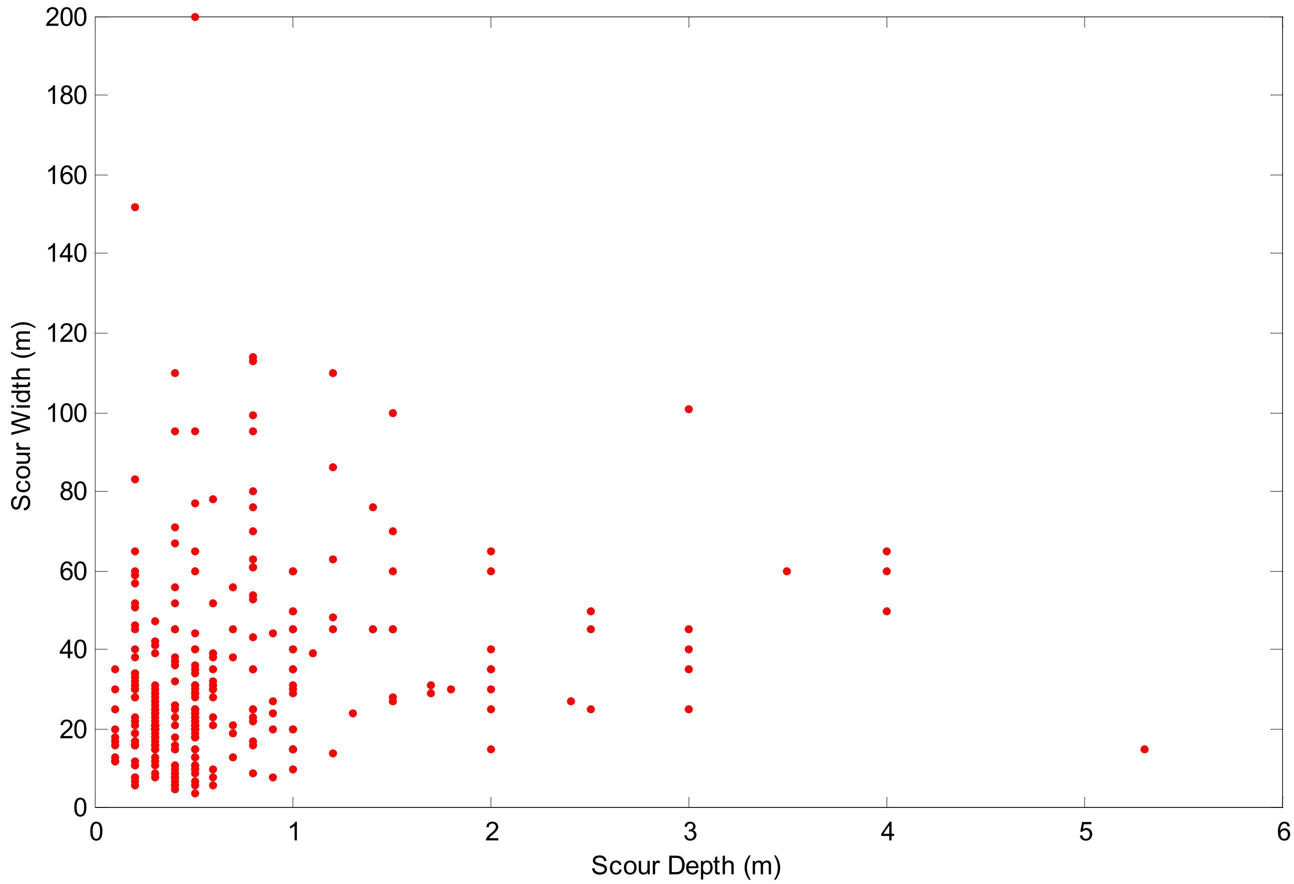

Figure A-5 Relationship between scour depth and scour width.

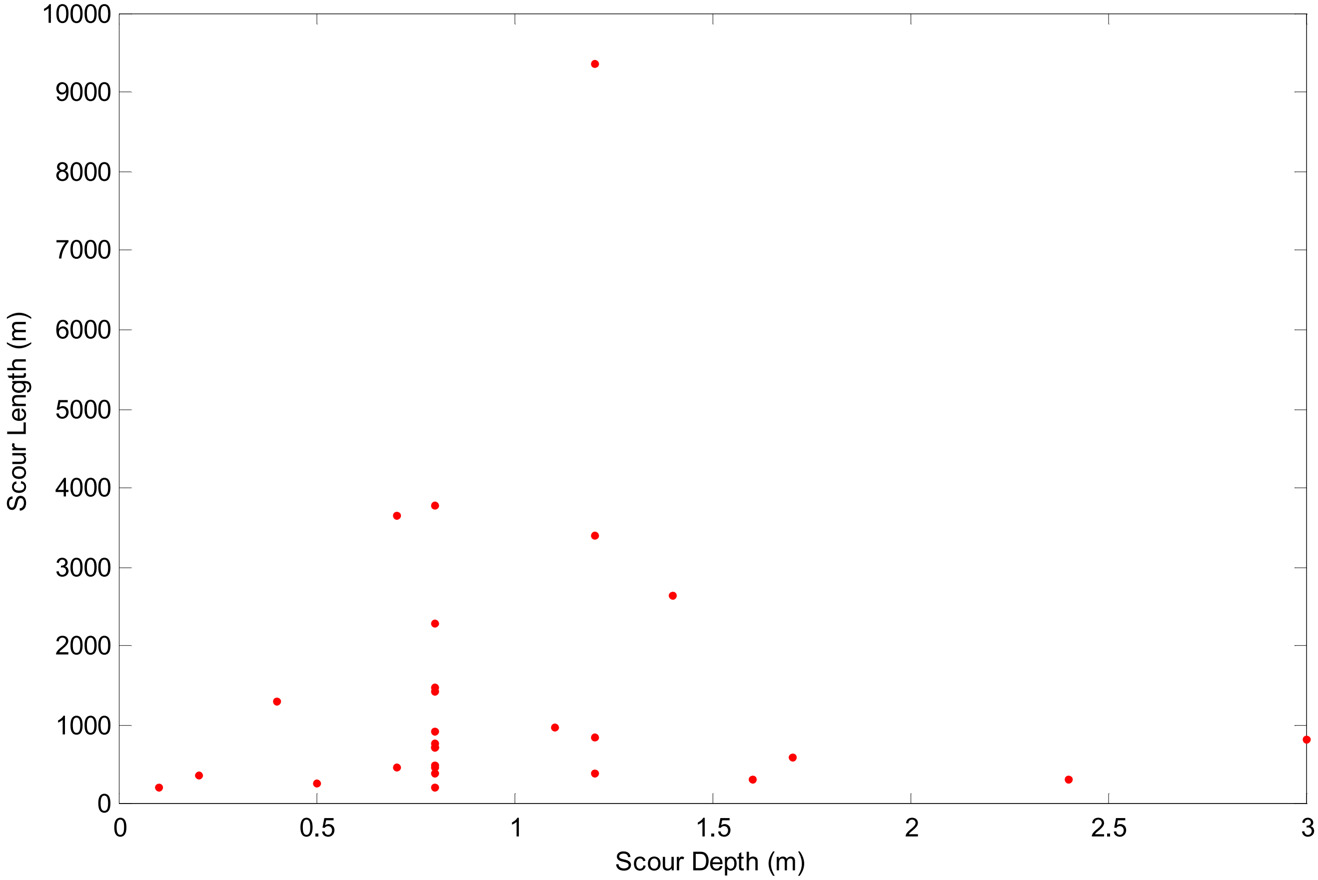

Figure A-6 Relationship between scour depth and scour length.

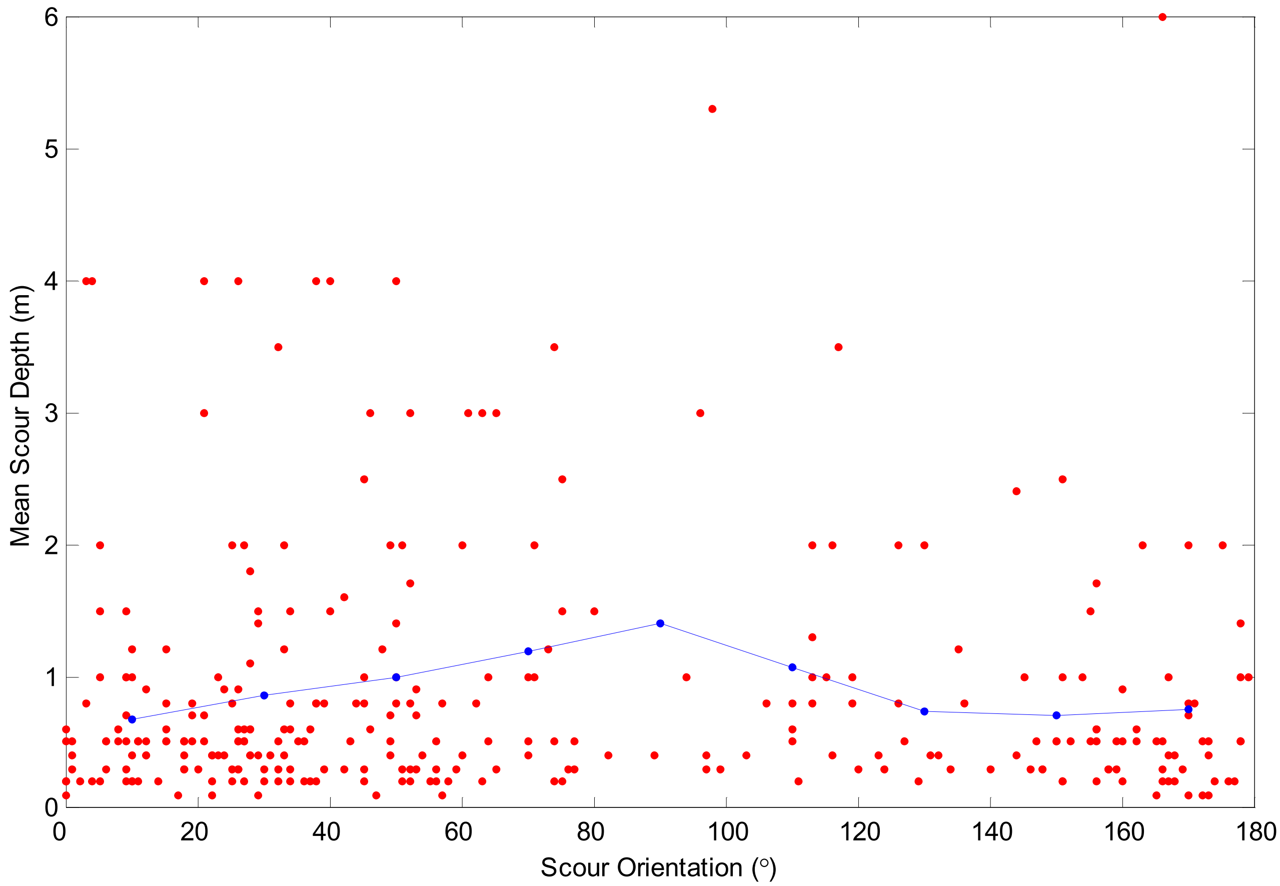

Figure A-7 Relationship between scour orientation and mean scour depth.

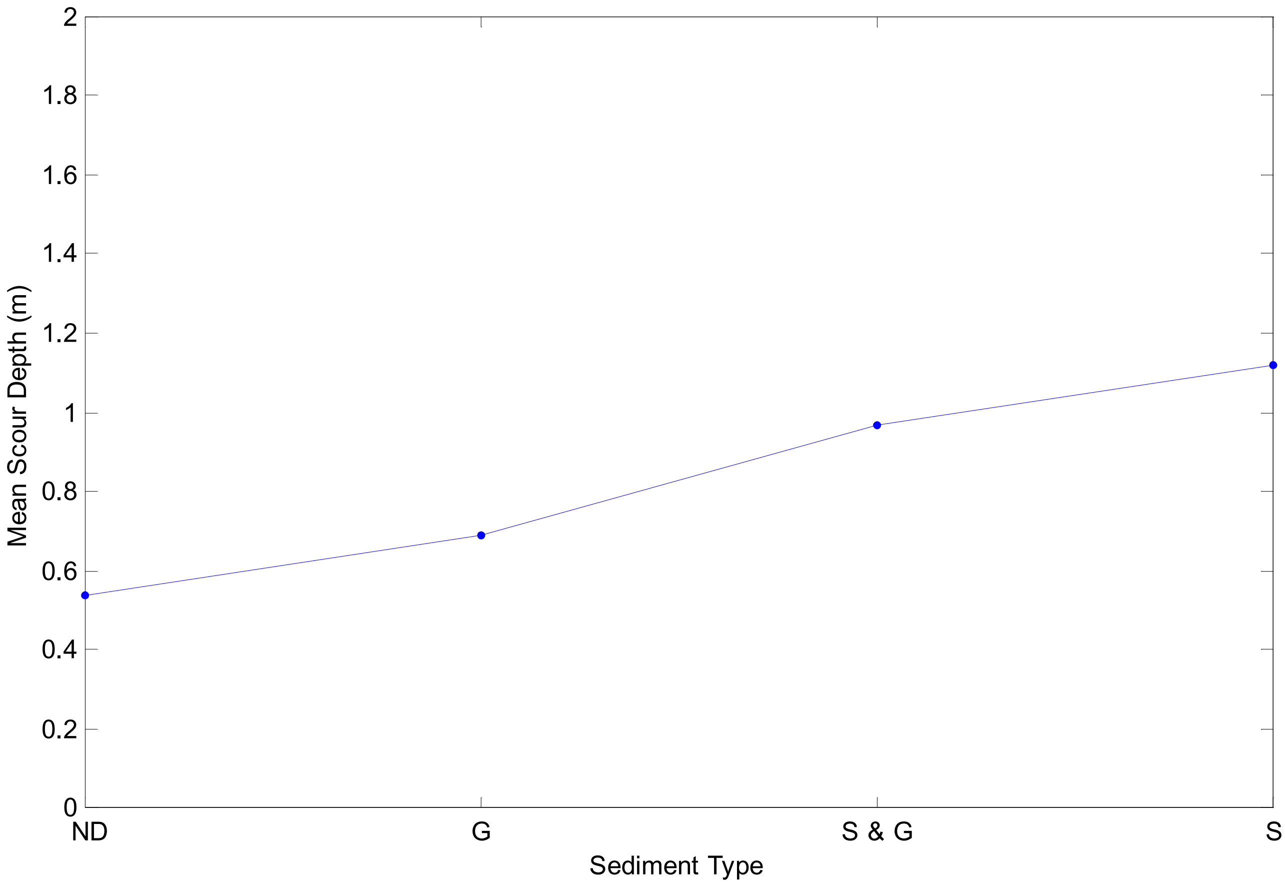

Figure A-8 Mean scour depth as a function of sediment type (ND = No Data; G = Gravel; S & G = Sand and Gravel; S = Sand).

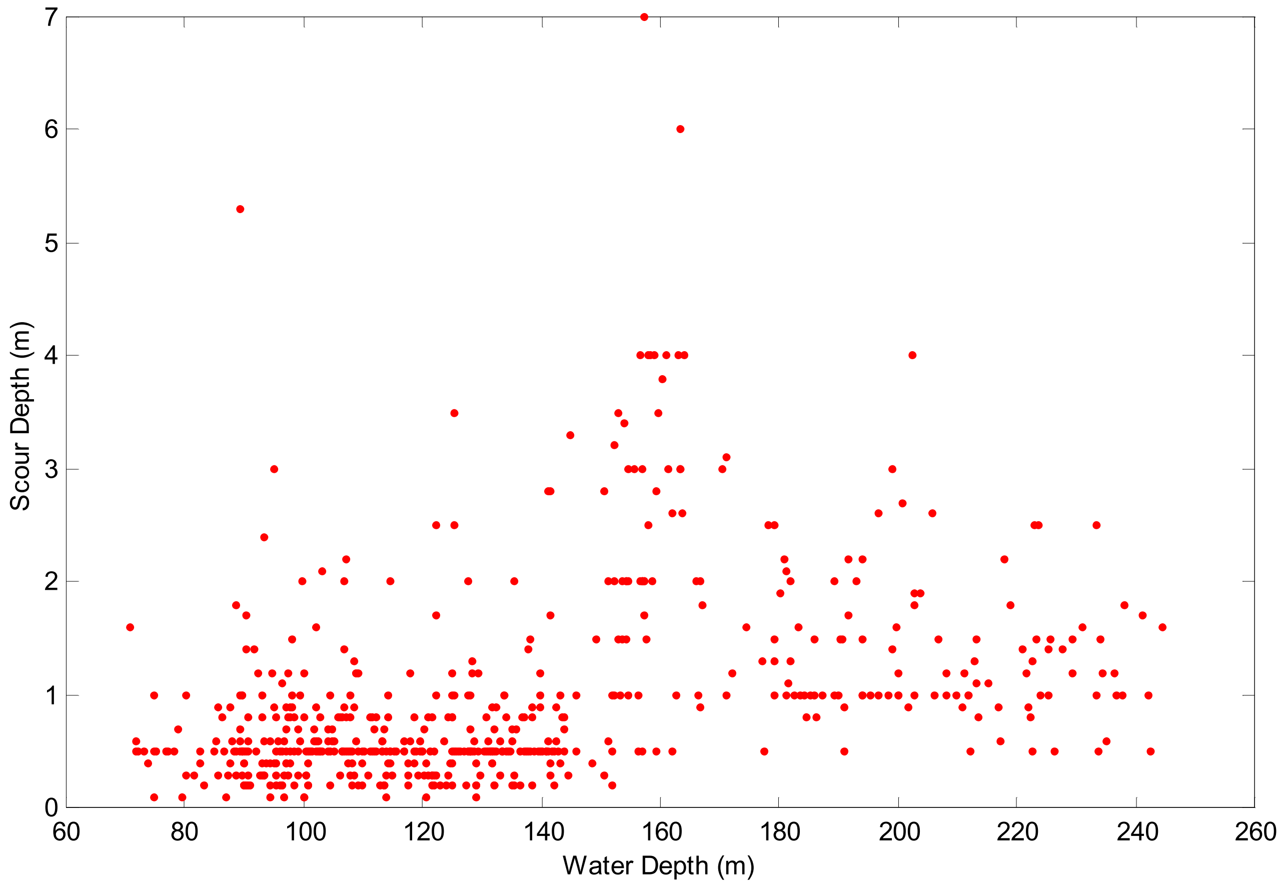

Figure A-9 Scour depth a function of water depth.

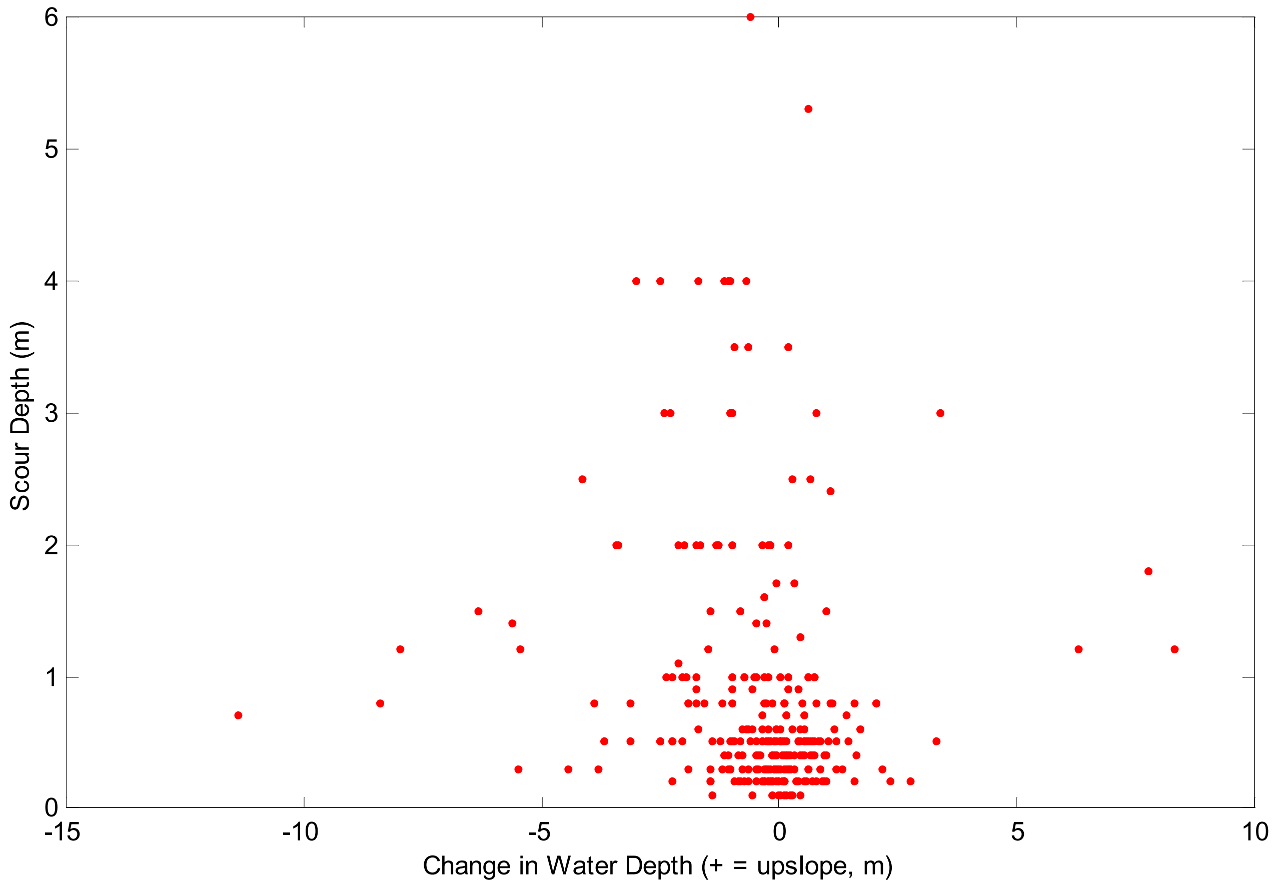

Figure A-10 Scour depth a function of change in water depth.

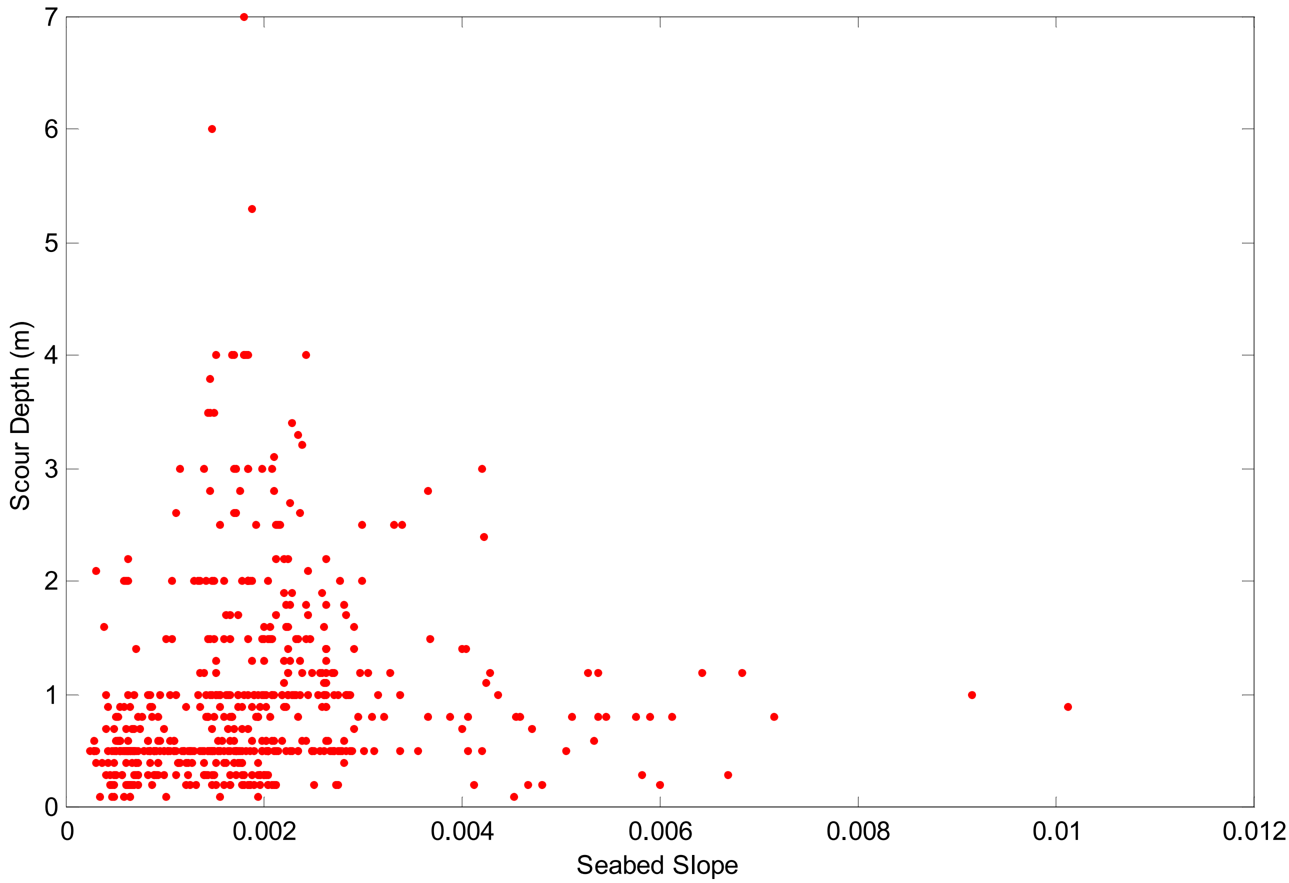

Figure A-11 Scour depth as a function of seabed slope.

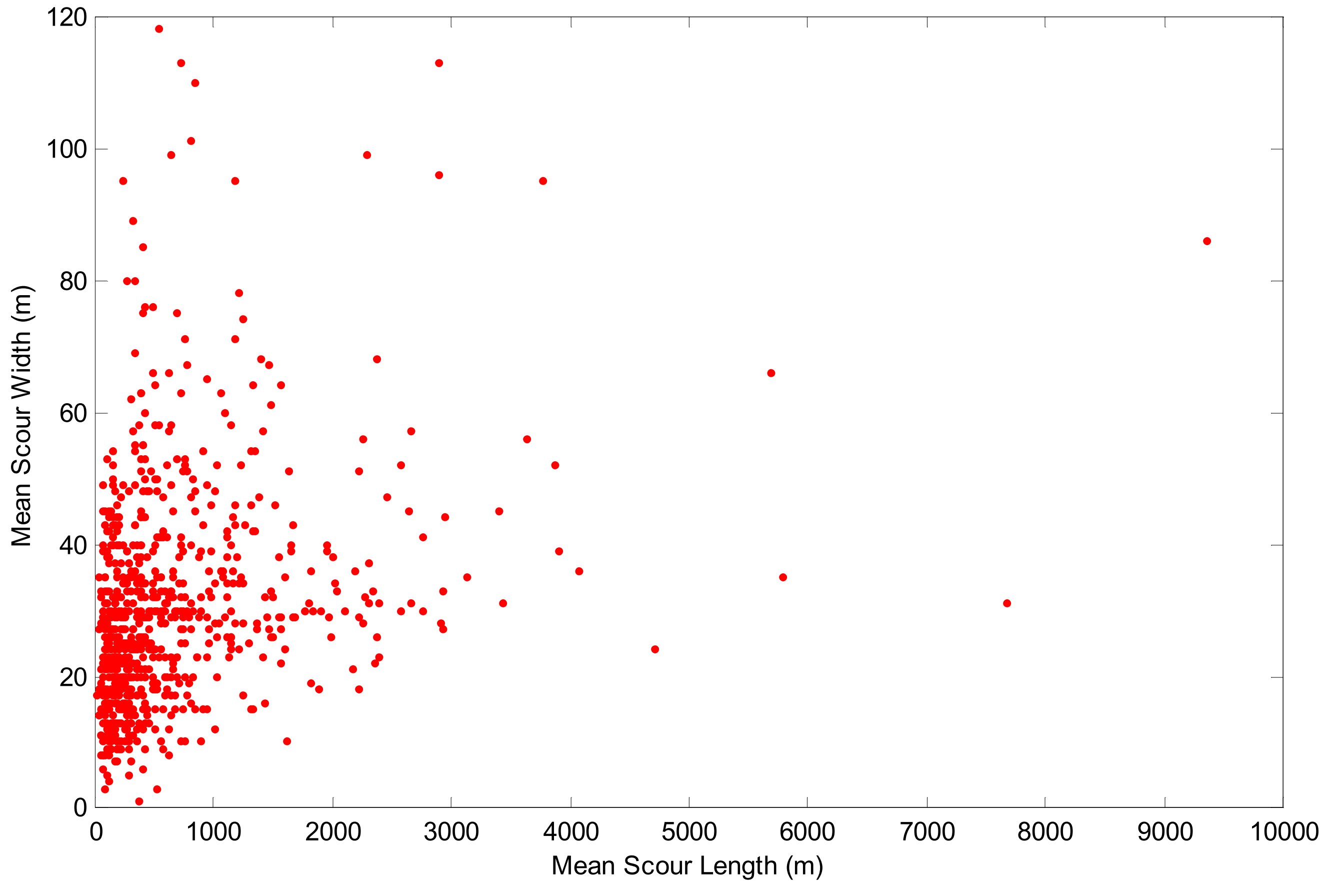

Figure A-12 Relationship between scour length and scour width.

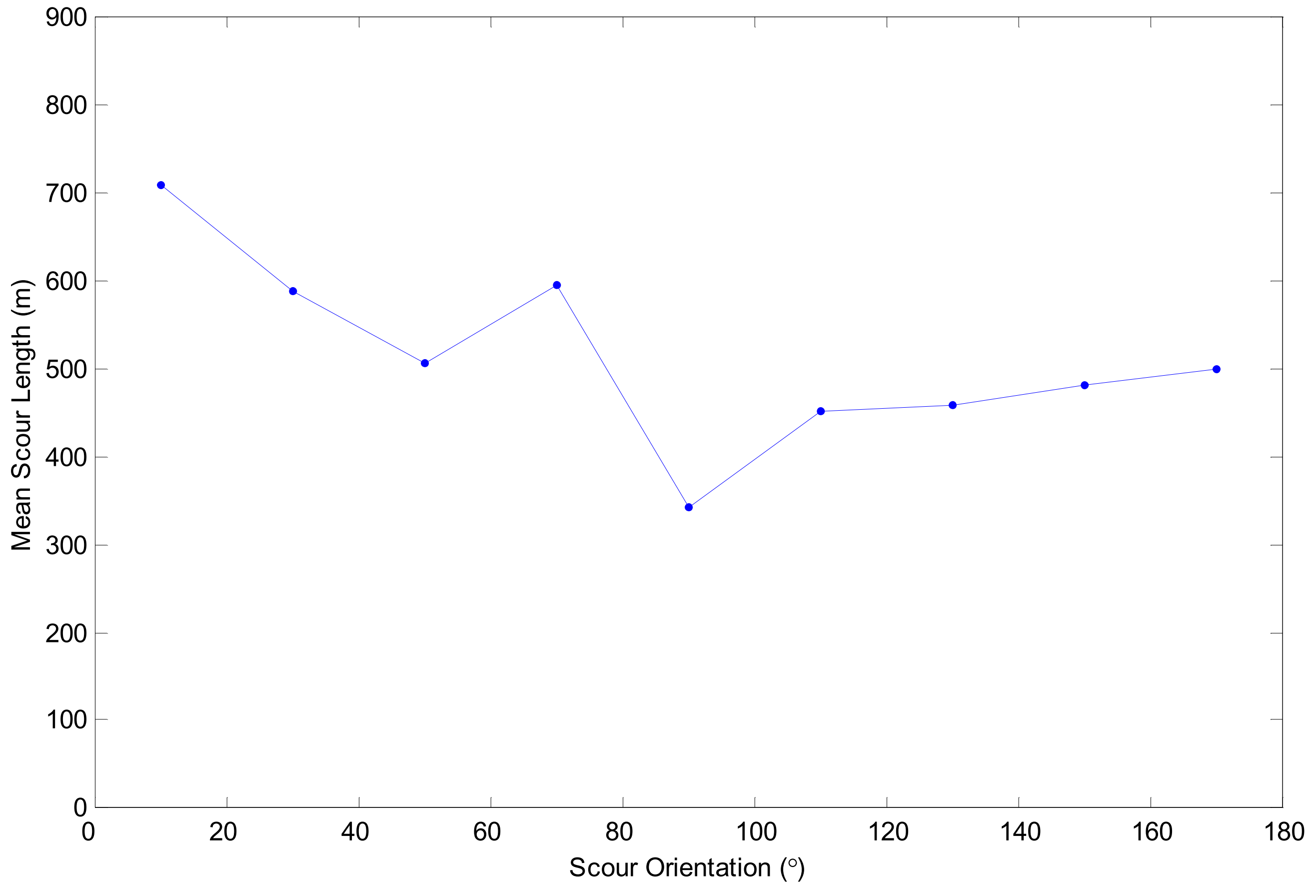

Figure A-13 Relationship between mean scour length and scour orientation.

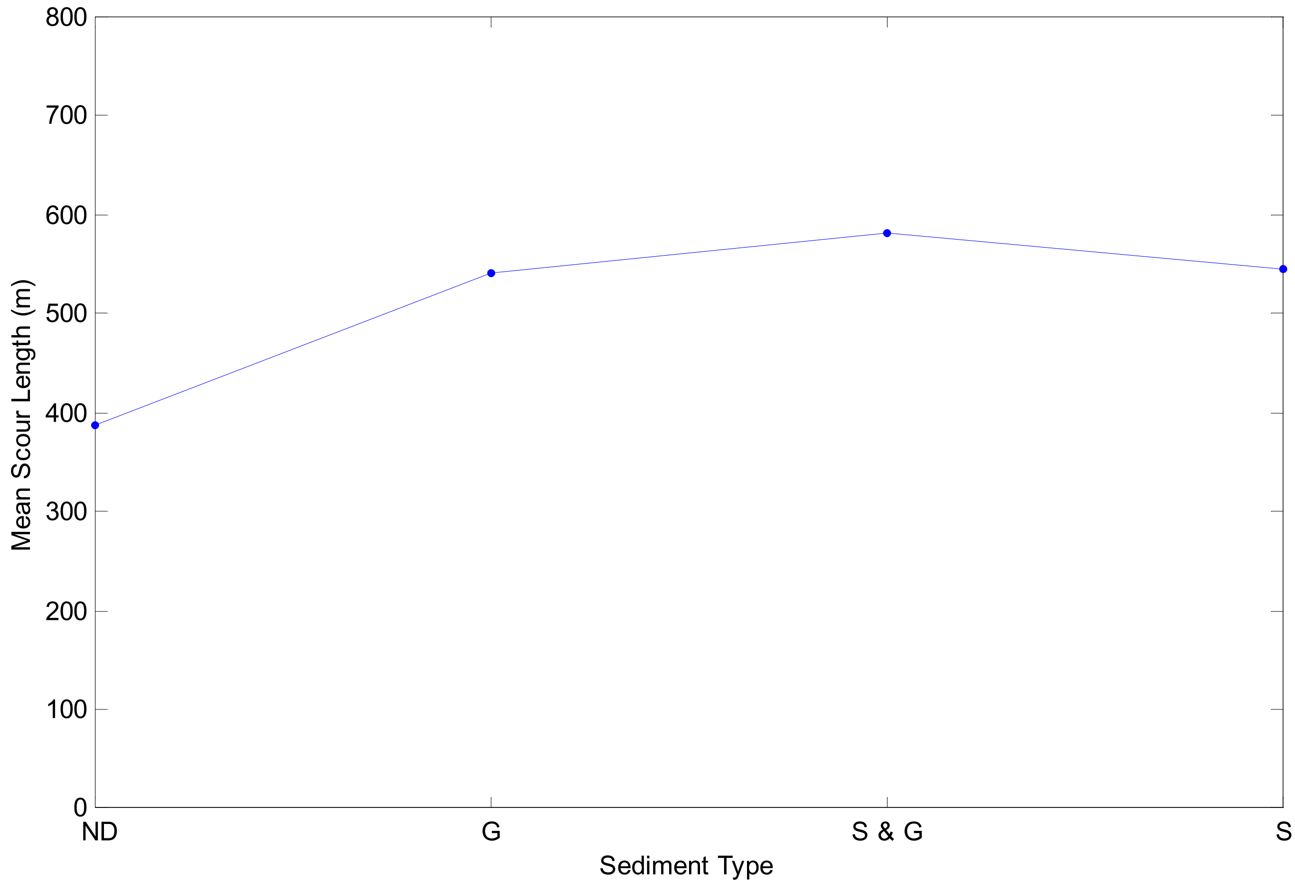

Figure A-14 Mean scour length as a function of sediment type.

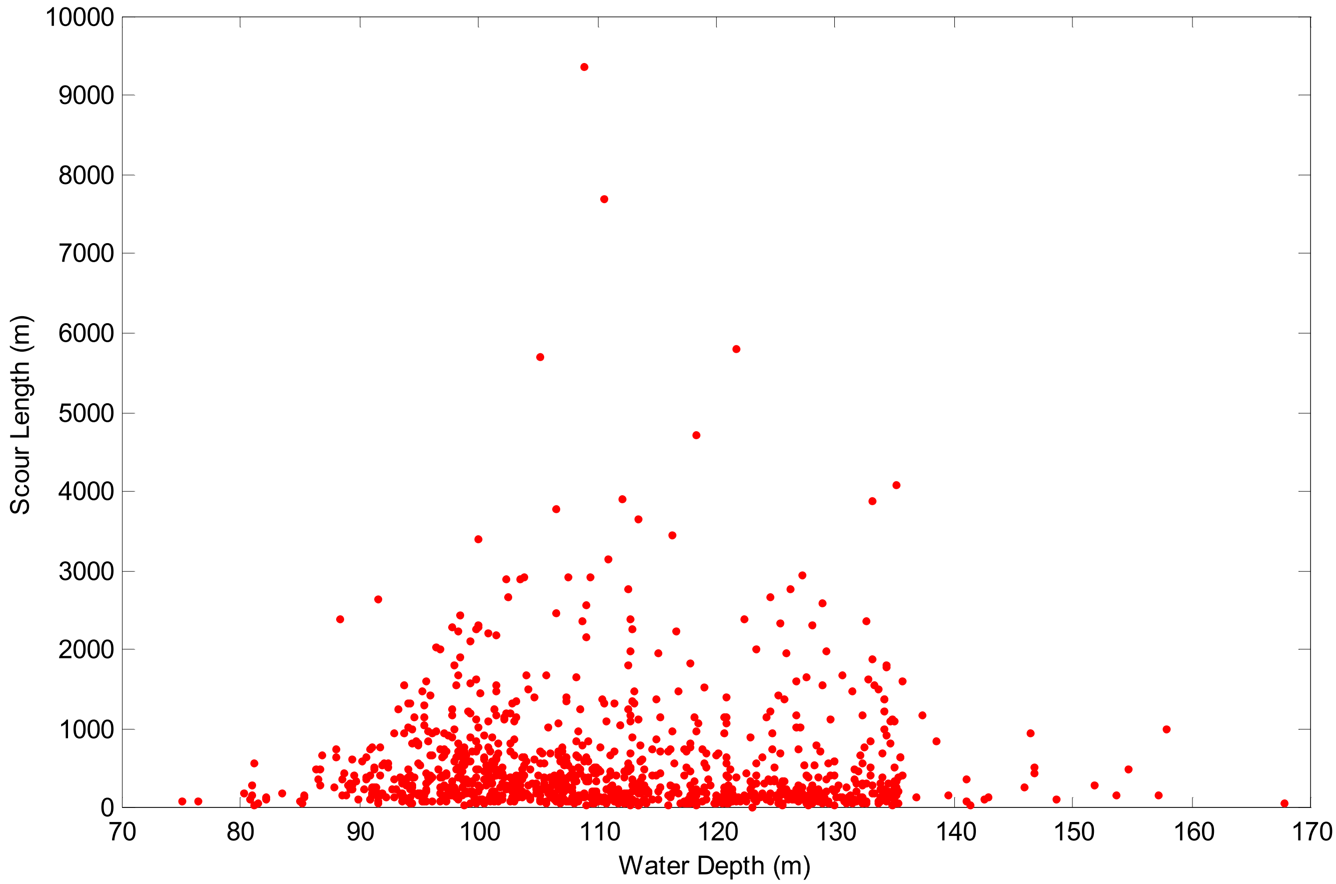

Figure A-15 Scour length as a function of water depth.

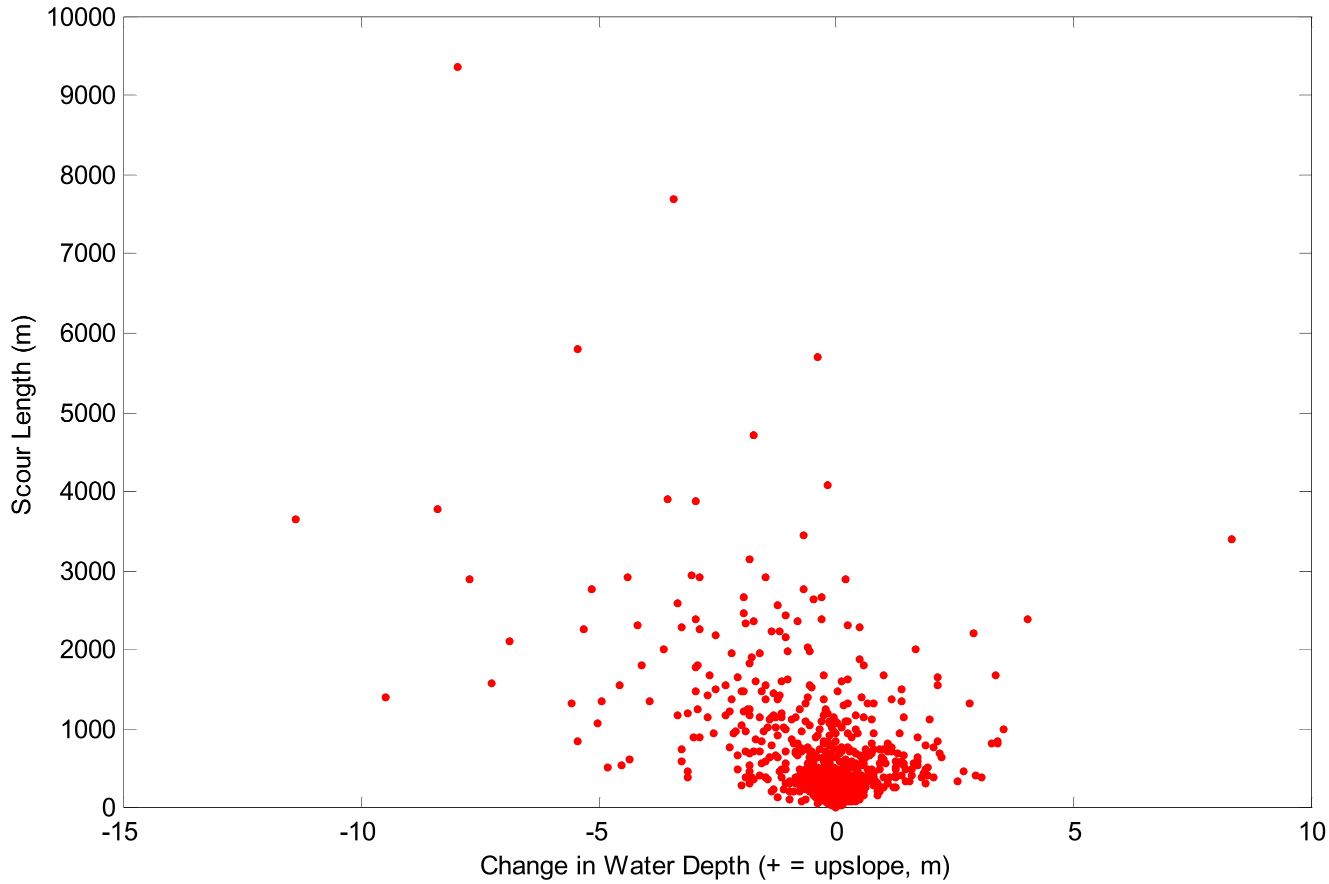

Figure A-16 Scour length as a function of change in water depth.

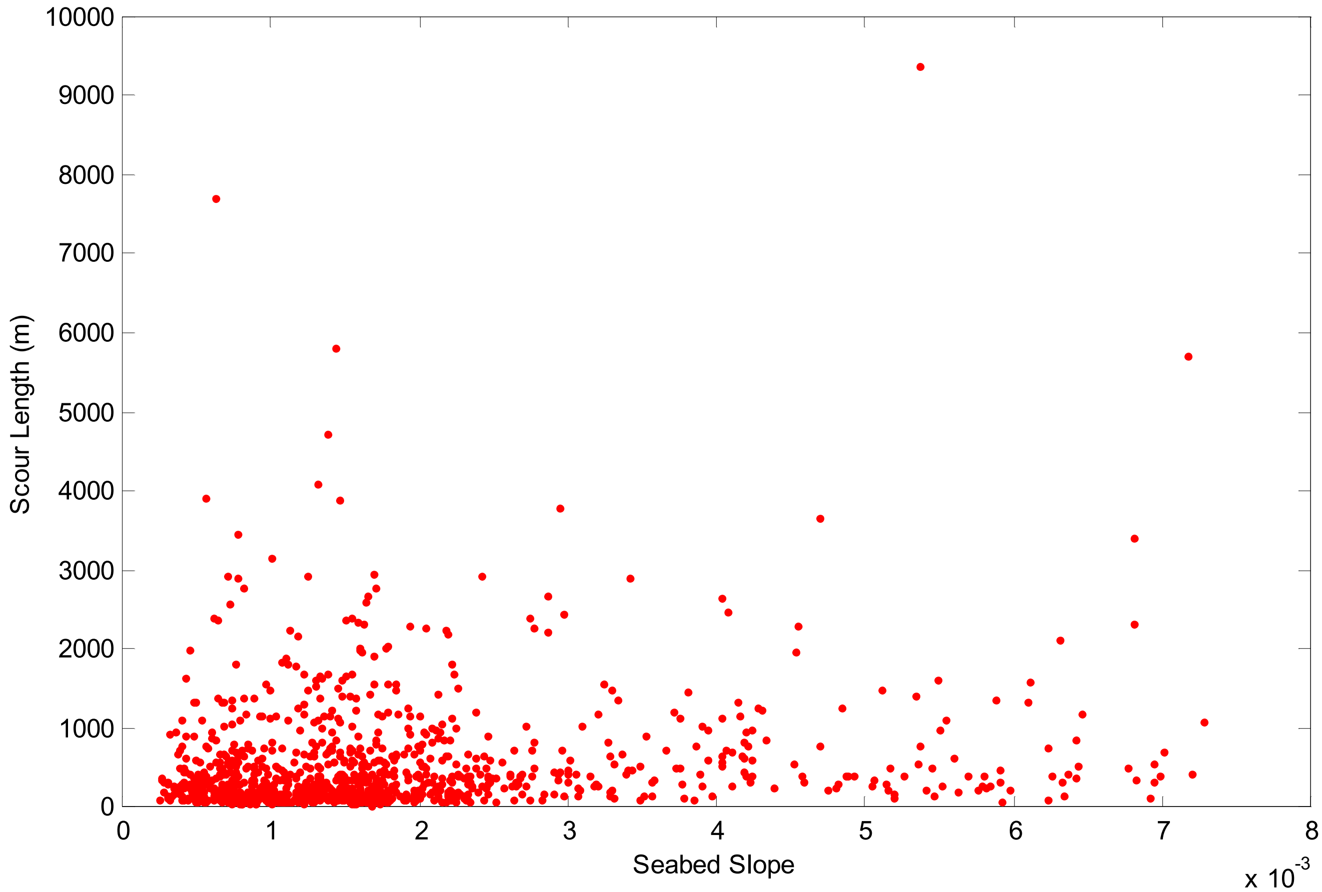

Figure A-17 Scour length as a function of seabed slope.

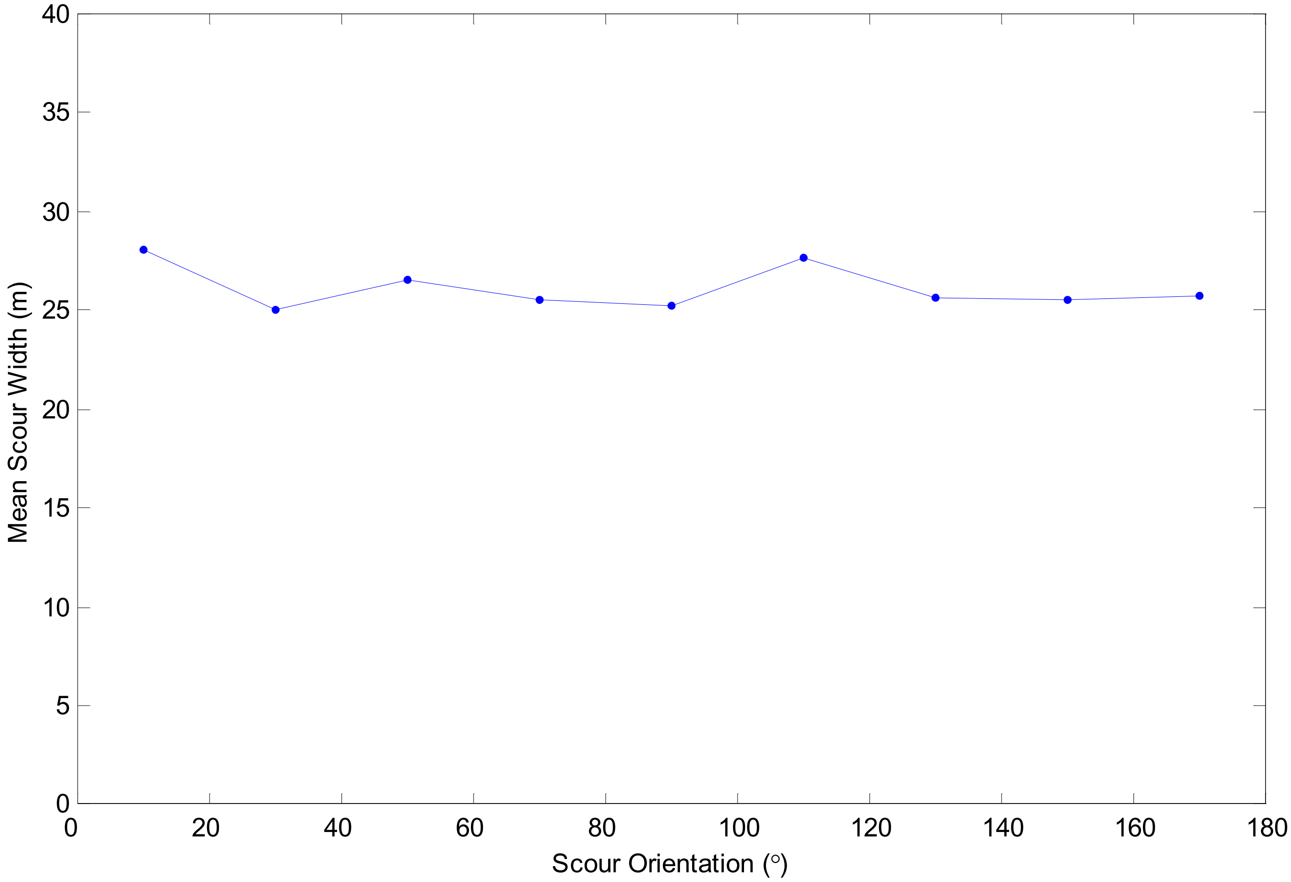

Figure A-18 Relationship between mean scour width and scour orientation.

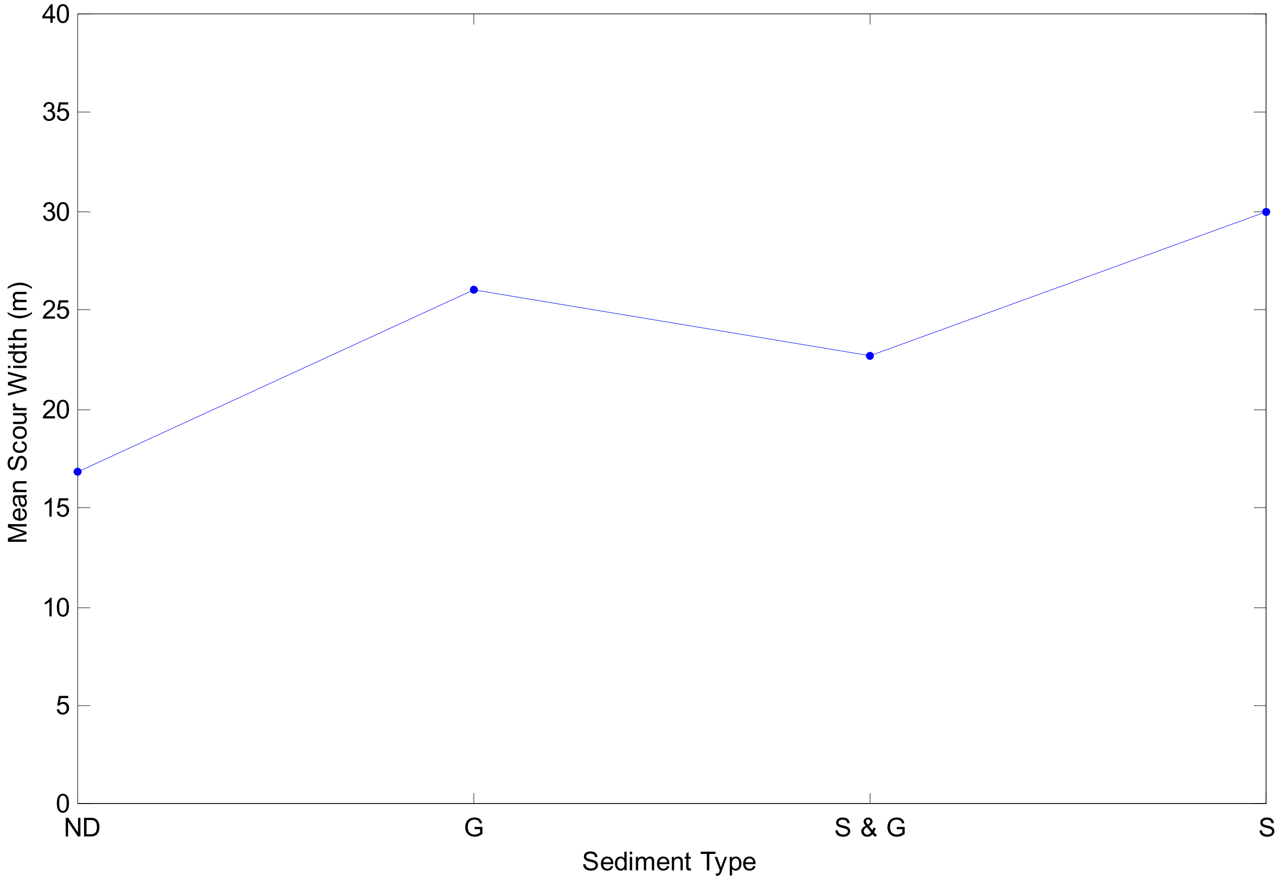

Figure A-19 Mean scour width as a function of sediment type.

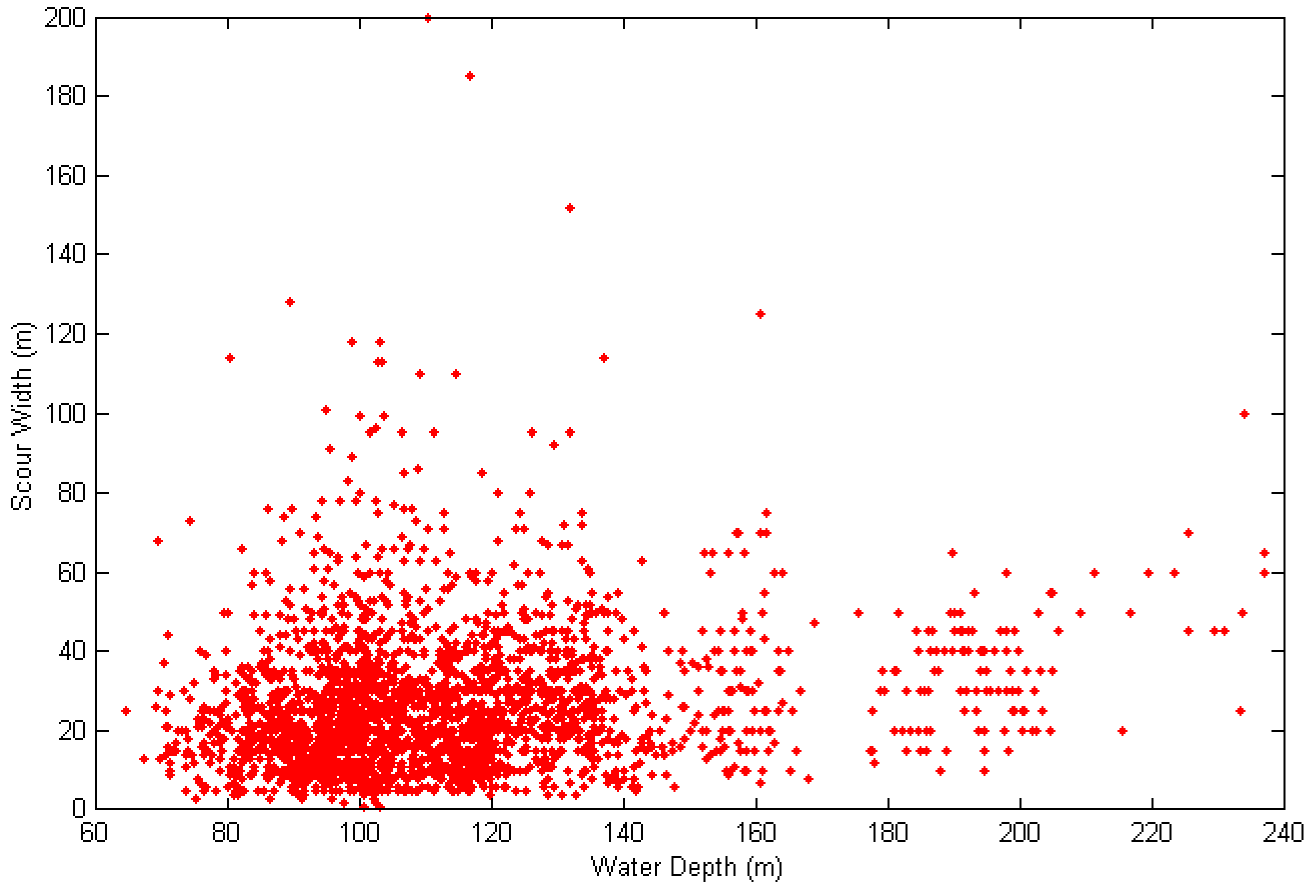

Figure A-20 Scour width as a function of water depth.

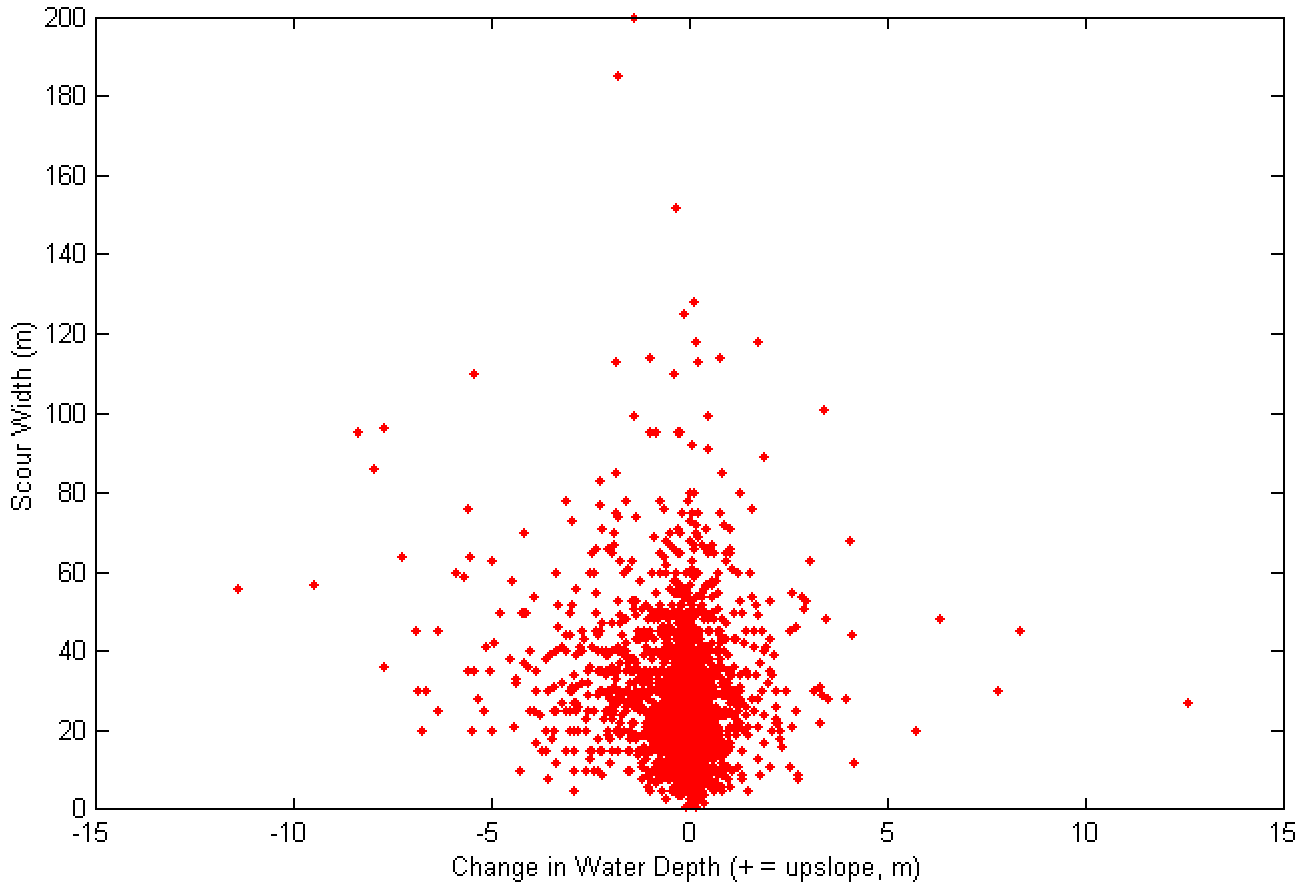

Figure A-21 Scour width as a function of change in water depth.

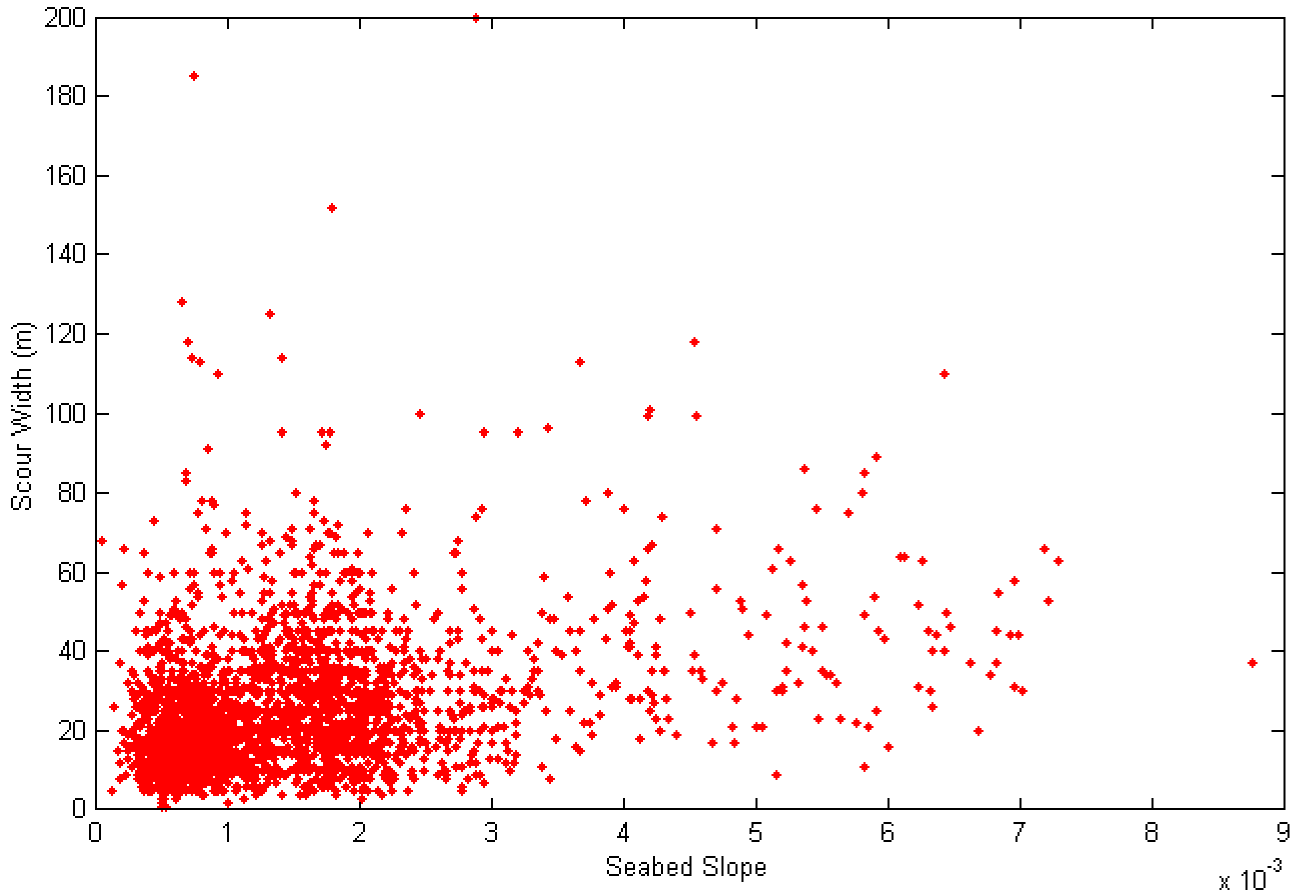

Figure A-22 Scour width as a function of seabed slope.

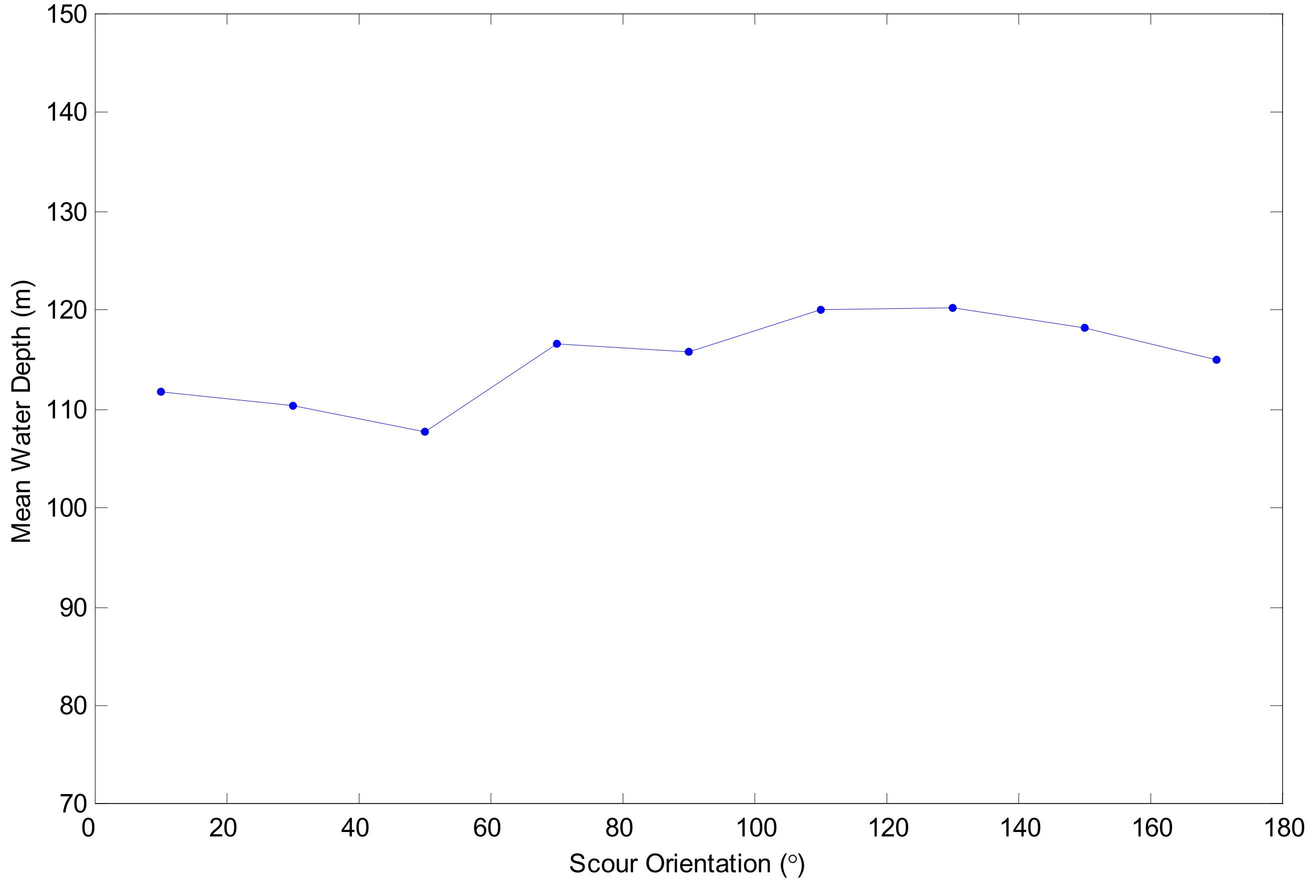

Figure A-23 Relationship between mean water depth and scour orientation.