Ice Scour and Gouging Effects with Respect to Pipeline and Wellhead

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Task 1 – Literature Review of Field Data

WOOD GROUP KENNY

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Executive Summary

The United States Geological Survey (USGS) completed a Circum-Arctic Resource Appraisal (CARA) [30] evaluating the oil and gas reserves in the Arctic region. The sum of the mean estimates for all provinces indicates 1,670 trillion cubic feet (tcf) of natural gas and 90 billion barrels of crude oil unexplored.

New, specially developed, innovative and relatively expensive technologies are essential in overcoming the harsh climate conditions prevalent in the Arctic. This challenging area is covered by ice most of the year. Permafrost, icebergs and seasonal pack ice present substantial challenges for oil exploration and production.

Ice Gouging

In this environment, subsea infrastructures and pipelines must be designed and engineered to account for ice gouging. The burial depth, especially for pipelines, is determined by the maximum depth of expected gouges in the work area. Special engineering techniques have to be implemented to avoid interaction of pipelines and wellheads with near sea-floor keels.

This interim report presents a comprehensive literature review of field data on ice scour and gouging collected in the Chukchi and Beaufort Seas. The data was collected with the objective of narrowing the gap of uncertainty in the parameters used to characterize ice gouging in the Arctic. This review focuses on the available data for bathymetry, ice frequency, and gouge characteristics. A brief summary compiling the history of surveys and the data reported in each survey is included in the report.

USGS issued documents describing ice gouging and geotechnical condition surveys performed in the Chukchi and Beaufort Seas in the 1970s and 1980s. These surveys provided usable ice gouging data set for ice gouging characterization. Although the surveys covered a large area of the Beaufort Sea seabed, they were limited to near-shore areas. Since each survey was performed for a specific purpose, the datasets presented several discrepancies and missed important information. For example, these early surveys were concerned only with the maximum gouge depth. The gouge width was not listed in all surveys. Gouge events data varied widely in these surveys. In general, the surveys did not follow a consistent gouge report approach.

This report also presents the results of the statistical analyses interpreting the datasets provided by the USGS and evaluates the limitations of the datasets. Additional handling of the datasets is essential to provide meaningful probabilistic distribution (i.e., separation of multiple and single gouges and gouge classification based on their depth of occurrence). Some analyses failed to provide meaningful distributions due to a lack of sufficient dataset population. As a result, the provided distributions have a low-confidence level for design purposes.

Findings and Recommendations

- The available dataset provided extensive information regarding gouge dimensions, location and intensity in the Chukchi and Beaufort Seas. In addition, some data differentiated between the single and multiple keel gouges. Surveys covered large areas in both seas and were performed for a wide range of water depths.
- Comparisons of the available datasets showed discrepancies and inconsistencies among surveys. A consistent surveying approach must be instituted. Single and multiple gouges must be differentiated, and all observed gouge widths must be listed in the surveys.
- Statistical analysis of the available datasets showed that the data may not be enough to provide a reliable probabilistic distribution. It is not recommended to use the distribution parameters, as they have a low-confidence level.
- It is highly recommended to perform additional USGS and independent ongoing surveys in the Chukchi and Beaufort Seas. Repetitive mapping must be performed periodically to record ice gouges changes. It is important to determine the age of gouges since this is a necessary parameter used to calculate the return rate of similar gouges.
- The available data did not included iceberg characteristics (mass, keel draft, keel geometry and near gouging keel distributions). There is not enough data available to recommend a design approach for wellhead placement (i.e., preventive or protective). Iceberg characteristic data listed above needs to be collected for both gouging keels and near gouging keels.

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1.0 Introduction

1.1 General

This interim report is written as part of the requirements included in the Statement of Work in Contract No E14PC00011 between the Bureau of Safety and Environmental Enforcement (BSEE) and MCS Kenny (now known as Wood Group Kenny). The project is entitled "Ice Scour and Gouging Effects with Respect to Pipeline and Wellhead Placement and Design."

The work under this contract is a result of a proposal submitted in response to Broad Agency Announcement (BAA) E14PC00011 titled "Arctic Safety of Oil and Gas Operations in the U.S. Outer Continental Shelf."

1.2 Objectives of this Project

The objective of this project is to identify knowledge gaps in ice scour and gouging effects with respect to pipeline and wellhead placement and design.

Wood Group Kenny (WGK) will perform the tasks listed below. Three interim reports will be provided for Tasks 1, 2 and 3. The findings of Tasks 1 to 3 will be provided in the Final Report to be published by BSEE.

Task 1 – Literature Review of Field Data

Task 2 – Literature Review of Test Data

Task 3 – Literature Review of Numerical Modelling

Task 4 – Final Report

This Interim Report No. 1 summarizes the findings of Task 1 in which WGK performed a comprehensive literature review of the field data collected by others for ice scour and gouging. The focus area of this study is the Beaufort and Chukchi Seas.

1.3 Scope of the Report

WGK performed a comprehensive literature review and compilation of field data that could narrow the currently large margin of uncertainty in the area of ice scour and gouging. The study reviews available data for bathymetry, ice gouging frequency, ice drift speed, keel draft distribution, ice-keel geometry and attack angle. The developed models for predicting ice keel grounding rates are site specific. An engineering review compiling available literature and data on the geotechnical conditions for all soil types within the Beaufort Sea has been performed. Ice keel drift tracks are also reviewed. The frequency of specific shapes and sizes of icebergs, together with the oceanography and wind climate, is taken into consideration to establish the near-grounding frequency that can potentially interact with wellheads and subsea structures. A gap analysis identifying deficiencies in the currently available data is presented here.

1.4 Abbreviations

Below is a list of abbreviations which have been used throughout the report.

ALIE	**Abnormal Level Ice Event**
BSEE	Bureau of Safety and Environmental Enforcement
EDC	Excavated Drill Center
MCSK	Marine Computation Services Kenny
MMS	Minerals Management Service
ROV	Remotely Operated Vehicle
USGS	United States Geological Survey
WGK	Wood Group Kenny

2.0 Arctic Oil and Gas Challenges

2.1 Introduction

The USGS Circum-Arctic Resource Appraisal (CARA) has estimated oil and gas reserves in the Arctic region of 1,670 trillion cubic feet (tcf) of natural gas and 90 billion barrels of crude oil [30]. This represents approximately 30% of the gas and 13% of gas reserves around the world. With the increasing decline in the oil and gas production from conventional reservoirs, oil and gas production in the Arctic region is gaining an economic advantage. Therefore, the Arctic region has high potential for exploration and production investment. The USGS estimated that $100 billion dollars will be invested in the Arctic region over the next decade. The cost of subsea structures represents a high percentage of those expected investments.

The Arctic region is covered with ice most of the time, almost eight months per year. Ice coverage and environmental conditions pose serious challenges that limit the opportunities for oil and gas field development. Due to the fact that access to the seabed is possible only during the spring and summer seasons, innovative and relatively expensive technologies are essential to overcome the challenges related to harsh climate conditions. In addition, subsea structures are subjected to hazards created by the harsh environment (i.e., permafrost, icebergs, and seasonal pack ice).

The Beaufort and Chukchi Seas fall within the Arctic Ocean and contain significant reserves of petroleum and natural gas. Exploration activities in the Beaufort and Chukchi Seas (between the 1950s and 1980s and the 1990s and 2000s) indicated that the region could be a promising area for oil and gas production.

The Arctic region is defined as the region above the Arctic Circle, an imaginary line that circles the globe at latitude 66° 32" N. At the North Pole, the sun rises once each year and sets once each year meaning that there are six months of continuous daylight and six months of continuous night. This region includes any locations in high latitudes where the average daily summer temperature does not rise above 50^{o} F (10^{o} C) [21]. Geographically, the Arctic covers about 10 million square miles (approximately 26 million square kilometers) or five (5) percent of the earth's surface, including areas onshore and offshore, ice and ice-free covered areas. In terms of oil and gas exploration, the Arctic is interpreted as a region with extremely low winter temperatures, long-term ice coverage, deep seas, very large fields, and extremely sensitive ecosystems. Areas of interest mainly include the Barents Sea, the Russian Arctic region, onshore Russia, Chukchi Sea, Beaufort Sea, the Canadian arctic islands, northern Canada, Alaska and the east coast of Greenland. Each area has different challenges; however, they are mostly related to climatic and environmental conditions.

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Figure 2.1: Arctic Map [21]

2.2 Key Arctic Challenges

Climate conditions in the Arctic include extremely low winter temperatures, ice gouging by pressure ridges, icebergs in shallow water depths, strudel scour, and permafrost thaw. The severe conditions in the Arctic have a direct effect on construction and installation processes (trenching and well interventions) as well as maintenance operations, such as leak detection, monitoring, inspection pigging, pipeline repair, and flow assurance. Figure 2.2 describes the key Arctic challenges.

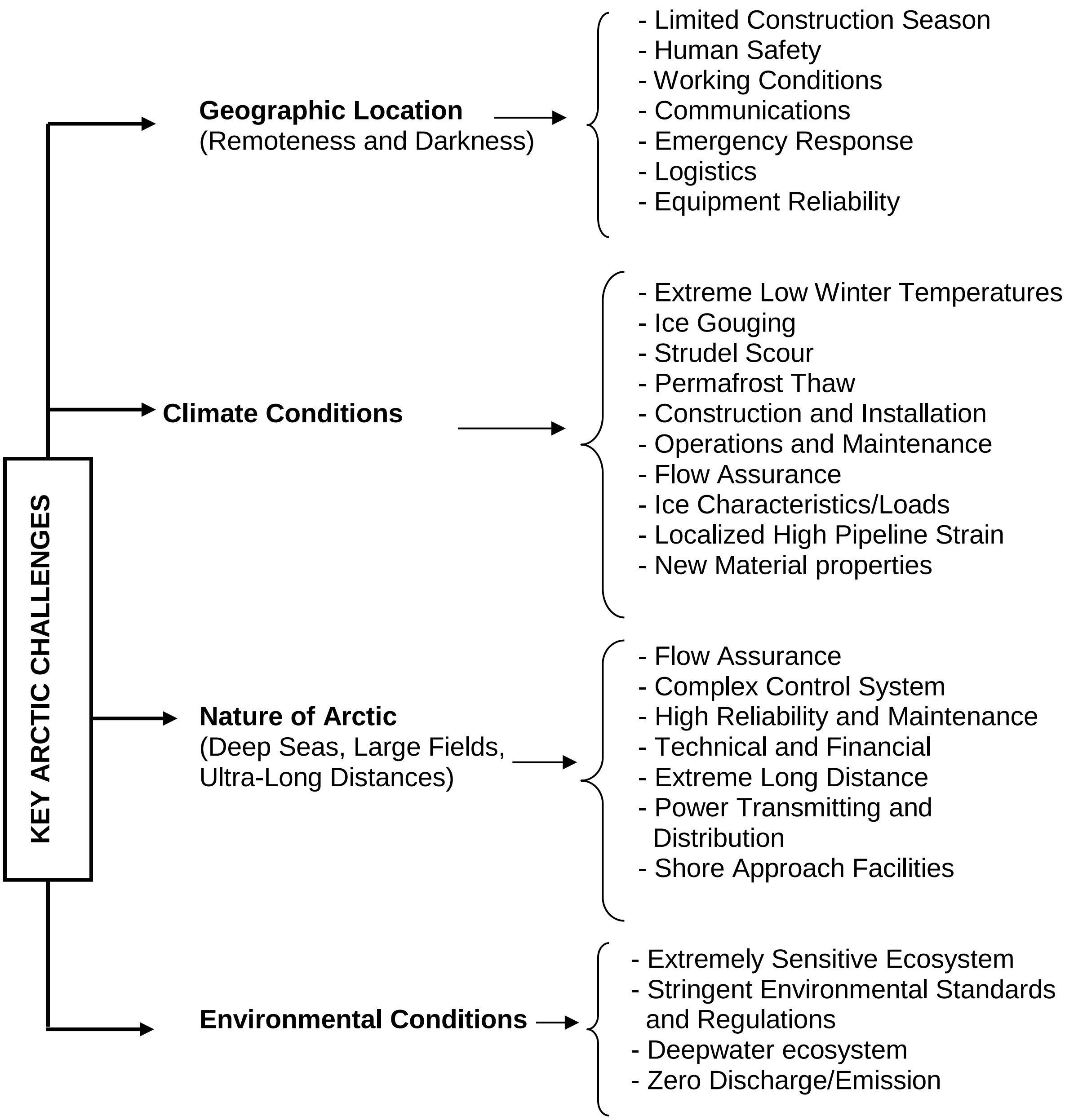


Figure 2.2: Key Arctic Challenges

2.3 Icebergs

Icebergs are large, floating fragments of ice detached from ice sheets or glacier edges. According to NOAA, to be classified as an "iceberg" an ice sheet must be greater than 16 ft above sea level, 98-164 ft thick, and cover an area of at least 5,382 square ft. The International Ice Patrol [7] estimated about 40,000 medium-to-large-sized icebergs breaking off, or calving, from Greenland glaciers. Only about 400-800 make it as far south as St. John's, but these numbers can vary greatly from year to year. Icebergs vary in size and shape and along their travelled path they melt, flip or break into smaller masses (Some iceberg masses may exceed 4.5 million tons). Table 2.1 lists the possible iceberg shapes [7]. The International Ice Patrol issued an iceberg characterization based on dimension and mass as shown in Table 2.2 [9].

Characteristics and crossings of icebergs are not easily predicted. Some icebergs travel more than 2,000 miles (approximately 3200 km) away from their origin, carried by ocean currents. Icebergs represent the biggest challenges for subsea structures in the Arctic region as the latter may be impacted several hundred times in their field life by icebergs, each one weighting several thousand tons.

Table 2.1: Iceberg Shapes (Iceberg Finder Website, 2007)[7]

Shape	Description
Tabular	A flat-topped iceberg. Most show horizontal banding. Usually width is greater than five times their height.
Dome	An iceberg which is smooth and rounded on top.
Pinnacle	An iceberg with a central spire, or pyramid, may have additional spires.
Wedge	An iceberg with flat surfaces steep on one side and gradually sloped to the water on the other forming a wedge shape.
Dry-dock	An iceberg which is eroded such that a U-shaped slot is formed near, or at, water level with two or more pinnacles or columns.
Block	A flat-topped iceberg with steep sides.

Table 2.2: Iceberg Characterization [9]

	ICEBERG SIZE / WEIGHT CLASSIFICATION				
Size Category	**Height**		**Length**		**Approx. Weight metric Tons (mT)**
	(ft)	**(m)**	**(ft)**	**(m)**	
Growler	less than 3.28	less than 1	less than 16.40	less than 5	<53
Bergy Bit	4.92-16.40	1.5-5	16.40-49.21	5-15	<1,400
Small	16.40- 49.21	5-15	49.21-196.85	15-60	91,000
Medium	49.21-164.04	15-50	196.85-393.70	60-120	730,000
Large	164.04-328.08	50-100	393.70- 721.78	120-220	4,500,000
Very Large	Over 328.08	Over 100	Over 721.78	Over 220	Over 4,500,000

2.4 Ice Gouging

Subsea infrastructure and pipelines must be designed taking ice gouging into consideration. The burial depth, in the case of a pipeline, is determined based on the maximum expected gouge depth in the area. Special techniques, as discussed in this report, may be adopted to place wellheads in areas minimizing interaction with near sea floor keels.

Ice gouging can be classified into single and multiple keel events, as shown in Figure 2.3. A single keel event occurs when one keel iceberg disturbs the seabed floor, causing a deep groove. The soil on each side of the gouge is pushed upward to form berms. On the other hand, multiple gouges can occur when a larger iceberg with multiple keels interacts with the sea floor.

Wind and currents are the environmental forces that drive icebergs. The gouging process starts when the tip of the keel interacts with the seabed. The keel pressure on the seabed forms a zone of over-consolidated soils. Due to increased friction and soil resistance around the keel surface, the entire iceberg might be tilted upward, decreasing the interaction between the keel and the soil, thus allowing the iceberg to move forward. When ice strength is a limiting factor, fracture of the keel tip may occur resulting in a smaller iceberg, which can travel further toward shallower water depths.

The dimensions of possible gouges may be estimated based on the general trend of gouge dimensions observed in the area of interest. The most important parameters for ice gouging risk assessment are the gouge dimensions (depth and width) and gouge rate. Gouge depth, also referred to as the incision depth, is measured from the seabed (before disturbance) to the deepest point in the gouge. Gouge width is measured inside the gouge and is the distance between two points lying on the same seabed level of that prior to the disturbance. Another critical parameter to take into consideration is gouge rate, which is expressed as the number of gouges passing per mile (kilometer), per year. Periodic mapping (surveying) of the sea floor is essential to record the new gouges, hence, estimating the return period of similar gouge events in the future.

Minerals Management Service (2008) [18] concluded that deeper gouges tend to be wider. This may be an indication that deep gouges are created by very large icebergs. Wide gouges, on the other hand, are not necessarily deep. This MMS report [18] stated that the current available data is not adequate to define the joint distribution of gouge width and depth. One of the technical challenges, when performing a comparative study of available field data, is that gouge width was not recorded in the early surveys as the focus , at that time, was on estimating the deepest required burial depth.

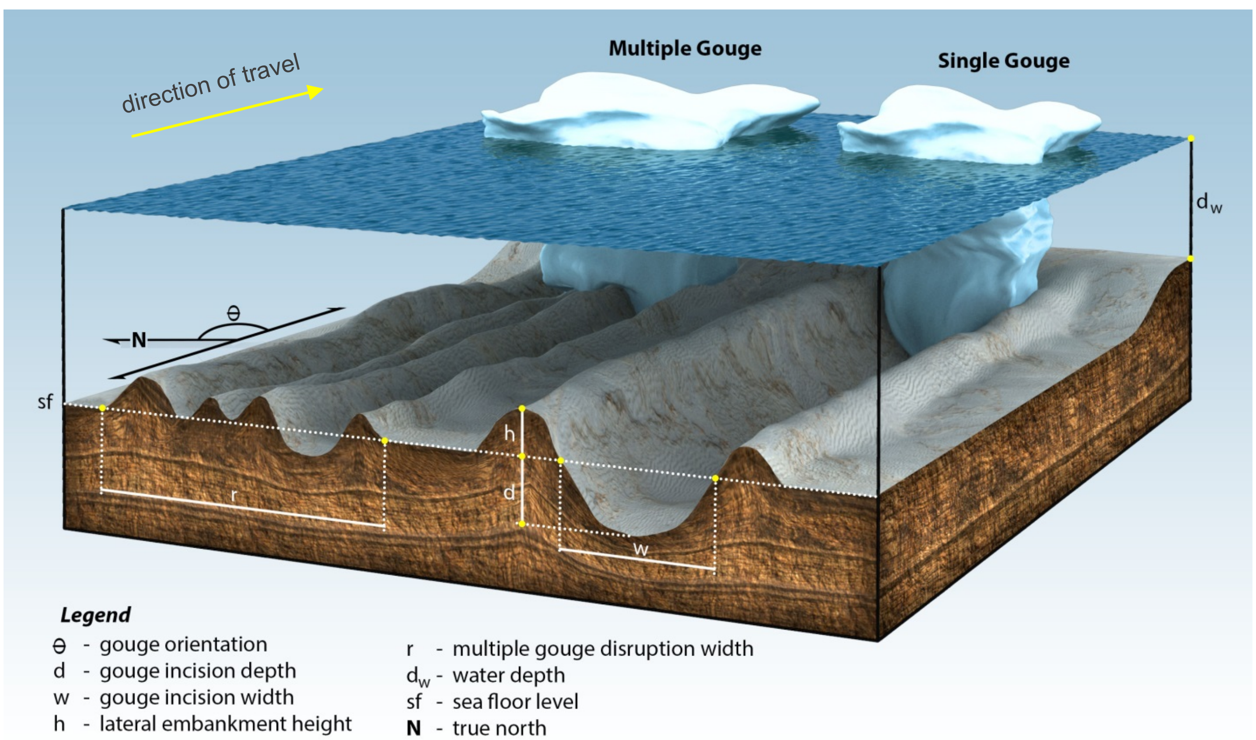


Figure 2.3: Single and Multiple Keel Icebergs (Modified by WGK) [25]

2.5 Subsea Wellhead

One of the most critical challenges in the Arctic environment is the design and placement of subsea wellheads, under the assumption of potential damage due to icebergs. Unlike pipelines, wellheads (also known as Christmas trees) are vertical structures which extend several meters above the seabed, as shown in Figure 2.4. They must be protected from damage produced by floating or gouging icebergs. Christmas trees are installed on top of the wells as a final stage of well completion. The trees are then able to provide complete control of the wells (i.e., maintenance, shut-in, injection, production, etc.).

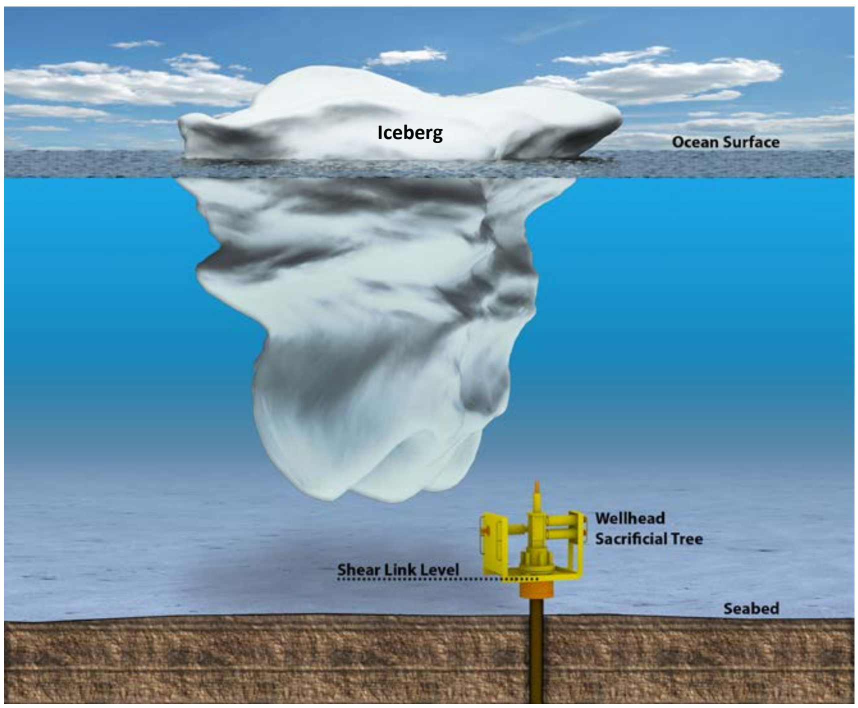


Figure 2.4: Effect of Ice Gouging on Wellhead

Several techniques have been adopted to protect a wellhead from icebergs. The techniques are classified as preventive, protective and sacrificial. Wellheads can be protected against contact with icebergs by placement in areas with a minimal crossing rate. A preventive technique assesses the characteristics and frequency of the possible gouge and minimizes the risk of contact by selecting the areas with the lowest risk. When the protective technique is used, wellheads are protected against contact with icebergs by placing them inside Excavated Drill Centers (EDC), also known as mudline cellars or glory holes. A mudline cellar allows for the subsea equipment to be installed below the seafloor at depths greater than the anticipated ice-gouge depth. A schematic of cased and uncased drill holes is shown in Figure 2.5 and Figure 2.6, respectively. This method requires excavating the drill center and placing all subsea equipment at the bottom of the excavation. The depth of the EDC takes into account the expected depth of the gouge from passing ice keels and the expected height of the highest portion of the subsea equipment. This technique requires the removal or evacuation of a substantial portion of the seabed and is often costly both in terms of financial cost but also in regards to its impact on the environment.

Ralph, et al. (2011) [5] presents three conceptual alternatives to EDCs:

1. Revised well casing design;
2. Protective truncated cone structure installed above the mudline; and
3. Sub-seafloor protective structure.

The first concept involves devising a mechanical Shear Connection Linkage such that, given an extreme ice keel loading event, displacement of the wellhead system is isolated to a zone near the mudline while maintaining the integrity of the downhole safety barriers. Ralph, et al (2012) [24] explain that the shear link, or failure joint, would act as a mechanical fuse designed to fail in a combination of shear, tension and buckling during keel loading. The failure joint minimizes the downhole structural response during iceberg keel loading on the production tree. The designed failure mechanism would allow the well to be re-entered by protecting the well casing from damage.

The second concept includes a protection structure at the mudline that sits over the top of a single wellhead system, protecting it from direct interaction with an iceberg keel. The protection structure absorbs energy through crushing of the ice keel and encourages the iceberg to deflect around and over the structure. The steel structure should be designed according to ultimate limit states accounting for energy absorption through elastic and plastic deformation of the structure. Design loads should correspond to an Abnormal Level Ice Event (ALIE) with an annual exceedance probability of 10^{-4}. The size of the frame is governed by the size of the wellhead and tree system, Remotely Operated Vehicle (ROV) access requirements, and slope to encourage iceberg keel deflection.

The third concept is applicable to single and small well cluster systems. It requires relatively smaller but more precise seabed excavation compared to the conventional EDCs. King, et al. (2012) [10] investigated the feasibility of protecting wellhead systems by housing them in a buried rectangular caisson.

While some of these concepts may eliminate environmental impact, these complex systems may be cost prohibitive for exploration wells and/or minimal or marginal field tie-in wells. The so called “sacrificial” technique is based on a probabilistic design approach. If the estimated probability of exceedance meets the acceptable risk level criteria the design may be adopted. Contact between the well head and the iceberg keel and shearing by the advancing keel is a possibility, hence a safety shutdown valve is installed below the anticipated gouge depth in order to prevent the release of hydrocarbons. However, there is a significant risk of malfunction of the safety valve involved and this approach is not recommended.

Design for wellhead placement requires additional information about iceberg's keel draft, keel angles, and near gouging keel distributions to determine the possibility of contact with floating and gouging icebergs. The available survey data from seabed scanning is only limited to induced gouges over a period of time. The crossing frequencies provided in the literature do not include near gouging events.

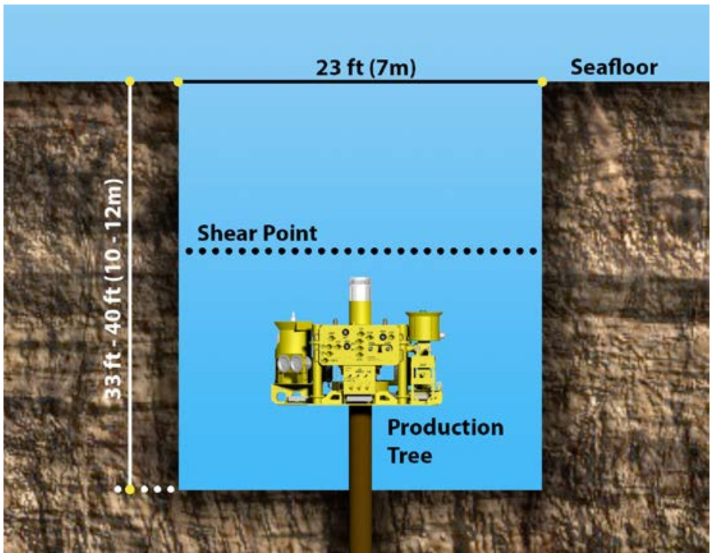


Figure 2.5: Cased Excavated Drilling Center Arrangement

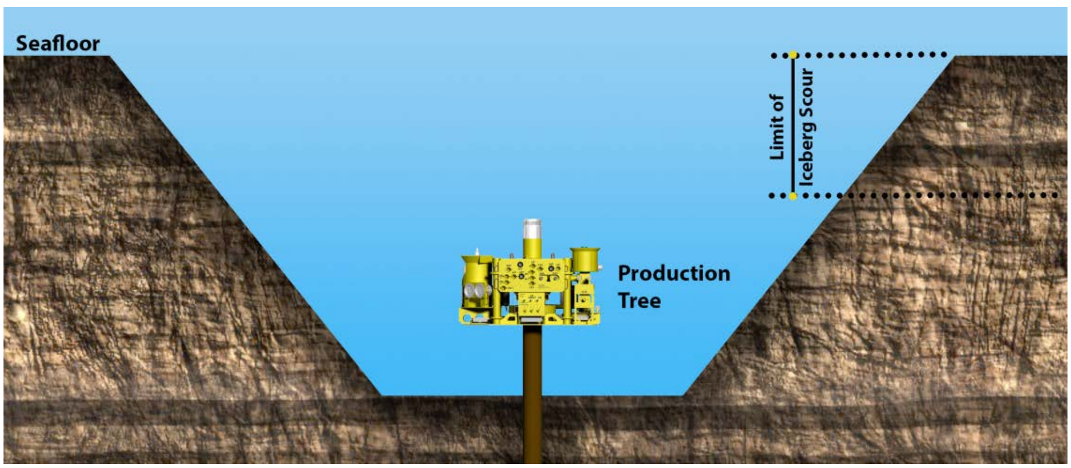


Figure 2.6: Uncased Excavated Drilling Center Arrangement

3.0 Geotechnical Characteristics of Beaufort Sea and Chukchi Sea

3.1 Beaufort Sea

The Beaufort Sea is located at the far edges of the Arctic Ocean to the north of the Alaska and Yukon shores. The shore of the U.S. Beaufort Sea extends between Point Barrow, Alaska to the south western edge of Prince Patrick Island. The deepest point of the Beaufort Sea is approximately 15,360 ft. (approx. 5000 m) and estimated surface area of the sea is 184,000 sq. mi (approx. 476,000 sq. km).

The Beaufort Sea is located in the north portion of the Arctic Sea and is characterized by severe weather conditions. It is covered with ice approximately nine months of the year and partially covered (5% to 30%) with ice during the summer. The continental shelf extends approximately 36 to 72 miles (58 -116 km) away from the shore at a water depth interval ranging from 200 to 230 ft. (61 to 70 m). Barrier islands extend several meters above sea level and form a chain of islands parallel to the shoreline at shallow waters (30 to 60 ft. (9-18 m)). Figure 3.2 shows the location plan and bathymetry of the Alaskan Beaufort Sea [17].

Intensive geotechnical surveys were performed to investigate the geotechnical profile of the seabed. A summary of all of the research findings are discussed in the following sub-sections.

3.1.1 Barnes and Reimnitz (1974)

Reimnitz, et al. [26] described soil characteristics in the Beaufort Sea based on vibrocore samples and in-situ testing collected at 23 locations. Locations of vibrocore samples and in-situ testing are shown in Figure 3.3.

Mean diameter of grain size distribution, sorting of sediment samples, and distribution of gravel in surface sediments are shown in Figure 3.4 to Figure 3.6. An additional location map was prepared by MMS [16] to show the sea surficial sediments in the near-shore areas, shown in Figure 3.7.

Barnes and Reimnitz [2] reported that soils in the Beaufort sea seabed surface can be classified into three main categories; poorly sorted, fairly well sorted fine grained sediments, and moderate to well sorted sand and silts. The poorly sorted soils are located along the shelf break and on the central shelf of Prudhoe Bay. The central shelf is characterized by fairly well sorted fine grained sediments, while the inner shelf contains well sorted sand and silt.

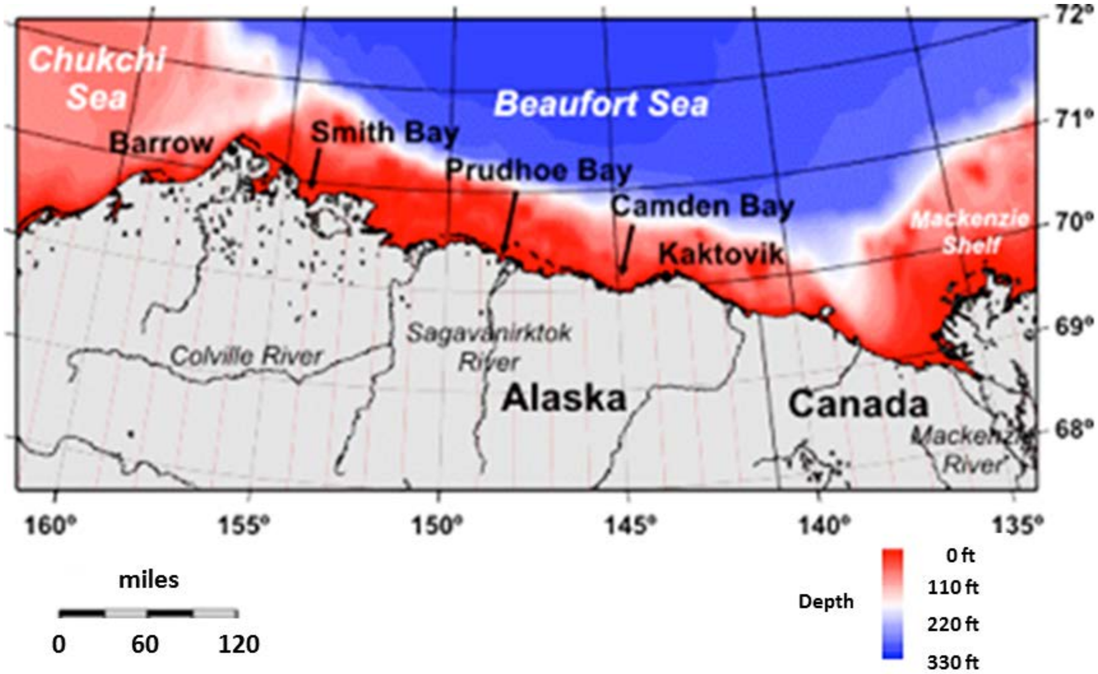


Figure 3.1: Alaskan Beaufort Sea Plan and Bathymetry [6]

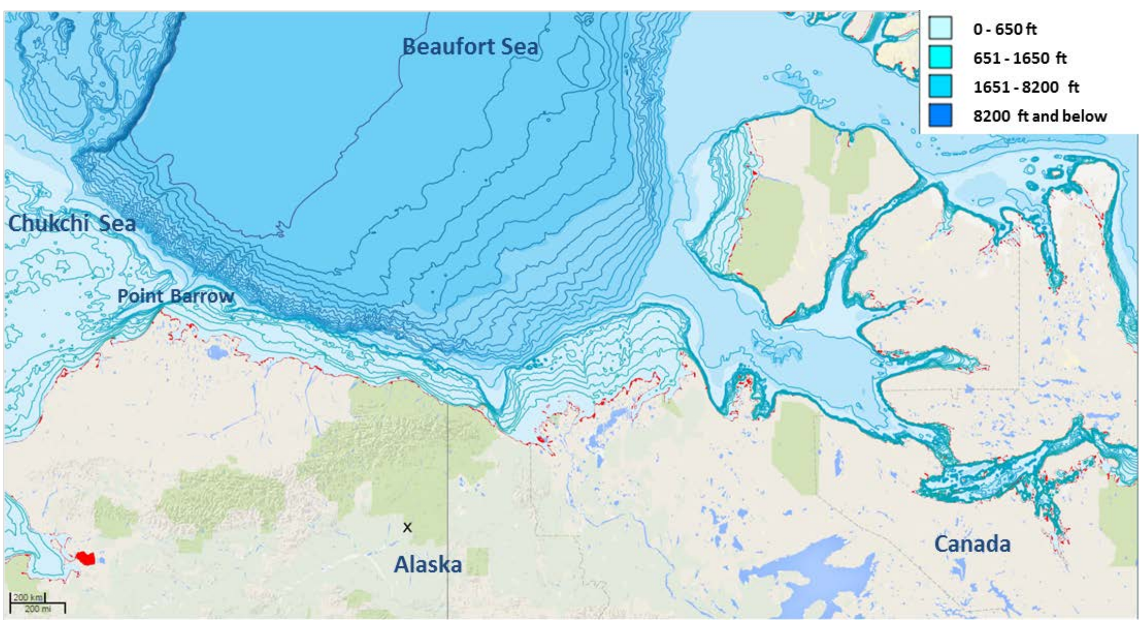


Figure 3.2: Alaskan Beaufort Sea Plan and Bathymetry [4]

3.1.2 Reimnitz, et al. (1977)

Additional investigations were performed by Reimnitz, et al. [27] to study the pore fluid salinity and temperature profiles of the Beaufort Sea at areas of interest with the intention to learn at what temperatures the sediments are most likely to freeze. Samples collected at the surface had very low shear strength, indicating a very soft seabed at testing locations. Reimnitz reported soil sample properties at the top 0.30 ft (9 cm) below the seabed. Samples collected around gouged areas may have been remolded by frequent gouging. Temperature profiles and soil samples were used to investigate the existence of ice-bonded permafrost, and borehole samples indicated that permafrost was limited to the Pleistocene deposits between 50 ft. and 200 ft. (15 m and 60 m) below the seabed. Reimnitz proposed four soil categories, based on shear strength, for the top 165 ft. (50 m) of seabed soils. A brief description of each category is listed in Table 3.1.

Table 3.1: Beaufort Seabed Soil Categories – Reimnitz, et al. (1977) [27]

#	Category	Composition	Material Strength	Location
1	Soft to medium stiff	Fine grained Holocene deltaic	~ 3 psi	Shoreward of the barrier islands in Prudhoe Bay and Mikkelsen Bay
2	Medium dense to very dense	Uniform fine sand with particle size ranges from of 0.11 and 0.19mm.	The measured internal angle of friction is 41° to 47°.	Offshore, the barrier islands are linked with underwater shoals
3	Stiff to hard	Silt and Clay deposits	Undrained shear strengths measured in the range of 7.25 to 43.5 psi, with an average value of 18.85psi	Between Cross Island and Stefansson Sound, and also to the east of the Maguire Islands.
4	Dense	Well graded Pleistocene sand and gravel	Reasonably well graded maximum of 50mm diameter particle size	

3.1.3 Miller & Bruggers (1980)

Miller & Bruggers [15] investigated the soil profile at 20 drilled boreholes intended to determine geotechnical and permafrost properties of the borehole locations. Figure 3.8 shows the location of the drilled holes and a summary of the extrapolated soil profile for the borehole soil samples as presented by Miller & Bruggers [15]. The data was used to create stratigraphic sections (AA, BB and CC) presented in Figure 3.8. Borehole locations are plotted in Figure 3.8 and summarized in Table 3.2. Figure 3.9 (a) shows the borehole logs for boreholes number 1 to 5. The stratigraphic cross-sections developed by Miller & Bruggers are shown in Figure 3.10.

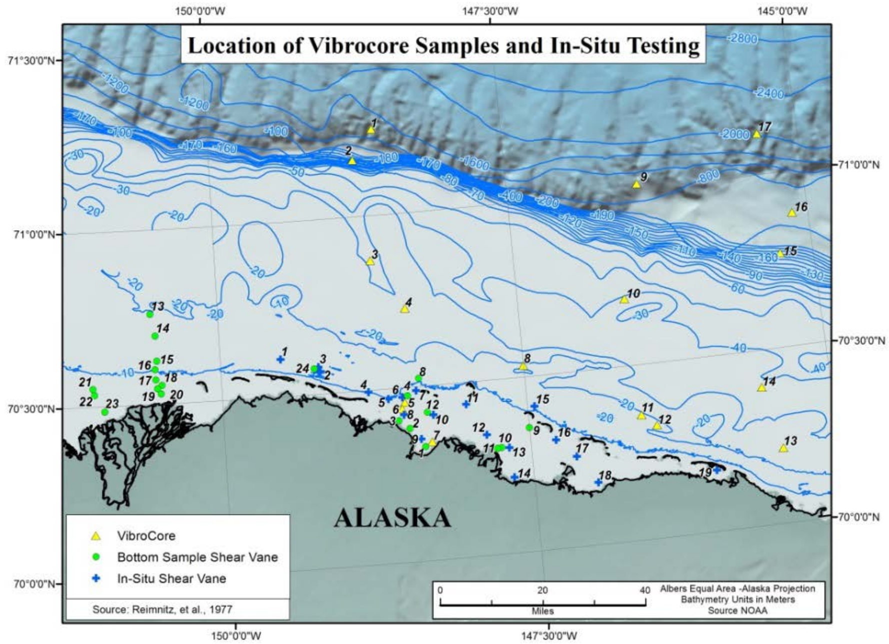


Figure 3.3: Location of Vibrocore Samples and In-Situ Testing (Reimnitz, et al., 1977) [27]

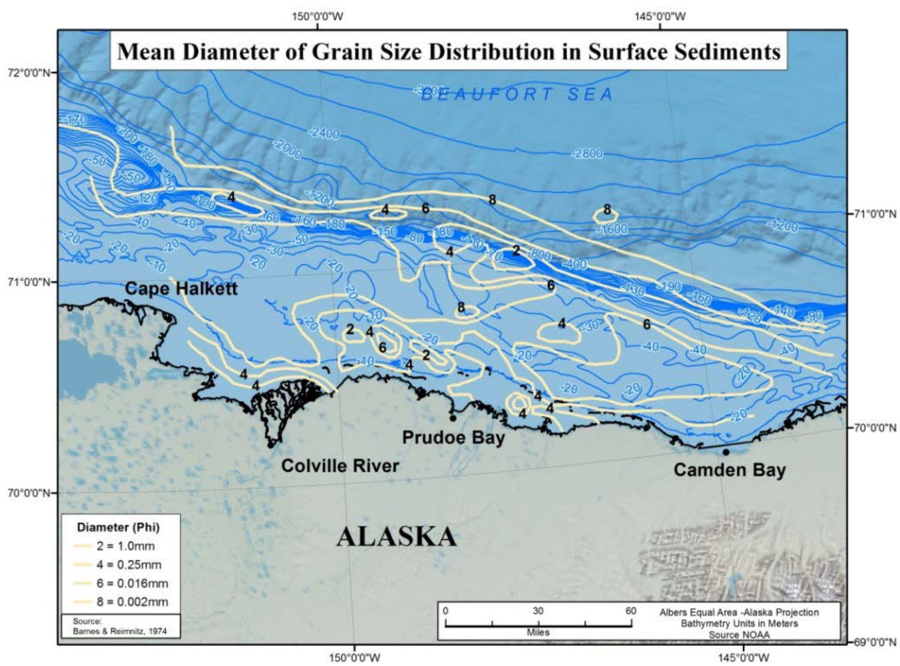


Figure 3.4: Mean Diameter of Grain Size Distribution in Surface Sediments (Barnes & Reimnitz, 1974) [2]

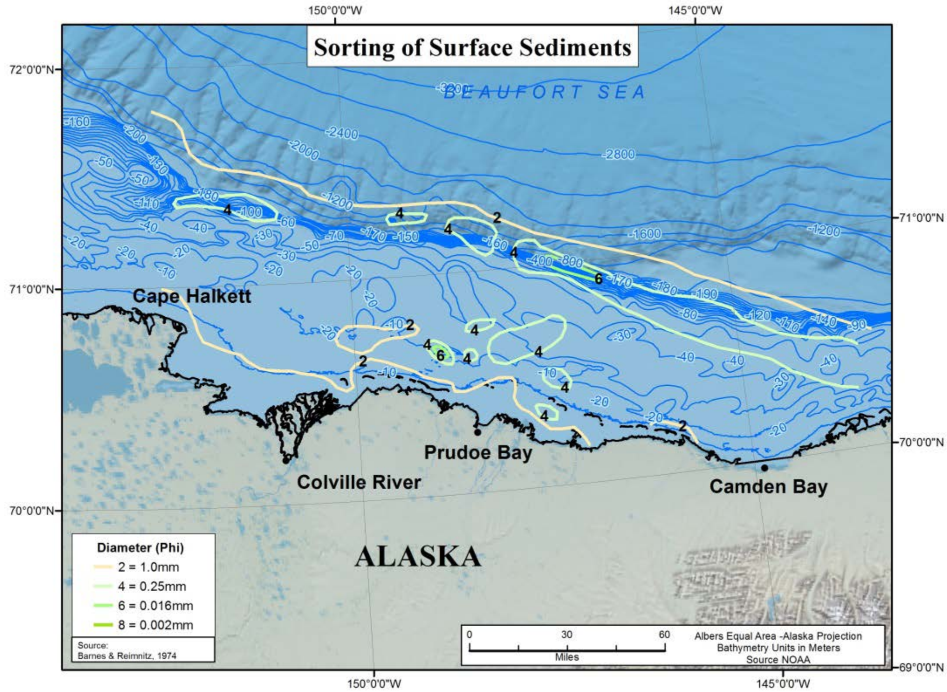


Figure 3.5: Sorting of Surface Sediment Samples (Barnes & Reimnitz, 1974) [2]

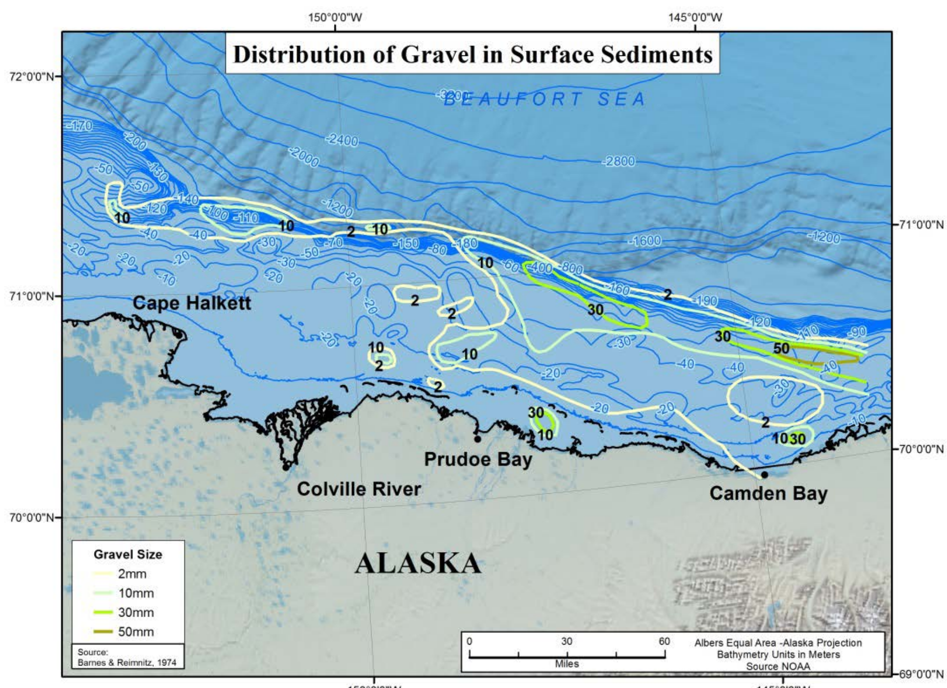


Figure 3.6: Distribution of Gravel in Surface Sediments (Barnes & Reimnitz, 1974) [2]

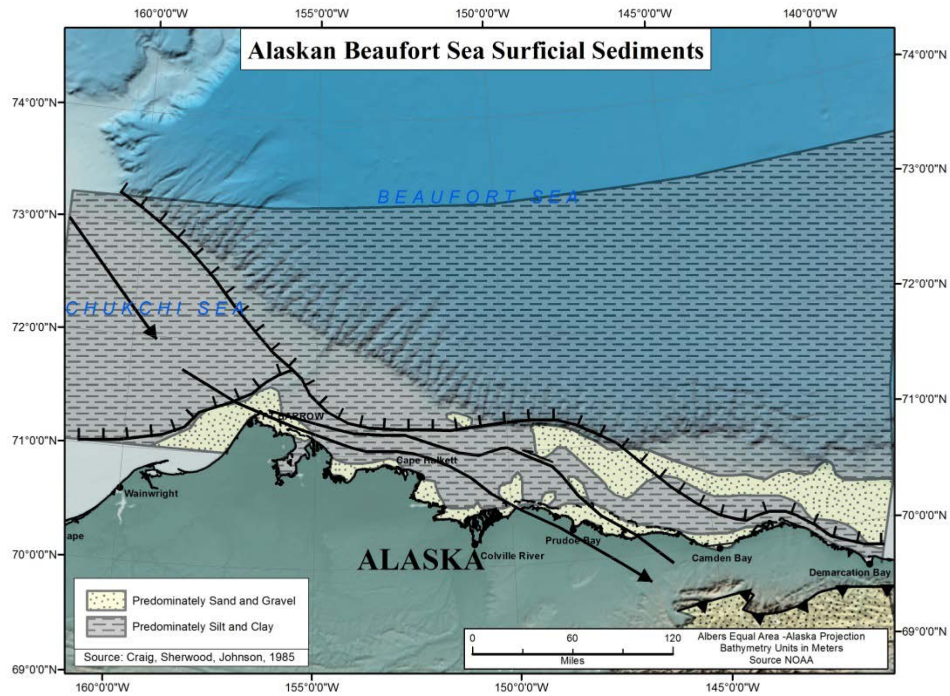


Figure 3.7: Alaskan Beaufort Sea Surficial Sediments (MMS, 1990) [16]

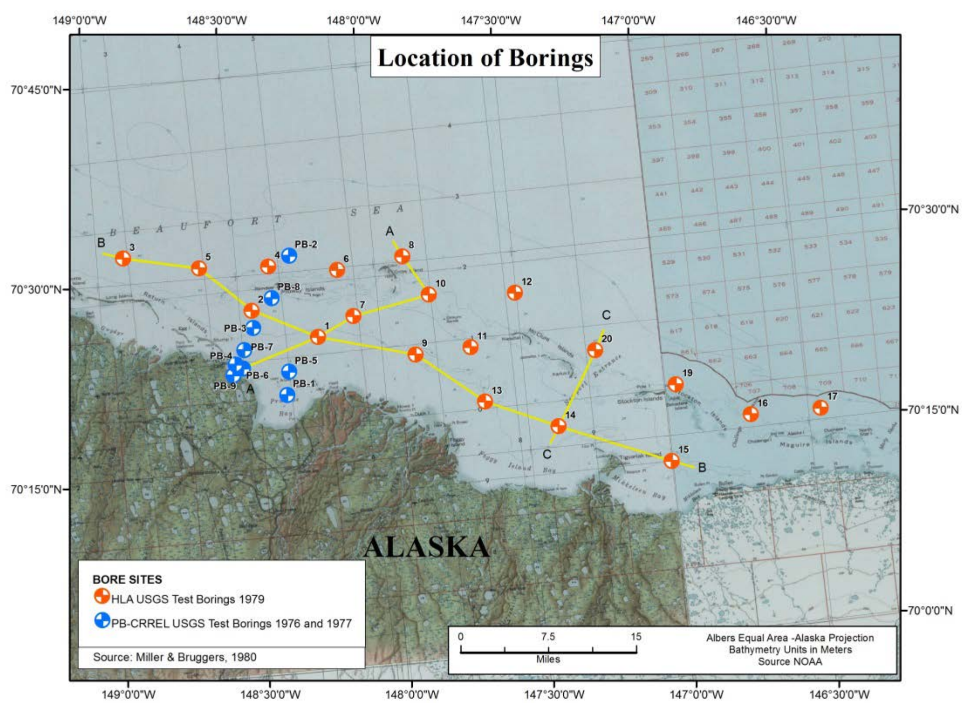


Figure 3.8: Locations of Borings (Miller & Bruggers, 1980) [15]

Table 3.2: Summary of Bore-Hole Locations (Miller & Bruggers, 1980) [15]

Boring Number	Water Depth (ft.)	Boring Depth (ft.)	Thickness of Holocene (ft.)		Depth to Top of Pleistocene (ft.)		Depth to Bonded Perma-frost (ft.)
			Fine-grain	Sand	Stiff Clay	Gravel	
1	16.5	81	33	-	NE	33	NE
2	22.8	101	19	-	NE	19	NE
3	4.2	95	10	-	NE	10	NE
4	27.9	102	-	12	12	53	40
5	42.1	300	15	-	NE	15	190
6	36.4	103	39	-	39	60	NE
7	25.4	100	39	-	39	51	NE
8	46.0	100	-	-	0	85	63
9	17.4	130	-	-	0	63	23
10	21.2	108	-	7	7	95	76
11	24.7	95	-	10	10	83	54
12	50.0	301	-	-	0	112	2
13	18.3	101	-	-	0	37	32
14	21.6	101	33	-	53	33&62	53
15	18.0	300	32	-	NE	32	42
16	30.3	110	-	4	4	97	72
17	47.7	103	-	-	0	-	85
18	37.0	303	-	-	0	-	42
19	34.5	116	43	-	43	102	73
20	37.0	114	-	-	0	112	21

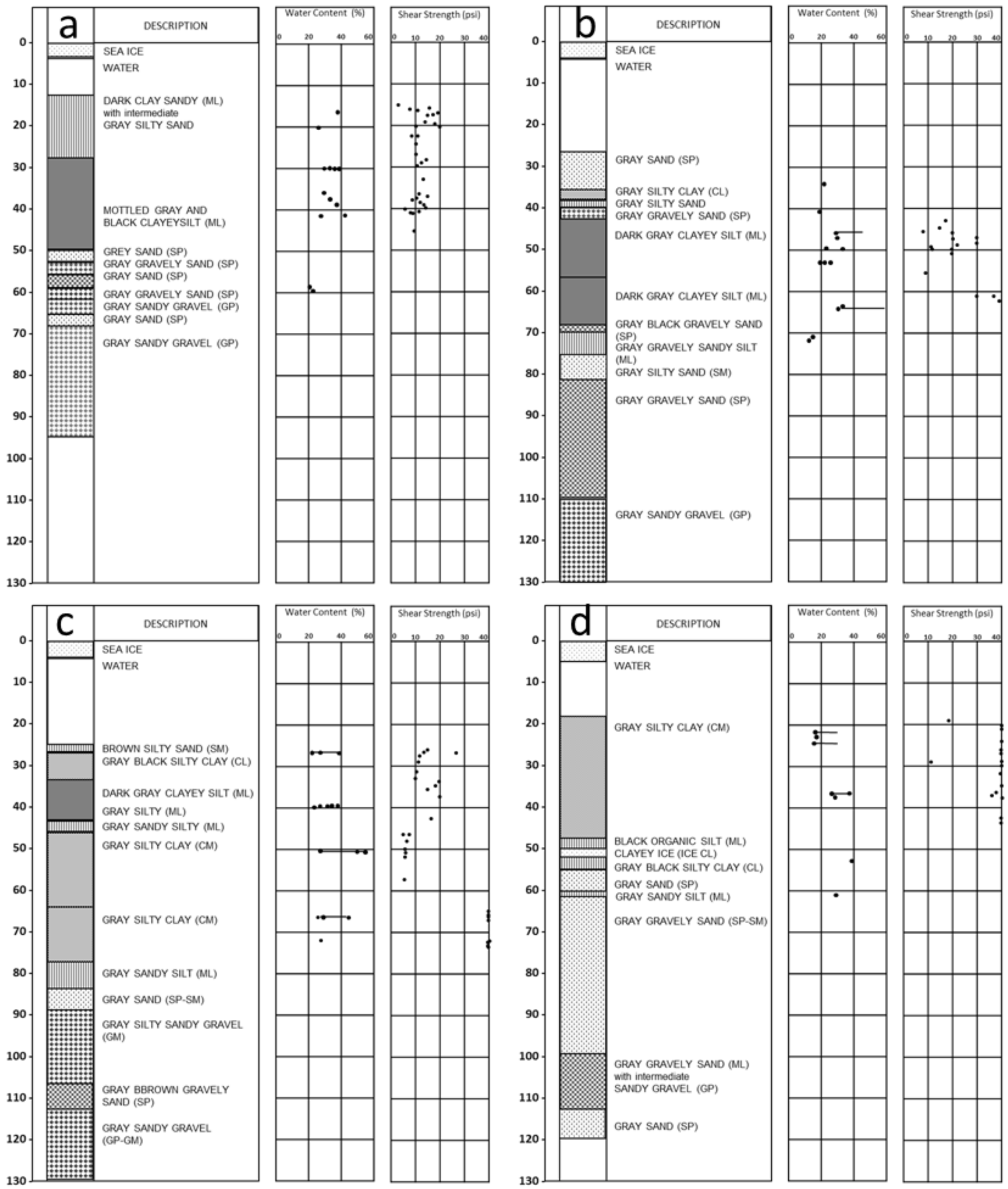


Figure 3.9: Borehole Logs (Miller & Bruggers, 1980) [15] (reproduced by MCSK)

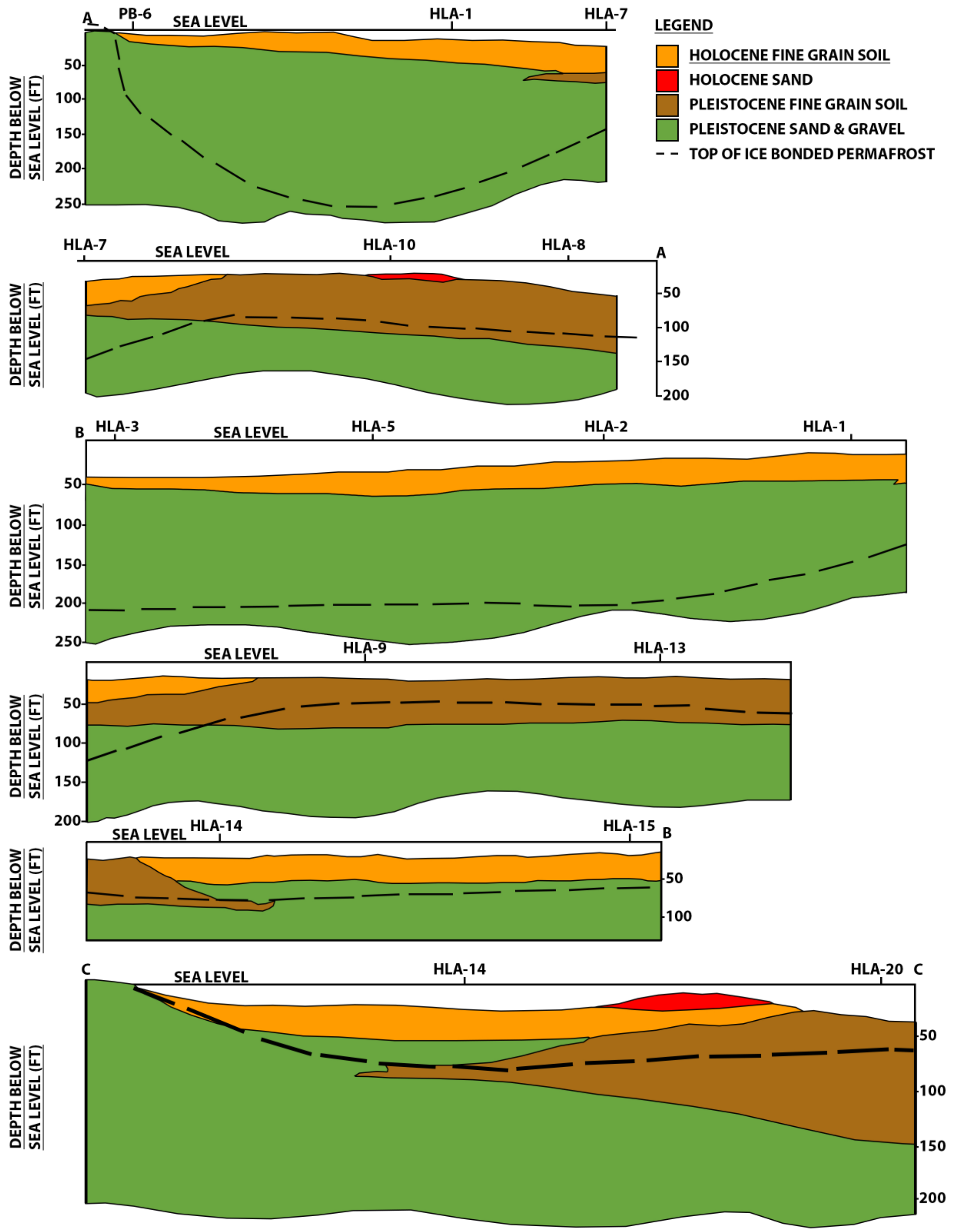


Figure 3.10: Stratigraphic Sections AA, BB and CC (Miller & Bruggers, 1980) [15]

3.2 Chukchi Sea

The US Chukchi Sea is located at the northwest section of the Alaskan coast, between Point Barrow to the east and Cape Prince of Wales to the west. Like most of the arctic area, the Chukchi Sea is covered with ice most of the year (approximately 8 months). The total approximate area of the Chukchi sea is 230,000 mi² (approx. 595,000 km²). A number of islands can be found in the area, and, in general, the sea is considered shallow. The Chukchi Sea Location Plan and Bathymetry is presented in Figure 3.12

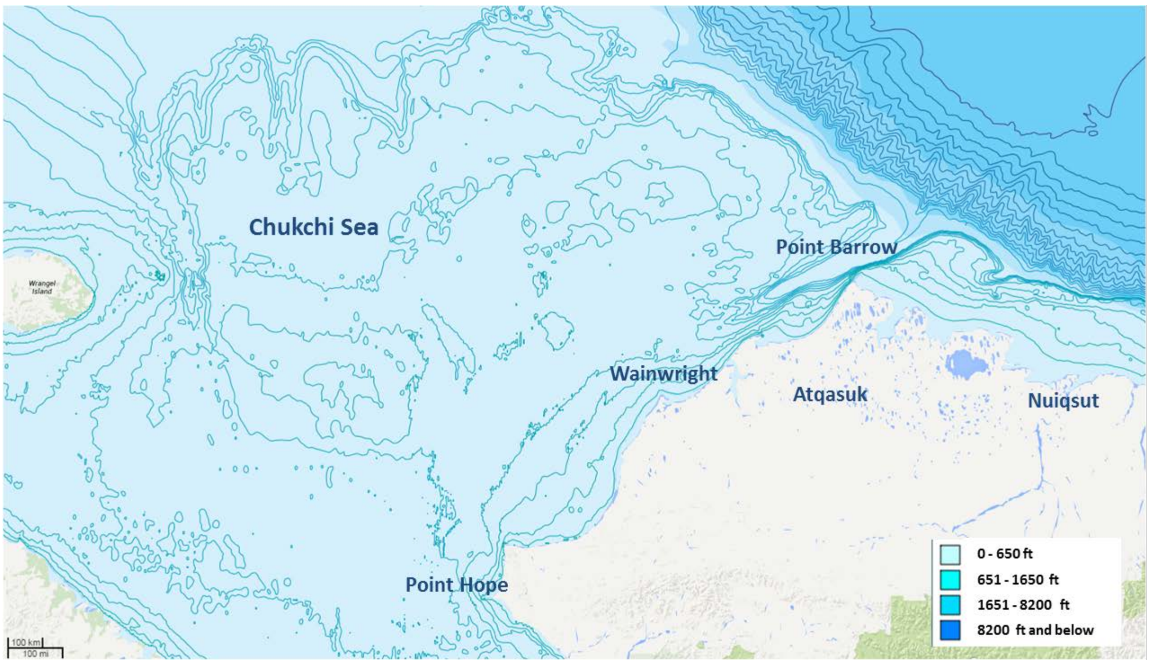


Figure 3.11: Chukchi Sea Bathymetry

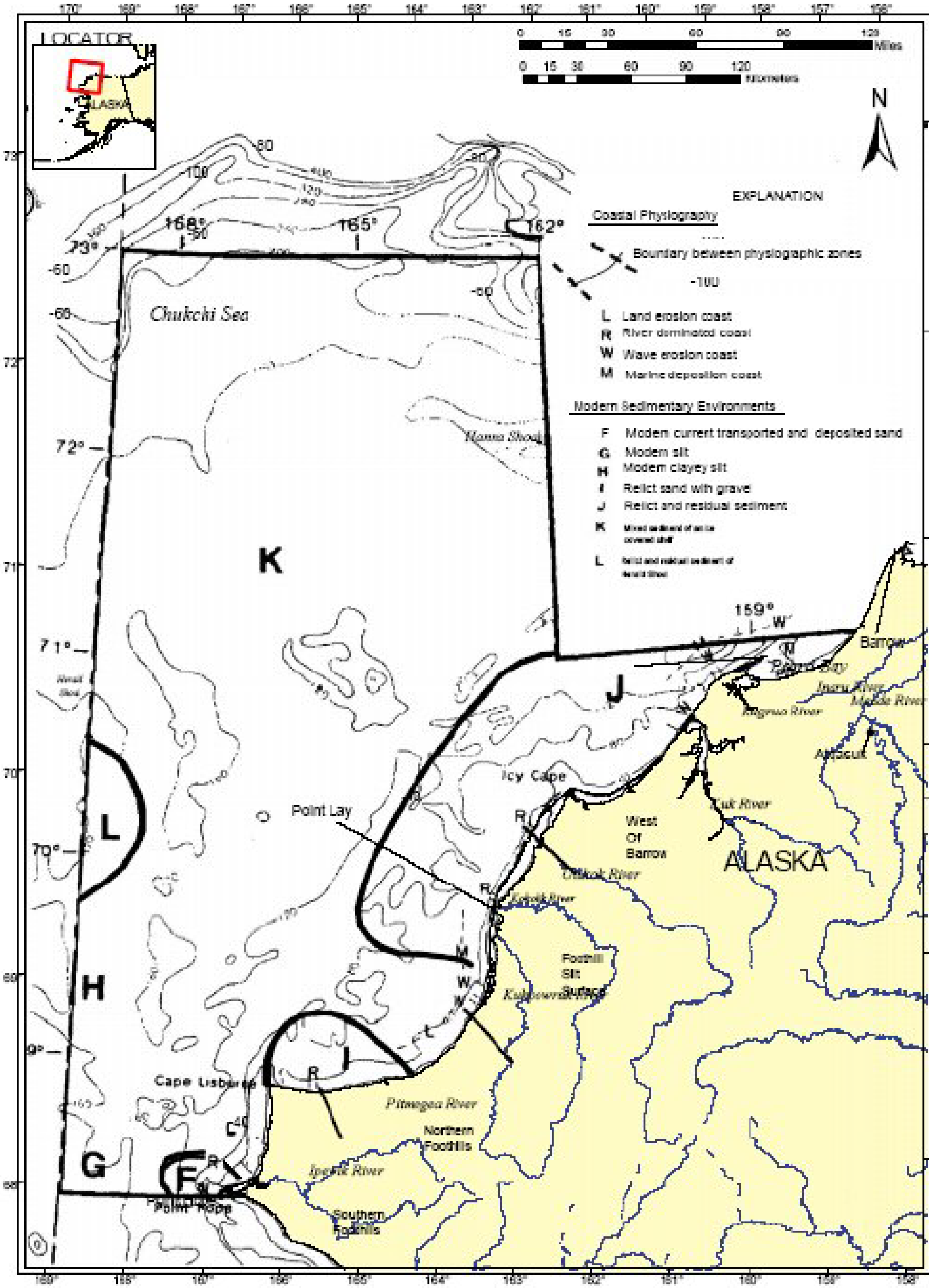
The most common sea depths are less than 164 ft. (50 m), and the depth drops sharply to more than 9,842 ft. (approx. 3,000m) close to the north limits of the study region. The east area of the sea has a deep channel 300 ft. deep (91 m) at the Barrow Valley, while the west border is relatively shallow, with 164 ft. (50 m) water depth. Some shoals exist at the shelf area, which extends 66 ft. (20 m) within the sea surface. Additional shoals exist near the shore side, along the northwest coast.

Figure 3.12: Chukchi Sea

3.2.1 McManus, et al (1969)

McManus, et al. [12] investigated the surficial characteristics of the Chukchi Sea sediments and were able to obtain the relative distribution of silts, sands and gravel across the shelf. MMS 2006 [17] presented McManus' [12] work and prepared a soil type location map, as shown in Figure 3.13. The following summarizes the findings of McManus, et al. (1969) [12]:

- Sandy soils are generally found over the shoal areas and may have been transported from eroded sea cliffs along the north Alaskan coast;
- Sand waves have been observed in water depths ranging from 49 ft. to 213 ft. (15 m to 65 m), and are considered to be active features due to their asymmetric form; and
- Gravel deposits occur on the Herald Shoal and along the coast north of the Lisburne Peninsula.



Source: McManus et al., 1969; Hartwell, 1973; Thurston and Theiss, 1987.

Figure 3.13: Distribution of Surficial Sediments (MMS, 2006) [17]

3.2.2 Winters and Lee (1984)

Winters and Lee (1984) [14], utilizing results from geotechnical testing performed on samples collected from seven boreholes, estimated the shear strength properties of the seabed soils. Water depth at the borehole drilling locations ranges from 154 ft. to 177 ft. (47 m to 54 m) (boring locations are listed in Table 3.3). Testing results showed that the surficial layer has a thickness between 3 ft. to 27 ft. (0.9 m to 8 m) with low shear strength of 2.9 ksi (20 kPa) and an underlying layer of stiff soils. The shear strength of the stiff layer is 29 ksi (200 kPa). The shear strength profile for the seven boreholes is presented in Figure 3.**14**. The authors found a correlations between thickness of the soft layer with the water depth. The depth of the bedrock line was not identified in the study.

Table 3.3: Winters and Lee (1984) Boring Locations

Boring	Latitude	Longitude	Water Depth (ft)	Location
2	70°40.014'N	167°19.594'W	176.83	Southern margin of North Chukchi Basin
3	70°40.014'N	167°19.594'W	176.83	Southern margin of North Chukchi Basin
4	70°27.676'N	167°05.205'W	167.98	Northern flank of Herald Arch
5	69°59.146'N	168°04.943'W	159.12	On Herald Arch
7	69°50.506'N	168°22.205'W	154.20	On Herald Arch
6	69°37.901 'N	168°51.785'W	162.07	Extreme Northern margin of Hope Basin
8	69°37.91 1 'N	168°51.776'W	173.89	Extreme Northern margin of Hope Basin
Borings 2 and 3 are spaced approximately 23 feet apart Borings 7 and 8 are spaced approximately 23 feet apart				

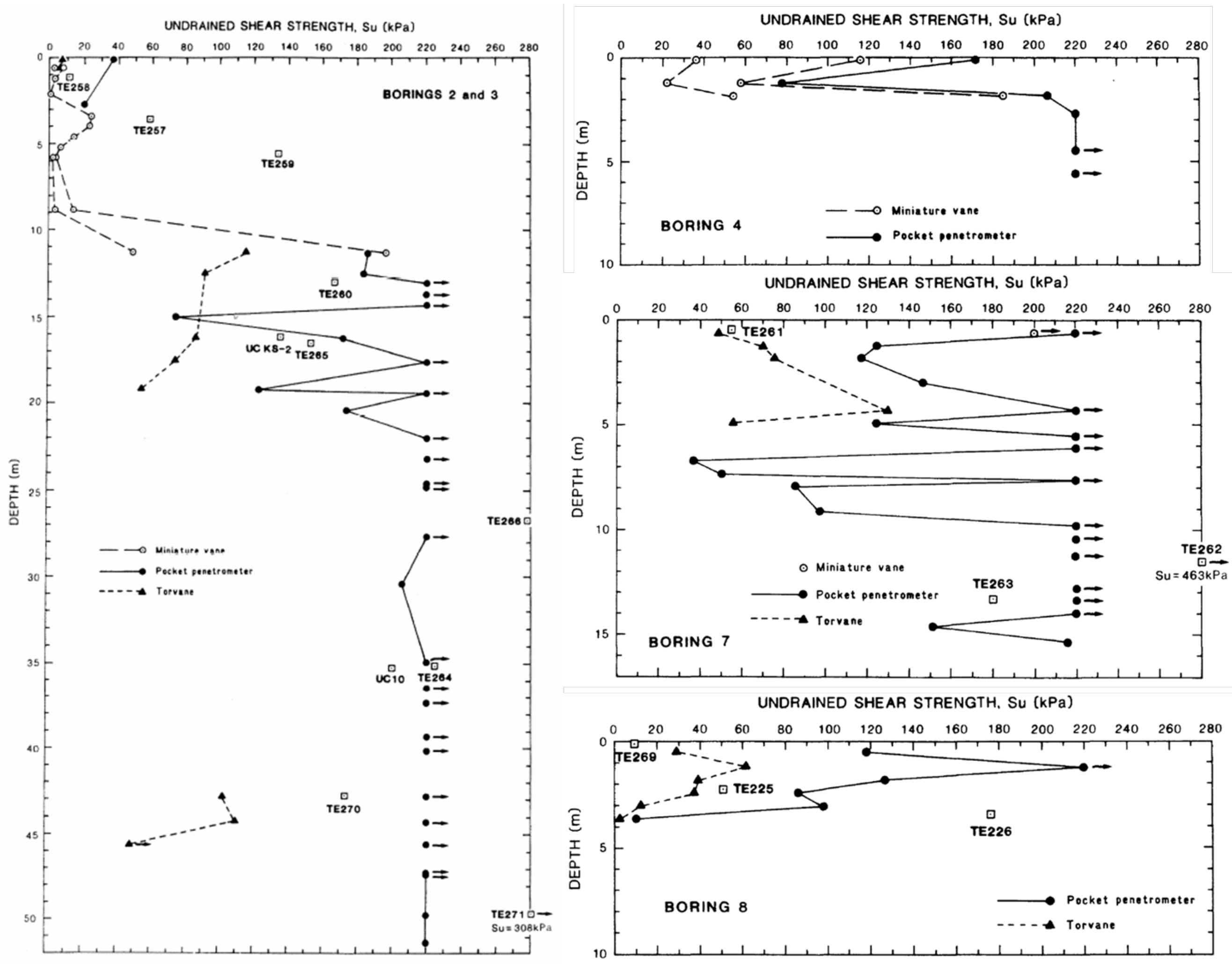


Figure 3.14: Undrained Shear Strength (Winters & Lee) [32]

3.2.3 Miley & Barnes (1986)

A geological survey was conducted by Milley & Barnes [14] to establish the sedimentary and geotechnical characteristics of ice and current impacted sediments in the Chukchi Sea and Beaufort Sea. Vibrocore and gravity core samples were collected in water depths between 59 ft. (18 m) and 1033 ft. (315 m). Figure 3.15 and Figure 3.16 show the map location of the samples. The study revealed that the majority of core samples are over-consolidated materials and, at some cases, samples may be considered mudstone. The Chukchi Sea central and inner shelf regions are underlain by layers of consolidated or over-consolidated muds and sandy muds.

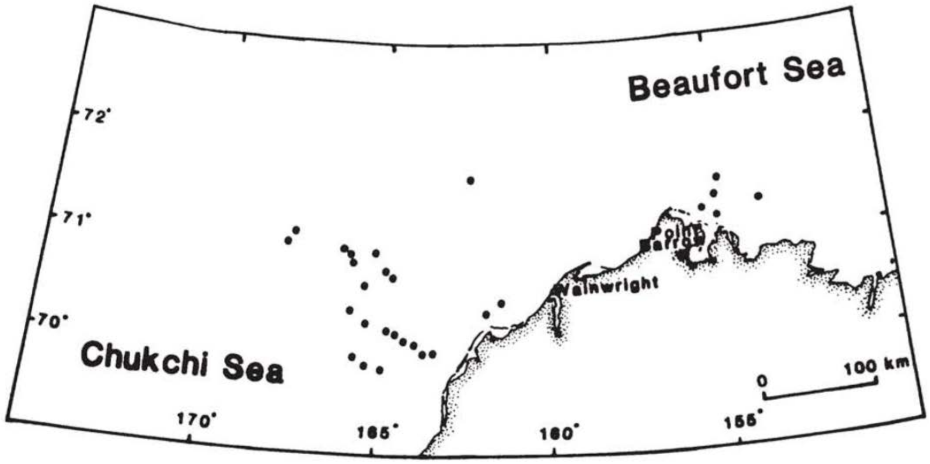


Figure 3.15: Location of Gravity Core (Miley & Barnes, 1986) [14]

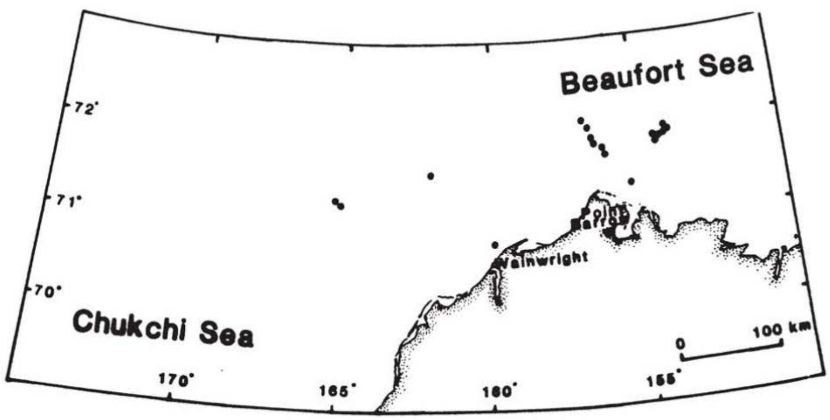


Figure 3.16: Location of Vibrocore Cores (Miley & Barnes, 1986) [14]

3.2.4 Phillips, et al (1988)

Phillips, et al. (1988) [23] investigated the surficial sediment. While the work of these scientists was limited to the inner shelf of the Chukchi Sea, they were able to identify a number of facies. Sedimentary facies are mappable subdivisions of a designated stratigraphic unit, distinguished from adjacent units on the basis of lithology, reflecting the depositional environment. Generally, facies are distinguished by the type of rock or sediment studied. Thus, facies based on petrological characters, such as grain size and mineralogy, are called lithofacies, whereas facies based on fossil content are called biofacies.

Figure 3.17 shows the distribution of the surficial sediment. Sediment thickness varied from 3.2 ft. (1.0 m) to 16.4 ft. (5.0 m) and was classified into four major facies.

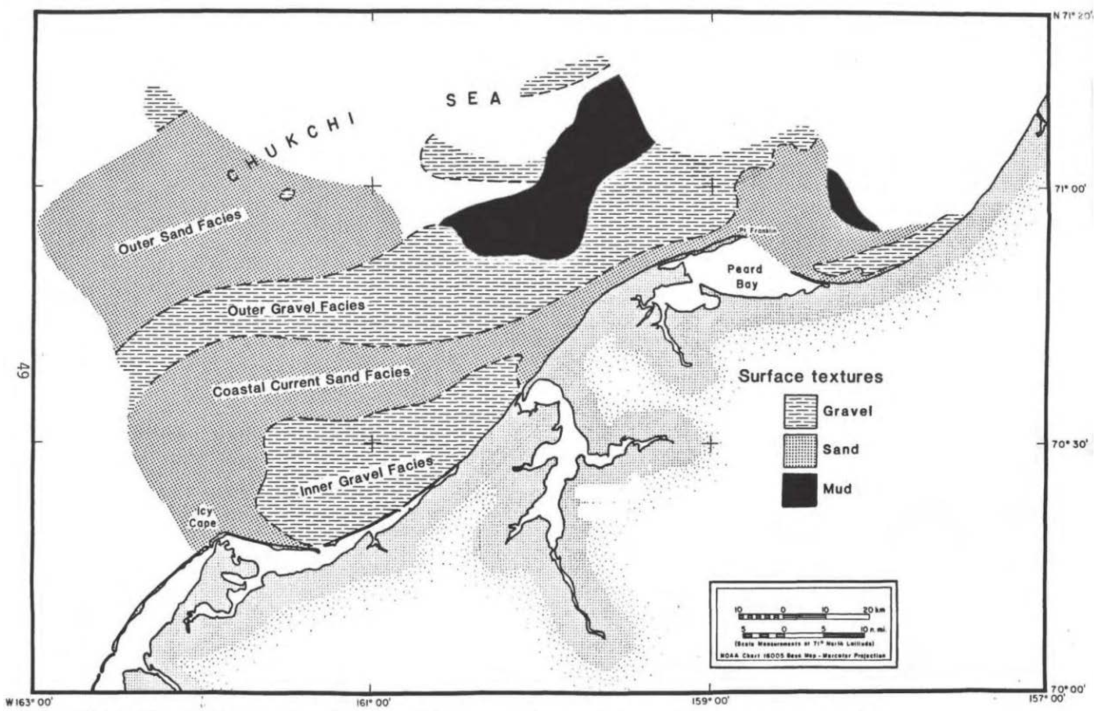


Figure 3.17: Major Surficial Sediment Types (Phillips, et al., 1988) [23]

- Outer sand facies – Occurs in water depths varying from 137.8 ft. (42 m) to 157.5 ft. (48 m) at the western flank of the Barrow Sea Valley. This facies is bounded from the eastern side of the Barrow Sea Valley with a large gravel field.
- Outer gravel facies – Occurs in water depths varying from 131 ft. (40 m) west of the ice cape to 197 ft. (60 m) in the north. It forms a 13.1 ft. (4 m) layer of gravel which lies on the top of the over consolidated muds layer.
- Coastal current sand facies – This facies, as seen in Figure 3.17, lies to the east of the outer gravel facies. Phillips, et al. (1988) [23] reported that this facies is distinct, containing abundant echinoids and recording active northward sediment transport represented by sand wave fields. Box cores samples indicated that the sand content of the coastal current sand facies varies from 82 to 98 percent. The texture of the sand ranges from slightly gravelly, muddy sand to sand.
- Inner gravel facies – This facies resides at the east side of the coastal current sand facies at relatively shallow water depths (ranging from approximately 94.4 ft. (29 m) to less than 16.4 ft. (5 m) near shore).

4.0 Beaufort Sea – Field Data

4.1 General

Repetitive surveys have been performed in the Canadian and U.S. Beaufort Seas. This chapter summarizes the ice gouging field data collected in the Beaufort Sea region.

4.2 Ice Gouging – Data Sets

The USGS provided two main documents which are available to the public; Rearic and McHendrie (1983) [26] and Weber, et al., (1989) [29]. While these documents presented adequate survey data for the U.S. Beaufort Sea, an additional survey by MMS (2002) [17] provided a set of usable data sets for gouges. Several studies have been conducted to develop ice gouging rate prediction models, and Tthe following sections describe the available datasets in more detail. An additional section was added to summarize MMS (2008) [19], which presented a brief comparison between the available datasets.

4.2.1 Rearic and McHendrie (1983)

Rearic and McHendrie (1983) [26] combined the data obtained by their earlier surveys (Rearic, et al. (1981) [25] and Reimnitz et al. (1982a) [28]). The surveys were conducted for the Alaskan Beaufort Sea to study size, density, orientation, and location of ice gouges. The study provided extensive information about gouge dimension (width, depth and length), and the data that was collected was included in the USGS report numbered 81-950 and 82-972. The files contain 2,071 records for the Beaufort Sea Shelf, west of the Canning River (longitude 146^{o} West) providing survey data for 1,394 miles (2,243 km) of track lines, in which 132,183 gouges were identified. Single and multiple gouges were also discussed in the study. However, data tabulated by Rearic and McHendrie (1983) [26] does not allow the distinction between single and multiple events since only the maximum number of incisions per gouge interval is provided.

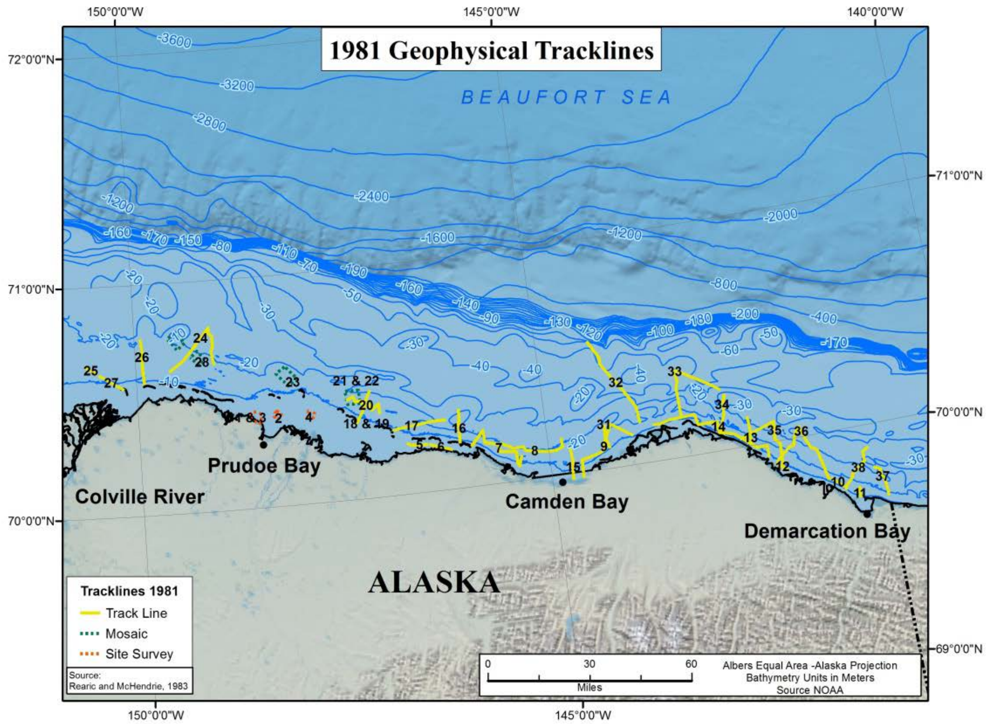


Figure 4.1: 1981 Geophysical Track Lines - Rearic and McHendrie (1983) [26]

4.2.2 Weber, et al. (1989)

Repetitive surveys collected from nine sites between 1977 and 1985 were tabulated by Weber, et al. (1989) [29]. The map of corridor locations is shown in Figure 4.2.

A total of 1,077 ft. (316 m) of track lines were surveyed in which 19,327 gouges were located. The study provided gouge data per segments (measured in km) indicating the water and the total number of existing gouges in each specific segment. Age of the gouges was also determined by comparing recent surveys with the previous surveys. Multiple gouge events and their dimensions were recorded and gouges were classified based on the depth of occurrence. Unfortunately, accurate coordinates of the gouge records were not provided, but associations made with depth and corridor location of data obtained by Barnes and Rearic (1985) linked the two surveys.

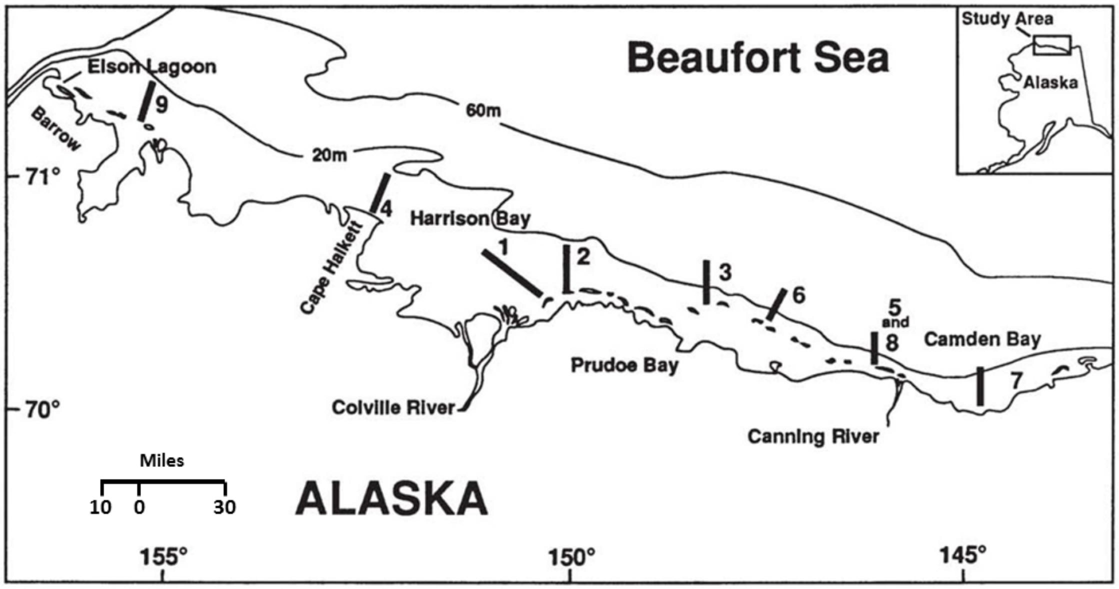


Figure 4.2: Location Map Indicating Corridor Locations and Generalized Bathymetry for the Alaskan Beaufort Sea – Weber, et al. (1989) [31]

4.2.3 Nessim and Hong (1992)

Nessim and Hong (1992) [22] interpreted the available data from the Canadian Beaufort Sea surveys to estimate gouge crossing rates. Approximately 808 miles (1,300 km) of track lines were surveyed. The deepest, newly induced gouge was noticed at water depths of 125 ft. (38 m). The average gouge/mi/yr ranges from 1.0 to 1.75 for a water depth interval of 16.5 to 98 ft. (5 to 30 m) with a sudden drop in gouge crossing rate for water depth more than 100 ft. (30 m). The highest crossing rate was noticed for a water depth interval of 65 to 82 ft. (20 to 25 m). The total tracks length surveyed in this water depth interval is 128 miles (206 km), consisting of 35 track lines. The average number of gouges/km/yr and standard deviation for each water depth intervals are shown in Table 4.1. Nessim and Hong (1982) [22] observations show similarity between gouges in the Canadian and U.S. Beaufort Seas.

Table 4.1: Frequency of New Gouges in Canadian Beaufort (Nessim and Hong, 1992) [22]

Water Depth		Average Number of Gouges (north)		Standard Deviation		Number of Tracks	Track Length	
(ft)	(m)	(miles/yr)	(km/yr)	(miles)	(km)		(miles)	(km)
16.40-32.81	5-10	1.26	2.02	1.67	2.68	24	133.33	214.58
32.81-49.21	10-15	1.09	1.75	0.7	1.12	30	167.01	268.78
49.21-65.62	15-20	1.33	2.14	1.22	1.97	32	113.67	182.93
65.62-82.02	20-25	1.73	2.78	1.64	2.64	35	128.32	206.51
82.02-98.43	25-30	1.01	1.63	0.92	1.48	44	122.56	197.24
98.43-114.83	30-35	0.25	0.40	0.31	0.50	19	54.74	88.10

4.2.4 Myers, et al. (1996)

Myers, et al. (1996) [20] prepared the location map for the track lines in the Canadian Beaufort Sea, as shown in Figure 4.3. The track lines were obtained from repetitive surveys performed by Canadian Seabed Research Ltd (CSR). The research was funded by the Environmental Studies and Research Funds (ESRF) in 1990 and aimed to update the database created in the previous survey that was performed in 1982. A total of 2,291 new scour events were recorded during the 1990 survey.

Myers, et al. [20] reported that approximately 3% of scours are more than 6.5 ft. (2 m) deep. The combined database has 5,329 scours, and the database set contains sufficient information that can be used to develop spatial and statistical data distribution. The data set represented by Myers, et al. [20] was collected for the Canadian Beaufort Sea, but it can be used as an indication for the crossing density and gouging dimensions for the entire U.S. Beaufort Section.

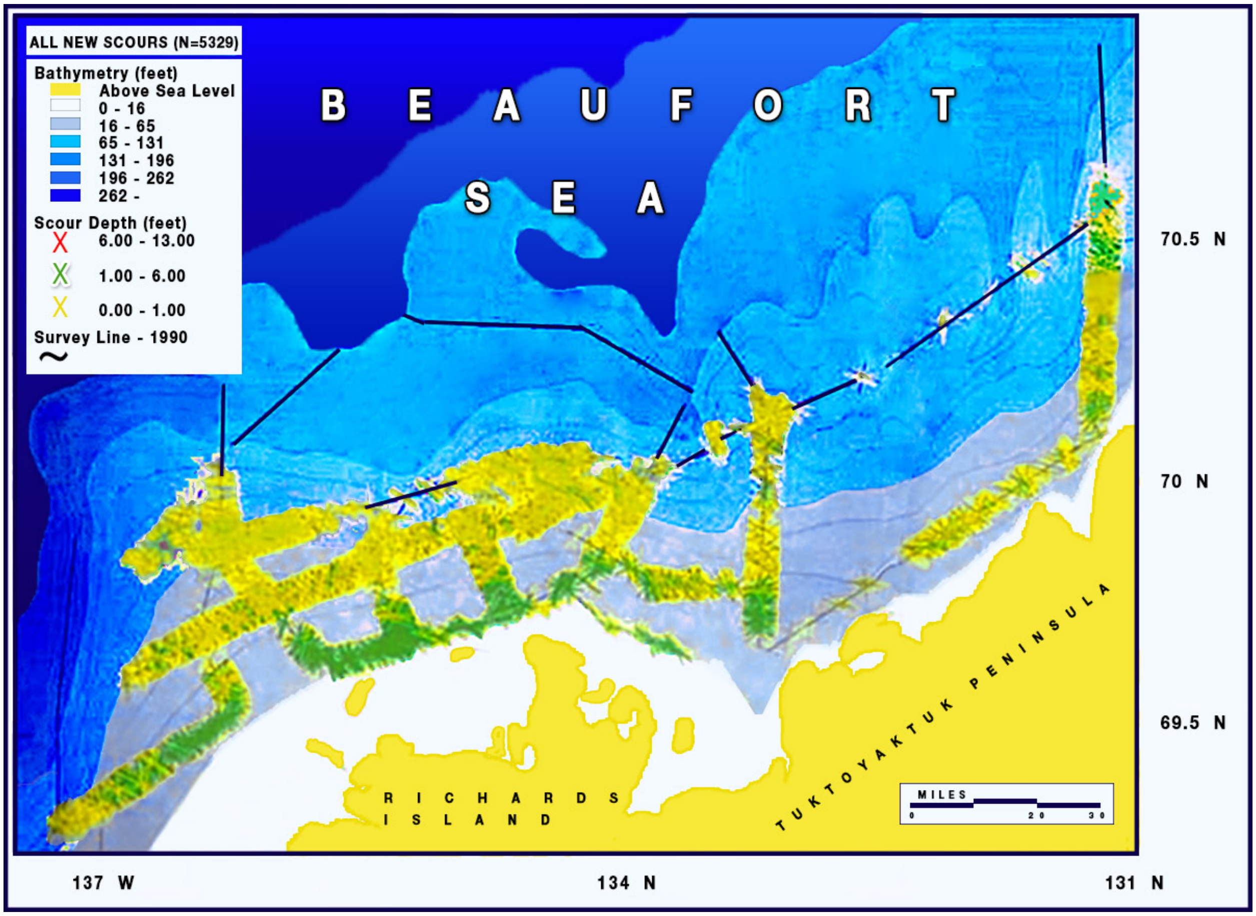


Figure 4.3: Canadian Beaufort Lines with Gouge Crossings (adopted from Myers, et al., 1996) [20]

4.2.5 MMS (2002)

MMS (2002) [17] performed additional surveys which recorded 836 ice gouge events. A location map for the gouge locations was prepared later by MMS (2008) [18] and is shown in Figure 4.4. The majority of the gouges that occurred within shallow waters were reported by MMS (2002) [17]. The GIS database only reported 307 gouges having usable gouge depth and width information, however, the surveys did not distinguish between single and multiple gouge events. Table 4.2 summarizes the dataset as prepared later by MMS (2008) [18].

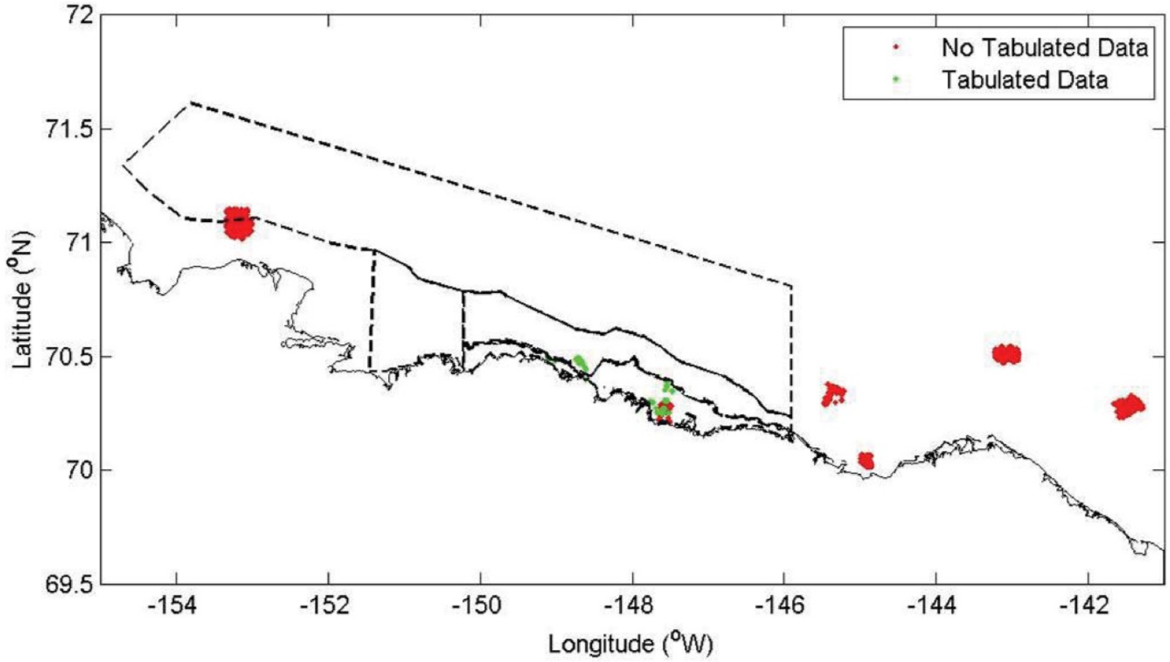


Figure 4.4: MMS (2002) GIS Database Ice Gouge Locations [17]

Table 4.2: Summary of MMS (2002) Data Sets – Prepared by MMS (2008) [18]

Parameter	GIS
Dates surveyed	1995 – 1998
Repetitive mapping used?	Y
Total no. of gouges recorded	836
Seabed soil type identified?	N
Gouge depths recorded	Y
Gouge width recorded	Y
Gouge widths recorded at the Northstar Site	120
Total number of gouges recorded at the Liberty Site	187

4.2.6 MMS (2008)

The MMS (2008) [18] recommended a division of the area of study in the U.S. Beaufort Sea into four zones (A, B, C and D). Each zone has its own distinctive environmental conditions and surface texture. The potential hazard for each zone was reported as a function of the bathymetry of each zone (Figure 4.5 shows the proposed zones as reported by MMS in 2002 [17]). The following section describes the general characteristics of each zone, and a summary of the basic characteristics of each zone is listed in Table 4.3.

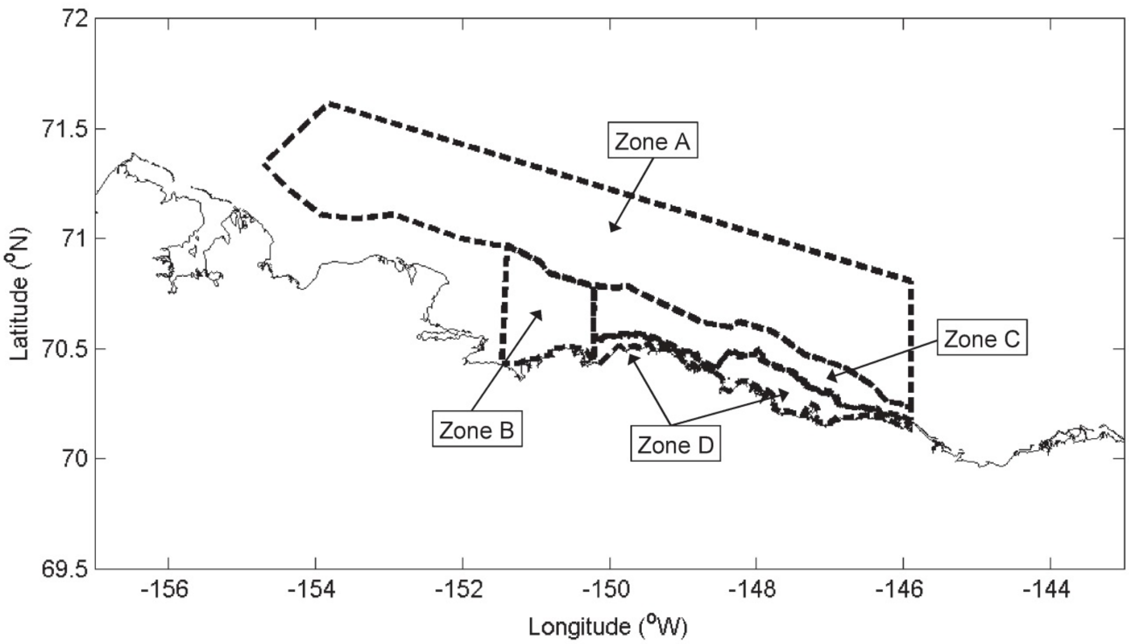


Figure 4.5: Beaufort Sea Case Study Zones (MMS 2002) [17]

- Zone A is the largest of the four zones and represents the outer limits of the continental shelf. The water depth is 60 to 180 ft. (15 m to 55 m) and the surface texture is primarily soft to stiff clay. Zone A has a high ice gouging probability.
- Zone B falls at the north of the Colville River and mostly soft soil is found all over this zone. The water depth is relatively shallow, which may attract ice gouging during freeze-up and thaw.
- Zone C consists of mainly dense sand or gravel and the water depth is 60 to 120 ft. (18 to 37 m). Due to the relatively shallow water depth, gouging frequency falls between medium to low.
- Zone D is located between the shallow water between the barrier islands and the shoreline. Barrier islands protect the zone from ridge movement. Figure 4.5 shows Zone D, which is made up of two contiguous sub-zones, labelled D1 and D2 in the figure.

In addition to the U.S. Beaufort Sea study zones, MMS (2008) [19] provided location maps for the track lines associated with the dataset in relation to the specified zones as tabulated by Rearic and McHendrie (1983). These track lines are shown in Figure 4.6. An additional location map was prepared for the repetitive mapping surveys collected from the nine sites based on the tabulated data that was provided by Weber, et al. (1989), as shown in Figure 4.7.

To understand the significant differences between the available datasets, MMS (2008) conducted a comparison between Rearic and McHendrie (1983) [26] and Weber, et al. (1989) [31] datasets, as shown in Table 4.4. The number of miles (kilometers) surveyed, as well as the total number of gouges recorded, was tabulated for each zone separately (there was no available data for Zone D in the Weber, et al. (1989) dataset). The study found clear discrepancies for Zone A data (i.e., total number of gouges recorded), which may be a result of the difference in the surveyed water depths 30 to 180 ft. (9 to 55 m) vs. 50 to 100 ft. (15 to 30 m) and the length of the track line 370 miles (595 km) vs. 10 miles (16 km).

Table 4.3: Environmental Parameters for Beaufort Sea Case Study Zones (MMS 2008) [18]

Zone	Soil Type	Ice Gouging Freq.
A	Soft to stiff clay 2.90 to 14.50 psi (20 to 100kPa)	High
B	Soft clay 1.45 to 4.35 psi (10 to 30kPa)	Low to medium
C	Dense sand and gravel 40 to 45°	Low to Medium
D	Soft to stiff clay 2.90 to 14.50 psi (20 to 100kPa)	Low

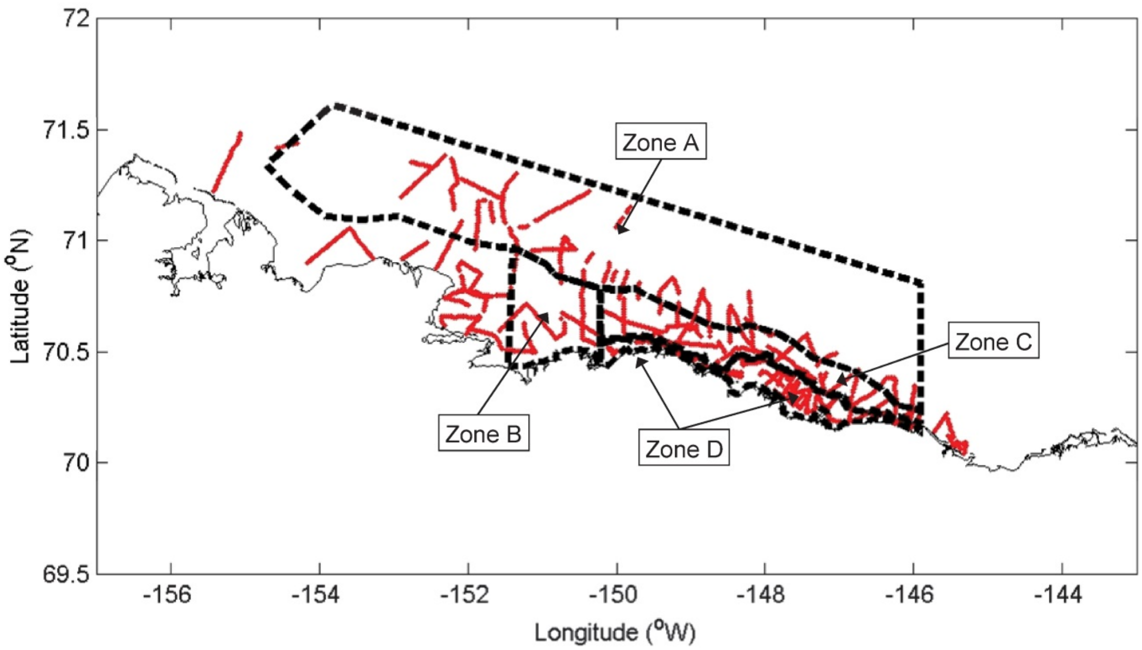


Figure 4.6: Rearic and McHendrie (1983) Track Lines (MMS 2008) [18]

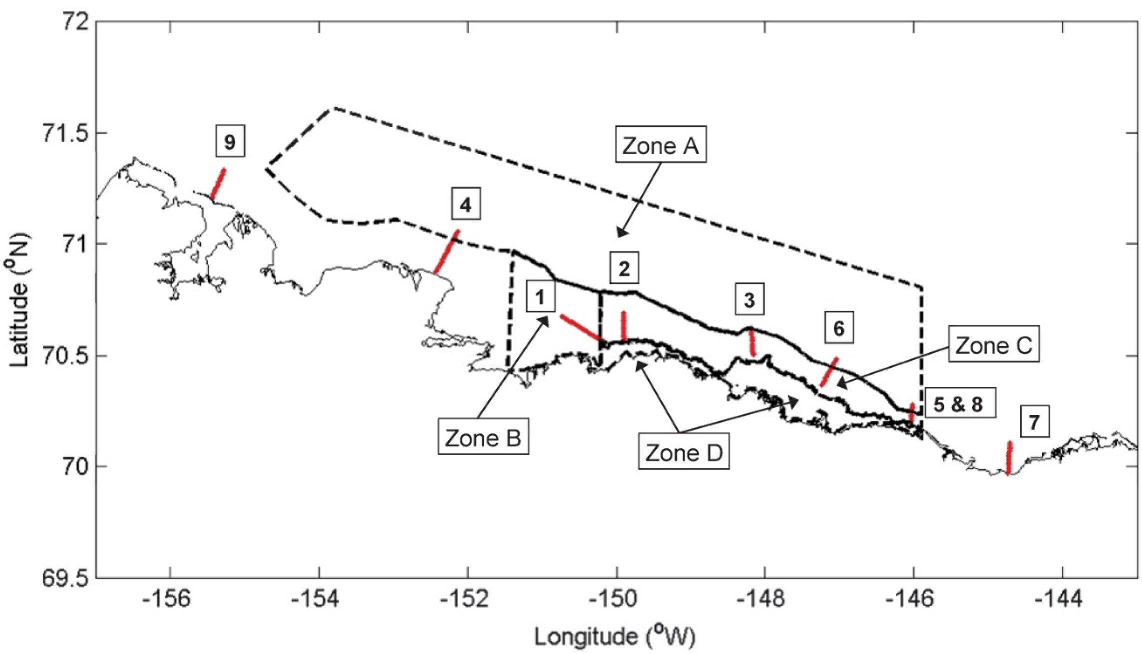


Figure 4.7: Weber, et al. (1989) Corridors - Modified by MMS (2008) [18]

Table 4.4: Summary of Data Sets – MMS (2008) [18]

Parameter	Rearic and McHendrie (1983)	Weber, et al (1989)
Dates surveyed	1972 – 1981	1977 - 1985
Repetitive mapping used?	N	Y
Total length surveyed	1518.01 miles (2443km)	196.35 miles (316km)
Total no. of gouges recorded (single	132183	19327 (s + m)
Seabed soil type identified?	Y	N
Gouge depths recorded	Y (s/m not differentiated)	Y (new gouges only)
Zone A		
Water depth covered	32.81-196.85 ft (10-60m)	49.21-98.43 ft (15-30m)
Length surveyed	382.14 miles (615km)	9.94 miles (16km)
Total number of gouges recorded	46885	2091
Number of new gouges recorded	-	33/31
Zone B		
Water depth covered	0-82.02 ft (0-25m)	16.40-65.62 ft (5-20m)
Length surveyed	72.70 miles (117 km)	54.06 miles (87 km)
Total number of gouges recorded	8534	5725
Number of new gouges recorded	-	254 / 124
Zone C		
Water depth covered	0-98.43 ft (0-30m)	16.40-82.02 ft (5-25m)
Length surveyed	288.32 miles (464 km)	67.11 miles (108 km)
Total number of gouges recorded	2583	2675
Number of new gouges recorded		286/88
Zone D		
Water depth covered	0-32.80ft (0-10m)	-
Length surveyed	234.25 miles (377 km)	-
Total number of gouges recorded	1197	-
Number of new gouges recorded	-	-

4.3 Analysis of Ice Gouging Data Sets

The following section describes the analyses of datasets aiming to provide sound correlations between the bathymetry as well as gouge location and characteristics (width, depth and crossing density). MMS (2008) provided an intensive analysis of the Rearic and McHendrie (1983) and Weber, et al. (1989) data sets. The gouge data in each dataset were categorized for each zone (A, B, C and D), and statistical analysis was performed, when possible.

4.3.1 Gouge Depth

4.3.1.1 Rearic and McHendrie (1983)

In order to allow for distribution functions to be applied, MMS (2008) [19] tabulated the data provided by Rearic and McHendrie (1983) [26] for 0.65 ft. (0.2 m) depth intervals. A mid-point for each gouge interval value was selected. Therefore, scatter plots in MMS work have a banded figure. Gouge depth falls within +/- 0.1m of the tabulated value.

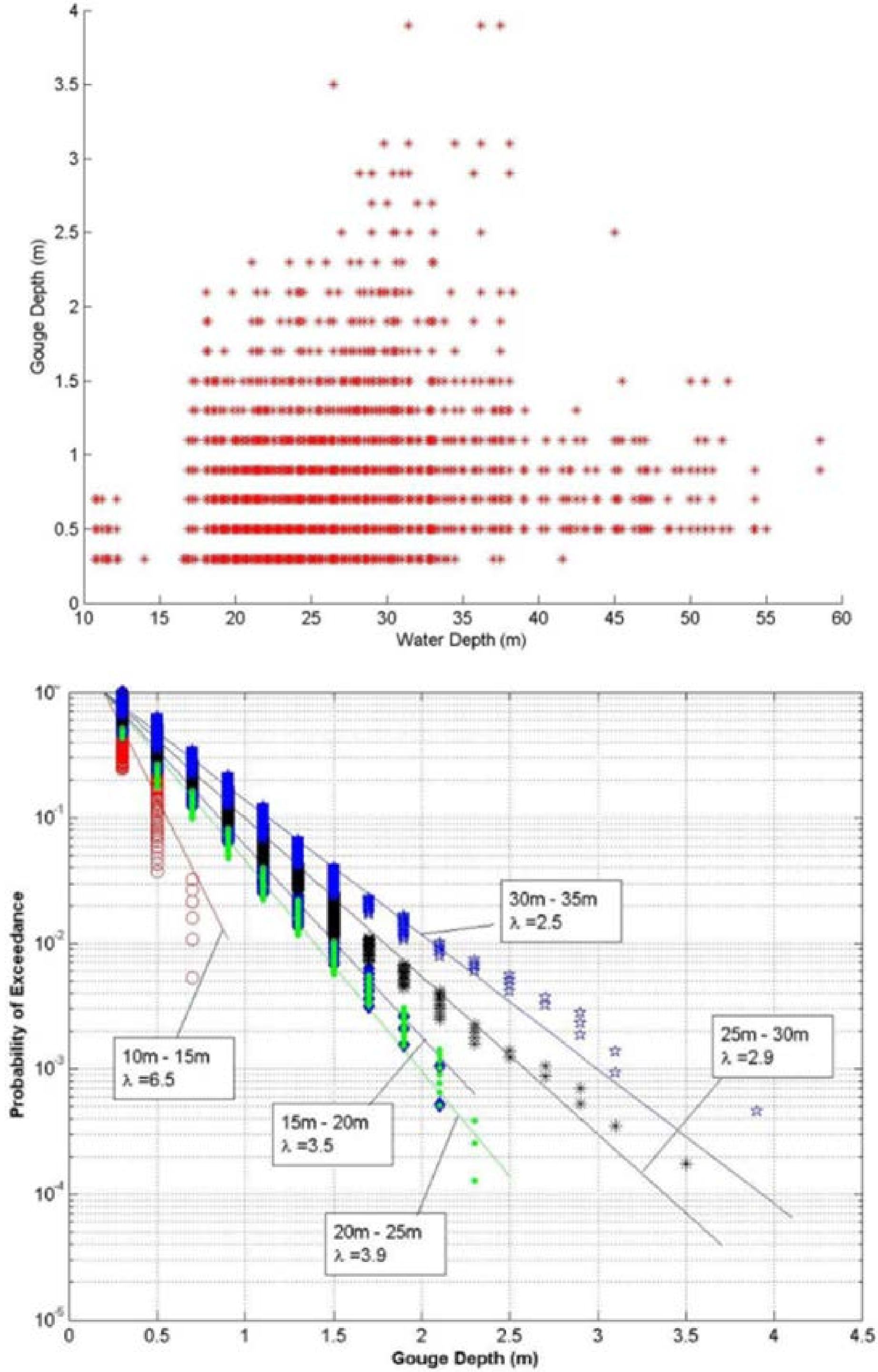
Table 4.5 presents the Rearic and McHendrie (1983) data as tabulated in the MMS (2008) report. A total of 24,481 gouges were listed. Zones A, B, C and D contained 18,392, 857, 5,204, 4, and 24 gouges, respectively. The deepest gouge for all of the zones was 12.8 ft. (3.9 m) deep and occurred within Zone A in the 115-164 ft. (35-50 m) water depth region. The mean value of the gouge depth was 1.6 ft. (0.5 m), which is relatively shallow but comparable to the mean value of gouge depth for each zone.

Statistical analysis was performed for each water depth separately. An exponential distribution was assumed for each water depth set of data. Maximum gouge depth, mean value, standard deviation and decay function were calculated. The tabulated data represents a useful guide during design processes. An exponential distribution for each water depth or zone of interest may be used if a more conservative approach is adopted during the design phase. Scatter and distribution plots for all of the zones are shown in Figure 4.8.

Table 4.5: Summary of Rearic and McHendrie (1983) Gouge Depths – MMS 2008 [18]

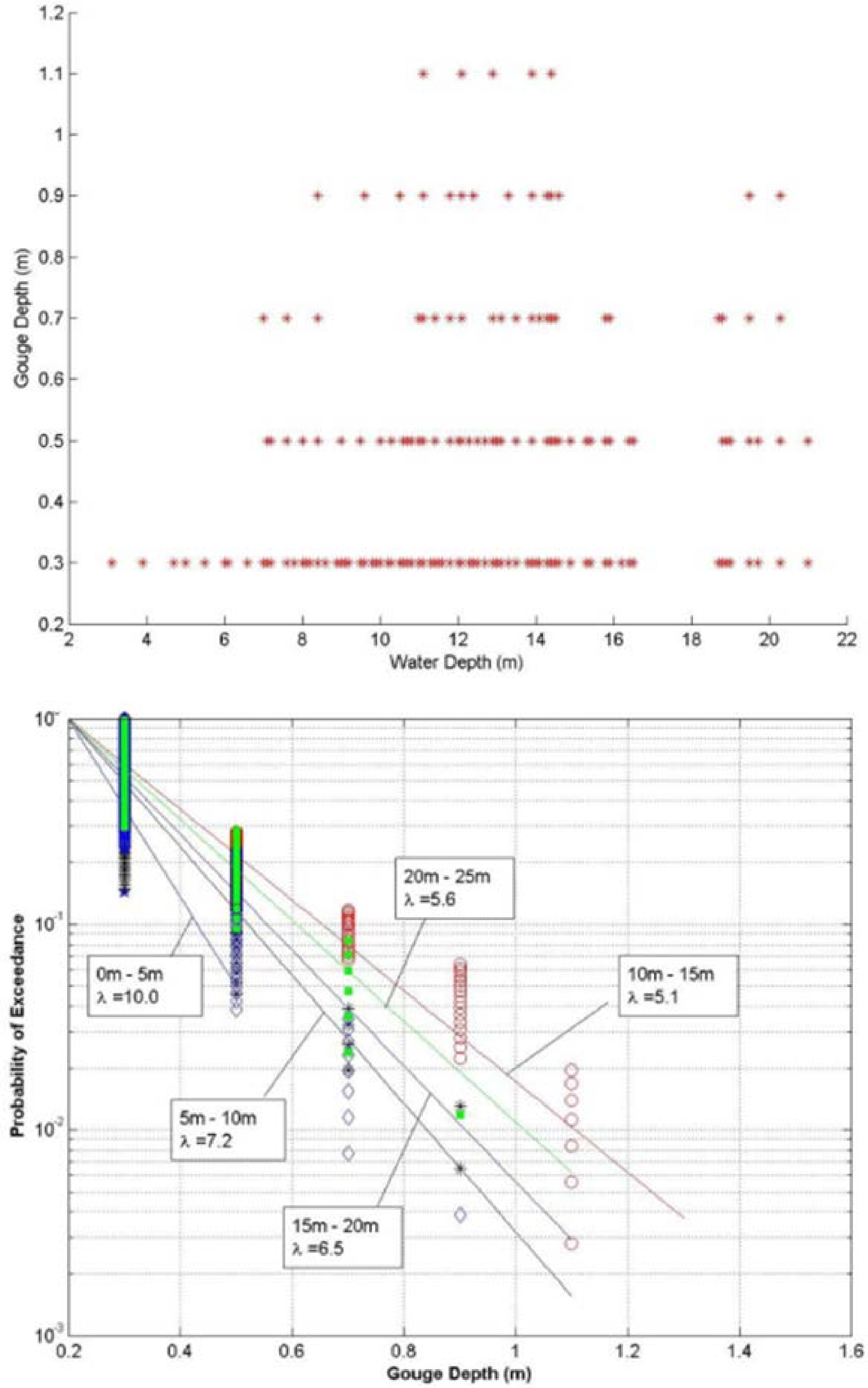
Water Depth ft (m)		Gouge Depth, ft (m)					
	Zone	A	B	C	D.1	D.2	ALL
0-16.40 (0-5)	No. Gouges		6	3	4	9	22
	Mean(ft)		0.98 (0.3)	1.31 (0.4)	1.31 (0.4)	0.98 (0.3)	0.98 (0.3)
	Max(ft)		0.98 (0.3)	1.64 (0.5)	1.64 (0.5)	2.30 (0.7)	2.30 (0.7)
	Std(ft)		0	0.33 (0.1)	0.33 (0.1)	0.33 (0.1)	0.33 (0.1)
	$\lambda(ft^{-1})$		3.05 (10)	1.83 (6)	2.04 (6.7)	2.10 (6.9)	2.25(7.4)
16.40-32.81 (5-10)	No. Gouges		153	52		15	220
	Mean(ft)		0.98 (0.3)	1.31 (0.4)		0.98 (0.3)	0.98 (0.3)
	Max(ft)		2.95 (0.9)	3.61 (1.1)		1.64 (0.5)	3.61 (1.1)
	Std(ft)		0.33 (0.1)	0.66 (0.2)		0.33 (0.1)	0.33 (0.1)
	$\lambda(ft^{-1})$		2.19(7.2)	1.80(5.9)		2.71 (8.9)	2.10(6.9)
32.81-49.21 (10-15)	No. Gouges	186	357	598			1141
	Mean(ft)	1.31 (0.4)	1.31 (0.4)	0.98 (0.3)			1.31 (0.4)
	Max(ft)	2.30 (0.7)	3.61 (1.1)	3.61 (1.1)			3.61 (1.1)
	Std(ft)	0.66 (0.2)	0.33 (0.1)	0.33 (0.1)			
	$\lambda(ft^{-1})$	1.98(6.5)	1.55(5.1)	2.13(7)			1.89(6.2)
32.81-49.21 (10-15)	No. Gouges	1910	258	1652			3820
	Mean(ft)	1.64 (0.5)	1.31 (0.4)	1.31 (0.4)			1.31 (0.4)
	Max(ft)	6.89 (2.1)	2.95 (0.9)	5.57 (1.7)			6.89 (2.1)
	Std(ft)	0.98 (0.3)	0.33 (0.1)	0.66 (0.2)			0.66 (0.2)
	$\lambda(ft^{-1})$	1.07(3.5)	1.98(6.5)	1.77(5.8)			1.34(4.4)
65.62-82.02 (20-25)	No. Gouges	7784	83	2383			10250
	Mean(ft)	1.64 (0.5)	1.31 (0.4)	1.31 (0.4)			1.31 (0.4)
	Max(ft)	7.55 (2.3)	2.95 (0.9)	5.57 (1.7)			7.55 (2.3)
	Std(ft)	0.98 (0.3)	0.33 (0.1)	0.66 (0.2)			0.66 (0.2)
	$\lambda(ft^{-1})$	1.19(3.9)	1.74(5.7)	1.40(4.6)			1.22(4)
82.02-98.43 (25-30)	No. Gouges	5694		516			6210
	Mean(ft)	1.64 (0.5)		1.64 (0.5)			1.64 (0.5)
	Max(ft)	11.48 (3.5)		4.92 (1.5)			11.48 (3.5)
	Std(ft)	0.98 (0.3)		0.98 (0.3)			0.98 (0.3)
	$\lambda(ft^{-1})$	0.88(2.9)		1.01(3.3)			0.88(2.9)
98.43-114.83 (30-35)	No. Gouges	2165					2165
	Mean(ft)	1.97 (0.6)					1.97 (0.6)
	Max(ft)	12.8 (3.9)					12.8 (3.9)
	Std(ft)	1.31 (0.4)					1.31 (0.4)
	$\lambda(ft^{-1})$	0.76(2.5)					0.76(2.5)

Water Depth ft (m)	Gouge Depth, ft (m)						
	Zone	A	B	C	D.1	D.2	ALL
114.83-131.23 (35-40)	No. Gouges	298					298
	Mean(ft)	2.95 (0.9)					2.95 (0.9)
	Max(ft)	12.8 (3.9)					12.8 (3.9)
	Std(ft)	1.97 (0.6)					1.97 (0.6)
	$\lambda(ft^{-1})$	0.46(1.5)					0.46(1.5)
131.23 - 147.64 (40-45)	No. Gouges	163					163
	Mean(ft)	1.97 (0.6)					1.97 (0.6)
	Max(ft)	8.20 (2.5)					8.20 (2.5)
	Std(ft)	0.66 (0.2)					0.66 (0.2)
	$\lambda(ft^{-1})$	0.73(2.4)					0.73(2.4)
147.64-164.04 (45-50)	No. Gouges	139					139
	Mean(ft)	1.97 (0.6)					1.97 (0.6)
	Max(ft)	4.92 (1.5)					4.92 (1.5)
	Std(ft)	0.66 (0.2)					0.66 (0.2)
	$\lambda(ft^{-1})$	0.73(2.4)					0.73(2.4)
164.04-180.45 (50-55)	No. Gouges	51					51
	Mean(ft)	2.30 (0.7)					2.30 (0.7)
	Max(ft)	4.92 (1.5)					4.92 (1.5)
	Std(ft)	0.98 (0.3)					0.98 (0.3)
	$\lambda(ft^{-1})$	0.64(2.1)					0.64(2.1)
180.45-196.85 (55-60)	No. Gouges	2					2
	Mean(ft)	3.28 (1)					3.28 (1)
	Max(ft)	3.61 (1.1)					3.61 (1.1)
	Std(ft)	0.33 (0.1)					0.33 (0.1)
	$\lambda(ft^{-1})$	0.40(1.3)					0.40(1.3)
Total	No. Gouges	18392	857	5204	4	24	24481
	Mean(ft)	1.64 (0.5)	1.31 (0.4)	1.31 (0.4)	1.31 (0.4)	0.98 (0.3)	1.64 (0.5)
	Max(ft)	12.8 (3.9)	3.61 (1.1)	5.58 (1.7)	1.64 (0.5)	2.30 (0.7)	12.80 (3.9)
	Std(ft)	0.98 (0.3)	0.33 (0.1)	0.66 (0.2)	0.33 (0.1)	0.33 (0.1)	0.98 (0.3)
	$\lambda(ft^{-1})$	0.98(3.2)	1.80(5.9)	1.49(4.9)	2.04(6.7)	2.44(8)	1.07(3.5)
Measurements in parenthesis are in meters (m)							



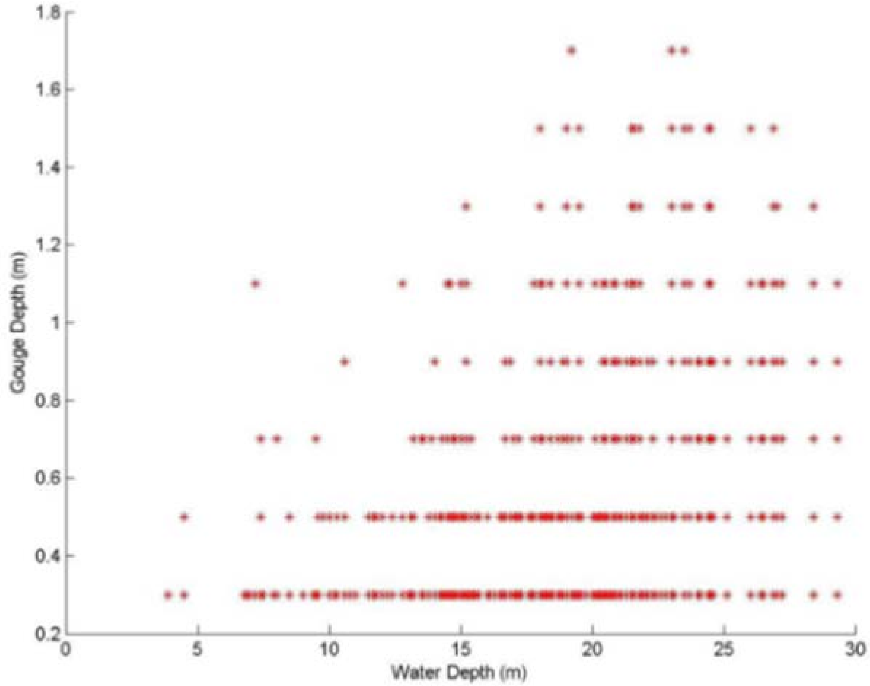
Zone A

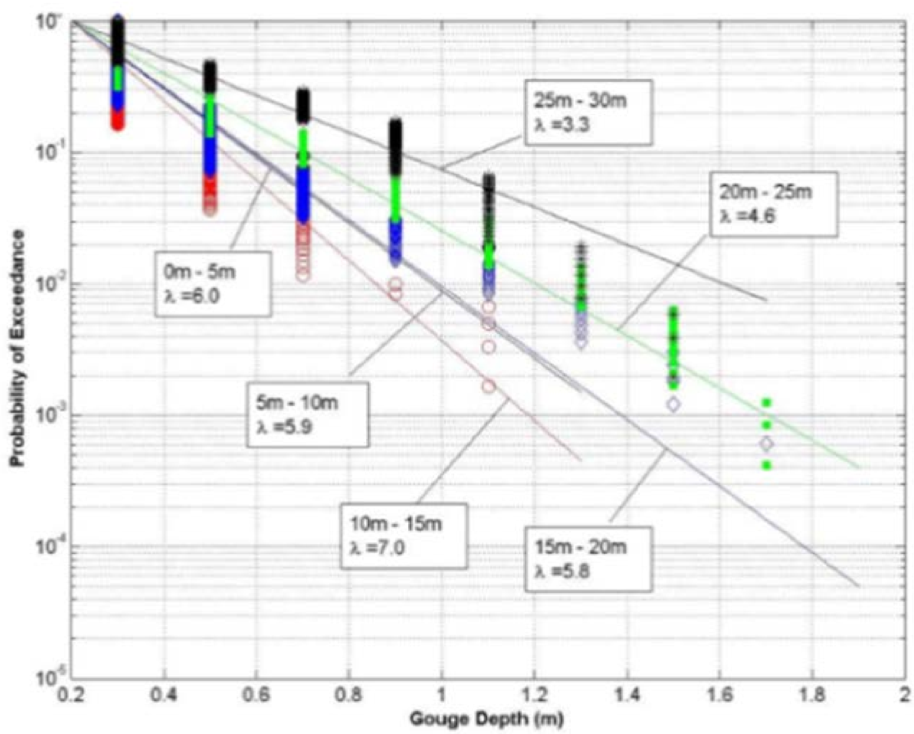
Figure 4.8 (a): Gouge Depth Summary (Rearic and McHendrie, 1983) – MMS (2008) [18]



Zone B

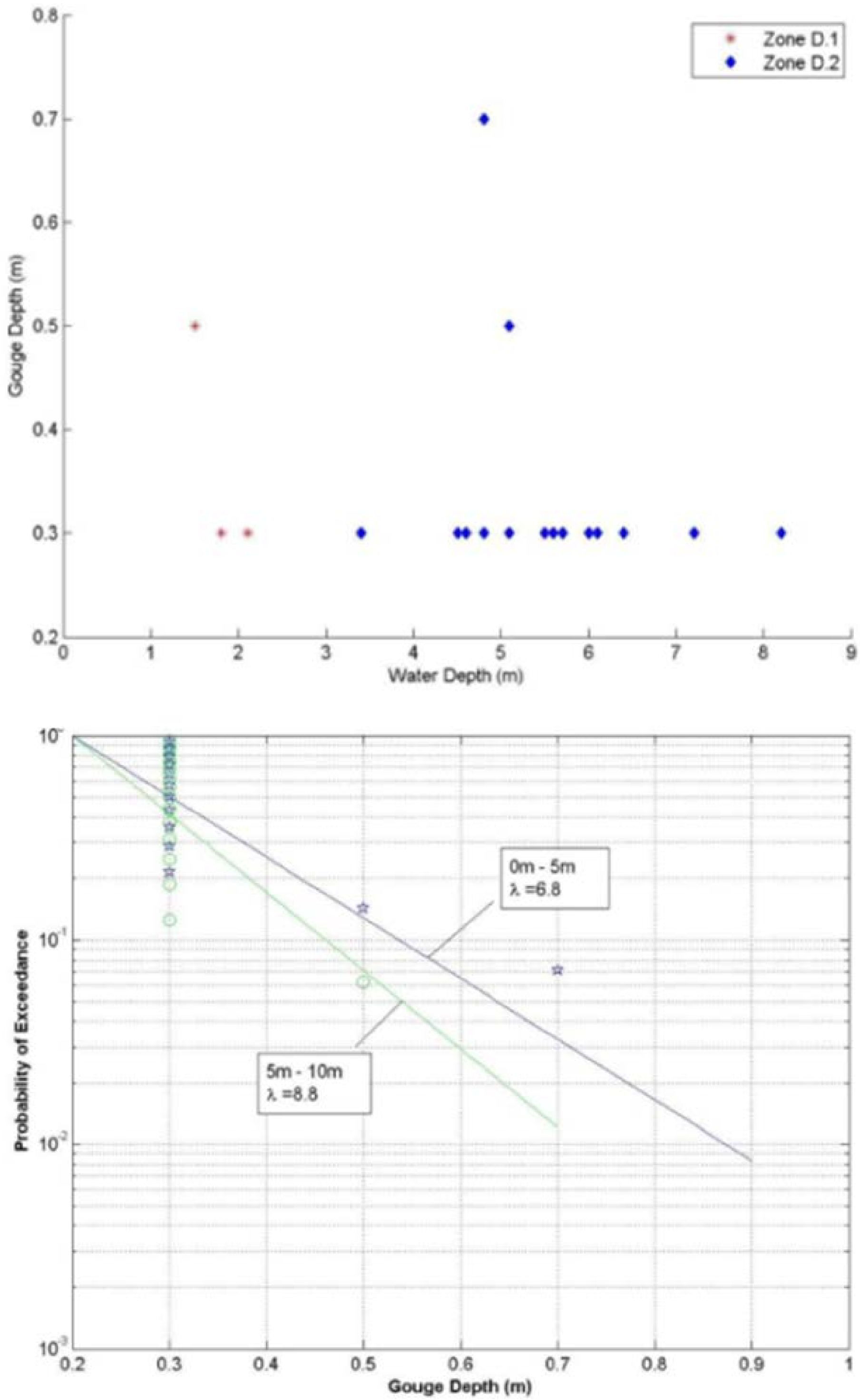
Figure 4.8 (b): Gouge Depth Summary (Rearic and McHendrie, 1983) – MMS (2008) [18]





Zone C

Figure 4.8 (c): Gouge Depth Summary (Rearic and McHendrie, 1983) – MMS (2008) [18]



Zone D

Figure 4.8 (d): Gouge Depth Summary (Rearic and McHendrie, 1983) – MMS (2008) [18]

4.3.1.2 Weber, et al (1989)

Table 4.6 summarizes the gouge data as presented by MMS (2008) [19]. To understand the characteristics of gouges for each water depth, gouge data was collected for each water depth interval and statistical analysis was performed for each water depth separately. An exponential distribution was assumed for each water depth set of data. The tabulated data presents a useful guide for design, however, the gouge dataset population may not be as sufficient as the data set provided by Rearic and McHendrie (1983). A total number of 48 single gouges was noticed for all of the zones and 38 multiple gouges.

The deepest single gouge was found within Zone B, in the 33-49 ft. (10-15 m) water depth interval. Zone B, in general, is relatively shallow, with water depths of 16.4-65.6 ft. (5-20 m). Only 27 single gouges were noticed in Zone B. The deepest single gouge for Zone A and C was less than 1.6 ft. (0.5 m) and 4.6 ft. (1.4 m), respectively. The mean gouge depth for all of the zones falls within a comparable range of 1.0 ft. (0.3 m) to 1.64 ft. (0.5 m). This may be considered as an indication of homogenous gouge depths, excluding some extreme events.

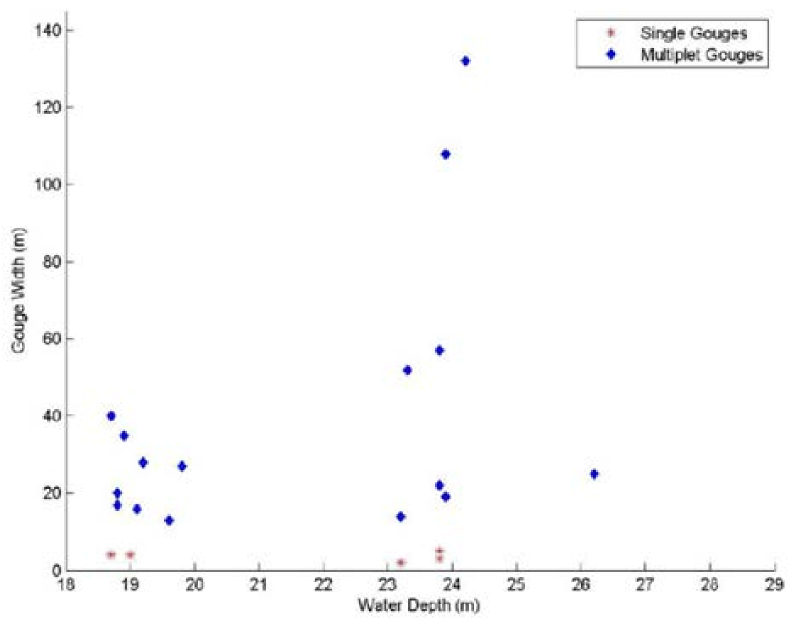
Data for multiple gouges is summarized in Table 4.7. The deepest gouge depth is 9.8 ft. (3 m) and it is found in Zone C in the 33-49 ft. (10-15) m water depth. The mean value and standard deviation for Zone C was calculated using a set of only five gouges. The standard deviation is 3.9 ft. (1.2 m), which is much higher than the standard deviation for Zones A and B, 1.0 ft. (0.3 m) and 0.32 ft. (0.1 m), respectively. The analysis for the complete dataset indicated that the mean and the standard deviation (38 gouges) are 1.6 ft. (0.5 m) and 1.6 ft. (0.5 m), respectively. Weber and co-workers recommended additional surveys to increase the population of gouges and to improve the prediction of distribution parameters (mean and standard deviation). Scatter plots for all of the zones are shown in Figure 4.8

Table 4.6: Single Gouge Depths (Weber, et al., 1989) – MMS (2008) [18]

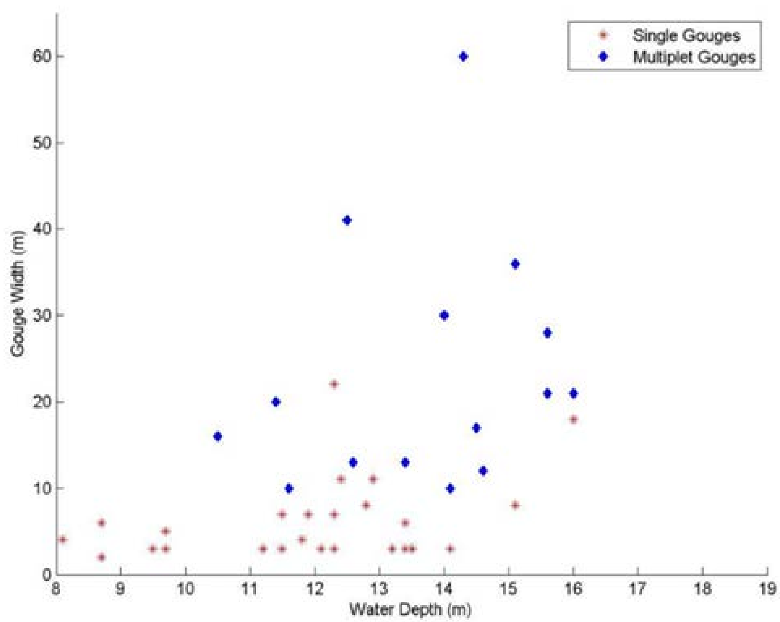
Water Depth ft. (m)	Gouge Depth, ft (m)				
	Zone	A	B	C	ALL
16.40-32.81 (5-10)	No. Gouges		7	2	9
	Mean(ft)		1.31 (0.4)	1.97 (0.6)	1.31 (0.4)
	Max(ft)		2.30 (0.7)	2.30 (0.7)	2.30 (0.7)
	Std(ft)		0.33 (0.1)	0.33 (0.1)	0.66 (0.2)
	$\lambda(ft^{-1})$		1.80(5.9)	0.76(2.5)	1.37(4.5)
32.81-49.21 (10-15)	No. Gouges		17	1	18
	Mean(ft)		1.97 (0.6)	1.31 (0.4)	1.97 (0.6)
	Max(ft)		9.84 (3)	1.31 (0.4)	9.84 (3)
	Std(ft)		2.30 (0.7)	0	1.97 (0.6)
	$\lambda(ft^{-1})$		0.82(2.7)	1.52(5)	0.86(2.8)
49.21-65.62 (15-20)	No. Gouges	2	3	12	17
	Mean(ft)	1.31 (0.4)	0.98 (0.3)	1.64 (0.5)	1.64 (0.5)
	Max(ft)	1.64 (0.5)	0.98 (0.3)	4.59 (1.4)	4.59 (1.4)
	Std(ft)	0.33 (0.1)	0	0.98 (0.3)	0.98 (0.3)
	$\lambda(ft^{-1})$	1.52(5)	3.05(10)	0.94(3.1)	1.12(3.7)
65.62-82.02 (20-25)	No. Gouges	4			4
	Mean(ft)	0.98 (0.3)			0.98 (0.3)
	Max(ft)	0.98 (0.3)			0.98 (0.3)
	Std(ft)	0			0
	$\lambda(ft^{-1})$	3.04(10)			3.04(10)
Total	No. Gouges	6	27	15	48
	Mean(ft)	0.98 (0.3)	1.64 (0.5)	1.64 (0.5)	1.64 (0.5)
	Max(ft)	1.64 (0.5)	9.84 (3)	4.59 (1.4)	9.84 (3)
	Std(ft)	0.33 (0.1)	1.64 (0.5)	0.98 (0.3)	1.31 (0.4)
	$\lambda(ft^{-1})$	2.29(7.5)	1.07(3.5)	0.95(3.1)	1.09(3.6)
Measurements in parenthesis are in meters (m)					

Table 4.7: Multiple Gouge Depths (Weber, et al., 1989) [29]

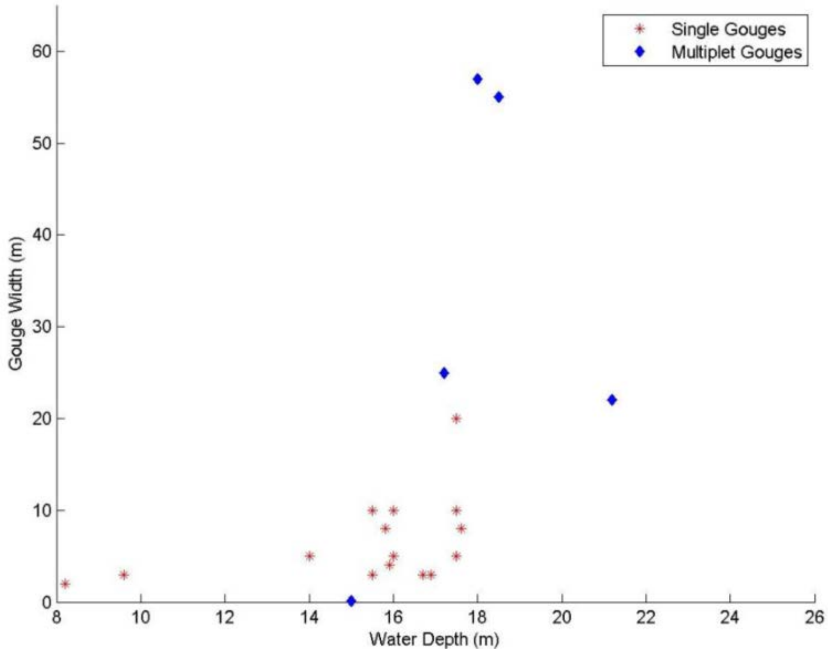
Water Depth ft. (m)	Gouge Depth, ft (m)				
	Zone	A	B	C	ALL
32.81-49.21 (10-15)	No. Gouges		12	1	13
	Mean(ft)		1.31 (0.4)	9.84 (3)	1.97 (0.6)
	Max(ft)		1.97 (0.6)	9.84 (3)	9.84 (3)
	Std(ft)		0.33 (0.1)	0	2.30 (0.7)
	$\lambda(ft^{-1})$		1.74(5.7)	0.12(0.4)	0.82(2.7)
49.21-65.62 (15-20)	No. Gouges	8	5	3	16
	Mean(ft)	1.64 (0.5)	1.64 (0.5)	1.31 (0.4)	1.64 (0.5)
	Max(ft)	3.93 (1.2)	2.62 (0.8)	1.64 (0.5)	3.93 (1.2)
	Std(ft)	0.98 (0.3)	0.66 (0.2)	0.33 (0.1)	0.66 (0.2)
	$\lambda(ft^{-1})$	1.10(3.6)	1.10(3.9)	1.31(4.3)	1.16(3.8)
65.62-82.02 (20-25)	No. Gouges	7		1	8
	Mean(ft)	1.97 (0.6)		0.98 (0.3)	1.64 (0.5)
	Max(ft)	2.62 (0.8)		0.98 (0.3)	2.62 (0.8)
	Std(ft)	0.66 (0.2)		0	0.66 (0.2)
	$\lambda(ft^{-1})$	0.85(2.8)		3.05(10)	0.95(3.1)
65.62-98.43 (20-30)	No. Gouges	1			1
	Mean(ft)	2.62 (0.8)			2.62 (0.8)
	Max(ft)	2.62 (0.8)			2.62 (0.8)
	Std(ft)	0			0
	$\lambda(ft^{-1})$	0.52(1.7)			0.52(1.7)
Total	No. Gouges	16	17	5	38
	Mean(ft)	1.64 (0.5)	1.31 (0.4)	2.95 (0.9)	1.64 (0.5)
	Max(ft)	3.93 (1.2)	2.62 (0.8)	9.84 (3)	9.84 (3)
	Std(ft)	0.98 (0.3)	0.33 (0.1)	3.93 (1.2)	1.64 (0.5)
	$\lambda(ft^{-1})$	0.91(3)	1.52(5)	0.43(1.4)	0.95(3.1)
Measurements in parenthesis are in meters (m)					


Single Gouges
Multiplet Gouges
Gouge Width (m)
Water Depth (m)
0
20
40
60
80
100
120
140
18
19
20
21
22
23
24
25
26
27
28
29

Zone A


Single Gouges
Multiplet Gouges
Gouge Width (m)
Water Depth (m)
0
10
20
30
40
50
60
8
9
10
11
12
13
14
15
16
17
18
19

Zone B



Zone C

Figure 4.8: Weber, et al. (1989) Gouge Width Data – MMS (2008) [18]

4.3.2 Gouge Width

4.3.2.1 Rearic and McHendrie (1983)

Rearic and McHendrie (1983) provided a relevant gouge database that tabulated the gouge depths over a wide area of the seabed. The dataset, unfortunately, did not accurately describe the width of the gouges and no distinction between single and multiple gouges was provided. The maximum gouge depth for each segment is indicated by the dataset. Therefore, MMS (2008) reported that the data may not be sufficient for further analysis. It may, however, still be used as an indication for the possible gouge widths.

4.3.2.2 Weber, et al (1989)

MMS (2008) analyzed the dataset provided by Weber, et al. (1989) looking for meaningful correlations between the seabed bathymetry and the gouge widths. Weber, et al. (1989) datasets provided the width of gouges. The width of the gouge is used by the designer to estimate the length of pipe that may be subjected to damage, if any, or the seabed surface area that is subjected to gouging hazard if a wellhead is to be placed at this location. A total number of 48 single gouges and 38 multiple gouges were listed by Weber, et al. (1989).

The data for single gouge widths are listed in Table 4.8, as reported by MMS (2008). Gouges were listed for each water depth interval and statistical analysis was performed for each zone as well. Additional analysis was performed for the complete data set, which showed that the maximum noticed width is 22 m wide and occurs within Zone B at the 33-49 ft. (10-15 m) water depth interval. Mean value and standard deviation for the whole set is 6 m and 4 m, respectively. Most of the gouges occur at Zones B and C, which are relatively shallower than Zone A (approximately, 88%). In addition, the width of gouges at Zone B and C are wider than the ones that occurred at Zone A. Due to this, it may be concluded as a general guideline, that an iceberg passing through zones A, B and C are wide and shallow and, therefore, become trapped in the shallow water zones (Zones C and D).

The same analysis procedure was followed for the multiple width gouges. Table 4.9 presents the dataset categorized for each zone and depth intervals as prepared by MMS (2008). A total number of 38 gouges were listed. The maximum gouge widths noticed in Zones C and D are 197 ft. (60 m) and 187 ft. (57 m), respectively. The mean value for zones A, B and C are 128, 75, and 104 ft. (39, 23, and 32 m), respectively. The average gouge width for the whole width is 31 m and the maximum noticed gouge width is 433 ft. (132 m) wide and was noticed at Zone A. This is six times wider than the maximum width noticed from single gouge 72 ft. (22 m). An exponential analysis was performed to calculate the standard deviation for each zone and whole dataset.

4.3.3 Crossing Density

4.3.3.1 Rearic and McHendrie (1983)

The dataset provided by Rearic and McHendrie (1983) [26] included extensive information about the gouge dimensions and locations, although the age of the gouges, was unknown. MMS (2008) [19] investigated the crossing densities using the data provided by Rearic and McHendrie (1983) [26].

Table 4.10 lists the gouge depths for each zone and is categorized based on the water depth interval of occurrence, as prepared by MMS (2008) [19]. A statistical analysis was performed for each water depth interval within each zone. Number of gouges, mean crossing density, maximum crossing density, and standard deviation were listed for each water depth interval.

Surveys were performed for segments along the track lines measured in kilometers. Zones A, B, C, D.1 and D.2 have 304, 90, 243, 42, 175 mile (489, 144, 391, 68 and 282 kilometers) intervals, respectively. The maximum crossing density was recorded within

Zone A (92 mi^{-1}) (147 km^{-1}) at water depths between 65 to 82 ft. (20 to 25 m). It can be noticed that the crossing densities increases up to a water depth interval of 65 to 82 ft. (20 to 25 m) then decreases rapidly. Zone D is excluded from this observation since it is shallower than the other zones. This may indicate that this interval acts like a barrier to capture most of the icebergs that have similar characteristics.

Table 4.8: Single Gouge Widths (Weber et al., 1989) – MMS (2008) [18]

Water Depth ft (m)		Gouge Width, ft (m)			
	Zone	A	B	C	ALL
16.40-32.81 (5-10)	No. Gouges	0	7	2	9
	Mean(ft)	0	13.12	9.84	9.84
	Max(ft)	0	19.69	9.84	19.69
	Std(ft)	0	3.28	3.28	3.28
32.81-49.21 (10-15)	No. Gouges	0	17	1	18
	Mean(ft)	0	19.69	16.40	19.69
	Max(ft)	0	72.18	16.40	72.18
	Std(ft)	0	16.40	0	16.40
49.21-65.62 (15-20)	No. Gouges	2	3	12	17
	Mean(ft)	13.12	36.09	22.97	26.25
	Max(ft)	13.12	59.06	65.62	65.62
	Std(ft)	0.00	19.69	16.40	16.40
65.62-82.02 (20-25)	No. Gouges	4			4
	Mean(ft)	9.84	0	0	9.84
	Max(ft)	16.40	0	0	16.40
	Std(ft)	3.28	0	0	3.28
Total	No. Gouges	6	27	15	48
	Mean(ft)	9.84	19.69	22.97	19.69
	Max(ft)	16.40	72.18	65.62	72.18
	Std(ft)	3.28	16.40	16.40	13.12

Measurements in parenthesis are in meters (m)

Table 4.9: Multiplet Gouge Widths (Weber et al., 1989) – MMS (2008) [18]

Water Depth ft (m)		Gouge Width, ft (m)			
	Zone	A	B	C	ALL
32.81-49.21 (10-15)	No. Gouges		12	1	13
	Mean(ft)	0.00	68.90	0.00	65.62
	Max(ft)	0.00	196.85	0.00	196.85
	Std(ft)	0.00	49.21	0.00	52.49
49.21-65.62 (15-20)	No. Gouges	8	5	3	16
	Mean(ft)	82.02	82.02	150.92	95.14
	Max(ft)	131.23	118.11	187.01	187.01
	Std(ft)	32.81	22.97	59.06	42.65
65.62-82.02 (20-25)	No. Gouges	7		1	8
	Mean(ft)	190.29	0.00	72.18	173.88
	Max(ft)	433.07	0.00	72.18	433.07
	Std(ft)	150.92	0.00	0.00	147.64
82.02-98.43 (25-30)	No. Gouges	1			1
	Mean(ft)	82.02	0.00	0.00	82.02
	Max(ft)	82.02	0.00	0.00	82.02
	Std(ft)	0.00	0.00	0.00	0.00
Total	No. Gouges	16	17	5	38
	Mean(ft)	127.95	75.46	104.99	101.71
	Max(ft)	433.07	196.85	187.01	433.07
	Std(ft)	111.55	42.65	78.74	85.30
Measurements in parenthesis are in meters (m)					

Table 4.10: Summary of Rearic and McHendrie (1983) [26] Gouge Crossing Density – MMS (2008) [18]

Water Depth ft (m)		Crossing Density (gouge/mile)					
	Zones	A	B	C	D.1	D.2	ALL
0-16.40 (0-5)	No. Gouges	0	1.72	0.43	3.65	6.49	12.28
	Mean(ft)	0	0.00	0.00	0.00	0.00	0.00
	Max(ft)	0	6.56	6.56	6.56	13.12	13.12
	Std(ft)	0	3.28	3.28	0.00	0.00	0.00
16.40-32.81 (5-10)	No. Gouges	0	2.15	3.86	0	8.85	14.91
	Mean(ft)	0	13.12	3.28	0	0.00	3.28
	Max(ft)	0	32.81	22.97	0	6.56	32.81
	Std(ft)	0	9.84	3.28	0	0	6.56
32.81-49.21 (10-15)	No. Gouges	0.97	2.79	7.72	0	0	11.48
	Mean(ft)	32.81	22.97	13.12	0	0	16.40
	Max(ft)	118.11	85.30	275.59	0	0	275.59
	Std(ft)	42.65	19.69	32.81	0	0	32.81
49.21-65.62 (15-20)	No. Gouges	3.76	0.97	5.63	0	0	10.35
	Mean(ft)	88.58	45.93	52.49	0	0	65.62
	Max(ft)	426.51	213.25	341.21	0	0	426.51
	Std(ft)	104.99	42.65	78.74	0	0	88.58
65.62-82.02 (20-25)	No. Gouges	7.46	0.11	2.79	0	0	10.35
	Mean(ft)	183.73	137.80	150.92	0	0	173.88
	Max(ft)	482.28	180.45	423.23	0	0	482.28
	Std(ft)	482.28	180.45	423.23	0	0	482.28

Water Depth ft (m)	Crossing Density (gouge/mile)						
	Zones	**A**	**B**	**C**	**D.1**	**D.2**	**ALL**
82.02-98.43 (25-30)	No. Gouges	104.99	62.34	91.86	0	0	104.99
	Mean(ft)	4.56	0	0.54	0	0	5.10
	Max(ft)	219.82	0	170.60	0	0	213.25
	Std(ft)	462.60	0	265.75	0	0	462.60
98.43-114.83 (30-35)	No. Gouges	108.27	0	52.49	0	0	104.99
	Mean(ft)	2.63	0	0	0	0	2.63
	Max(ft)	144.36	0	0	0	0	144.36
	Std(ft)	301.84	0	0	0	0	301.84
114.83 - 131.23 (35-40)	No. Gouges	68.90	0	0	0	0	68.90
	Mean(ft)	0.75	0	0	0	0	0.75
	Max(ft)	68.90	0	0	0	0	68.90
	Std(ft)	127.95	0	0	0	0	127.95
131.23-147.64 (40-45)	No. Gouges	36.09	0	0	0	0	36.09
	Mean(ft)	1.66	0	0	0	0	1.66
	Max(ft)	16.40	0	0	0	0	16.40
	Std(ft)	101.71	0	0	0	0	101.71
147.64-164.04 (45-50)	No. Gouges	22.97	0	0	0	0	16.40
	Mean(ft)	1.50	0	0	0	0	1.50
	Max(ft)	16.40	0	0	0	0	16.40
	Std(ft)	72.18	0	0	0	0	72.18
164.04-180.45 (50-55)	No. Gouges	19.69	0	0	0	0	19.69
	Mean(ft)	1.34	0	0	0	0	1.34
	Max(ft)	6.56	0	0	0	0	6.56
	Std(ft)	29.53	0	0	0	0	29.53
180.45-196.85 (55-60)	No. Gouges	9.84	0	0	0	0	9.84
	Mean(ft)	0.64	0	0	0	0	0.64
	Max(ft)	0.00	0	0	0	0	0.00
	Std(ft)	6.56	0	0	0	0	6.56

Measurements in parenthesis are in meters (m)

4.3.3.2 Weber, et al (1989)

MMS (2008) [19] followed the same approach to describe the gouging crossing density using the dataset listed by Weber, et al. (1989) [31]. The analysis was performed assuming a cut-off depth of 0.32 ft (0.1 m). All depths below 0.32 ft (0.1 m) were removed from the data.

Zones A, B and C contain a total of 10.6, 54.0 and 66.5 miles (17, 87 and 107 km) intervals, respectively. The maximum crossing density is 167 gouges/mile (268 gouges/km) and is noticed within Zone A at a water depth interval of 65 to 82 ft. (20 to 25 m). The mean value of crossing density increases with a water depth up to the 65 to 82 ft. (20 to 25 m) interval. The mean crossing densities are 77, 41, 15 gouges/mi (123, 66, 24 gouges/km) for Zones A, B and C, respectively. Table 4.11 summarizes gouging crossing density as prepared by MMS (2008).

Table 4.11: Summary of Weber, et al. (1989) Gouge Crossing Density – MMS (2008) [18]

Water Depth ft (m)	Crossing Density (gouge/mile)				
	Zone	A	B	C	ALL
0-16.40 (0-5)	No. mile Intervals	0	0	111.85	111.85
	Mean (gouge/mile)	0	0	0.11	0.11
	Max (gouge/mile)	0	0	0.21	0.21
	Std (gouge/mile)	0	0	0.11	0.11
16.40-32.81 (5-10)	No. mile Intervals	0	782.93	894.78	1677.70
	Mean (gouge/mile)	0	0.64	0.43	0.51
	Max (gouge/mile)	0	1.72	1.45	1.72
	Std (gouge/mile)	0	0.51	0.46	0.48
32.81-49.21 (10-15)	No. mile Intervals	0	2125.09	1938.68	4063.77
	Mean (gouge/mile)	0	2.09	0.48	1.34
	Max (gouge/mile)	0	4.59	1.66	4.59
	Std (gouge/mile)	0	1.02	0.43	1.13

Water Depth ft (m)	Crossing Density (gouge/mile)				
	Zone	A	B	C	ALL
49.21-65.62 (15-20)	No. mile Intervals	260.98	335.54	745.65	1342.16
	Mean (gouge/mile)	3.19	2.31	0.80	1.64
	Max (gouge/mile)	5.04	3.17	3.54	5.04
	Std (gouge/mile)	0.99	0.51	1.02	1.34
65.62-82.02 (20-25)	No. mile Intervals	186.41	0	298.26	484.67
	Mean (gouge/mile)	4.43	0	2.25	3.08
	Max (gouge/mile)	7.19	0	3.41	7.19
	Std (gouge/mile)	1.61	0	0.78	1.56
82.02-98.43 (25-30)	No. mile Intervals	186.41	0	0	186.41
	Mean (gouge/mile)	2.31	0	0	2.31
	Max (gouge/mile)	3.46	0	0	3.46
	Std (gouge/mile)	1.31	0	0	1.31
Measurements in parenthesis are in meters (m)					

4.3.4 Crossing Frequencies

Repetitive mapping can be used to calculate the crossing densities as presented in the previous section. In addition, repetitive mapping can be used to calculate the crossing frequency by comparing the surveys conducted at the same portion of seabed. The MMS (2008) [19] report investigated the crossing frequency in the Beaufort Sea utilizing the available datasets. The crossing density for the Beaufort Sea, since it has a long survey line, was expressed in terms of the number of gouge crossings per unit distance of survey line per unit time (i.e., $Km^{-1}yr^{-1}$). The report hinted that there was some inconsistencies in the data since a lot of the multi-keel gouges were counted as single keel gouge events. The report recommended that each gouge in a multi-keel event should be considered as single entity. In addition, MMS (2008) [19] excluded gouges below a certain depth threshold to improve the estimation of the gouge crossing density.

An additional approach may be adopted to estimate the age gouging, if repetitive survey data is not available. The degree of degradation of the gouge signature can estimate the age of the gouges and is a technique that was presented by Lever (1999) [11].

4.3.4.1 Rearic and McHendrie (1983)

The age of the gouges was not listed or estimated in the dataset that was prepared by Rearic and McHendrie (1983) [26].Therefore, a crossing frequency calculation was not performed by MMS (2008).

4.3.4.2 Weber, et al. (1989)

The MMS report used the data set provided by Weber, et al. (1989) [31], which contained repetitive mapping performed for the US Beaufort Sea for the time period between 1977 and 1985. Gouges with a depth lower than 0.65 ft. (0.2 m) were not included in the analysis to improve the estimation of the crossing frequency.

As stated earlier, the MMS report divided the sea floor into four zones; detailed descriptions of each zone's texture characteristics were presented in previous sections.

Table 4.12 summarizes the analysis prepared by MMS (2008). The maximum crossing frequency was observed within Zone C in the water depth interval from 49 to 65 ft. (15 to 20 m). The calculated mean and standard deviation is equal to 1 (gouge/km/year) and 1 (gouge/km/year), respectively. The average crossing frequency for the 49 to 65 ft. (15 to 20 m) water depth interval, assuming data from all of the zones, is equal to 6 (gouge/km/year) with a standard deviation of 1 (gouge/km/year).

Table 4.12: Summary of Weber, et al. (1989) Gouge Crossing Frequencies

Water Depth ft (m)	Crossing Density (gouge/mile/yr)				
	Zones	A	B	C	ALL
16.40-32.81 (5-10)	No. mile Intervals	0	782.93	857.49	1640.42
	Mean (gouge/mile)	0	0	0	0
	Max (gouge/mile)	0	0.05	0.03	0.05
	Std (gouge/mile)	0	0.03	0.00	0.03
32.81-49.21 (10-15)	No. mile Intervals	0	2125.09	1640.42	3765.51
	Mean (gouge/mile)	0	0.03	0	0
	Max (gouge/mile)	0	0.08	0.03	0.08
	Std (gouge/mile)	0	0.03	0	0.03
49.21-65.62 (15-20)	No. mile Intervals	74.56	186.41	521.95	782.93
	Mean (gouge/mile)	0.03	0	0.03	0.03
	Max (gouge/mile)	0.03	0.03	0.16	0.16
	Std (gouge/mile)	0	0	0.05	0.03
Measurements in parenthesis are in meters (m)					

5.0 Chukchi Sea – Field Data

This chapter presents the ice gouging field data for the Chukchi Sea. The following section describes in detail the finding of a field survey that was conducted in 1974 by members of the Office of Marine Geology of the U.S. Geological Survey in cooperation with the U.S. Coast Guard aboard the U.S.S. Burton Island. Since that survey took place, no repetitive mapping has been performed. As a result, the age of gouge was not identified and the study was limited to an understanding of the general trend of gouging in the Chukchi Sea.

5.1 Toimil (1978)

Toimil (1978) [29] studied ice gouging using the data obtained from side-scan sonar and bathymetric measurements performed during the 1974 field operations. The study reports that Furrow-like linear depressions produced by gouging of the seabed by ice keels were noticed along the track lines. The general texture of the seabed was significantly disturbed by single and multiple gouging events. Side-scan sonar studies were conducted to cover approximately 96,500 square miles (or approx. 250,000 km^2) of the Chukchi Sea. This area of study is shown in Figure 5.1

Survey data was analyzed to locate ice gouging in the seabed. Surveys were performed for 1,118 miles (1,800 km) of track line at the eastern Chukchi Sea continental shelf. A large number of individual gouges (10,200) were identified in the water depth between 66 and 230 ft. (20 and 70 m) and gouges were examined to identify the possible future gouges' orientation, incision depth, width, and relative abundance over the shelf. Figure 5.2 presents the location of side-scan sonar track lines, as determined by satellite navigation fixes, which were taken by the U.S. Burton Island and are considered to be accurate within about 0.3 miles (0.5 km).

Toimil (1978) [29] indicated that the general dominant ice gouge drift is parallel to the bathymetric contours which are shown in Figure 5.3. This is consistent with the direction of the sea current, which is moving west to east.

5.1.1 Bathymetry

Toimil (1978) [29] prepared a bathymetric map of the study area using the National Ocean Survey chart number 9,402 and data from bathymetric measurements made by the U.S. Burton Island in 1972 and 1974, as presented in Figure 5.3, which was modified by WGK to highlight the major bathymetry features. Survey data were compiled by Holmes (1975) [6] and were also included in the Toimil's Chart. The following summarizes remarks by Toimil (1978) [29] regarding the bathymetric features of the

Chukchi Sea:

- The shelf is characterized by an extremely subtle topographic relief.
- The shelf has four major conspicuous features - Hope Sea Valley, Barrow Sea Valley, Herald Shoal, and Hanna Shoal. Both Herald Shoal and Hanna Shoal serve as a natural barrier to capture and hold deep draft ice.
- Herald Shoal occupies approximately 10,560 miles (17,000 km) with a maximum relief of 104 ft. (32 m). It rises to 66 ft. (20 m) above the sea level. The slope gradient ranges from 2.6 to 20.8 ft/mile (0.79 to 6.3 m/km) and the crustal ridge trends east-west. The Shoals are marked by an irregular relief (Holmes,1975) [6].
- Hanna Shoal extends 155 miles (250 km) west from Point Barrow and serves as a natural barrier to capture and hold deep draft ice. The shoal rises to within 56 ft. (17 m) of sea level, near 72 00.5 N, 161 55.0 W.
- Numerous isolated shoals exist near the shore forming irregular bathymetry. Blossom Shoal is noticed near the shore, as shown in Figure 5.4.

5.1.2 Gouging Densities

Toimil (1978) [29] investigated the gouging density using the available survey data track line segments. Figure 5.4 shows the areal distribution of maximum ice gouge densities. Ice gouges are regionally widespread but not uniformly distributed. In addition, several track line segments are void of ice gouges. In general, gouging density at the south of Cape Lisburne is low. The highest noticed ice gouge densities range between 17.6/mile (11/km) and 25.6/mile (16/km), occurring along the western flank and northern portions of Cape Prince of Wales Shoal.

Gouging densities of 102.4/mile (64/km) and 41.6/mile (26/km) are noticed at the 78.7 ft. and 85 ft. (24 m and 26 m) isopachs, respectively. Isopachs between 65.6 ft. and 115 ft. (20 m and 35 m) have common gouge densities of 80/mile (50/km). It was noticed that zones with high gouge densities 160/mile (100/km) are often adjacent to low gouging density zones, which may be due to the difference in water depth.

Figure 5.5 shows a scatter plot of the normalized maximum ice gouge density over the similar bathymetric setting. Ice gouge densities of over 320/mile (200/km) are found over about 5% of the total track line coverage at water depths between 69ft. and 115 ft. (21 and 35 m). A rapid decrease in the gouging density for water depths more than 50 m was noted. The maximum noticed value for the water depths deeper than 164 ft. (50 m) was 16/mile (10/km) and no gouges were noticed for depths deeper than 291 ft. (89 m). Table 5.1 summarizes the findings by Toimil (1978) [29].

5.1.3 Gouge Depth

The analysis of survey data showed that the maximum gouge incision depth per km of track line is greatest in water depths between 115 ft. and 164 ft. (35 and 50 m). The maximum noticed incision depth is equal to 14.7 ft. (4.5 m) in the 115 ft. to 164 ft. (35 to 50 m) water depth interval. Gouges with depths of 6.6 ft. (2.0 m) were noticed in the 69 to 82 ft. (21 to -25 m) water depth intervals. This data was summarized and added to Table 5.1

5.1.4 Gouging Width

Toimil (1978) [29] reported that maximum gouge widths are produced by multi-keeled ice fragments. Gouges wider than 328 ft. (100 m) occur within the 118 to 131 ft. (36 to 40 m) depth interval. The maximum occurrence of wide gouges occurs between gouges in water depths of 101 to 147 ft. (31 to 45 m).

Table 5.1: Summary of Ice Gouge Densities

Water Depth Interval		Max. Ice Gouge Densities		Max. Gouge Depth		Gouge Width	
(ft)	(m)	(/mile)	(/km)	(ft)	(m)	(ft)	(m)
68.9 - 114.82	21 - 35	124.27	200	14.76	4.5	NA	
118.11-147.64	36 - 45	NA		NA		>328.08	>100
183.73	< 56	6.21	10	3.28	1	NA	
190.29	< 58	None		None		None	

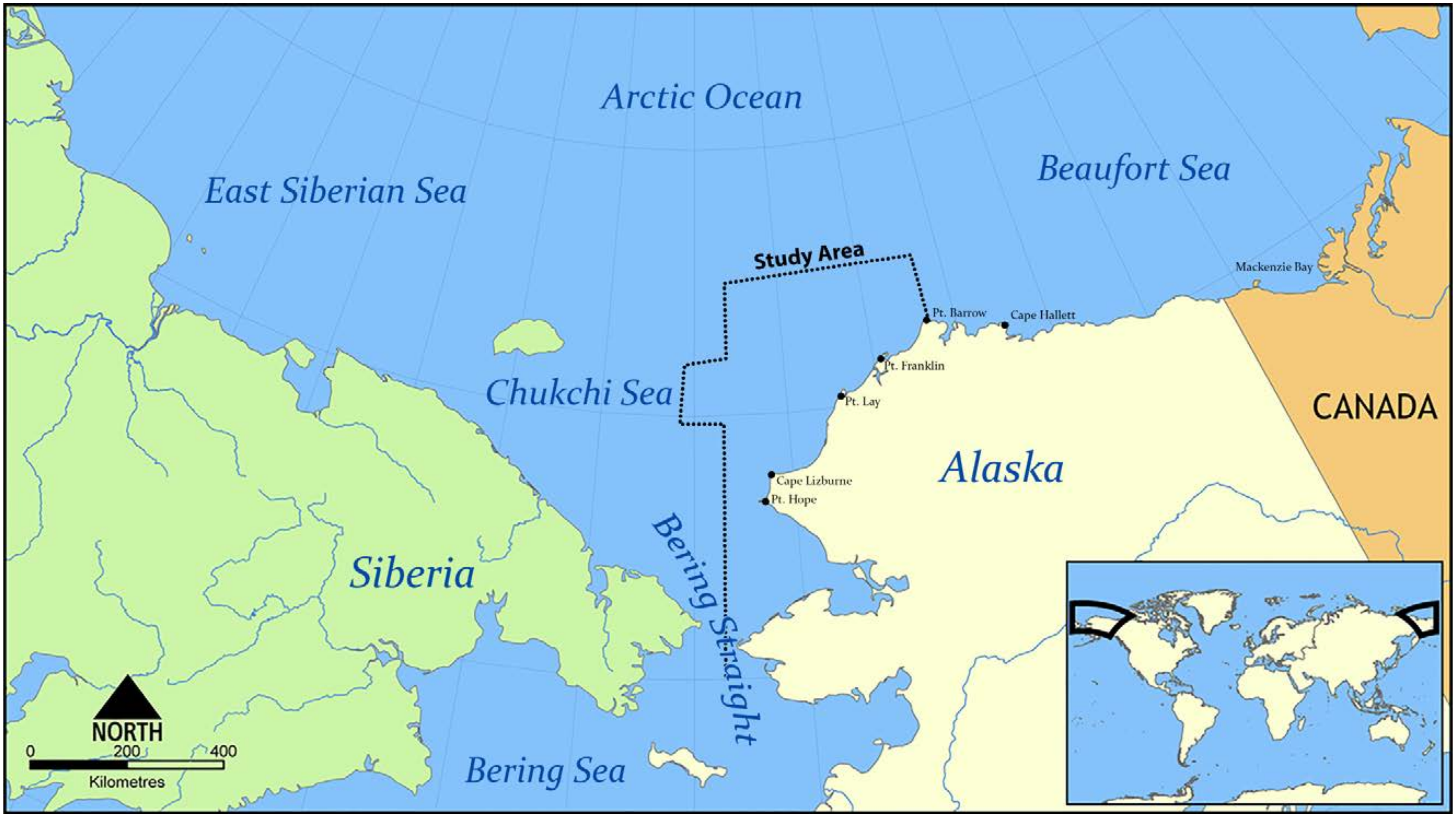


Figure 5.1: Area of Study – Toimil (1978) [29]

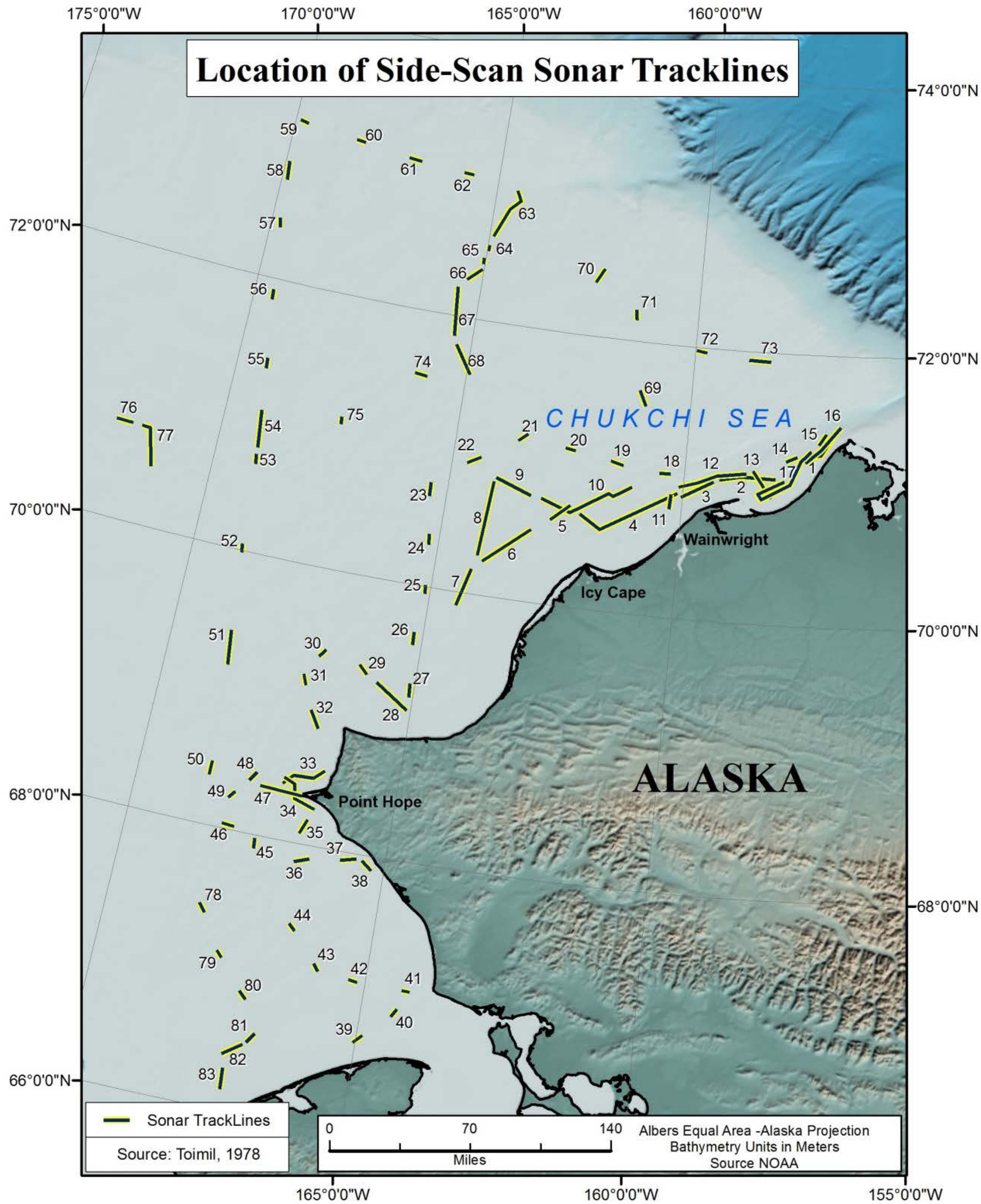


Figure 5.2: Location of Side-Scan Sonar Tracklines as Determined by Satellite – Toimil (1978) [29]

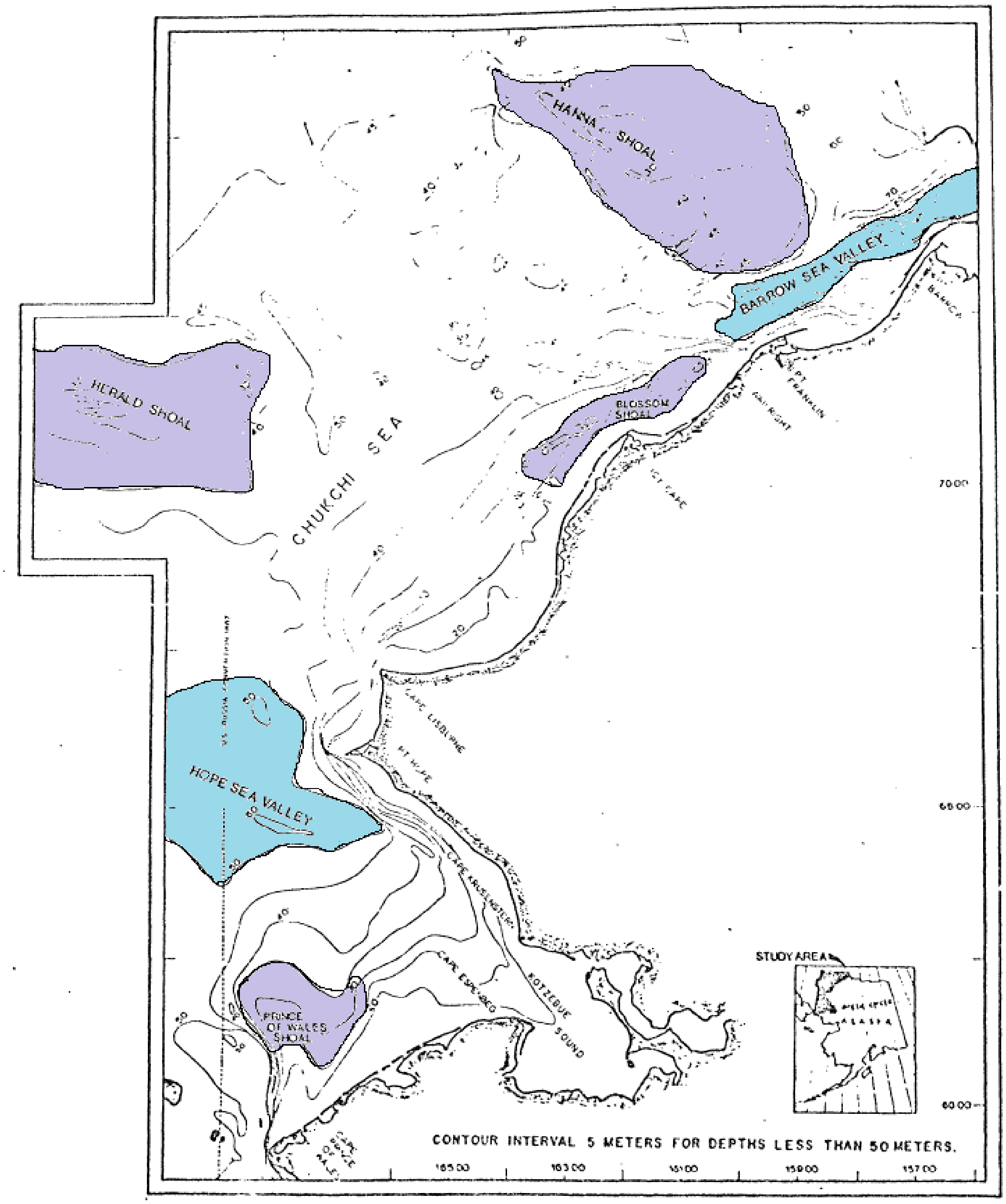


Figure 5.3: Bathymetric Data Compiled by Holmes (1975) [6], and U.S. Geological Survey Data – Toimil (1978) [29] – Modified by WGK

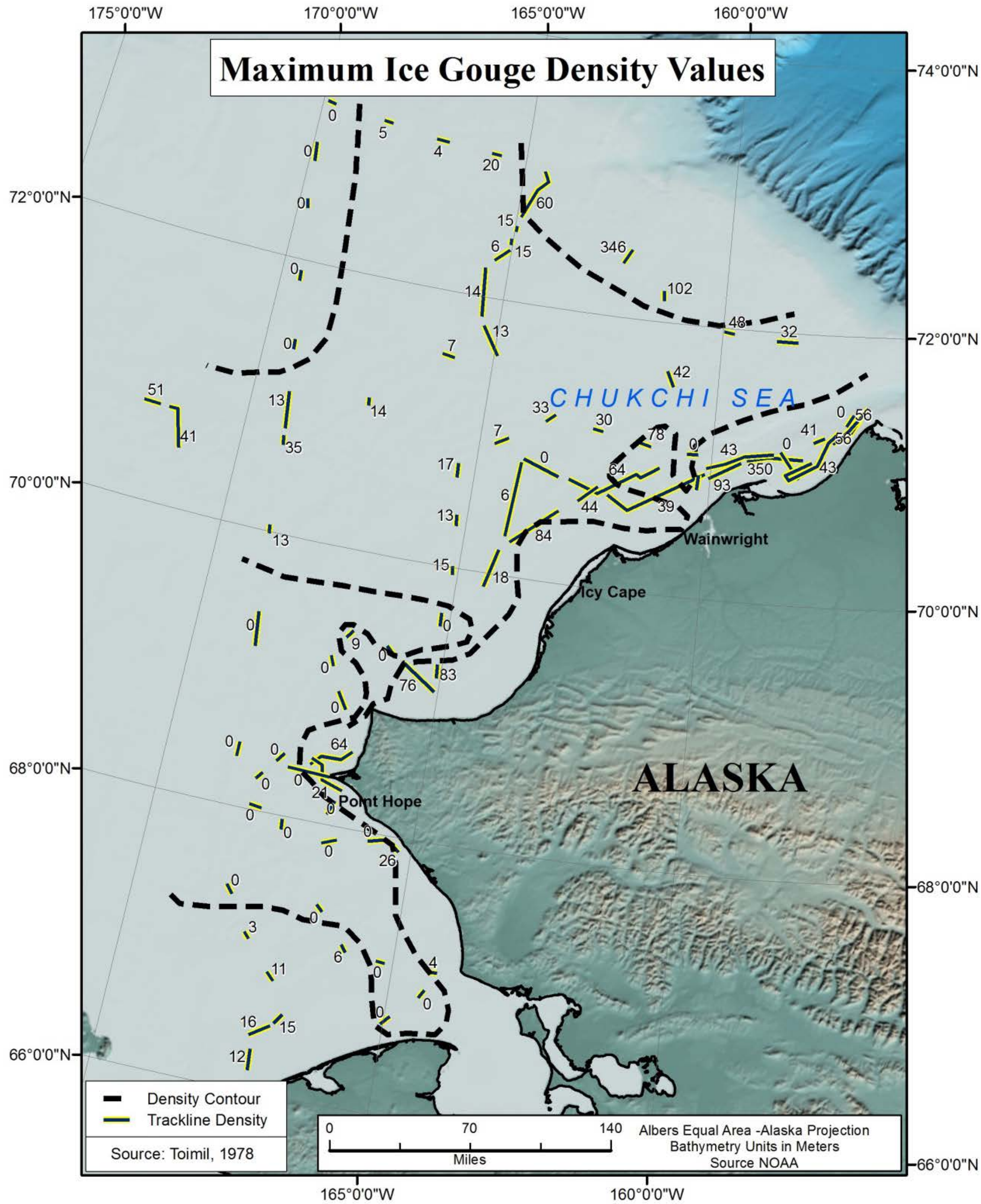


Figure 5.4: Maximum Ice Gouge Density Values over Complete Trackline Segment – Toimil (1978) [29]

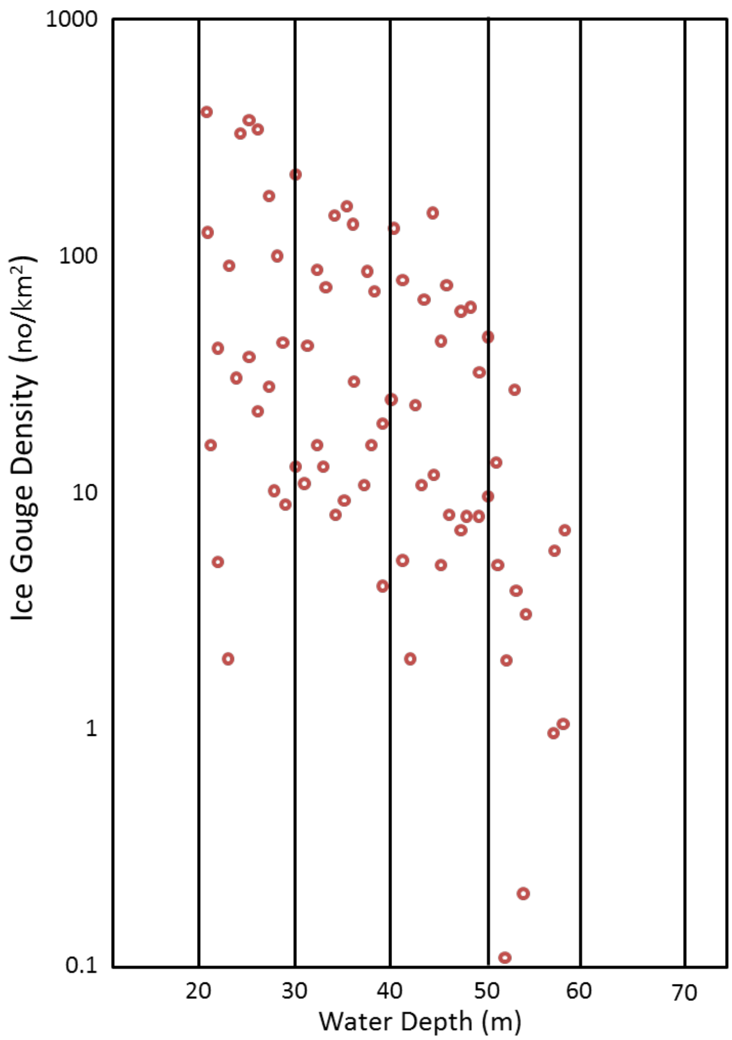


Figure 5.5: Normalized Maximum Ice Gouge Mean Ice Gouge Density Values Plotted Over One Meter Water Depth Intervals

5.2 MMS (2008)

Minerals Management Service (MMS) [19] investigated ice gouging in the Chukchi Sea utilizing the literature survey data. The study was conducted in 2008 aiming to assess the gouge geometry (depth and width), and density. MMS reported a shortage of the data available, which limited the outcome of the study and concluded that a repetitive survey should be conducted in order to provide a feasible dataset and estimate the return frequency of icebergs. In addition, as reported by MMS (2008) [19], previous studies and surveys failed to identify the age of gouges. Therefore, the work performed by MMS could present useful correlations between gouge dimensions (width and depth), water depth, and bathymetry. Additional surveys were recommended as to improve the return rate estimation.

The MMS (2008) [19] report utilized the tabulated data that was provided by Toimil (1978) [29] to perform statistical analyses of the ice gouging probabilities to estimate the depth and width of the gouges. The report recommended dividing the Chukchi Sea into three main zones, which would be categorized based on differences between the environmental conditions such as hazard regime. Ice gouges were separately studied for each zone since each had their own characteristics (bathymetry, soil and location).

Figure 5.6 shows the three recommended zones. Zone A is the largest area among the three studied areas. Table 5.2 summarizes soil types/condition and ice gouging frequency, as reported by MMS (2008) [19] for each zone.

- Zone A – The first zone represents the seabed of the Chukchi Sea, which is relatively shallow and the water depth varies from 98 to 197 ft. (30 to 60 m). Surficial sediments are generally sand and gravel overlaying stiff consolidated clay or dense sand. MMS (2008) [19] reported significant ice gouging in Zone A.
- Zone B – This zone represents the Herald and Hanna Shoals, which fall within Zone B. The bathymetry of the Shoals rise up to 131 ft. (40 m) from the surrounding sea floor. At some locations on the shoals, the bathymetry has a maximum height of 82 ft. (25 m). These shoals serve as barriers which protect the seabed from iceberg gouging.
- Zone C – The third zone is the near-shore shallow water with a water depth less than 98 ft. (30 m) and a low rate of ice gouging.

5.2.1 Survey Data

MMS (2008) [19] studied the dataset of 10,200 individual ice gouge observations that were tabulated by Toimil (1978) [29]. As stated in a previous section, Toimil (1978) [29] studied ice gouging geometry collected from 1,118 miles (1,800 km) track lines along a total of 83 separate track lines. The recorded depths had a resolution of 1.6 ft. (0.5 m). Recorded ice gouge data includes the observation date, time, ship speed and course, gouges observed, along with maximum gouge depth and maximum gouge width. The main shortcoming of the Toimil (1978) study was the lack of repetitive mapping which is essential to calculate the crossing rates for the zoned areas. Figure 5.6 provides the location of track lines used in the Toimil (1978) study and the study zones as proposed by MMS (2008) [19]. A summary of the dataset is listed in Table 5.3.

Table 5.2: Environmental Parameters for Chukchi Sea Case Study Zones – MMS (2008) [18]

Zone	Soil Type	Ice Gouging Freq.
A	Stiff clay 14.50 to 29 psi (100kPa - 200kPa) and dense sand 40° to 45°	High
B	Stiff clay 14.50 to 29 psi (100-200kPa) and dense sand 40° to 45°	Low to medium
C	Dense sand and gravel 40° to 45°	Medium

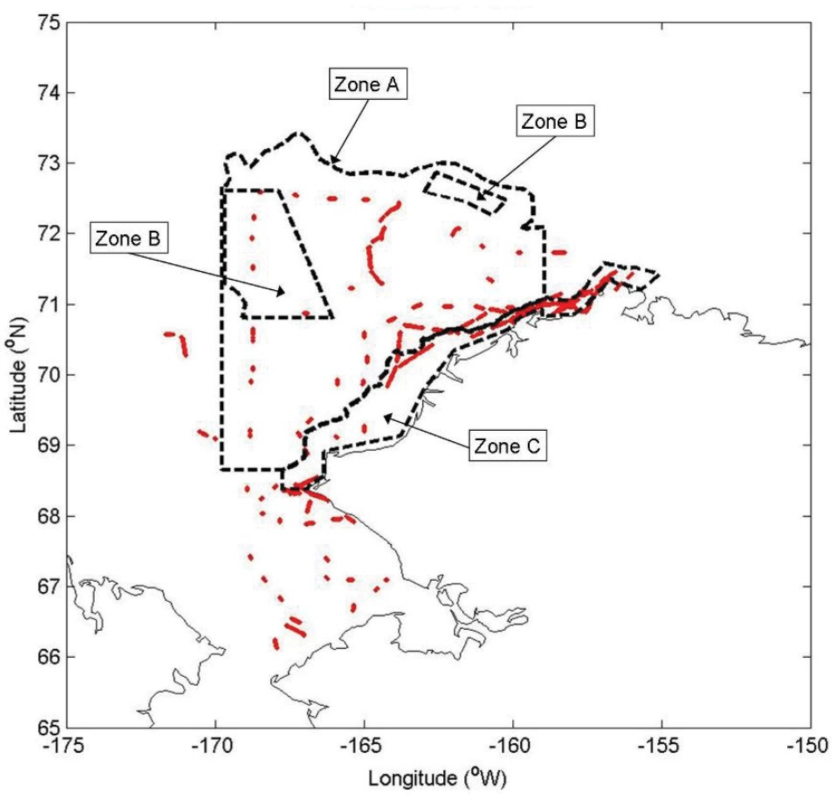


Figure 5.6: Chukchi Sea Case Study Zones – MMS (2008) [18]

Table 5.3: Summary of Toimil (1978) [29] Dataset Used in MMS (2008) Study [18].

Parameter	Toimil (1978)
Dates surveyed	1974
Repetitive mapping used?	N
Total length surveyed	847.55 miles (1,364 km)
Total no. of gouges recorded *	436
Seabed soil type identified?	N
Gouge depths recorded	584
Gouge widths recorded	245
Zone A	
Water depth covered	65.62 - 246.06 ft (20-75 m)
Length surveyed	257.86 miles (415 km)
Total number of gouges recorded *	2825
Zone B	
Water depth covered	82.02 - 164.04 ft (25-50 m)
Length surveyed	16.16 miles (26 km)
Total number of gouges recorded *	6
Zone C	
Water depth covered	65.62 - 360.89 ft (20-110m)
Length surveyed	349.21 miles (562km)
Total number of gouges recorded *	6,522

5.2.2 Gouge Depth

Gouge depths recorded by Toimil (1978) [29] were investigated in the MMS (2008) [19] report. Zone B does not contain enough gouges to be used for analysis and, therefore, the study focuses only on zones, A and C. Scatter plots for gouge depth versus water depth for zones A and C are presented in Figure 5.7. Statistical analysis was performed for each zone independently. Additionally, statistical analysis was performed using data for the gouges that occurred in the same water depths from different zones. The water depth summary, as categorized by the MMS report, is shown in Table 5.4. No gouges were recorded in water depths greater than 197 ft. (60 m).

In Zone A, which is relatively shallow with a water depth between 98 and 197 ft. (30 to 60 m), 219 gouges were studied. The deepest gouge depth noticed was 14.7 ft. (4.5 m), which was recorded within a water depth interval of 115 to 131 ft. (35 to 40 m). A lognormal distribution was recommended for the dataset and shown in Figure 5.6. The calculated mean and standard deviation for the entire zone are 2.6 ft. (0.8 m) and 2 ft. (0.6 m), respectively. Lack of sufficient data sets limited the usefulness of the proposed distribution. After reviewing Table 5.4, it was concluded that approximately 75% of the gouges occurred at depth intervals from 98 to 164 ft. (30 to 50 m). This data can be used to determine the general trend, but with a limited level of confidence.

To understand the general trend of gouging near shore, the gouges in Zone C were investigated. The maximum depth noticed was 16.4 ft. (5 m). The mean gouge depth observed was 2.6 ft. (0.8 m). Approximately 83% of the gouges occurred at depth intervals between 98 and 164 ft. (30 and 50 m). The average gouge depth observed was 2.4 ft. (0.73 m). The combined analysis of Zone A and Zone C indicates that approximately 90% of the gouges (out of 494 total gouges) occurred between water depth intervals of 98 to 164 ft. (30 to 50 m).

5.2.3 Gouge Width

Similar to the gouge depth analysis in the previous section, MMS (2008) analyzed a set of data which described the gouge width as presented by Toimil (1978). The maximum gouge width was listed for each of the tracking line segments. The tabulated data does list whether gouges are single or multiple gouges, however, gouge widths are estimated and they do include a conservative margin of error. The data, summarized by MMS (2008), is tabulated in Table 5.5.

MMS (2008) [19] prepared a scatter plot for a set of 86 gouge widths, which were measured in water depth intervals between 82 and 165 ft. (25 to 50 m) and identified to fall within Zone A. The findings found that the maximum gouge width of 311 ft. (95 m) was measured in water depth intervals of 115 to 130 ft. (35 to 40 m). A lognormal distribution was used to fit the gouge width data. The report stated that the distribution match was not definitive, due to lack of data.

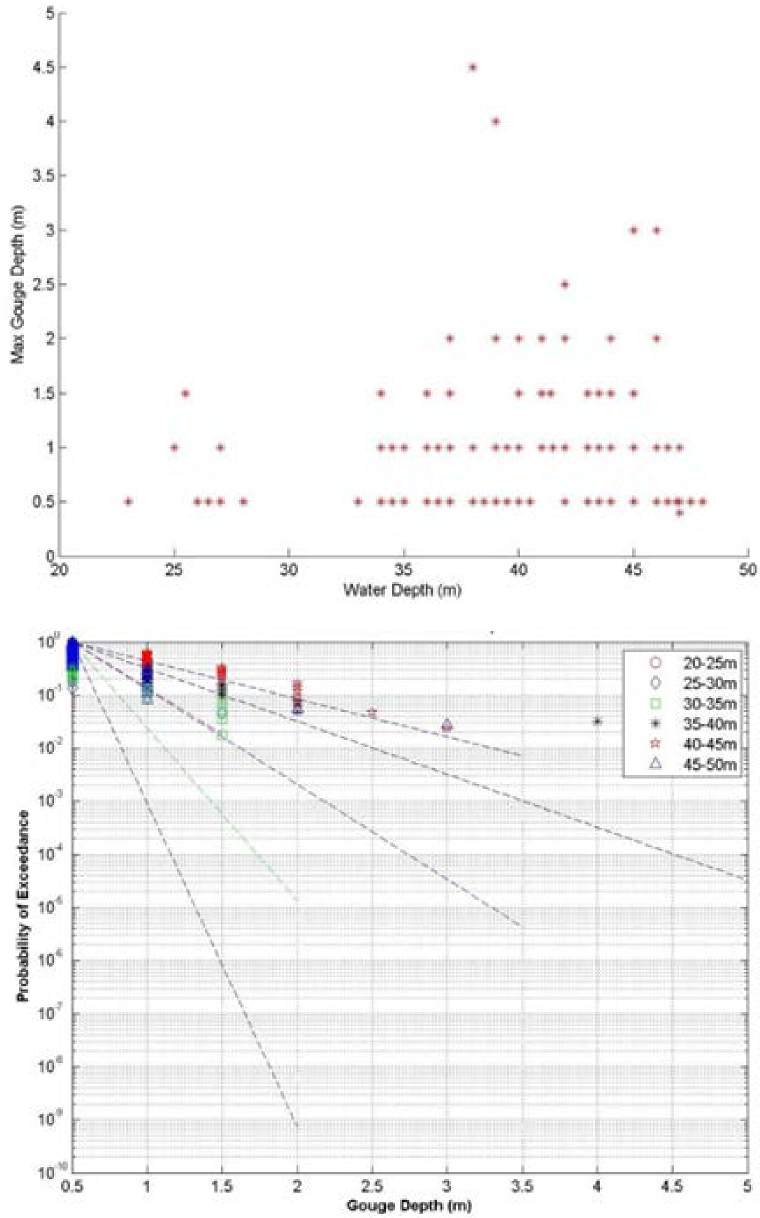
An additional scatter plot was prepared using 128 gouge widths in Zone C. A maximum gouge width of 180 ft. (55 m) occurred three times at water depth intervals between 82 and 150 ft. (25 to 46 m). A lognormal distribution was prepared for the data. Zone C had a mean gouge width of 45 ft. (14 m) and standard deviation of 36 ft. (11 m). The MMS report determined that the data lacks sufficient number gouge widths, which reduces the confidence in the fitted data. Scatter plots for Zones A and C are shown in Figure 5.7

5.2.4 Crossing Density

The data tabulated by Toimil (1978) did not included the age of gouges as that information was not collected in the study. Therefore, MMS (2008) estimated the number of gouges per kilometer (km^{-1}). Zone A contained a total of 382 intervals with a maximum crossing rate of 140 gouges in a water depth interval of 82 to 98 ft. (25 to 30 m). Figure 5.8 shows the scatter plot of the data. The average of the zone is 11 gouges/mile (7.0 gouges/km) and the standard deviation is equal to 25.6 gouges/mile (16 gouges/km). MMS (2008) [19] reported that the crossing density decreases with increasing water depths beyond 30 m, then becomes nearly constant to a water depth of 164 ft. (50 m).

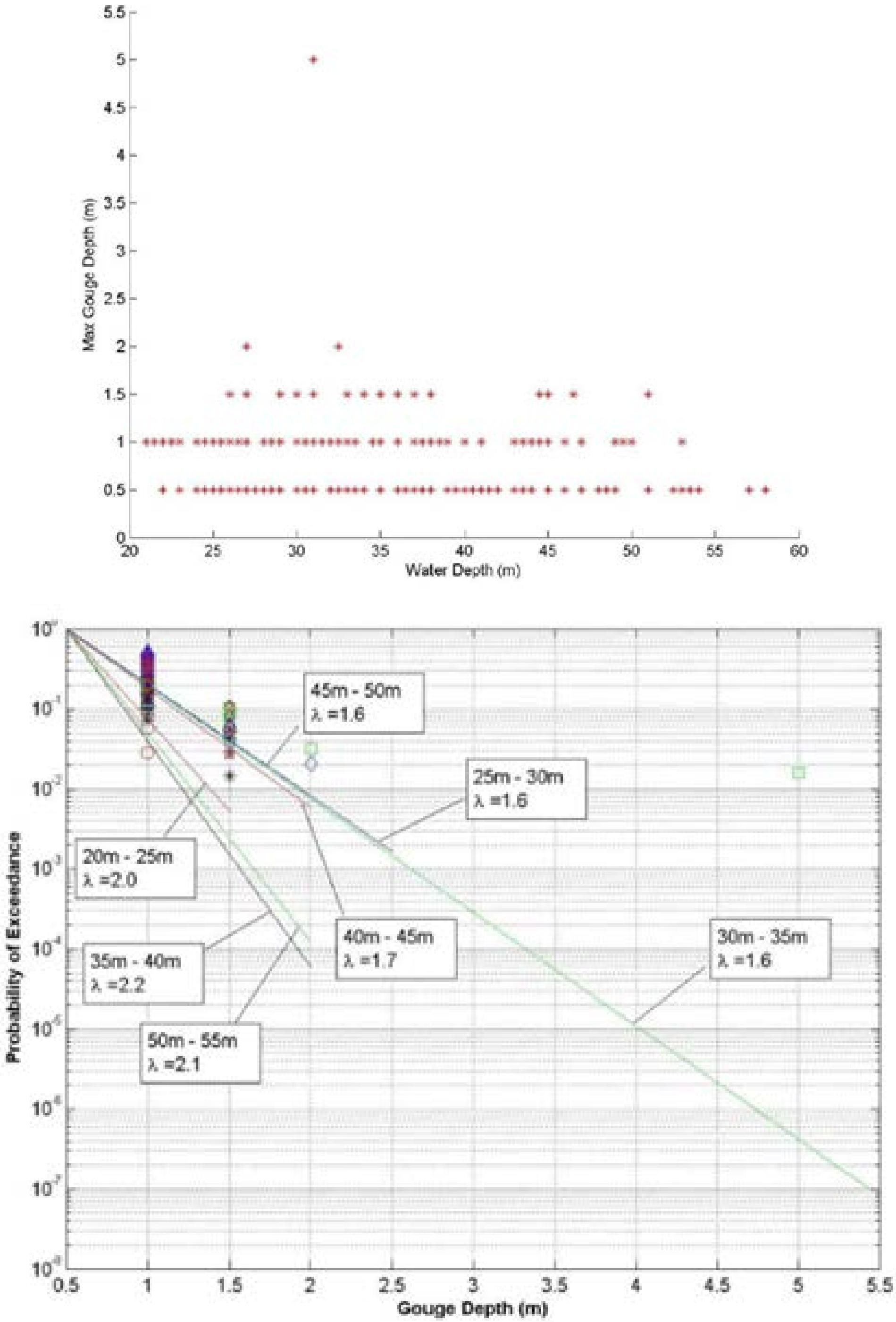
It was not possible to obtain a correlation for Zone B using the available data. Only 21 intervals were recorded for Zone B with a maximum crossing density of 5 gouges/mile or 3 gouges/km. During the survey, water depth was not recorded. MMS (2008) [19] provided a poor lognormal curve fitting for Zone B. The Zone B data is listed in Table 5.6

A similar approach was applied to Zone C. A set of 535 intervals, with a maximum crossing rate of 379.2 gouges/mile (237 gouges/ km), were noticed for this zone. The majority of crossings occurred in a water depth range of 115 to 131 ft. (35 to 40 m). Figure 5.8 shows a scatter plot of the crossing density of at Zone C. Fitting the data to a lognormal distribution showed a mean value of the crossing density equal to 18 gouges/mile (11 gouges/ km) and a standard deviation of 32 gouges/ mile (20 gouges/ km).



Zone A

Figure 5.7(a): Analysis of Toimil (1978) Gouge Depth Data as Prepared by MMS (2008) [18]



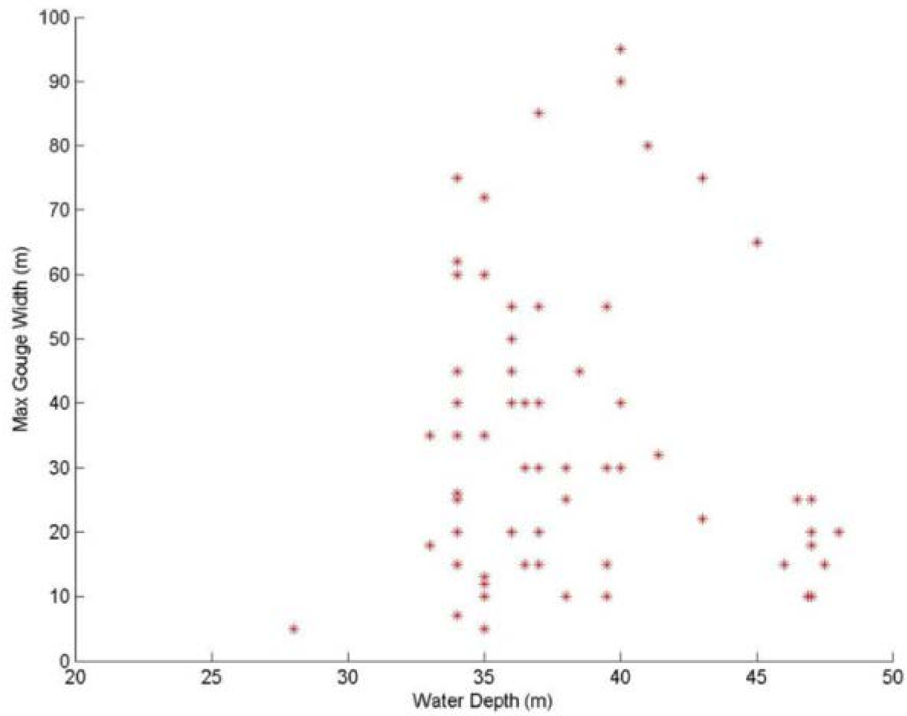
Zone C

Figure 5.7: Analysis of Toimil (1978) Gouge Depth Data as Prepared by MMS (2008) [18]

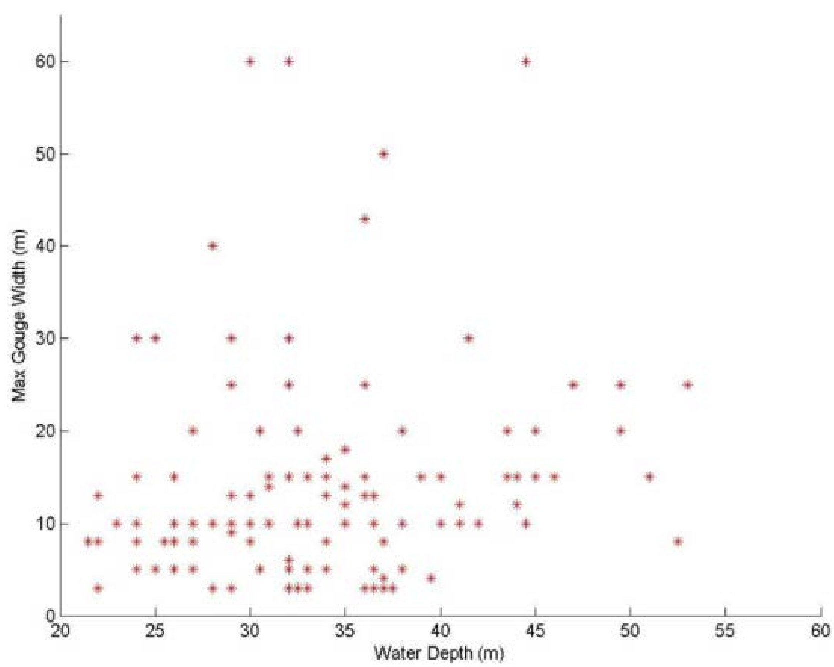
Table 5.4: Summary of Toimil (1978) Gouge Depths [29]

Water Depth ft (m)	Gouge Depth, ft (m)				
	Zone	A	B	C	ALL
65.62-82.02 (20-25)	No. Gouges	**2**	0	**34**	**36**
	Mean(m)	2.62	0	2.30	2.30
	Max(m)	3.28	0	3.28	3.28
	Std(m)	1.31	0	0.66	0.66
82.02-98.43 (25-30)	No. Gouges	21	0	48	69
	Mean(m)	1.97	0	2.62	2.30
	Max(m)	4.92	0	6.56	6.56
	Std(m)	0.66	0	1.31	0.98
98.43-114.83 (30-35)	No. Gouges	56	0	62	118
	Mean(m)	1.97	0	2.62	2.30
	Max(m)	4.92	0	16.40	16.40
	Std(m)	0.98	0	1.97	1.64
114.83 -131.23 (35-40)	No. Gouges	62	0	68	130
	Mean(m)	2.95	0	2.30	2.62
	Max(m)	14.76	0	4.92	14.76
	Std(m)	2.30	0	0.98	1.97
131.23-147.64 (40-45)	No. Gouges	42	0	36	78
	Mean(m)	3.61	0	2.62	3.28
	Max(m)	9.84	0	4.92	9.84
	Std(m)	1.97	0	0.98	1.64
147.64-164.04	No. Gouges	36	0	16	52

Water Depth ft (m)	Gouge Depth, ft (m)				
	Zone	A	B	C	ALL
(45-50)	Mean(m)	2.30	0	2.62	2.62
	Max(m)	9.84	0	4.92	9.84
	Std(m)	1.64	0	0.98	1.31
164.04-180.45 (50-55)	No. Gouges	0	0	9	9
	Mean(m)	0	0	2.30	2.30
	Max(m)	0	0	4.92	4.92
	Std(m)	0	0	1.31	1.31
180.45- 196.85 (55-60)	No. Gouges	0	0	2	2
	Mean(m)	0	0	1.64	1.64
	Max(m)	0	0	1.64	1.64
	Std(m)	0	0	0	0
>196.85 (>60)	No. Gouges	0	0	0	0
	Mean(m)	0	0	0	0
	Max(m)	0	0	0	0
	Std(m)	0	0	0	0
Measurements in parenthesis are in meters (m)					



Zone A



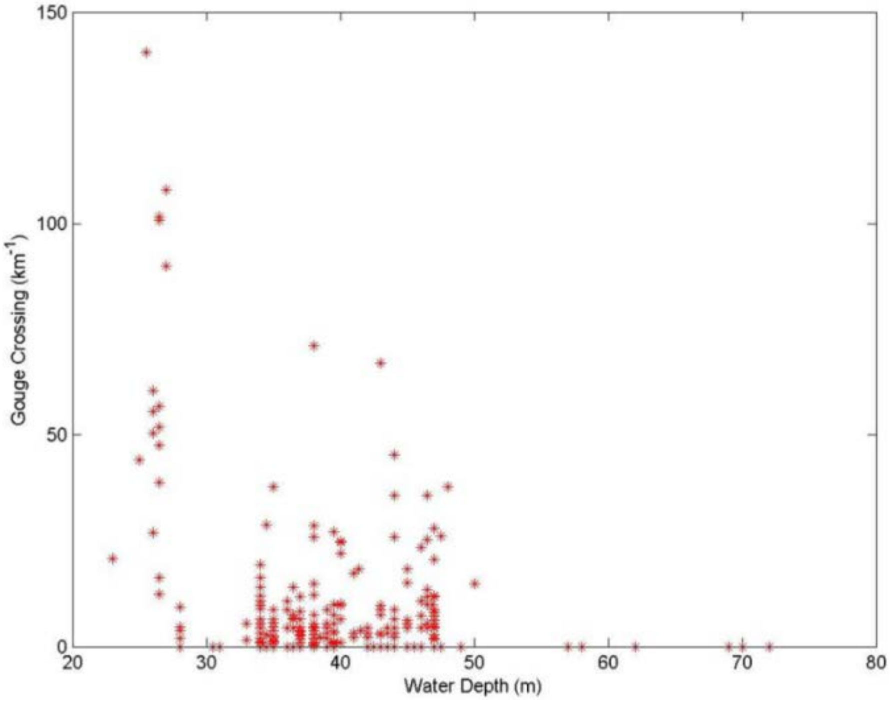
Zone C

Figure 5.7: Analysis of Toimil (1978) Gouge Width Data as Prepared by MMS (2008) [18]

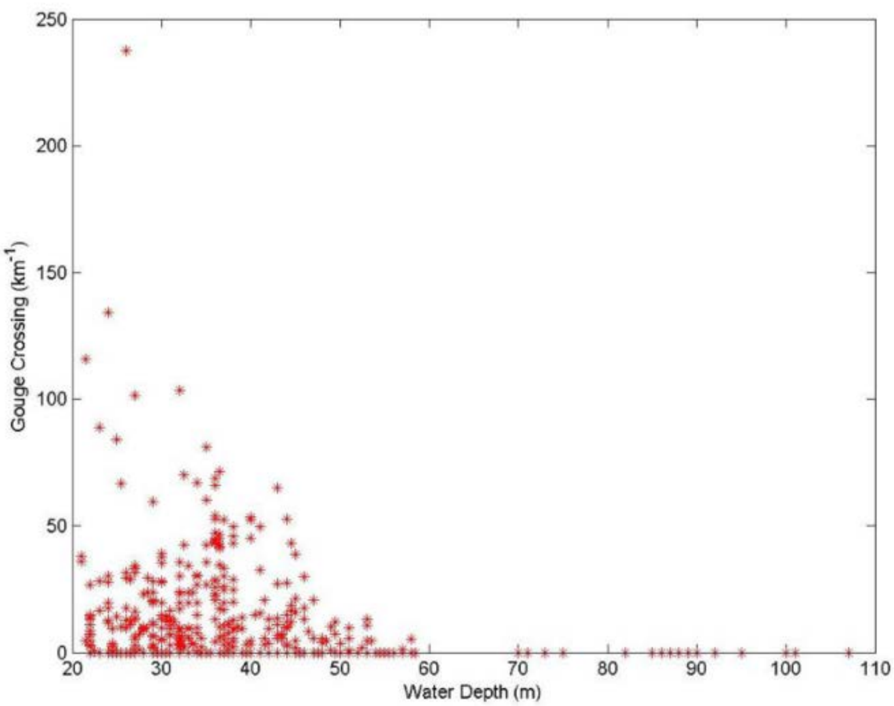
Table 5.5: Summary of Toimil (1978) Gouge Width [29]

Water Depth ft (m)	Gouge Width, ft (m)				
	Zones	A	B	C	ALL
65.62-82.02 (20-25)	No. Gouges			14	14
	Mean(ft)	0	0	39.37	39.37
	Max(ft)	0	0	98.43	98.43
	Std(ft)	0	0	26.25	26.25
82.02-98.43 (25-30)	No. Gouges	2.00	0	27.00	29.00
	Mean(ft)	49.21	0	45.93	45.93
	Max(ft)	82.02	0	196.85	196.85
	Std(ft)	45.93	0	42.65	39.37
98.43-114.83 (30-35)	No. Gouges	32.00	0	35.00	67.00
	Mean(ft)	108.27	0	42.65	75.46
	Max(ft)	246.06	0	196.85	246.06
	Std(ft)	75.46	0	32.81	65.62
114.83 -131.23 (35-40)	No. Gouges	31.00	0	32.00	63.00
	Mean(ft)	114.83	0	45.93	78.74
	Max(ft)	311.68	0	164.04	311.68
	Std(ft)	75.46	0	42.65	68.90
131.23-147.64 (40-45)	No. Gouges	5.00	0	13.00	18.00
	Mean(ft)	180.45	0	59.06	95.14
	Max(ft)	262.47	0	196.85	262.47
	Std(ft)	85.30	0	45.93	78.74
147.64-164.04	No. Gouges	16.00	0	4.00	20.00

Water Depth ft (m)	Gouge Width, ft (m)				
	Zones	A	B	C	ALL
(45-50)	Mean(ft)	62.34	0	68.90	62.34
	Max(ft)	82.02	0	82.02	82.02
	Std(ft)	19.69	0	16.40	19.69
164.04-180.45 (50-55)	No. Gouges	0	0	3.00	3.00
	Mean(ft)	0	0	52.49	52.49
	Max(ft)	0	0	82.02	82.02
	Std(ft)	0	0	29.53	29.53
180.45- 196.85 (55-60)	No. Gouges	0	0	0	0
	Mean(ft)	0	0	0	0
	Max(ft)	0	0	0	0
	Std(ft)	0	0	0	0
>196.85 (>60)	No. Gouges	0	0	0	0
	Mean(ft)	0	0	0	0
	Max(ft)	0	0	0	0
	Std(ft)	0	0	0	0
Measurements in parenthesis are in meters (m)					



Zone A



Zone C

Figure 5.8: Analysis of Toimil (1978)] Gouge Crossing Density Data as Prepared by MMS (2008) [18]

Table 5.6: Summary of Toimil (1978) Gouge Density [29]

Water Depth ft (m)	Gouge Density (gouge/mile)				
	Zone	A	B	C	ALL
65.62-82.02 (20-25)	No. mile Intervals	74.56	0	3877.36	3951.92
	Mean (gouge/mile)	0.86	0	0.21	0.21
	Max (gouge/mile)	1.18	0	3.59	3.59
	Std (gouge/mile)	0.46	0	0.59	0.59
82.02-98.43 (25-30)	No. mile Intervals	1528.57	0	3280.84	4809.42
	Mean (gouge/mile)	0.64	0	0.40	0.48
	Max (gouge/mile)	3.76	0	6.38	6.38
	Std (gouge/mile)	1.02	0	0.78	0.86
98.43-114.83 (30-35)	No. mile Intervals	3914.64	0	2982.58	6897.23
	Mean (gouge/mile)	0.11	0	0.40	0.24
	Max (gouge/mile)	1.02	0	2.79	2.79
	Std (gouge/mile)	0.21	0	0.54	0.40
114.83 -131.23 (35-40)	No. mile Intervals	3877.36	0	3019.87	6897.23
	Mean (gouge/mile)	0.13	0	0.56	0.32
	Max (gouge/mile)	1.90	0	1.90	1.90
	Std (gouge/mile)	0.24	0	0.54	0.46
131.23-147.64 (40-45)	No. mile Intervals	2274.22	298.26	2013.24	4585.72
	Mean (gouge/mile)	0.16	0	0.32	0.21
	Max (gouge/mile)	1.80	0	1.74	1.80
	Std (gouge/mile)	0.32	0	0.40	0.35
147.64-164.04 (45-50)	No. mile Intervals	2087.81	298.26	1342.16	3728.23
	Mean (gouge/mile)	0.19	0	0.11	0.13
	Max (gouge/mile)	1.02	0	0.80	1.02

	Std (gouge/mile)	**0.24**	**0**	**0.19**	**0.21**
164.04-180.45 (50-55)	No. mile Intervals	0.00	0	1081.19	1081.19
	Mean (gouge/mile)	0.00	0	0.05	0.05
	Max (gouge/mile)	0.00	0	0.35	0.35
	Std (gouge/mile)	0.00	0	0.11	0.11
180.45- 196.85 (55-60)	No. mile Intervals	111.85	0	410.11	521.95
	Mean (gouge/mile)	0.00	0	0.03	0.00
	Max (gouge/mile)	0.00	0	0.13	0.13
	Std (gouge/mile)	0.00	0	0.05	0.03
>196.85 (>60)	No. mile Intervals	149.13	0	820.21	969.34
	Mean (gouge/mile)	0	0	0	0
	Max (gouge/mile)	0	0	0	0
	Std (gouge/mile)	0	0	0	0
Unknown Depth	No. mile Intervals	223.69	186.41	1118.47	1528.57
	Mean (gouge/mile)	0.21	0.03	0.05	0.08
	Max (gouge/mile)	0.48	0.08	0.86	0.86
	Std (gouge/mile)	0.19	0.03	0.16	0.16
Total	No. mile Intervals	14241.84	782.93	19946.03	34970.80
	Mean (gouge/mile)	0.19	0	0.30	0.24
	Max (gouge/mile)	3.76	0.08	6.38	6.38
	Std (gouge/mile)	0.43	0.03	0.54	0.51
Measurements in parenthesis are in meters (m)					

6.0 Summary and Recommendations

6.1 Summary

A comprehensive field data review of ice scour and gouging in the Chukchi and Beaufort Seas is presented in the previous sections of this interim report. The literature review focused on the geotechnical characteristics of the seabed for both seas and the available data for bathymetry, ice frequency, and gouge characteristics. The USGS documents describe the ice gouging and geotechnical investigation surveys in both the Chukchi and Beaufort Seas during a two-decade timeframe between the 1970s and 1980s.

Beaufort Sea

The Beaufort Sea is located at the far edges of the Arctic Ocean to the north of the Alaska and Yukon shores. Intensive geotechnical surveys were performed to investigate the geotechnical characteristics of this seabed. Nearby barrier islands extend several feet (meters) above the sea level and form a chain of islands parallel to the shoreline in shallow water depths from 30 to 60 ft. (9 to 18 m). Additional shoals exist around the shoreline which capture and store icebergs. The mean diameter of grain size distribution, categorization of surface sediment samples, and gravel distribution in surface sediments were prepared based on these surveys. Shear strength estimation, based on shallow sampling of the seabed, suggests that the seabed at testing locations is predominantly very soft (approx. 35 kPa). In 1980, 20 borehole logs were drilled to a depth of approximately 114 ft. (35 m) deep.

Chukchi Sea

Similarly, the geotechnical configuration of the Chukchi Sea was investigated through intensive surveys. The U.S. Chukchi Sea is located between Point Barrow, to the east, and Cape Prince of Wales, to the west, at the northwest section of the Alaskan coast. Shoals exist at the shelf area, which extends 66 ft. (20 m) below the sea surface. Additionally, a few shoals exist near the shore side (along the northwest coast). The seabed surface is composed mainly of sandy soils and gravel deposits located on the Herald Shoal along the coast north of the Lisburne Peninsula. Test results showed that the surficial layer with a thickness between 3-to-30 ft. (0.9 to 9 m) has low shear strength of 3.0 psi (20 kPa) with an underlying layer of stiff soils. Boreholes were drilled to a depth of approximately 165 ft. (50 m).

Past Performance Surveys

The USGS provided two main documents that are available to the public - Rearic and McHendrie (1983) [26] and Weber, et al. (1989) [29]. These studies were performed in the Beaufort Sea. Analysis of the available survey data showed that the deepest ice gouge identified was 13 ft. (3.9 m) deep. The maximum noticed depths for single and multiple gouges were observed at water depths from 72 to 473 ft. (22 and 132 m). The maximum number of gouges occurred in the water depth intervals between 82 and 131 ft. (25 to 40 m). The highest calculated crossing density is 235 gauge/mile (147 gouge/km) and was observed within the 66 to 82 ft. (20-25 m) water depth interval. Thorough analysis was not able to be conducted due to lack of a sufficient dataset population.

Similarly, survey data was reviewed to locate ice gouging in the Chukchi Sea. Surveys were performed for 1,120 miles (1,802 km) of track line at the eastern Chukchi Sea continental shelf. An estimated 10,200 individual gouges were identified in the water depth interval between 60 to 210 ft. (18 to 64 m). The maximum noticed incision depth is equal to 15 ft. (4.5 m) in the 115 to 130 ft. (35 to 40 m) water depth interval. Two meter deep gouges were noticed in the 69 to 82 ft. (21 to 25 m) water depth intervals. Gouges wider than 300 ft. (91 m) occurred at 118 to 131 ft. (36 to 40 m) water depths. The maximum occurrence of wide gouges occurred in the water depth interval of 101 to 148 ft. (31 to 45 m). The statistical analyses of the Chukchi Sea survey data failed to provide meaningful results due to the lack of sufficient data.

6.2 Recommendations

The following study recommendations should be considered.

- Comparisons of the available datasets showed discrepancies and inconsistencies between different surveys. A consistent surveying approach must be followed. Single-and-multiple gouges must be distinguished within the surveys. The width of the gouge must be listed for all of the gouges observed.
- Statistical analysis showed available data may not be enough to provide a reliable probabilistic distribution. It is not recommended to use the distribution parameters, as they have a low-confidence level.
- Additional surveys are highly recommended in the Chukchi and Beaufort Seas. Repetitive mapping must be performed periodically to record new ice gouges. In order to calculate the return rate of similar gouges, it is necessary to determine the age of gouges along with other parameters.
- The available data does not contain information regarding the iceberg characteristics (mass, keel draft, keel geometry and near gouging keel

distributions), therefore, there is not sufficient data available to recommend a design approach for wellhead placement (i.e., preventive or protective). Ongoing iceberg characteristics data should be collected for both gouging keels and near gouging keels.

7.0 References

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