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Regional Assessment of Seabed Geohazard Conditions Canadian Beaufort Outer Shelf and Upper Slope: Legacy Data Synthesis

Évaluation régionale des géorisques du fond marin, plate-forme continentale externe et talus supérieur de la portion canadienne de la mer de Beaufort : synthèse des données existantes

Canada

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REGIONAL ASSESSMENT OF SEABED GEOHAZARD CONDITIONS CANADIAN BEAUFORT OUTER SHELF AND UPPER SLOPE: LEGACY DATA SYNTHESIS

Section 3

GEOTECHNICAL DATA COMPILATION (1965-2010) AND SEABED CHARACTERIZATION OF THE OUTER SHELF AND CONTINENTAL SLOPE AREAS OF THE CANADIAN BEAUFORT SEA

MacKillop, K[1], Mitchelmore, P[2], Loewen, N[2], Jarrett, K[1],

[1] Natural Resources Canada
[2]Mitchelmore Engineering Company Ltd. (Meco)

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1.0 INTRODUCTION

The Canadian Beaufort Sea was the center of extensive hydrocarbon exploration in the 1970s and 1980s where drilling activity was confined to the Beaufort Shelf in water depths of less than 70 m. Renewed offshore hydrocarbon exploration programs include the potential for oil and gas wells on the Beaufort Slope in water depths of greater than 100 m. The Geological Survey of Canada in collaboration with other government and non-government agencies has undertaken a comprehensive and integrated geoscience program to understand geologic processes and potential geohazards on the Beaufort Shelf and Slope within the regional framework. The results of the program will provide a regional perspective of seabed characteristics.

The GSCA was contracted by ESRF to compile legacy geotechnical data in the Canadian Beaufort Sea. The primary objective of this contract is a compilation of a database of geotechnical data from surficial (< 10 m) sediment cores and industry borehole data from the Beaufort Sea. A synthesis of the geotechnical legacy data has been completed in order to locate, catalogue, digitize, database and analyze geotechnical data acquired in the Canadian Beaufort Sea from 1965 through 2010. The analysis of the compiled geotechnical data has been used to characterize geotechnical properties of the surficial sediments and assess seabed foundation conditions, slope stability and potential geohazards. Laboratory testing has been conducted on recent (2008 through 2010) GSCA samples in order to provide additional geotechnical properties to enhance the engineering analysis of the compiled data set. The primary area of focus includes the outer Beaufort Shelf and Beaufort Slope from 55 m to 1500 m water depths and a corridor in the Amauligak discovery area to water depths of 25 m (Figure 1.1).

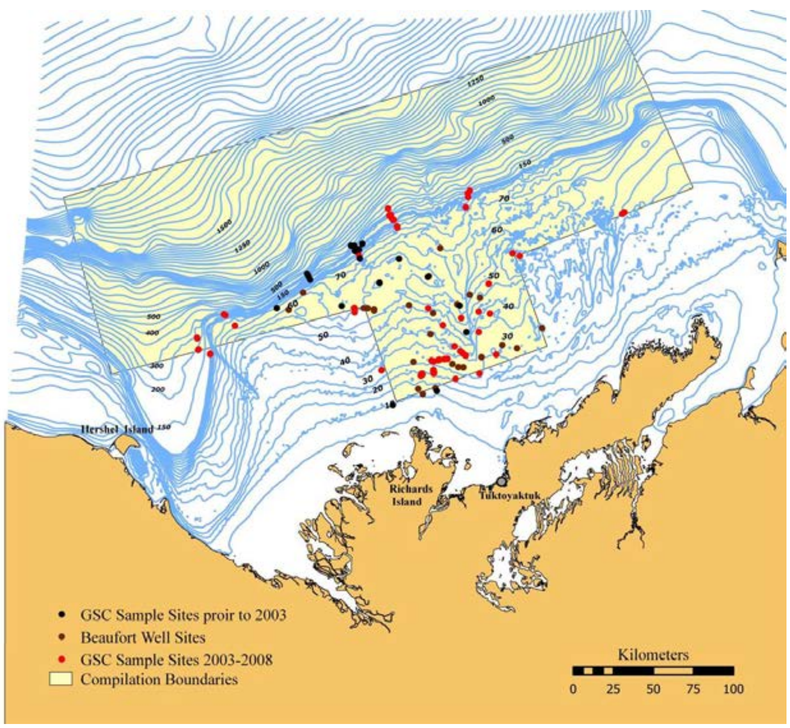

Figure 1.1 Location of compilation area.

2.0 DATA SOURCES

The data sources used in the study are primarily industry boreholes and the GSC surficial (< 10 mbsf) sediment cores.

2.1 Industry Data

The primary industry data are in the form of well site geotechnical borehole reports. These reports consist of borehole locations, logs and summary tables containing geotechnical data. Typical borehole logs (Figure 2.1A) consist of a sediment description, lithological units, and geotechnical plots of index properties (Atterberg Limits, bulk density, water content) and undrained shear strength. The undrained shear strength plots include discrete measurements and CPT data. The CPT data are only presented graphically which reduces the value of the data. The physical location of the majority of these reports is at the GSCA in the Bedford Institute of Oceanography in Dartmouth, Nova Scotia.

2.2 Government Data

The GSCA has conducted research cruises in the Beaufort Sea since 1975. In the 1980s two cruises in 1982 and 1983 collected seabed samples within the compilation area. There was no seabed sampling in the compilation area from 1983 until 2003. With renewed hydrocarbon interest in the Beaufort Sea, the GSCA began a surficial (<10 mbsf) seabed sampling program to assess regional geohazards. The programs consisted of gravity and box cores from 2003 through 2008 and piston and box cores in 2009 and 2010. The sampling from 2003-2007 concentrated on the Beaufort Shelf. In 2008, 2009 and 2010, several cores were also taken on the outer shelf and slope (Figure 1.1).

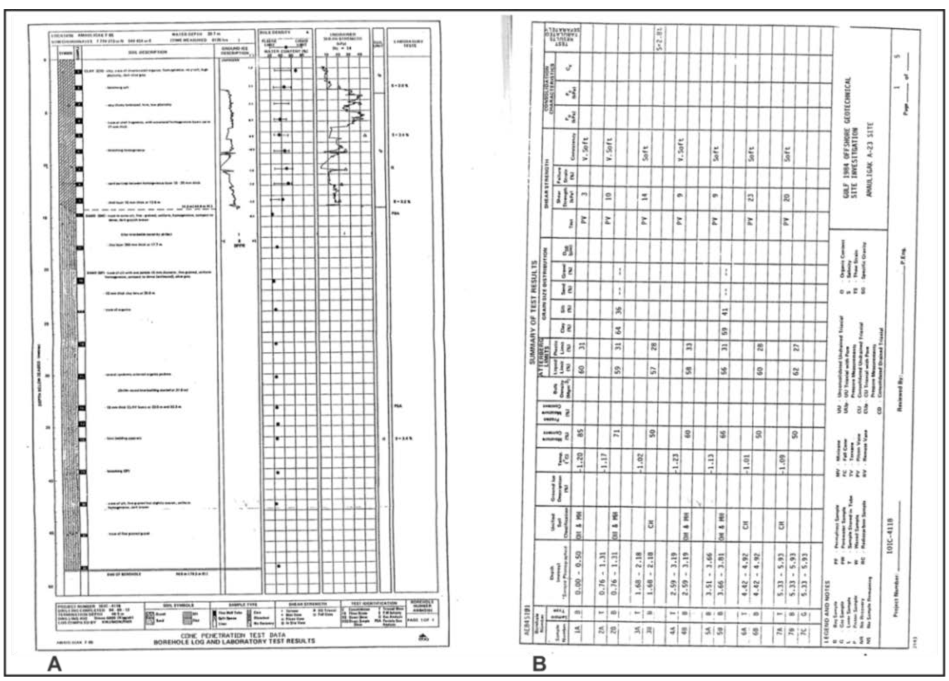

Figure 2.1Typical borehole log (A) and geotechnical data summary table (B) from well site reports.

3.0 DATA COMPILATION 1965-2010

All data for the Beaufort Sea region were provided for this report by the GSCA from various sources, including industry and government. The GSCA provided the data in the following formats:

- Catalogued listing of Beaufort Sea industry and government reports stored at GSCA
- Microsoft Excel files with coordinates of the identified sites within the compilation area
- Microsoft Excel data files from government cruises.

3.1 Methodology

Compilation and cataloguing of data were completed in two phases, identification and review of available data and compilation of relevant data. The objective of Phase 1 which was completed in early 2011was to:

- Identify sample sites located within the project area
- Review catalogued listings of industry reports and identify reports requiring further assessment of the value of geotechnical data
- Locate copies of industry reports and GSCA data files for the pertinent sites
- Assess the relevance of geotechnical data from these industry reports and GSCA data files
- Digitize industry reports from 1965-2008. The majority of the reports and data resides with GSCA.

There are two catalogued lists of analogue industry well site geotechnical reports as well as miscellaneous analogue industry and government reports that are stored in the GSCA sample repository. One catalogue listing contains 838 entries of reports that have been stored at GSCA since the 1980s. The second catalogue listing consists of industry and government reports which were recently (2011) obtained by the GSCA from O'Connor and Associates. That catalogue contained 285 listings and was created by Arctic Institute of North America (AINA). The catalogues were reviewed to determine which reports showed potential to contain geotechnical data from sites located in the project area. All reports that had the potential to contain relevant geotechnical data were flagged as requiring further review.

The objective of the Phase 2 work was to compile the relevant geotechnical data for the sample sites identified in Phase 1 into Excel data files. The steps included:

- Classification of the geotechnical data based on how the data were presented for the sample sites identified in phase 1.
- Create summary tables – one each for industry and government data used in the compilation. The tables contain well site ID, station ID, geographic coordinates, geotechnical data available and whether the data was digital or graphical.
- Convert analog industry well site borehole and government data into digital format and compile these data into Excel files.
- Create geotechnical profiles consisting of shear strength, index properties and stress state for sites that contain sufficient geotechnical data.
- Construct 3 cross-shelf transects delineating the sediments using descriptions from the well site borehole logs.

3.2 Results

The initial data identified during Phase 1 included 1422 industry and GSCA sample sites. All data were reviewed and 341 duplicates or redundancies were identified that reduced the number of sites to 1081. These sites were imported into an ArcMap GIS computer software program, and a map of the project area with all sites containing geotechnical information within the boundary was produced. This process resulted in the identification of a total of 287 sample sites which contained suitable geotechnical data.

There is a significant difference between the GSCA and industry data sets. The sampling frequency for GSCA data is based on a range of centimetres (for multi-sensor core logger or MSCL) to 10 centimetres (for laboratory miniature shear strength tests) whereas the industry data sampling frequency was typically on a metre scale. The GSCA MSCL data include magnetic susceptibility, acoustic velocity and resistivity which were not measured for the industry borehole sites. Also the GSCA sample sites are confined to the upper 8 mbsf whereas the industry boreholes range up to 94 mbsf. The government and industry data are therefore presented in different formats in the compiled Excel files and the summary data files.

3.2.1 Government Data

There was a total of 183 GSCA sample sites identified in the compilation area which consisted of 28 piston cores, 11 trigger weight cores, 86 push cores from box cores, 36 gravity cores and 36 CPT. The sampled depth was ≤ 10 mbsf for all GSCA sites. The GSCA seabed sampling programs included CCGS Nahidik cruises in 1982, 1983, 2003 through 2008. CCGS Amundsen cruises on the slope and outer shelf were carried out in 2009 and 2010 (Figure 3.1). The distribution of the sample types with water depth is outlined in Table 3.1.

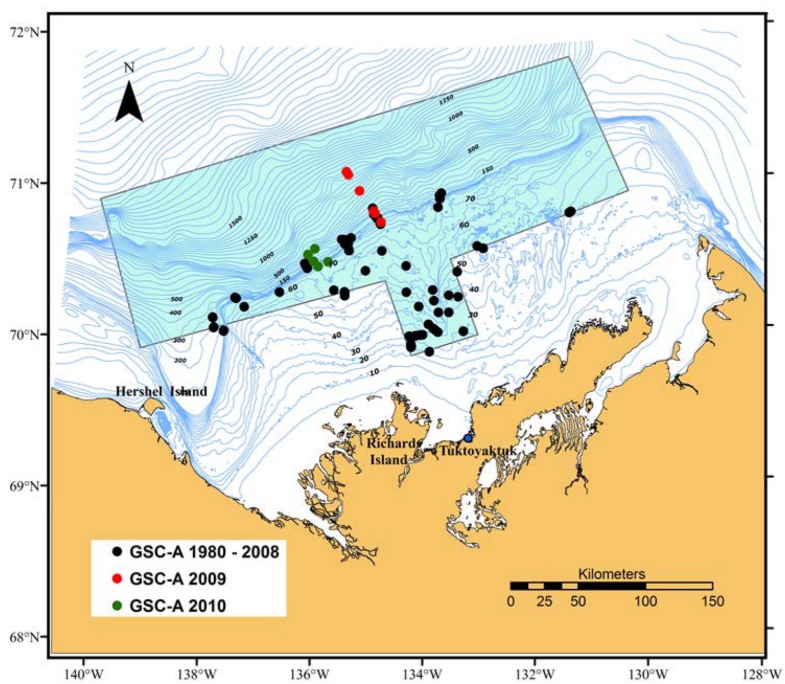

Figure 3.1Location of GSC sample sites.

Table 3.1 Distribution of government sample types with water depths.

Government	0-75 m	75-150 m	>150 m	Total
CPT	36	0	o	36
Gravity Cores	8	8	6	22
Piston	8	5	15	28
Push cores	47	18	21	86
Trigger Weight Cores	2	1	8	11
Total	101	32	50	183

The CPTs were conducted as part of a GSCA and industry collaborative ice scour study in 2007. The study included 36 CPTs and 30 push cores conducted in 3 ice scours defined by multibeam data in the Amauligak development area. The CPTs were conducted by ConeTec Inc. of Vancouver BC who used their minicone system deployed from the small foredeck of the CCGS Nahidik.

Routine geotechnical testing conducted at GSCA on cores collected after 2003 includes Multi-Sensor Core Logger (bulk density, p-wave velocity and magnetic susceptibility), discrete bulk density and water content, and discrete laboratory miniature laboratory vane peak and remolded undrained shear strength. Additional advanced geotechnical testing was conducted on select cores from the 2008 to 2010 sampling programs. The tests included back-pressured consolidation tests and CIU compressional triaxial tests. The government CPT and core processing geotechnical data are compiled into individual Excel files grouped by cruise number (i.e. *Government Data\Core Physical Property Data\2004801 Physical Property Data\2004801_003Apushcore*). Government Atterberg data are presented as a table in the Excel file *Government Data\Government Atterberg Data*. A summary table of all the sample sites and available geotechnical data at each site is presented in the Excel file (*Government Data\Government Data Inventory Summary)*. All the government core physical property data are presented in Appendix A. Consolidation and triaxial data are presented as test reports in Appendices B and C.

3.2.2 Industry Data

There were 21 industry locations identified in the compilation area (Figure 3.2). The primary industry data are in the form of geotechnical reports. The reports were obtained for all the sites with the exception of Aiverk I-45, Koakoak O-22, Orvilruk O-03 and Siulik I-45. The reports consist of a combination of boreholes, CPTs and vibracores and total 141 sites from the 17 locations. The geotechnical reports were identified from 2 catalogue listings of well site and miscellaneous reports stored at the GSCA sample repository in Dartmouth NS. There was a total of 30 geotechnical borehole reports obtained.

The reports used have been scanned and are included as individual PDF files located in *Industry Data\Scanned Industry Borehole Reports\Scanned Industry Reports*. AINA was given copies of the PDF files. A listing of the scanned reports is presented in the Excel file *Industry Data\Scanned Industry Borehole Reports\ESRF_Inventory of Scanned Industry Reports*. There are 3 areas which contain multiple sites including Amauligak (6), Kopanoar (2) and Tingmiark (3). Also several sites contain multiple borehole, vibracore logs and/or CPT data in graphical format.

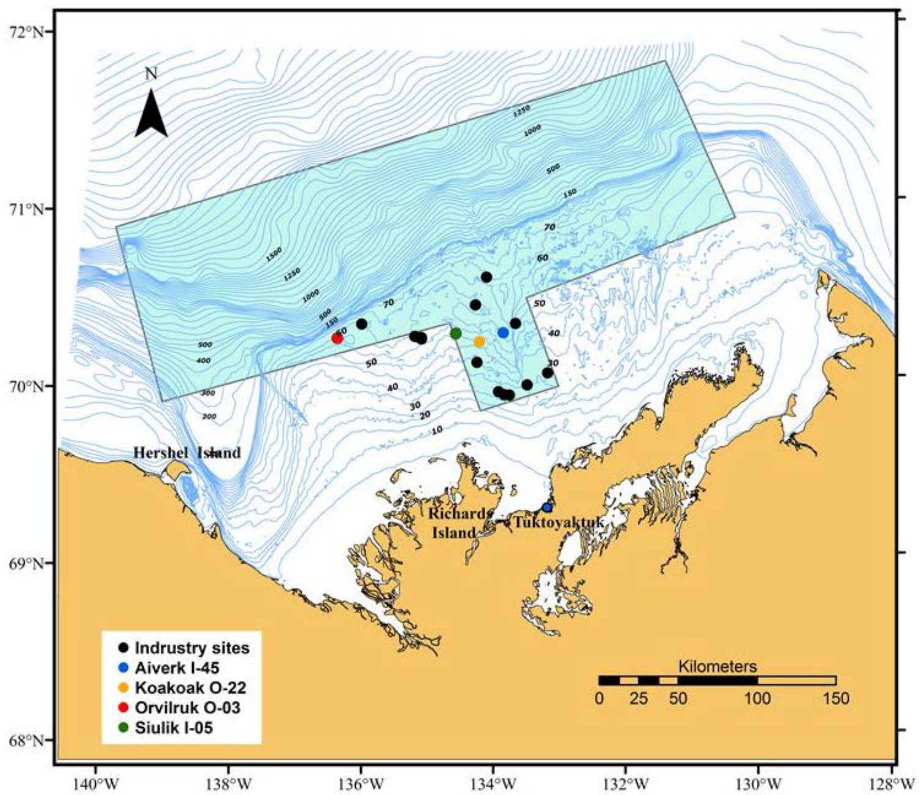

Figure 3.2 Location of industry sample sites. Geotechnical reports were not located for 4 sites (Aiverk I-45, Koakoak O-22, Orvilruk O-03 and Siulik I-45).

Of note is the location Nerlerk where there are 42 sites. The industry sites are in < 60 m water depth with the exception of Kenalooak J-94 (67.4 m). The total number of sample sites found in the reports was 144 including 77 boreholes, 27 vibracores and 40 CPTs. The maximum penetration depth is 124 mbsf, however the majority of the depths is less than 50 mbsf. The last sites were done in 1987 as part of a seabed pipeline study from Amauligak to North Head.

The major source of geotechnical data was summary tables within the reports. These data were converted to digital format as Excel files. There are individual Excel files for each borehole and also a single Excel file containing all the geotechnical data. The individual files contain a geotechnical profile with plots of available data including bulk density, water content, Atterberg Limits, shear strength, effective stress and contact between frozen and unfrozen sediments. The data were plotted on a scale of 0-130 m and 0-15 m. An example of a geotechnical profile from Kenalooak J-94 is presented in Figure 3.3.

In total there are 14,674 discrete data entries and 104 individual files. The geotechnical data were standardized with respect to units. A summary file containing the area, site ID, penetration depth and geotechnical data available in each borehole is presented in the Excel file *Industry Data\Industry Inventory Borehole summary*. The individual data files are found in (as an example) *Industry Data\Industry Borehole Data Files\West Tingmiark\West Tingmiark Individual Borehole Logs.*

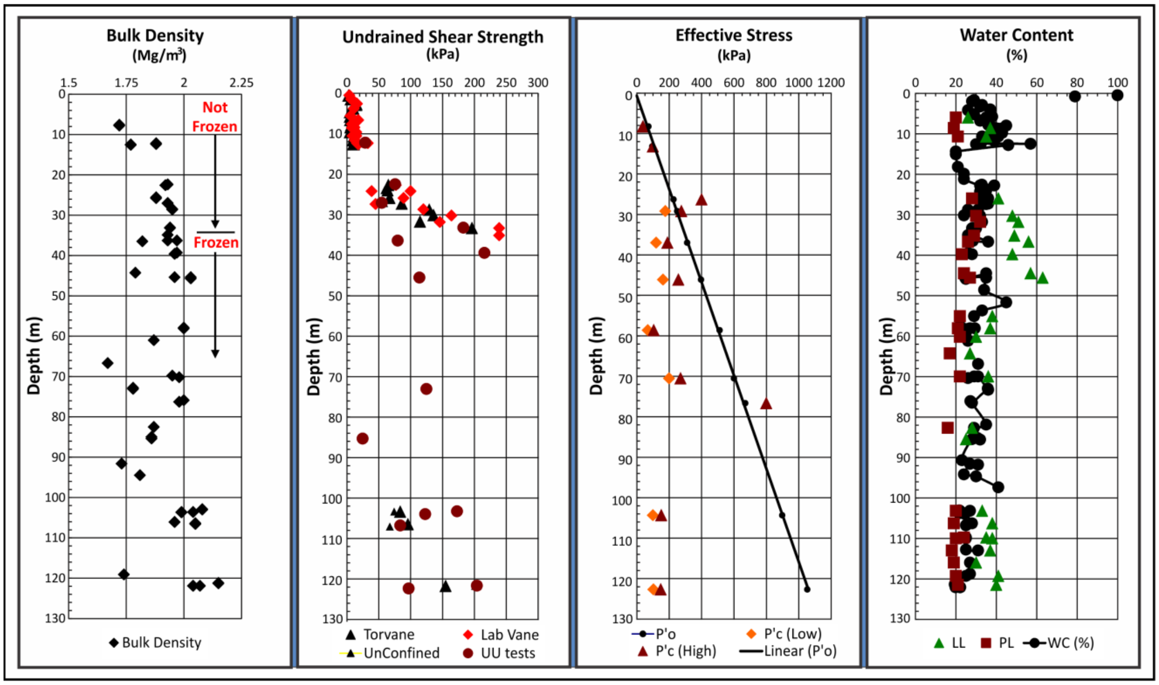

Figure 3.3 Kenalooak J-94 Geotechnical profile.

All the compiled industry data are contained in a single Excel file *Industry Data\ESRF Beaufort Sea Industry Borehole Data Compilation*. The industry data are also presented in Appendix D.

The CPT data are only presented graphically which reduces the usability of the data. Data in graphical format, including the CPT profiles, were not included in the Excel file. PDF files containing scanned images of available CPT plots are included in *Industry Data\Industry Graphic CPT Logs* and presented in Appendix E. A total of 40 CPT test plots were scanned. Of these 27 CPTs are from the Amauligak area. The scanned geotechnical borehole reports are presented in Appendix F.

3.3 Quality Assurance of Data

Prior to generating a geotechnical model, all industry well site reports from GSCA were assessed to determine the relevance of the geotechnical data. The location of borings contained in reports with suitable data were plotted to ensure that the locations were within the project area.

GSCA seabed sampling data were provided for this compilation as Excel digital files containing geographic coordinates and geotechnical data. The GSCA sample sites were imported into the project ArcMap model to determine which locations lay within the project area.

QA/QC of the geotechnical data was completed by performing spot checks of select geotechnical data points contained in the Excel data files. Geotechnical data in the Excel data files were selected at random and the geotechnical borehole report from which the data originated was retrieved. The data from the Excel data files and the report were compared to ensure accuracy of the data entered in the Excel data files. If data did not match then additional spot checks were completed for geotechnical data for the sample site from which the initial inaccurate data originated. QA/QC of the geotechnical profiles was completed by reviewing each profile individually ensuring that cell references were correct for each plot. If the cell references were not accurate than they were adjusted to reference the correct cells.

4.0 GEOTECHNICAL CHARACTERIZATION

The index properties, Atterberg limits, strength data and stratigraphic descriptions were used to characterize the sediments and establish geotechnical units within the compilation area. The characterization is difficult due to the limited number of sample sites outside of the Amauligak development area and the limited depth of the GSCA cores.

In order to characterize the sediments extending from the Amauligak development area to the outer shelf, a series of cross-shelf transects were created (Figure 4.1). The characterization was completed using the geotechnical data from the 13 industry sites and the GSCA sites located along the transects. The GSCA data were constrained to the upper 7.5 m and as a result the geotechnical data are limited to recent marine sediments. These data from 2009 and 2010 are used to characterize the Beaufort slope recent sediments.

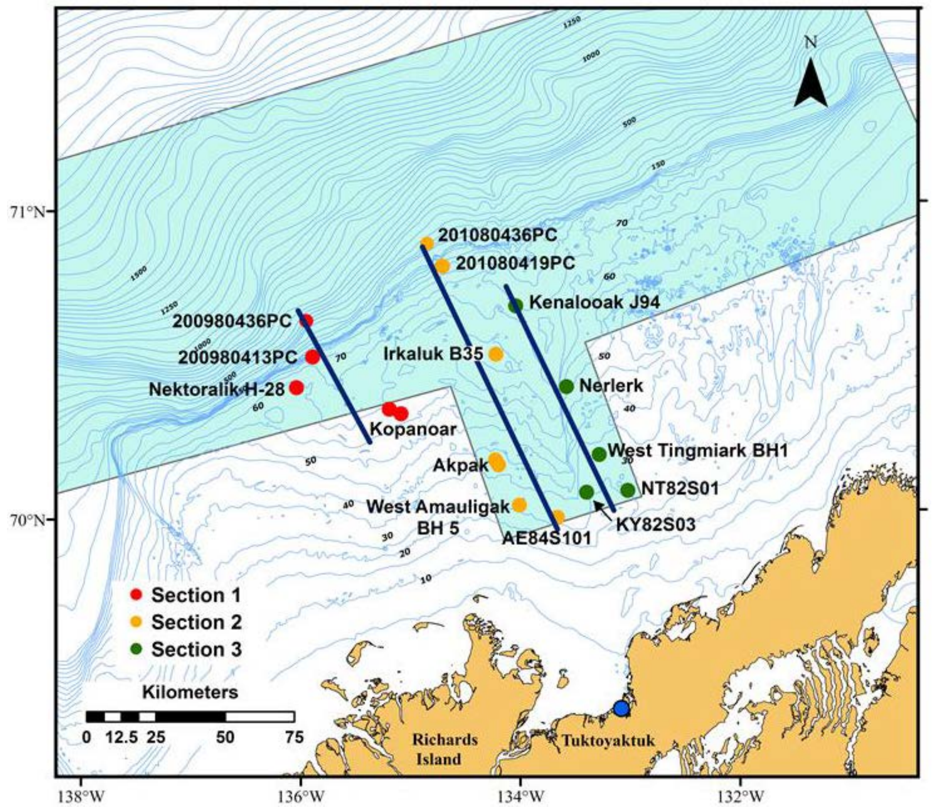

Figure 4.1 Location of cross shelf transects

4.1 Permafrost

The occurrence of ice bearing permafrost in the Beaufort Sea sediments is widespread across the Beaufort Shelf. The definition of permafrost is any earth material that has been at or below the freezing temperature of water for a prolonged period of time without regard to the state of any moisture present in the soil fabric. Generally the smaller the grain size of the sediment the lower the freezing point. Sandy sediment can appear and feel frozen at the same temperature that clay sediments will appear and feel unfrozen.

The ground ice conditions in the geotechnical borehole logs are described as not frozen or frozen. The materials were classified as frozen if there was visible ice and the measured temperature of the samples was below 0°C. Permafrost/frozen ground conditions were identified in sands as well as silts and clays. The effect that permafrost has on geotechnical data was difficult to determine. The fact is the test results are also dependant on the state (frozen or thawed) of the sediment when the test was conducted. For example, the geotechnical profile at Kenalooak (Figure 3.3) illustrates a marked change in pre-consolidation pressures and shear strength values at and below the contact between unfrozen and frozen sediments.

4.2 Geotechnical Data

Geotechnical units were created based on the sediment stratigraphy transferred to the 3 cross sections developed in Phase II of the data compilation and characterization program. The geotechnical data used for the characterization include grain size, bulk density, USCS classification and strength parameters. At the initial assessment level, soils are generally classified as either cohesive or cohesionless. For classification purposes, cohesionless soils are defined as possessing more than 50% by weight of sand sizes or greater and have their shear strength defined by angle of internal friction. The corollary is that all soils with less than 50% by weight of sand sizes are cohesive and have their strength defined by both cohesion and angle of internal friction. In cases where there was a small percentage of grain size analysis that contradicted a classification, it was assumed that the geotechnical unit may be interbedded. Interbedding of soil is recognized by others (O'Connor, 1981) and is common in transgressive deposition environments.

4.2.1 Classification Data

There are 229 grain size distribution test results for sample sites in the 3 transects. Descriptive statistics on the grain size distribution tests as they relate to the 3 sections are summarized in Table 4.1.

Bulk density is used in differentiating geotechnical units for each borehole but its use was limited by lack of data. There were 310 bulk density measurement tests. There are only 37 bulk density values from sites along transect 2 with 30 of these measurements from GSCA sites 20108040024PC (11) 20108040036PC (19). Along transect 3 95% of the values are from the Kenalooak J-94 (86) and Nerlerk F-Ner 2:3 (30) sites. Descriptive statistics on the bulk density values as they relate to the 3 sections are given in Table 4.2

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Table 4.1 Distribution of grain size data used in analysis.

		Clay (%)			Silt (%)			Sand (%)		
Section	Tests	Min	Max	Average	Min	Max	Average	Min	Max	Average
1	91	3.0	70.0	32.0	8.0	89.0	58.4	0.0	92.0	12.9
2	47	0.0	64.0	22.4	1.0	79.0	25.7	1.0	99.0	61.1
3	91	0.0	80.0	20.4	2.0	93.0	36.9	0.0	99.0	56.4

Table 4.2 Distribution of discrete bulk density data used in analysis.

		Bulk Density (Mg/m^3)		
Section	Tests	Min	Max	Average
Section 1	170	1.12	2.07	1.76
Section 2	54	1.89	2.13	1.99
Section 3	89	1.50	2.20	1.90

Cohesive soils are further described in terms of plasticity measured by Atterberg Limits tests. There are 215 Atterberg Limit test results in the 3 sections (Table 4.3).The distribution of the Atterberg Limits along the transects is good with the exception of section 2 where 81% of the tests are from AE84SI01 (24) and WA BH5 (10).

Table 4.3 Distribution of Atterberg Limits data used in the analysis.

		Liquid Limit (%)			Plastic Limit (%)			Plasticity Index (%)		
Section	Tests	Min	Max	Average	Min	Max	Average	Min	Max	Average
Section 1	95	21.0	94.0	42.5	13.0	35.0	23.0	3.0	60.0	19.6
Section 2	48	30.0	62.0	41.5	20.0	33.0	26.9	3.0	35.0	14.7
Section 3	72	25.0	68.0	42.6	16.0	33.0	24.8	3.0	39.0	18.3

The Atterberg Limits data were an excellent parameter for identifying differences between sediment types. These data when plotted on the plasticity chart (Figure 4.2) were approximately divided into 3 groups which are centered on liquid limits of 35%, 50% and 60%.

USCS classifications were completed for those sections of the sample sites that have the proper combination of grain size and Atterberg Limit data. The sediment was designated a silt or clay (ML, MH, CL or CH or a combination of these) if it had Atterberg Limit values and there were more than 50% fines (based on grain size data). The sediment was designated in the sand category (SW, SP, SM or SC or a combination of these) if it had less than 50% fines.

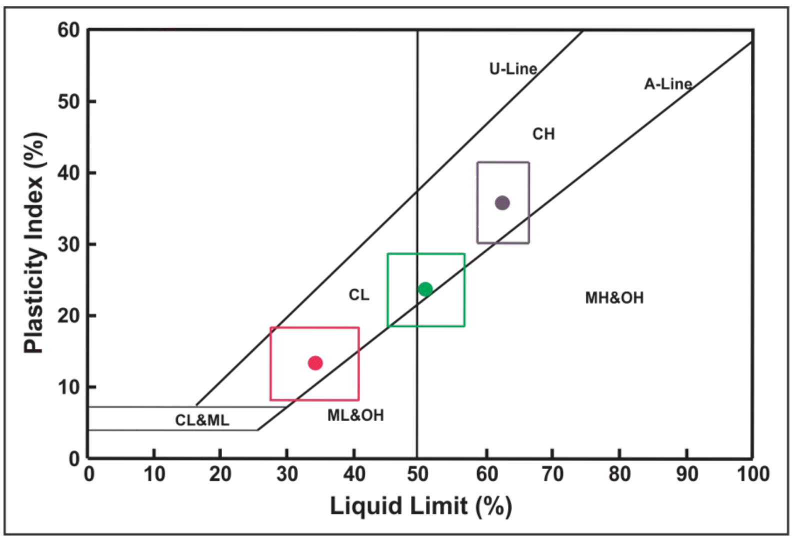

Figure 4.2 Plasticity chart outlining 3 groups

4.2.2 Shear Strength

Undrained shear strength results were measured during completion of the CPT tests and on recovered samples using a variety of test methods including laboratory mini-vane, field torvane, pocket penetrometer, fall cone, remote vane, unconfined compression, and through unconsolidated unconfined triaxial tests. The only digital CPT values were from the GSCA/industry ice scour program. These data are limited to the upper 10 mbsf and were not included in the characterization analysis. Available graphical CPT plots were scanned but were not included in the analysis. There are 595 test results along the 3 transects. The distribution of the undrained shear strength data

(Table 4.4) was good with the exception of transect 2 where 95% of the measurements are from 2 GSCA cores (75%) and 2 boreholes NT82S01 (13.9%) and KY82S03 (24.1%). Note that none of the values have been normalized. A detailed summary of the number of undrained shear strength measurements for each sample site for the 3 transects is presented in Table 4.4.

Table 4.4 Distribution of discrete undrained shear strength measurements used in the analysis.

			Peak Undrained Shear Strength (kPa)		
Section	Site Penetration Depth (m)	Tests	Min	Max	Average
Section 1	124.0	290	1.0	600.0	47.2
Section 2	75.7	158	3.0	435.0	130.4
Section 3	121.9	147	1.0	250.0	118.9

Consolidated undrained (CU) and consolidated drained (CD) triaxial data from industry wellsites are limited. There was a total of 33 CU and 9 CD triaxial tests identified in the entire industry data set. There were only 8 corresponding cohesion values (C') and friction angles (ϕ'). The majority of the tests were from West Amauligak boreholes (16 CU) and the Kopanoar (6 CU, 9 CD) site. In contrast, the GSCA data (from 11 sites) included 11 multistage CU tests with corresponding friction angles and estimated normalized strength ratios (Su/P_o). The distribution of the tests is listed in Table 4.5.

4.2.3 Consolidation Testing

There was a total of 88 consolidation test results for the compilation area with 63 tests from sites along the 3 sections. The distribution of the consolidation results along the 3 transects is presented in Table 4.6. Consolidation test data are included in the industry Excel file *ESRF Beaufort Sea Industry Borehole Data Compilation* and *ESRF Beaufort Sea Government Consolidation Data*. Of note, 54% of all consolidation tests are from 5 industry boreholes (Koapanoar I44, Nektoralik, AE84SI01, F-Ner 2:3, Kenalooak J-94) whereas 17% are from the 2009 and 2010 government locations.

4.3 Geotechnical Units

The Beaufort Sea submarine surface can be generally described as a continental shelf extending from shoreline at a relatively flat slope to a depth of between 75 and 100 m below sea level (75 to 100 mbsl), followed by a steeper continental slope extending to a depth of around 1500 m before the slope flattens again at the continental rise.

Table 4.5 Distribution of all CU and CD triaxial data with the number of measured friction angles.

Site	Station	Tests	Cu	CD
Koapanor M-13	Boring 3	2		2
Koapanor M-13	CPT Borehole	2	1	1
Koapanor I-44	Boring 2	11	5	6
Weat Amaligauk	BH1 to BH5	16	16	
West Tingmiark	BH1	2	2	
2009013PC		1	1	
2009019PC		1	1	
2009026PC		1	1	
2009036PC		2	2	
2010024PC		1	1	
2010036PC		1	1	
2010056PC		1	1	
2010056PC		1	1	
2010069PC		1	1	
2010070PC		1	1	

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Table 4.6 Distribution of consolidation test results used in the analysis.

		Cc			OCR		
Site	Tests	Min	Max	Average	Min	Max	Average
Section 1	19	0.09	0.77	0.50	0.14	2.81	1.56
Section 2	19	0.23	0.63	0.44	1.40	3.20	2.35
Section 3	25	0.12	0.41	0.24	0.10	1.76	1.06

The shelf is comprised of sediments of different deposition environments. None of the sample sites encountered bedrock. The majority of subsurface investigation was completed on the continental shelf in relatively shallow water. The sediment units observed in these investigations include sandy sediments and fine grained sediments and have been described and characterized by others (O'Connor et. al). In general, on the Shelf, the data suggest there is a fine grained sediment that behaves similar to clay near surface which is underlain by interbedded sand, silt and clay sediments.

Geotechnical units were defined by comparing geotechnical index parameters with sediment descriptors in the 3 sections. Six geotechnical units were defined:

- Unit 1 – Sand (SP) – Fine grained, noncohesive …
- Unit 2 - Silty Sand (SM) - Coarse grained, noncohesive …
- Unit 3 - Silt (ML) – Fine grained, cohesive …
- Unit 4 – Clayey Silt (CL) - Fine grained, cohesive …
- Unit 5 - Lean Clay (CL) - Fine grained, cohesive …
- Unit 6 - Fat Clay (CH) - Fine grained, cohesive …

The 6 units are classified based on the available data for each sample site. The geotechnical model for the 6 units is developed in the 3 cross sections as presented in figures 4.3 through 4.5.

The sediment geotechnical characteristics available for these sections are discussed below for specific sample sites. The triaxial data used to define Mohr Coulomb parameters (C', ϕ') for the Units are listed in Table 8. Note that both friction angles and cohesion values were found at only 2 industry sites.

Section 1 (Figure 4.3) is located in the western part of the compilation area and extends from 54 m water depth to 444 m water depth. The section is comprised of 3 industry boreholes and 2 GSCA piston cores collected in 2009. There are numerous geotechnical data from the industry boreholes at Kopanoar and Nektoralik H-28. Kopanoar has data for CU and CD triaxial tests and 8 consolidation tests while Nektoralik H-28 has data for 8 consolidation tests. The units along this transect are more cohesive in nature, Unit 3, silt to Unit 6, fat clay with the exception of Kopanoar M13 which contains amounts of Unit 1, sand and Unit 2 silty sand. The unfrozen/frozen contact occurs in clayey silt (CL) at both Kopanoar and Nektoralik. At Kopanoar the contact varies in depth at 3 boreholes from 26 mbsf to 70 mbsf.

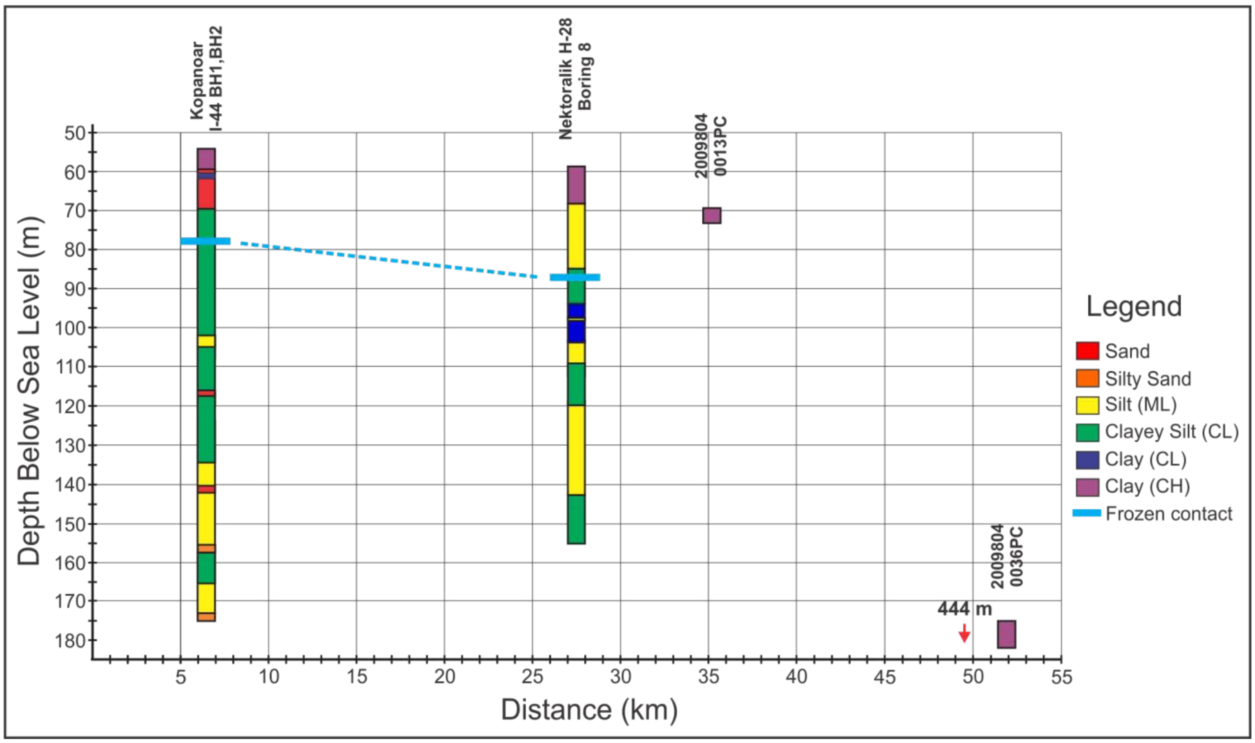

Figure 4.3 Distribution of geotechnical units along section 1.

Section 2 is a cross shelf transect from the Amauligak development area to a water depth of 250 m (Figure 4.4). This cross section contains a poor vertical and horizontal distribution of geotechnical data with the majority of the data in the Amauligak area. Unit 1 sand is the dominant unit with a surficial layer of Unit 5, lean clay and Unit 6, fat clay. Unit 4, clayey silt is present in the Amauligak boreholes starting at 30-40 mbsf.

Section 3 is a cross shelf transect from North Tingmiark at a water depth of 35 m to Kenalooak J-94 at a water depth of 67 m (Figure 4.5). The distribution of the geotechnical data is good, however there are no triaxial data available from the locations. The geotechnical units change from predominately non-cohesive Unit 1 sand to predominantly silt Unit 3 and Unit 4 clayey silt at Kenalooak J-94.

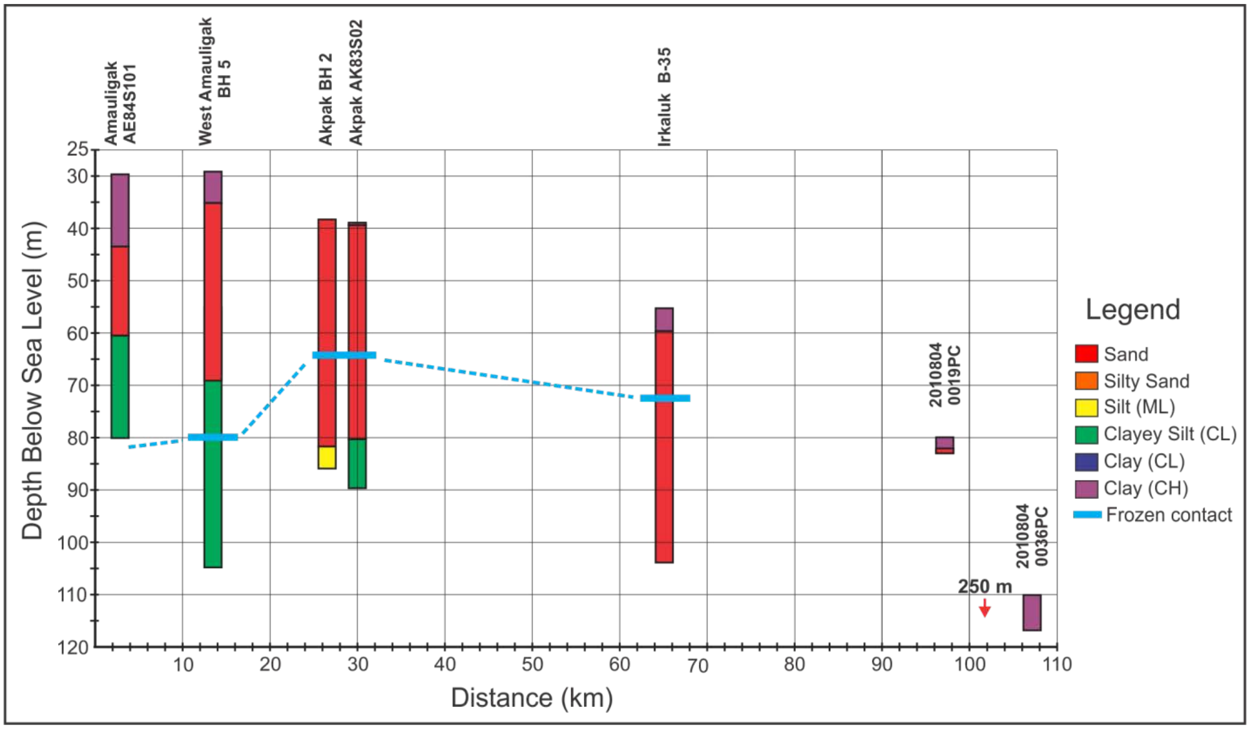

Figure 4.4 Distribution of geotechnical units along section 2

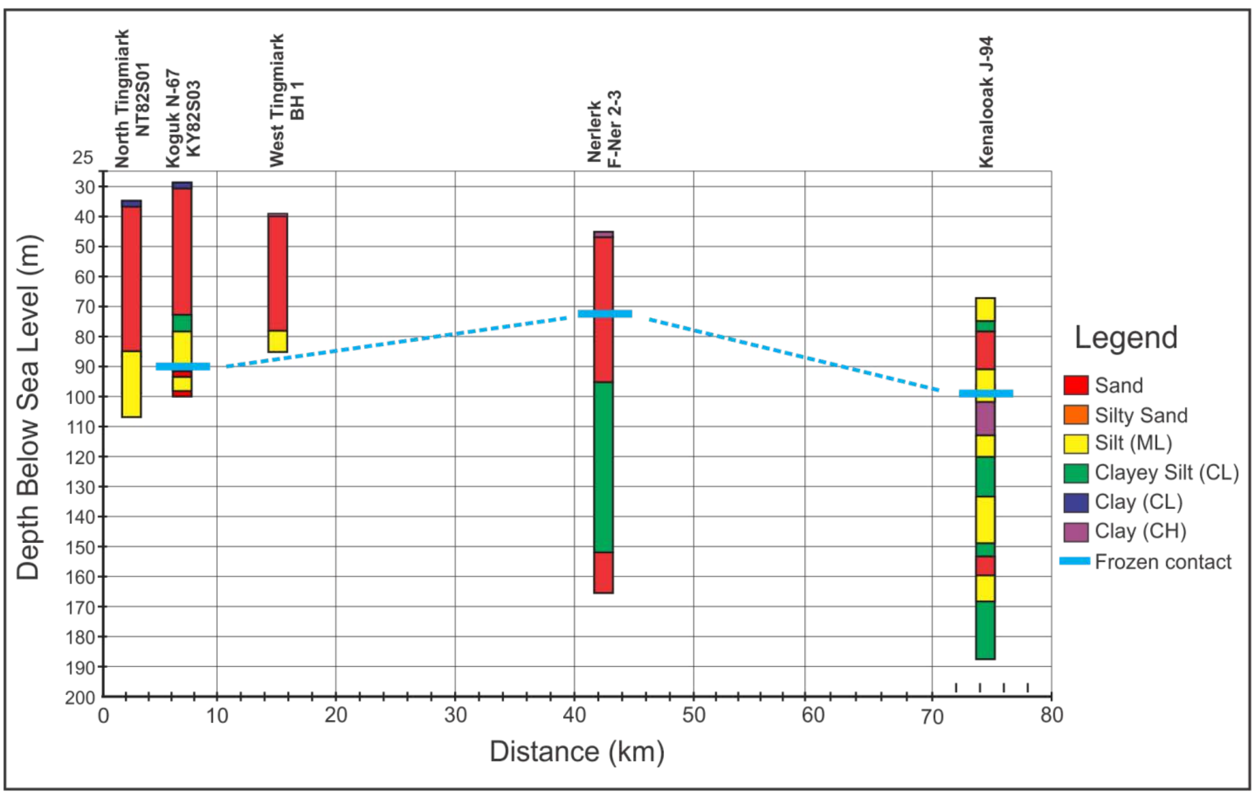

Figure 4.5 Distribution of geotechnical units along section 3.

5.0 GEOTECHNICAL MODEL

A geotechnical model was developed using the 6 geotechnical sediment units previously described. The continental slope and rise are not as well investigated and characterization of the upper sediments is largely defined by recent GSCA data. The shelf break occurs between the 75 and 100 m isobaths, shallower progressing westward. The slope angle varies from 1.5 to 6 degrees before rising to a more gradual 1-2 degrees at the 1000-3000 m isobaths.

5.1 Strength Parameters

The quantity of undrained shear strength data exceeds the quantity of drained shear strength data due to the relatively simpler recovery of the former relative to the latter. Sources of undrained shear strength included various vane measurements, fall cone, pocket penetrometer, and CU triaxial test results. Drained shear strength values were obtained from CD triaxial tests. Note that the near surface 2007 CPT data were not included in the analysis. The data from the triaxial tests are included in Table 5.1.

Table 5.1 Summary of Triaxial Data used

Unit	Site	Station Number	Depth (m)	Tests	Test Type	ϕ' (^{0})	C′	Normalized Strength Ratio
1	Koapanor I-44	Boring 2	9.3-15.2	6	CD	36.0	14.0	
3	Koapanor I-44	Boring 2	81.5-81.6	2	CU	30.0	26.0	
3	Koapanor I-44	Boring 2	87.7,89.2	2	CU	33.0	21.0	
1	Koapanor M-13	Boring 3	7.5	1	CD	36.0	0.0	
1	Koapanor M-13	Boring 3	17.5	1	CD	38.0	0.0	
1	Koapanor M-13	CPT Borehole	21.6	1	CD	28.0	28.0	
1	Koapanor M-13	CPT Borehole	30.5	1	CU	33.0	20.0	
4	West Amaligauk	BH3	45.7-46.5	1	CU	26.0	22.0	
6	2008802044A	-	0.3	1	CIU	26.4	0.1	0.28
6	2009804013PC	-	1.1	1	CIU	18.2	2.2	0.23
6	2009804019PC	-	2.1	1	CIU	25.2	2.0	0.27
6	2009804026PC	-	2.3	1	CIU	21.4	0.4	0.26
6	2009804036PC	-	2.4	1	CIU	19.2	1.1	0.21
6	2009804036PC		6.9	1	CIU	20.6	4.1	0.24
5	2010804024PC	-	2.6	1	CIU	22.8	6.1	0.33
6	2010804036PC	-	7.0	1	CIU	22.7	2.5	0.26
6	2010804056PC	-	4.1	1	CIU	17.5	2.7	0.21
6	2010804069PC	-	3.9	1	CIU	25.9	0.0	0.27
6	2010804070PC	-	4.1	1	CIU	23.5	0.0	0.27

5.1.1 Cohesive Sediments

The undrained shear strength is used to define sediment resistance for cohesive sediments during rapid loading. Undrained shear strength values for Geotechnical Units 3, 4, 5 and 6 are estimated from the various sources of data available, as discussed.

Undrained shear strength for normally consolidated sediment will increase with depth and its absolute values are of little value without a corresponding depth. It should therefore be expressed as the ratio of undrained shear strength to effective overburden pressure (S_u/P_o). The system known as Stress History and Normalized Soil Engineering Properties (SHANSEP) is used in characterizing shear strength for sediments and is expressed as

$$(\frac{S_u}{P_o})_{OC} = (\frac{S_u}{P_o})_{NC} OCR^m \qquad \text{Equation 1}$$

where S_u is the peak undrained shear strength, P_o is the effective overburden stress, OCR is the overconsolidated ratio, and m is a sediment constant. The SHANSEP principle is used for triaxial data from the post 2008 dataset. The results are presented in Figure 5.1. Using the differentiation of units from changes in Atterberg Limits defined in Figure 6, the post 2008 dataset consists of predominantly Fat Clay (Unit 6) with lesser amounts of Lean Clay (Unit 5). The average values for cohesion, angle of internal friction and normalized strength ratio S_u/P_o are presented in Table 5.2.

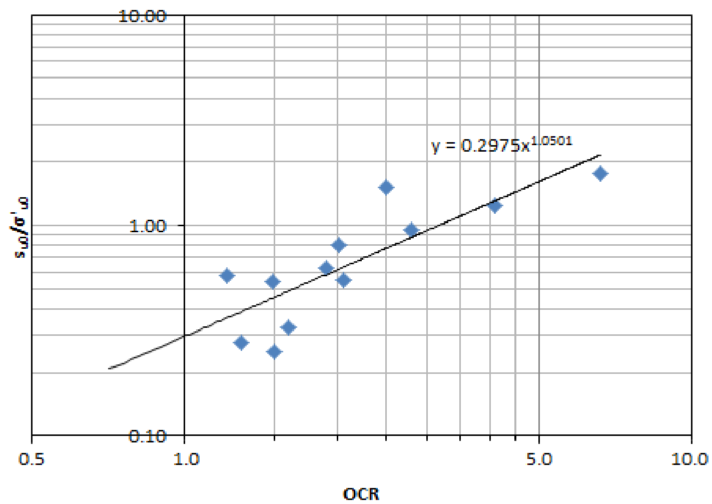

Figure 5.1 SHANSEP method for Fat Clay

Characterizing shear strength parameters for geotechnical units 3 and 4 was achieved using the small amount of available triaxial data from the industry boreholes. At Kopanoar I-44 the friction angles of 33 and 30 degrees and cohesion values of 21 kPa and 26 kPa were obtained from 4 CU triaxial tests. At West Amauligak BH 3, the results from several CU triaxial tests resulted in an average friction angle of 26° and cohesion intercept of 22 kPa.

5.2.2 Non-Cohesive Soils

Mohr Coulomb drained shear strength is derived from cohesive strength and angle of internal friction. Drained shear strength results are obtained using consolidated drained triaxial tests. Triaxial tests require undisturbed samples and are difficult to conduct and, as a result, they are not as common as undrained shear strength tests.

Consolidated drained triaxial tests for Unit 1 were done on samples from Kopanoar I-44 and Kopanoar M-13 only. The average friction angles measured were 34° for Unit 1. As a comparison, references in the literature of typical values for angle of internal friction based on index sediment properties have been developed. McCarthy (2002) provides friction angle values for peak states of 30-35° for fine to medium sand, 30-33° silty sand and 30-35° for nonplastic silt. The estimated shear friction angles used for the geotechnical model for Unit 1 are 34° and 32° for Unit 2

Table 5.2 Strength Parameters for Geotechnical Units 3, 4, 5 and 6

Unit	ϕ'	C'	Normalized Strength Ratio
3	31.5	23.5	NA
4	26.0	22.0	NA
5	22.9	6.2	0.31
6	22.2	2.9	0.26

5.2 Stress History

The stress history of the area was determined from available consolidation tests. The stress state appears to be depth dependant. The near surface sediments are overconsolidated and generally become normal to underconsolidated with depth (Figure 5.2).

The sediments at Amauligak (AE84S101) are noticeably more overconsolidated in the upper 15 mbsf. The recent government consolidation tests on samples from the slope area are also overconsolidated near the seafloor and become normally consolidated at approximately 3 m (Figure 5.2). The near surface overconsolidation can be quite extreme in the upper 30 cm mbsf and is considered to be due to apparent overconsolidation typical of shallow (0-2 mbsf) marine clays. OCR values of 15 to 30 have been measured on sediments from the Beaufort Slope (Appendix A).

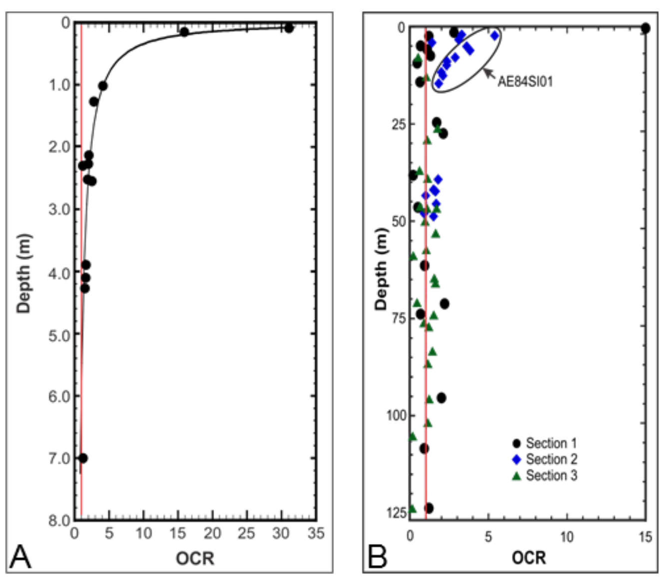

Figure 5.2 OCR values from consolidation tests of recent marine sediments on the Beaufort Slope (A) and industry data on the Beaufort Shelf (B).

6.0 GEOPHYSICAL AND GEOTECHNICAL COMPARISON

A comparison of geophysical data and the geotechnical boreholes used in the 3 geotechnical sections was attempted. The validity of the comparison is limited due to the number of boreholes and the lack of proximity (up to 42 km) of boreholes to the seismic cross sections. Geophysical data were used to generate 2 orthogonal schematic sections (Figure 6.1). The geophysical schematics (Figure 6.2 and Figure 6.3) used in this comparison were generated from the interpretation of 800 km of regional subbottom, shallow seismic and shallow multichannel reflection seismic profiles acquired in the area from 1984 through 2009 (Carr et. al., in prep). Of particular interest is the top of the permafrost frozen layer which is identified as frozen sediments in the geotechnical borehole logs and the hummocky APF on the seismic sections.

Geotechnical profiles were compiled from data at boreholes Irkaluk (B-35), Kenalooak (J-94), Kopanoar (I-44) and Nektoralik (H-28). The geotechnical data include plots of grain size, natural water content, Atterberg Limits, undrained shear strength, stress state, bulk density and the downhole distribution of the geotechnical units defined in this report. The profiles were plotted next to the associated geophysical schematic segment (Appendix G).

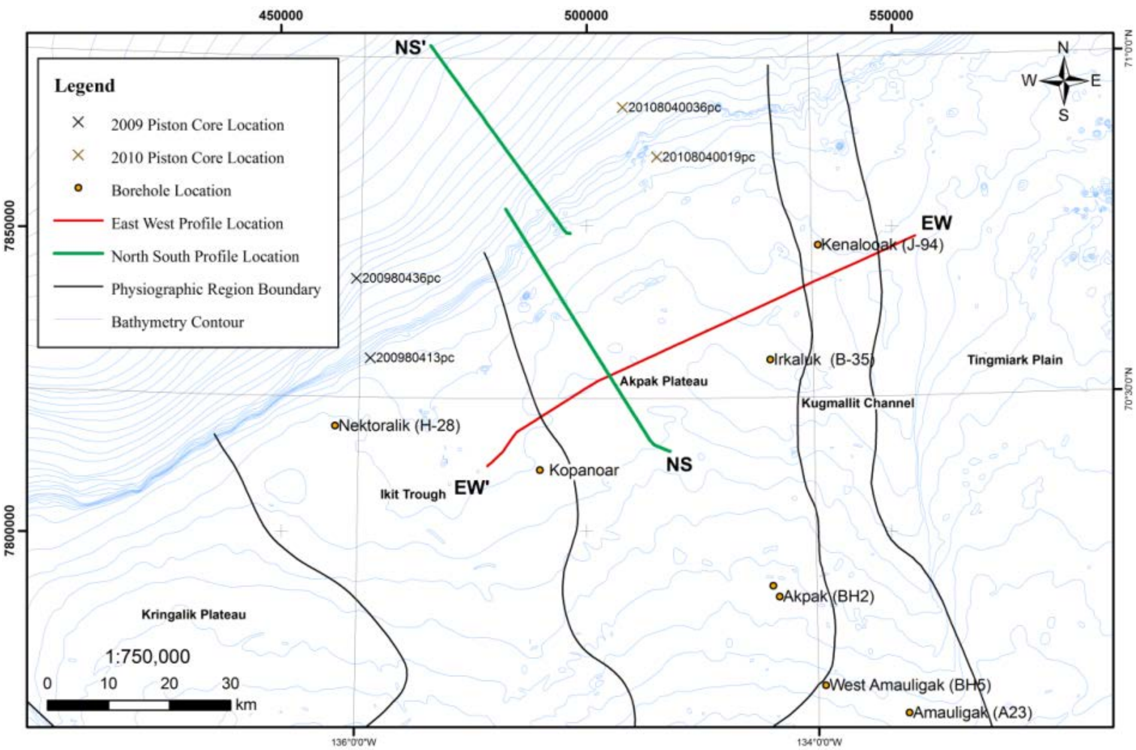

Figure 6.1 Location of geophysical schematics and industry boreholes used in the geophysical and geotechnical comparison.

6.1 E-W Seismic Section

The E-W seismic schematic extends from Tingmiark Plain to Ikit Trough. Four geotechnical boreholes were used to compare the geotechnical data and the seismic section (Figure 6.2). The top of the frozen sediments recorded in the boreholes (Figures G1 to G4) ranges from 17 at Irkaluk to 70 m at Kopanoar. Kopanoar however has frozen sediment at 25 m and 30 m in different boreholes.

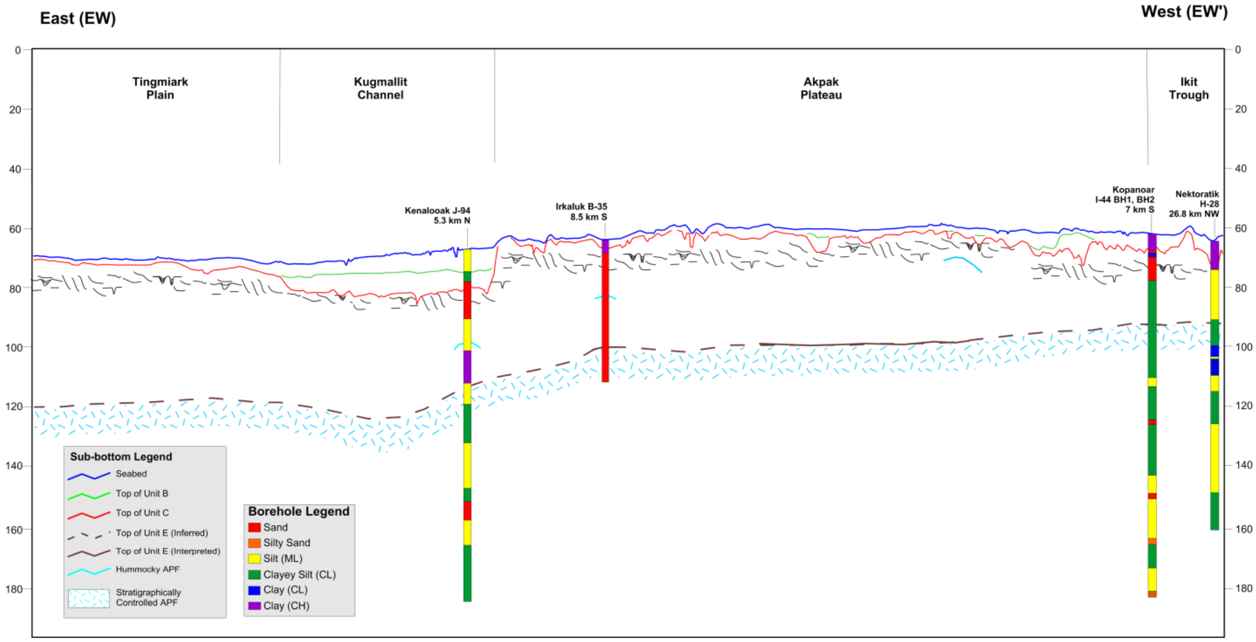

Figure 6.2 E-W schematic seismic section and geotechnical units.

The stratigraphically controlled Acoustic Permafrost (APF) (Blasco et. al., 1990) appears to correlate to changes in geotechnical units at Kenalooak and Nektoralik. The APF at Kenalooak lies beneath a layer of high plasticity clay, classified as geotechnical unit 6 (CH). This CH clay was not recovered at this depth in the other boreholes and may indicate a limited extent. This deeper CH clay may be similar in nature to the recent near surface CH unit on the shelf and the slope. The APF at Nektoralik correlates to a change from silt (ML, geotechnical unit 3) to clayey silt (CL, geotechnical unit 4).

The seismic stratigraphic contacts appear to correlate with changes in geotechnical units. At Kenalooak the upper seismic contact is interpreted as the top of unit B. This marks a change from silt (ML, Unit 3) to clayey silt (CL, Unit 4). The upper seismic contact at the remaining 3 boreholes is identified as the top of Unit C. This correlates to the change from clay (CH) to sand or silt (ML). Table 6.1 attempts to summarize the correlation between the 2 data sets. It appears that the geotechnical unit CH is not observed in the seismic data. The geotechnical unit 1 (sand) correlates well with the SS unit C. (See Section 2 for acoustic units.)

Table 6.1 Summary of correlation of seismic and geotechnical units on E-W schematic.

Kenalooak			Irkaluk			Kopanoar			Nektoralik		
Depth (m)	Seismic Stratigraphy Unit	Geotechnical Unit	Depth (m)	Seismic Stratigraphy Unit	Geotechnical Unit	Depth (m)	Seismic Stratigraphy Unit	Geotechnical Unit	Depth (m)	Seismic Stratigraphy Unit	Geotechnical Unit
0-8	A	ML (3)	0-4	B	CH (6)	0-5	B	CH (6)	0-10	B	CH (6)
8-12	B	CL (4)	4-?	C	Sand (1)	4-??	C	Sand (1)	10-??	C	ML (3)
12-?	C	Sand (1)	35	APF	Sand (1)	30	APF	CL (4)	30	APF	CL (4)
50	APF	CH (6) to ML(3)									

6.2 N-S Seismic Section

The N-S seismic section starts at a water depth of 40 m on the Akpak Plateau to a water depth of 800 m. Three geotechnical boreholes were used to compare the geotechnical data and the seismic section (Figure 6.1). The top of the frozen sediments recorded in the boreholes (Figures G5 to G7) range from 17 at Irkaluk to 70 m at Kopanoar. The stratigraphically controlled APF does not appear to correlate with changes in geotechnical units. The upper seismic contact at the location of the 3 boreholes is identified as the top of Unit C. This correlates to the change from clay (CH) to sand or silt (ML). Table 6.2 attempts to summarize the correlation between the 2 data sets. It appears that the geotechnical unit CH is not observed in the seismic data. The geotechnical unit 1 (sand) correlates well with the SS unit C.

Table 6. 2 Summary of correlation of seismic and geotechnical units on N-S schematic.

Irkaluk			Kopanoar			Nektoralik		
Depth (m)	Seismic Stratigraphy Unit	Geotechnical Unit	Depth (m)	Seismic Stratigraphy Unit	Geotechnical Unit	Depth (m)	Seismic Stratigraphy Unit	Geotechnical Unit
0-4	B	CH (6)	0-10	B	CH (6)	0-8	B	CH (6)
4-?	C	Sand (1)	10-30	C and D	Sand (1) and CL (4)	8-35	C and D	ML (3) and CL (4)
35	APF	Sand (1)	30	APF	CL (4)	30	APF	CL (4)

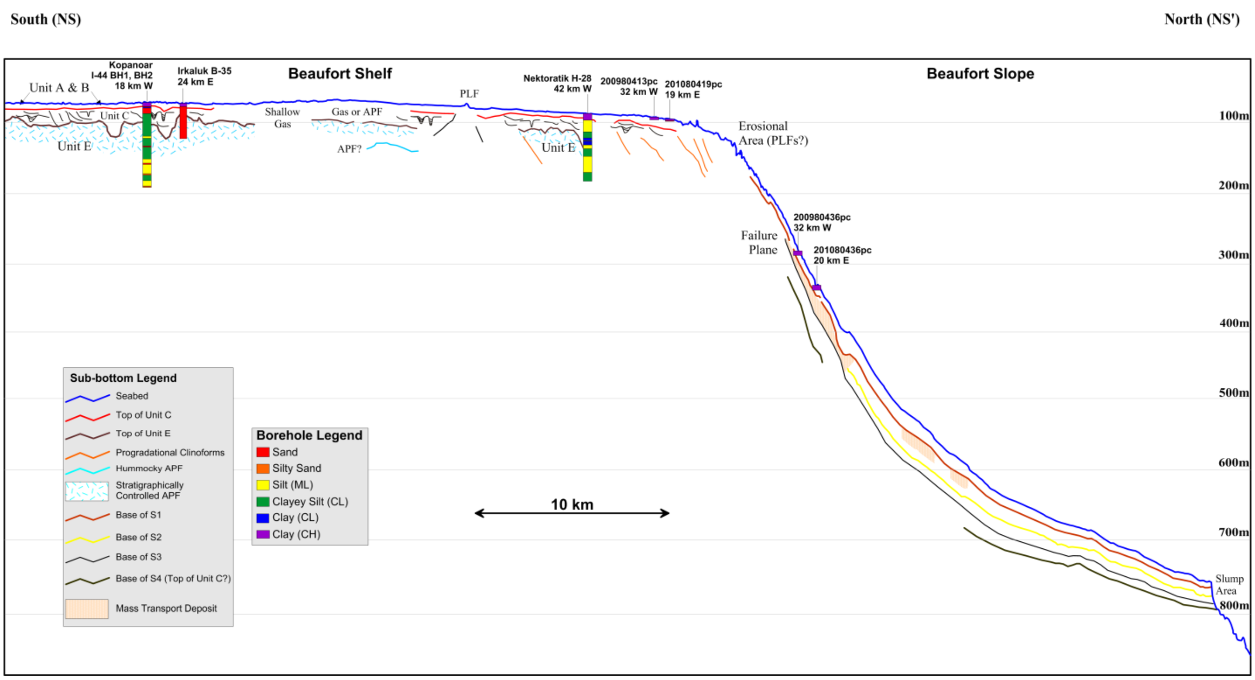

Figure 6.3 N-S schematic seismic section and geotechnical units.

7.0 SLOPE STABILITY MODEL

An assessment of stability of near surface sediment on the continental shelf was performed using a Total Stress Analysis (TSA) and Effective Stress Analysis (ESA). In cohesive or low permeability sediments, the former is typically applicable to temporary or short term loading conditions and the latter to long term stability. In non-cohesive sediments with high permeability, an ESA is most appropriate.

7.1 Slope Stability Methods

The ESA analysis uses a standards-based approach to assess slope stability in the Geo-studio software suite, specifically SLOPE/W, to calculate the minimum factor of safety using the limit equilibrium, *Morgenstern-Price* method. The pore-water pressure conditions are represented with a Ru value of 0.5. The “Grid and Radius” slip surface option is selected to generate the critical, circular slip surface. A minimum slip surface depth of 2 m is defined to prevent negligible surficial failure surfaces. Frozen ground, assumed to be a horizontal surface at -150 mbsl, is modeled as an impenetrable boundary.

The TSA analysis uses a critical thickness metric assuming a factor of safety of unity as the governing criterion. The critical height (H_c) is obtained using the infinite slope method. The resulting equation is

$$H_c = \frac{2S_u}{\gamma_b \sin(2\beta)} \qquad \text{Equation 2}$$

where S_u is the undrained peak shear strength, γ_b is the effective overburden pressure and β is the slope angle.

7.2 Trigger Mechanisms

Specific triggers for the initiation of submarine landslides include:

1. Oversteepening (Static Load),
2. Seismic Loading (Dynamic Load),
3. Storm Wave Loading (Dynamic Load),
4. Rapid Accumulation and Underconsolidation (Static Load),
5. Gas Charging (Static Load),
6. Gas Hydrate Disassociation (Static Load),
7. Low Tides (Static Load),
8. Seepage (Static Load),
9. Glacial Loading (Static Load),
10. Volcanic Island Growth (Dynamic).

For the project area, loads due to Volcanic Island Growth (trigger 10), Low Tides (7), and Storm Wave Loading (3) are not considered because of the depth of the seabed and the inactive volcanic environment. Historically, glacial loading may potentially have contributed to instability of the continental slope but the current impact is expected to be minimal since the shelf break is 75 m below current sea level. Seepage forces (8), Gas Hydrate Disassociation (6) and Gas Charging (5) have not been considered to date but may have an influence during drainage of excess pore pressures. The challenge in assessing these forces is to reliably predict their magnitude and the form of their impact (i.e., whether they behave the same as hydrostatic forces or seepage forces).

The effects of oversteepening can be assessed by altering the seabed slope angle to determine the *critical slope* ($\beta_{c.}$). Seismic Loading (2) can be assessed using a pseudo- static analysis to develop a critical coefficient due to seismic acceleration (K_h) where the dynamic force caused by earthquake loading is represented by an equivalent static force (E) in the horizontal direction. These mechanisms should be evaluated further following an assessment of their likelihood to occur.

A very preliminary analysis was undertaken to assess rapid accumulation as a trigger. Rapid Accumulation and Underconsolidation (4) can occur if there is a sudden deposition and buildup of sediment on the shelf that could overstress a lower section of the slope (possibly occurring during rapid glacial retreat). The results of this analysis are provided in Section 6.3 using both effective strength (ESA) and total strength (TSA) techniques.

7.3 Results

The slope stability model uses slope gradients determined from multibeam bathymetric data. Slope profiles are developed for the 3 cross sections shown in Figure 4.1. The model is developed by transposing the sediment stratigraphy, identified in the 3 sections, to the continental slope. The unit 6 Fat Clay continental slope sediment is the primary shallow sediment cover on the outer shelf and upper slope where a major failure has been identified on multibeam data. The thickness of the unit 6 sediment is a minimum of 10 m.

The slope stability model for the ESA is presented in Figure 7.1. Results of the model are presented in Figure 7.2. For the normal slope without accumulation, the factor of safety is greater than 7 for a sediment thickness of up to 50 m as shown in Figure 7.2. There is no further significant reduction in factor of safety with increasing sediment thicknesses.

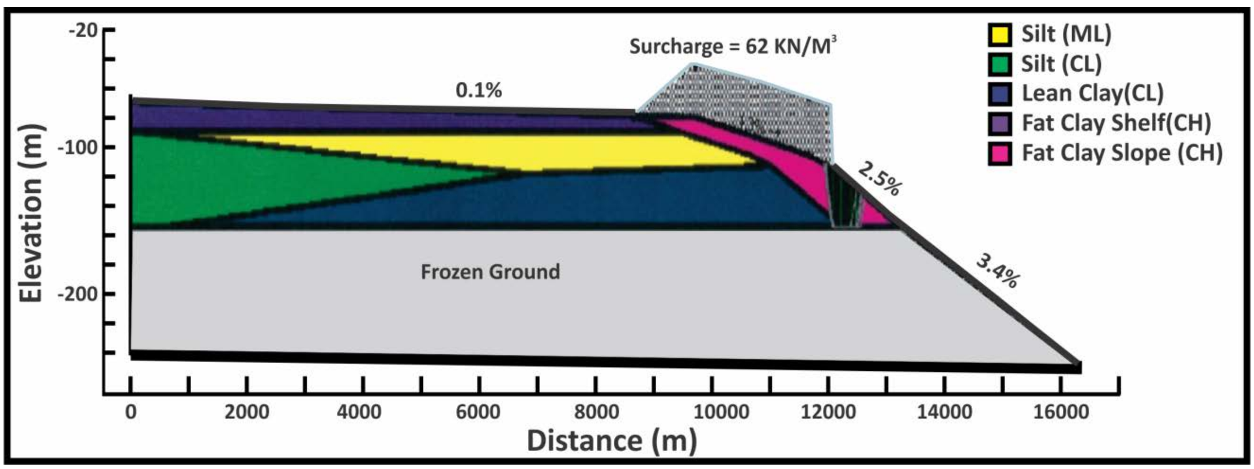

Figure 7.1 GeoStudio slope stability model with surcharge load of 62 KN/m3. Slope sediment is 1000 m wide.

If the unit 6 sediment in the vicinity of the slope break is loaded with a sudden sediment accumulation, Surcharge, as identified in Figure 7.1, the factor of safety will reduce to less than 1 under certain conditions, as shown in Figure 7.2. For a 1.25 m thick surficial sediment, the surcharge would have to be approximately 80 kPa, or about approximately 15 to 16 m thick. If the thickness of the surficial sediment is around 40 m, the thickness of the accumulation on the slope is on the order of 7 to 8 m. The sediment thickness is estimated using the effective overburden pressure, calculated form MSCL density data, and the depth down core relationship for 2009 GSCA piston cores.

The slope stability model for the TSA uses the infinite slope method of analysis assuming undrained loading conditions. As noted (equation 2) the critical thickness of unit 6 sediment is a function of buoyant unit weight, seabed slope angle and undrained shear strength. Using bulk density for unit 6 and converting to buoyant unit weight, a power function is developed to equate critical sediment unit 6 thickness (H_c) to undrained shear strength

$$H_c = \frac{11S_u}{\beta} \qquad \text{Equation 3}$$

where S_u is the undrained peak shear strength, and β is the slope angle. Equation 3 suggests that at existing slope profiles, the critical thickness is on the order of 15 to 20 m for the undrained condition.

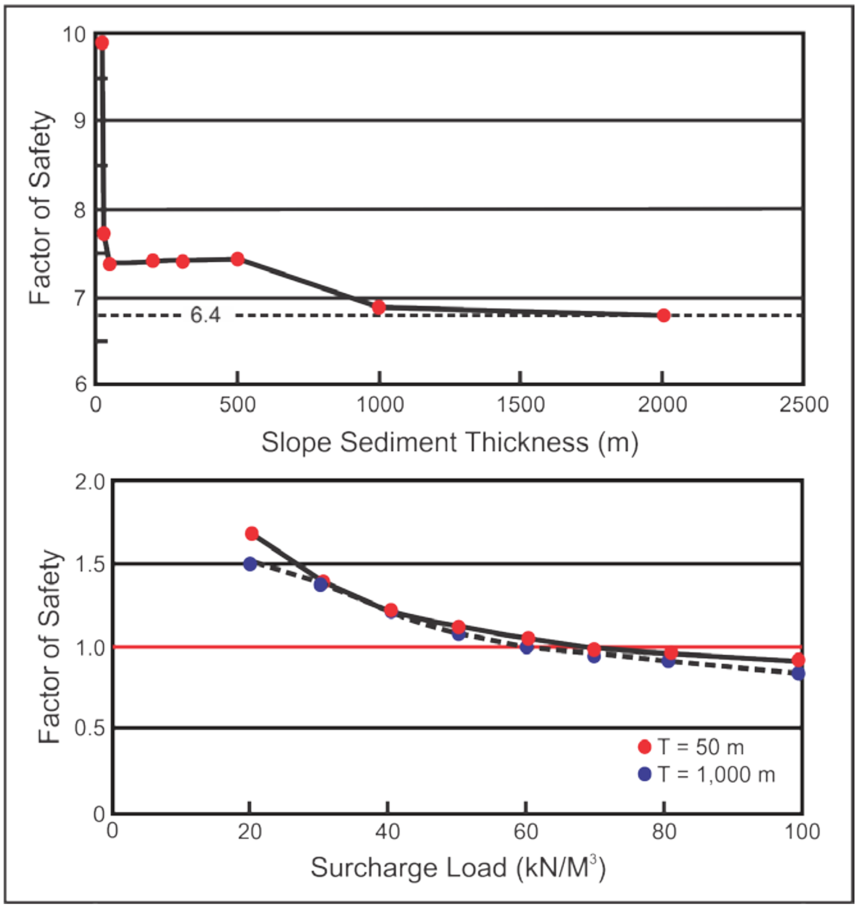

Figure 7.2 Section 1 GeoStudio slope stability graphical results.

8.0 SUMMARY

Interest in the geotechnical properties and geological origin of the Canadian Beaufort Shelf and slope has increased recently due to the potential for development of oil and gas wells on the Beaufort Slope in water depths of greater than 100 m. The Geological Survey of Canada Atlantic (GSCA) compiled legacy data (1965-2008) and recent data (2008-2010) to assess geotechnical properties and develop a slope stability model for the continental slope. After a thorough review of the sources of data and locations, the dataset was reduced to 141 industry sites including 77 boreholes, 27 vibracores, and 37 CPT and 183 GSCA sample sites, including 36 CPT sites in the Amauligak area. Geotechnical data was reviewed and summarized in digital format for 104 industry sites and 183 government sample sites.

Although the sample sites are geographically dispersed and limited in number 3 cross shelf transects were created to generate a geotechnical model. Geotechnical units were generated based on the sediment properties and interpolated to develop the 3 cross sections. The geotechnical data included grain size, bulk density, Atterberg Limits and USCS classification system. Comparing the different material test properties at sample sites with sediment descriptors, a geotechnical model was developed that includes 6 units.

An understanding of the stress history of the continental shelf and the continental slope was attempted by assessing over consolidation ratios obtained from consolidation tests for the different units. Overall, the results indicate the sediments at depth on the shelf are either normally consolidated or underconsolidated, while the near surface sediments (10 mbsf) on the continental shelf and the upper 2 mbsf on the continental slope are overconsolidated.

A preliminary slope stability assessment of near surface sediment on the continental shelf was performed using a Total Stress Analysis (TSA) and Effective Stress Analysis (ESA). The only potential triggering event considered was rapid accumulation of sediment on the continental slope. The TSA analysis used the infinite slope method to determine a critical thickness of sediment that would potentially fail under self-weight in an undrained condition. The conclusion was that it is unlikely that rapid accumulation will result in an undrained failure. The ESA analysis used the Morgenstern Price method to determine factor of safety for the slope with a load imposed. The results indicate slope failure could result for less than 10 m of sediment if only the upper slope is loaded, such as in a rapid accumulation scenario.

9.0 RECOMMENDATIONS

The GSCA curates a variety of geotechnical data types for the Beaufort Sea, consisting of a mix of Government and Industry reports. The majority of data has been gathered from the continental shelf and was recovered in the 1980s related to oil and gas development activity. This study has revealed that limited geotechnical data exist for the Beaufort outer shelf and upper slope. The existing data in the deeper water are largely limited to shallow sediments. The quality of the geotechnical model of the Beaufort Sea and the slope will be improved as more sample sites are explored offshore.

The scarcity of sample sites requires substantial extrapolation to develop a generic geotechnical model. The model discussed uses 3 cross sections but the variance in the 3 has minimal effects on slope stability. As such, a generic slope stability model has limited purpose. Site specific geotechnical models may be more beneficial in identifying risk.

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