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MASTER THESIS

Seismic Facies und Structure Interpretation from 2D Profiles in the Vicinity of Herschel Island, Yukon, Canada

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Abstract

Herschel Island (Qiqiktaruk in Inuvialuktun) in the southern Canadian Beaufort Sea was formed as an ice push moraine by the advance of the Laurentide Ice Sheet during the Last Glacial Maximum in the late Wisconsinan. In the vicinity of the island the Herschel Basin was formed contemporarily by that process. Nevertheless we are still lacking evidence for the basin generation and its evolution after creation and the ice sheet retreat. To gain new information about the depositional history and the conditions during and after generation of the basin, I studied seismic two-dimensional profiles from parametric echosounding that were recorded in the basin during expeditions in 2006 and 2013. A big part of the work of this thesis was constituted of the processing and enhancement of these profiles using the programs OpendTect and SeiSee to guarantee high quality datasets. The interpretation of those data together with older geohphysical and borehole logs improved our knowledge of the basin history. The structures and facies that were discovered by this analysis were formed in different states of the basin evolution and provide sufficient new data to reconstruct its generation and development as a depositional centre afterwards. The interpretation supports the hypothesis that the basin was formed as the Laurentide Ice Sheet advanced to its maximum extent, was exposed to the atmosphere after its retreat and became part of the Beaufort Sea after flooding subsequently. Additionally to its interpretation, the echosounding data was used to enhance the existing bathymetric data for the basin as the former maps were not convenient enough for future tasks.

Zusammenfassung

Herschel Island (Qiqiktaruk auf Inuvialuktun) in der kanadische Beaufortsee wurde als Eisrandlage durch das Ausdehnen des Laurentidischen Eisschilds während des Letzeiszeitlichen Maximums im späten Wisconsinan aufgebaut. In unmittelbarer Nähe der Insel entstand simultan das Herschelbecken durch diesen Prozess. Uns fehlen jedoch immer noch Beweise für die Beckenentstehung und seine Entwicklung nach dem Rückzug des Eisschildes. Um neue Informationen über die Ablagerungsgeschichte und die Bedingungen während und nach der Entstehung des Beckens zu gewinnen, habe ich zweidimensionale seismische Profile analysiert, die mit einem parametrischen Echolot während zweier Expeditionen in den Jahren 2006 und 2013 aufgenommen wurden. Ein großer Teil der Arbeit dieser Studie bestand im Prozessieren und Verbessern der Profile mit den Programmen OpendTect und SeiSee, um hochqualitative Datensätze zu garantieren. Die Interpretation dieser Daten zusammen mit älteren geophysikalischen und Bohrlochdaten verbesserte unser Wissen der Geschichte des Beckens. Die durch die Analyse entdeckten Strukturen und Fazien sind während verschiedener Stadien der Beckenentwicklung entstanden und liefern so genügend neue Daten, um die Entstehung des Beckens und seine Fortentwicklung hin zum Depositionszentrum zu rekonstruieren. Die Interpretation unterstützt die Hypothese das Becken sei entstanden als der Laurentidische Eisschild auf seine maximale Ausdehnung anwuchs, nach dessen Rückzug mit der Atmosphäre in Kontakt stand, anschließend geflutet und so Teil der Beaufortsee wurde. Zusätzlich zu ihrer Interpretation wurden die Echolot-Daten genutzt, um die vorhandenen Tiefenkarten aufzuwerten, da diese eine nicht ausreichend gute Qualität für zukünftige Herausforderungen aufwiesen.

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First of all I want to thank my supervisor Prof. Dr. Hugues Lantuit, leader of the COPER group at the AWI Potsdam. His door was always open for me and I could rely on him giving me advice on writing whenever needed though still leaving this to be my thesis. A big thank you goes to Boris Radosavljevic, my second supervisor. Not only was he responsible for collecting the data which already makes him great part of this thesis. But he always encouraged me to go my way in processing and analyzing the data giving me total freedom to explore all options and thus learn a great deal of new skills, from data management all the way to the most unnecessary filter applications.

Thanks to the people that discussed my thesis proceedings and the results with me giving me feedback and encouraging me. Namely Paul Overduin, Dustin Whalen, Georg Schwamborn, Guido Grosse.

I want to further thank my other colleagues of the COPER Junior Research Group. Samuel, George, Anna, Steffi, Caro, Justine, Juliane, Micha... you made our office a great place to work and chat on science and the world outside. I really enjoyed talking to you whenever I could, be it standing in the sun with a coffee in your hand or eating little treats during our legendary meetings. You know you are more than just colleagues to me and I wish you all the best for your future.

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A huge acknowledgement has to go to Annabell. She was the reason I kept going on even during night times or crazy early mornings. Still she made sure that I would eat, sleep and see sunshine from time to time especially in the last period of this work. Without your support this would not have been possible.

Contents

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List of Abbreviations

AWI	**A**lfred **W**egener **I**nstitute for Polar and Marine Research
CCS	**C**anadian **C**ontinental **S**helf
DIAND	**D**epartment of **I**ndian **A**ffairs and **N**orthern **D**evelopment
GSC	**G**eological **S**urvey of **C**anada
LGM	**L**ast **G**lacial **M**aximum
LIS	**L**aurentide **I**ce **S**heet
PLF	**P**ingo-**L**ike **F**eatures
YCS	**Y**ukon **C**oastal **S**helf

List of Symbols

Symbol	Name	SI Unit
f	Frequency	s^{-1}
Q	Quality Factor	
v	Velocity/Speed	$\mathrm{m\,s}^{-1}$
α	Absorption Coefficient	m^{-1}
κ	Bulk Modulus	$\mathrm{N\,m}^{-2}$
λ	Wavelength	m
ρ	Density	$\mathrm{kg\,m}^{-3}$

Dedicated to mrówka. . .

1 Introduction

1.1 Background

The Arctic Regions have come to the centre of public attention more and more in recent years due to climate change and its severe implications specifically for this region (IPCC, 2013). The carbon stored in these regions in permafrost is of particular interest as thawing of this permafrost and the release of carbon might lead to a positive feedback mechanism for climate change (Grosse et al., 2016). But although this region is a major research focus and many studies are done there, large uncertainties remain about a lot of processes that are going on or took place in the past. Plenty of studies have been focussing on terrestrial elements and processes like thermokarst landscapes (Grosse, Jones, and Arp, 2013), coastal erosion (Lantuit and Pollard, 2008) and terrestrial permafrost (Vonk and Gustafsson, 2013). To date these terrestrial components are rather well studied and still subject to many publications. In contrast there still exist large uncertainties about past and present processes occurring in the Arctic Ocean. The major focuses of most studies about the Arctic Ocean are its tectonic evolution (Jokat, Ickrath, and O'Connor, 2013) and the timing and extent (Figure 1.1) of the glacial-interglacial cycles (Hughes, Gibbard, and Ehlers, 2013; Jakobsson et al., 2014).

We have a rather small knowledge about the subsurface of the Arctic Ocean compared to other regions. That is partly because of the regional settings of course as it remains challenging to conduct surveys in such an extreme environment. Most geophysical studies on the subsurface were done by private companies mainly interested in oil and gas reservoirs that are believed to be present in large parts of the Arctic. That means most of those data are either not accessible to the public or contain very little information on subsurface parameters possibly being useful for others than the companies themselves. Due to the lack of data for most of the area, seismic surveys were carried out in the Herschel Basin in the Yukon Territories, Northwest Canada by the Geological Survey of Canada (GSC) in 2006 and the Alfred Wegener Institute for Polar and Marine Research (AWI) in 2013. These surveys aimed at gathering geological information on the subsurface structures and lithologies present in that basin. Parametric Echosounders were used to record the data. Its principles will be explained later on in chapter **??**. The idea was to study the depositional environment there by identifying characteristic elements (Radosavljevic et al., 2013) that define the subsurface of the basin underneath the water column.

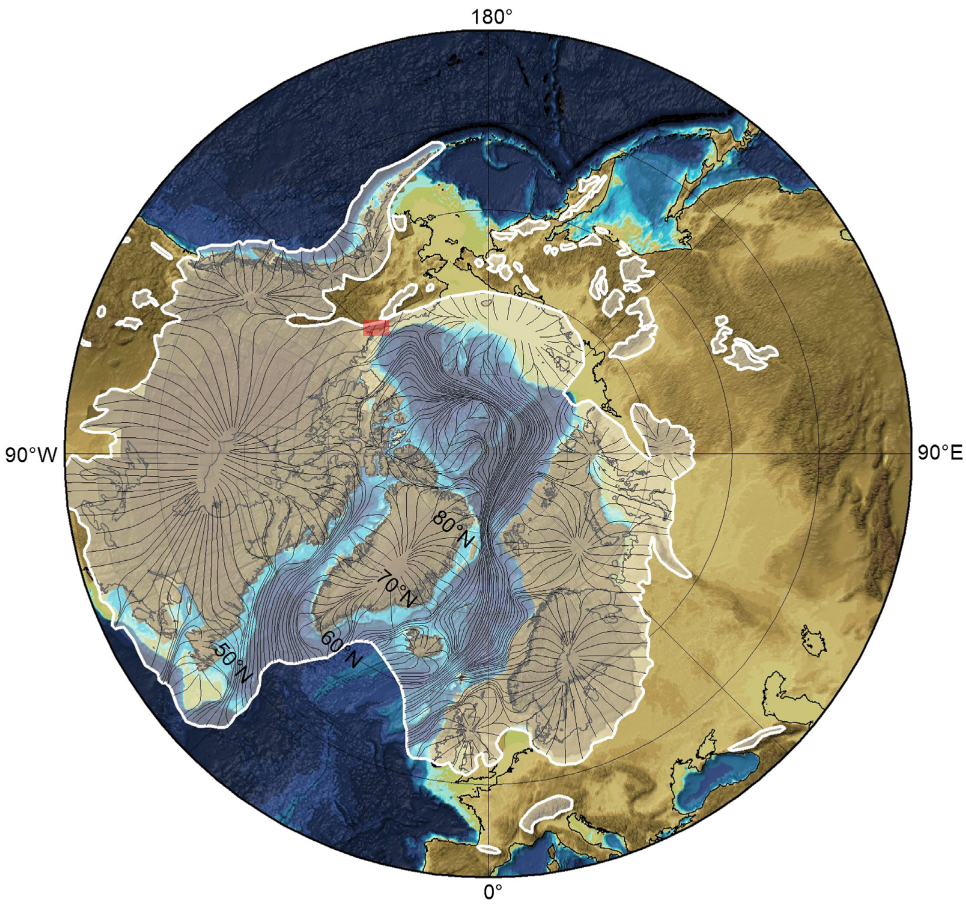


FIGURE 1.1: The maximum extent of the Arctic ice sheet during the LGM in the late Winsconsinan including glaciation of all Arctic continental shelves after Hughes, Denton, and Grosswald, 1977; Jakobsson et al., 2014. The small red square marks the area of the Yukon Continental Shelf at the margin of the ice sheet.

1.2 Study Objectives

the Herschel Basin is believed to be created by the advance of the Laurentide ice Sheet (LIS) during the late Wisconsian (Mackay, 1959). During its advance the ice sheet supposedly carved out the basin pushing the loose material to its front margin forming Herschel Island as an ice push moraine (Fritz et al., 2012; Rampton, 1982). This study aims to use the data from the two seismic surveys to test the hypothesis by answering the following questions:

- What seismic structures and lithologies can be found in the basin?
- When and under what conditions did these structures form with respect to the basin generation?
- How did the basin evolve over time?
- How well can parametric echosounding be used for this kind of study and what information can be gathered from the data record?

Answering these questions and getting a better image of the seafloor and its subsurface will result in an improved knowledge about the basin evolution. This example leads to a better understanding of not only basin formation in Polar Regions but also the processes that go along with the advance and retreat cycles of ice sheets or glaciers in the past and possibly also for the future.

Older data are available for the area with information on subsurface parameters as well. Unfortunately those datasets were not sufficient enough to answer these questions. Hence these new surveys were conducted to gather more adequate data. The aims of those older studies were always focused on resources and answering very specific questions regarding those. There have been studies looking for prospective oil and gas reservoirs (Morrell et al., 1995) though those data were not available for this study. But we had access to reports compiled in the 1970s and 1980s when the Department of Indian Affairs and Northern Development (DIAND) Canada requested investigations to locate prospective areas for offshore sand and gravel resources (M.J. O'Connor & Associates Ltd., 1985) in the

Beaufort Sea. These resources were to be used to build infrastructure in the area to accommodate its possible future importance as a transport route as climate change gives way for new paths across the Arctic Ocean. This report had a specific goal and hence the data were only interpreted for that particular purpose making it harder to gather additional information from it. Nevertheless the report together with more of the same subject (EBA Engineering Consultans Ltd., 1984, 1993; Kaiser, 1994; MacLeod, 1993; McElhanney Geosurveys Ltd., 1988; O'Connor, 1983) as well as borehole logs (EBA Engineering Consultans Ltd., 1988b) were used in this study as supplemental information sources on interpreting the geophysical data of the region.

2 Study Area

2.1 Regional Setting

The Herschel Basin is a sedimentary basin in the Yukon Territories in Northwest Canada and is part of the Beaufort Sea. It is located close to the Canadian-Alaskan border on the Canadian Continental Shelf (CCS) between Herschel Island in the northwest and Philips Bay in the southeast. Its margins are confined by the Yukon Coast in the southwest and the Herschel Sill stretching from Collinson Head to Kay Point in the northeast that separates it from the Mackenzie Trough. The geographic location "Herschel Basin" also includes parts of the Yukon Coastal Shelf (YCS), called Thetis Bay in this specific area, in the north and west and the Babbage River Paleochannel in the south. The basin itself measures about 20km in length from northwest to southeast and 8km in width (Figure 2.1). Its depth ranges from 14m to 70m below sea level. The YCS around it has a comparably gentler slope until it reaches 14m of depth. The profiles for this study are located in the basin itself and on the YCS close to Herschel Island. Though for simplicity the whole study area will be referred to as Herschel Basin. The bathymetry of the Canadian continental shelf has a generally gentle slope stretching from the coast to the shelf break at around 800m below present sea level. The Herschel Basin is a major exception in this environment providing much steeper slopes. It is isolated by the Herschel Sill from another irregular feature, the Mackenzie Trough. This is a 150km long depression extending in a north-northwest direction from the Mackenzie Delta to the open ocean. This rather deep trough is a major factor in making the area a highly dynamic environment (Batchelor, Dowdeswell, and Pietras, 2013).

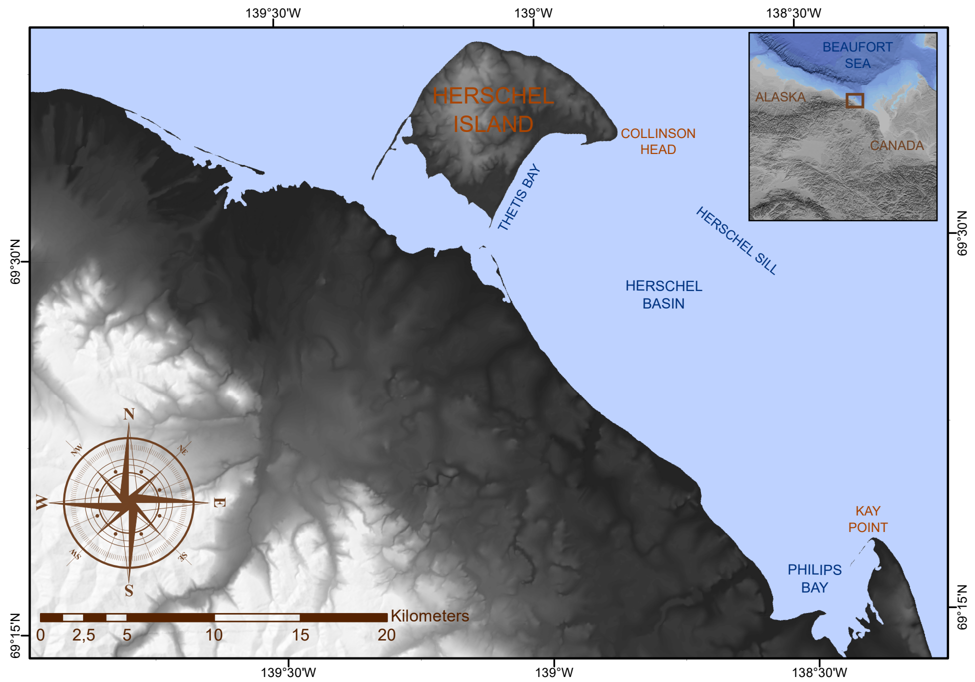


FIGURE 2.1: The Herschel Basin is located between Herschel Island and Philips Bay in NW Canada in the Beaufort Sea. The overview map shows its location in the Canadian Beaufort Sea close to the Alaskan border.

2.2 Herschel Basin

The whole basin is surrounded by coastal areas consisting of hummocky and ridged moraines (Geological Survey of Canada, 1981). Its consistency over the coastal area is clearly seen in the geological map in figure 2.2). The moraines contain preglacial, glacial and postglacial deposits after Bouchard, 1974. The upper stratigraphy of the basin is thought to be mainly marine sediments though this study aims to provide further knowledge about that. There are not too many studies giving a complete image of how the basin was formed but the following hypothesis will be subject of the thesis. The basin was supposedly created by the advance of the LIS during the late Wisconsian (Radosavljevic et al., 2016) from the southeast. After the Last Glacial Maximum (LGS) the ice sheet retreated exposing the basin to the atmosphere for the first time. During that time lacustrine sediments must have been deposited in the basin as it represented a terrestrial lake environment. Through exposure to the air, terrestrial permafrost formed in the subsurface of the basin. The still present Herschel Sill prevented the basin to be joined to the Beaufort Sea. The Sill today has only about 12m of maximum water depth and hence shielded the basin from being flooded even after the retreat of the ice sheet. The relative sea-level curve of the Beaufort Sea showed a total rise of 140m since 27ka BP (Hill et al., 1985) meaning the basin got flooded at some point during that time bringing marine sediments into it. Though about 20ka BP and 10ka BP the sea-level dropped to a minimum of 70m below present day's level (O'Connor, 1984) marking two points of possible drainage events of the basin. Lacustrine sediments must have been deposited in the basin again dating back to those events giving alternations of lacustrine and marine successions in the subsurface. Since then the basin was supposedly never drained again leaving thick layers of marine sediments as the uppermost stratigraphy on the ground to date.

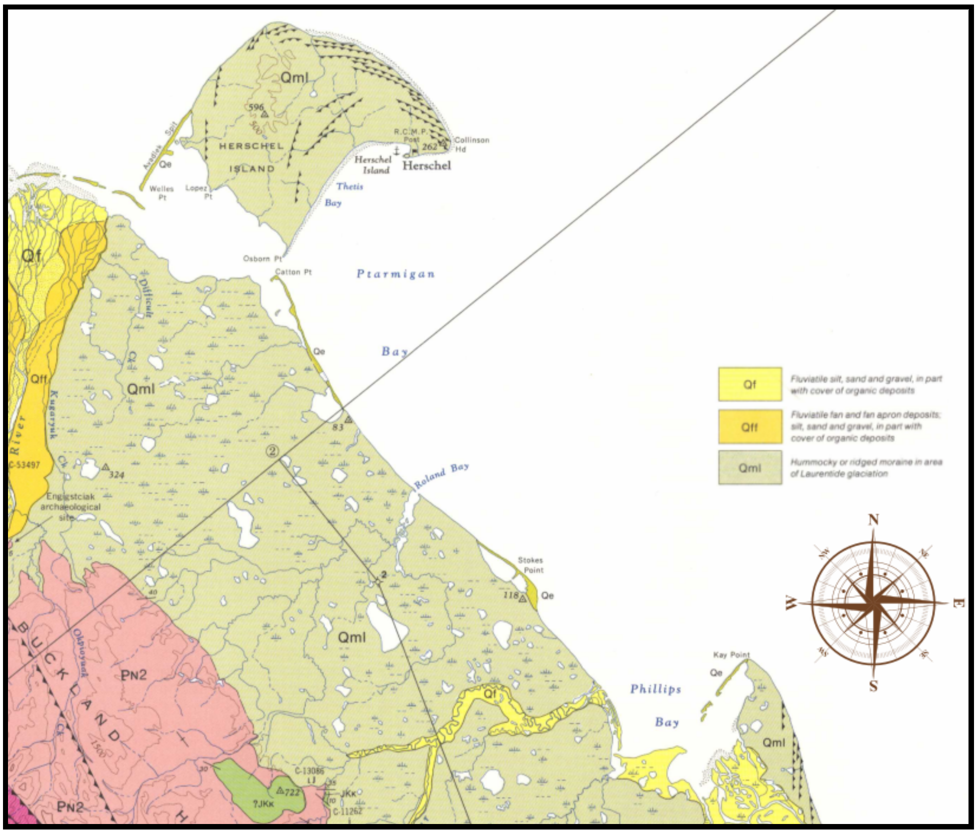


FIGURE 2.2: The coastal area around the Herschel Basin consists of hummocky and ridged moraines (Qml). Only at the coast at Philips Bay Fluviatile Silt (Qf) is in direct contact with the basin delivering those sediments into the basin. This map was modified after Geological Survey of Canada, 1981.

3 Methodology

3.1 Data Overview

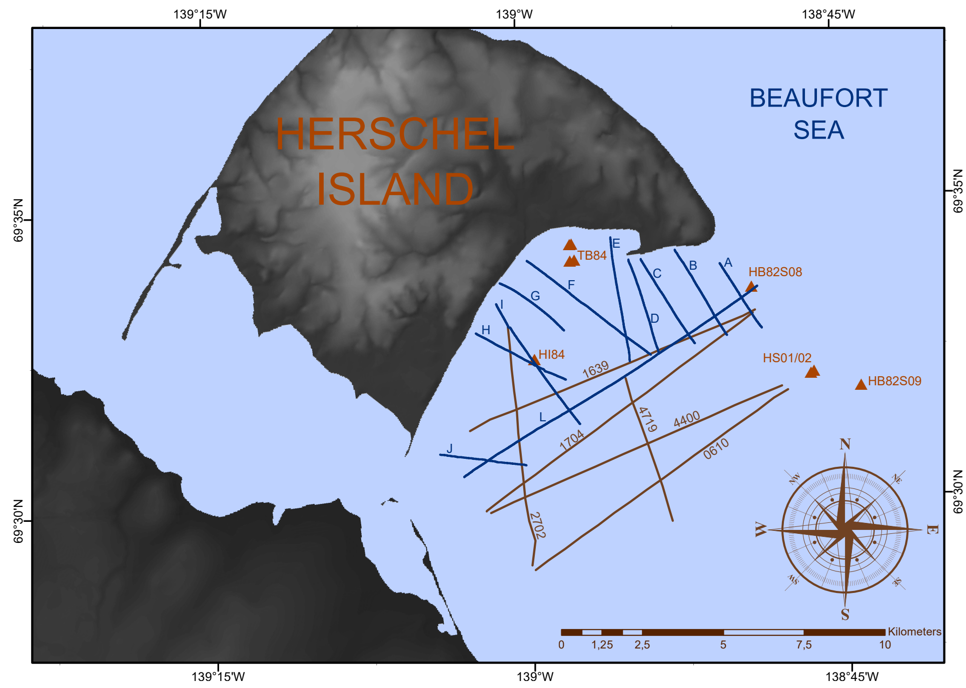


FIGURE 3.1: This overview shows the spatial distribution and notations of the data that were used in this study. The lines represent the echosounding profiles, the brown ones were recorded by the GSC in 2006, the blue ones by the AWI in 2013. Additionally the locations of the boreholes whose logs were used in the study are shown by light brown triangles. The were recorded by the EBA Engineering Consultant Ltd. in the 1980s.

Various types of data were used for this study. Bathymetry data was already available for the Herschel Basin and the Beaufort Sea. It was used to get a general understanding of the structures and the setup of the basin and its oceanic surroundings and was supposed to be enhanced by this study. The seismic data that was used consisted of a total of 17 two-dimensional profiles in the basin with a total length of about 95km. Six of these profiles with a total length of 51km were recorded during an expedition by the (GSC) in 2006. The other eleven profiles in the basin with a total length of 44km were part of a record by the AWI expedition of 2013, when a total of 78km in seismic profiles were obtained and are shown in figure 3.1. Additionally old non-digital paper profiles (M.J. O'Connor & Associates Ltd., 1985) were used as a supplementary information source. Log data from boreholes that were drilled the 1970s and 1980s for a granular resource study in the area (EBA Engineering Consultans Ltd., 1988b) provided additional knowledge about stratigraphic evolution in the area.

3.2 Bathymetric Maps

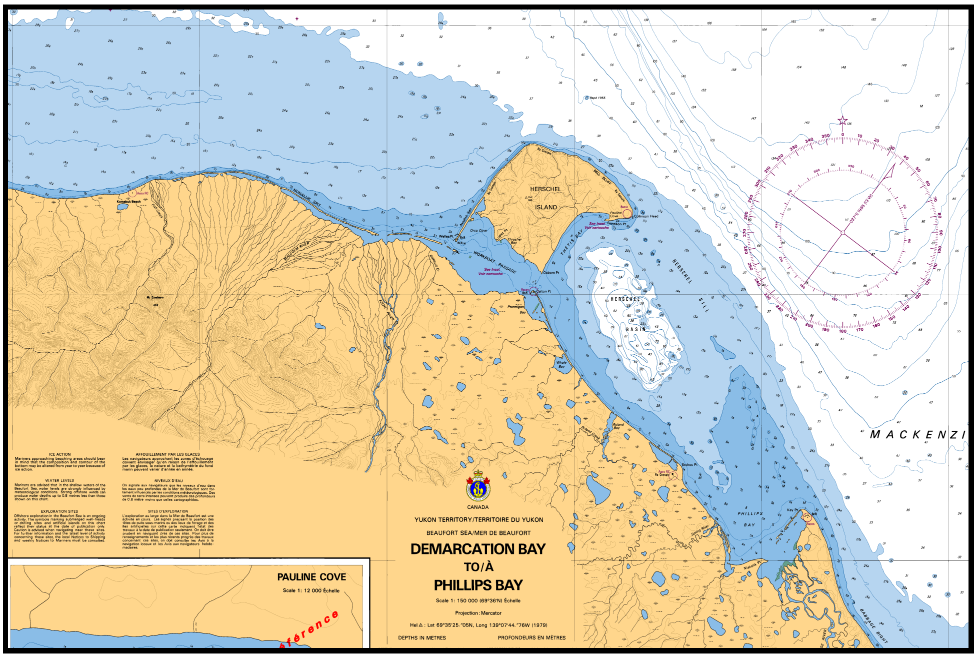


FIGURE 3.2: This old map of the bathymetry of the Beaufort Sea between Demarcation Point to the west and Philips Bay to the east was one of supplementary datasets used in this study. It is an example for the data quality of some data of the area.

The bathymetry data used in this study was composed of contour maps of different extent and resolution. The data for these maps came from different sources. The Canadian Hydrographic Service together with the National Oceanic and Atmospheric Administration and Natural Resources Canada provide bathymetry maps for navigation in the area. The data I was using in this study contained changes made over time mainly by Steve Solomon of the Geological Survey of Canada and his team as well as scientists of the Alfred Wegener Institute. Most of the data is based on point measurements although some data were also recorded using multibeam sonars operated from the AWI vessel "Christine" in the area. To use the data in a convenient way, the shapefiles containing the isolines were converted to rasters to be utilized as 3D horizons later when working together with the seismic data in a three-dimensional environment. The data had to be converted from a depth value in meters to a time unit as OpendTect is using seconds [s] and milliseconds [ms] as measurement for depth due to the specifications of most seismic data. The seismic velocity $c = 1500 \mathrm{m\,s^{-1}}$ was used as the conversion factor for this operation (Christensen and Carmichael, 1982).

3.3 Sub Bottom Profiling

FIGURE 3.3: The Parametric Echosounder Innomar SES-2000 mounted onto the AWI vessel "Christine" that was used to record the profiles in the Herschel Basin in 2013 (Photo by M. Fritz).

The seismic profiles were recorded by parametric echosounding. The device used for it was the Innomar SES-2000 (Innomar Technologie GmbH, 2009) mounted onto an inflatable Zodiac as shown in Figure 3.3. It sends out an acoustic signal towards the bottom. That signal creates a soundwave travelling through the water column with a certain speed. This speed is usually called sound velocity c, although the term velocity is not quite correct in this case as the sound does not have a directional vector which would define it as a velocity, it is rather speed. That sound speed highly depends on the properties of the water. The temperature is the most important factor influencing it. But also the salinity plays a role as well as the pressure which is proportional to the depth in a regular environment. The surface of the seafloor reflects the sound signal and it travels back towards the device where the two-way-traveltime is recorded at any location. The device also measures amplitudes and signal strength of the reflected signals. Yet not only the seafloor reflects the signal, it can also penetrate the subsurface underneath it (Kearey, Brooks, and Hill, 2013). Depending on the frequency f and hence the wavelength λ, it can penetrate different depths of the subsurface. The signal gets attenuated as it travels along its path, mainly by geometrical spreading and absorption. That occurs far more in the subsurface than in the water column itself. Higher frequencies get attenuated more than lower ones. The relation is given by the Quality factor Q of a certain material (Dentith and Mudge, 2014) with α being the absorption coefficient and λ the particular wavelength.

$$Q = \frac{\pi}{\alpha\lambda} \tag{3.1}$$

The acoustic wave propagates through bodies deforming them temporarily by exposing it to a strain. The speed v with which this wave travels through a body is defined by its density ρ and its elastic modulus, in this case the axial modulus Ψ (Dentith and Mudge, 2014).

$$v = \sqrt{\frac{\Psi}{\rho}} \tag{3.2}$$

This speed can be dissimilar in different directions in rocks, especially in laminated or sedimentary rocks where the wave travels faster along the lamination or layering than across it. This phenomenon is called seismic anisotropy, but can be neglected in large part in this study as the waves that are emitted and recorded travel mostly vertically up- and downwards between the device mounted on a boat at the sea surface and the seafloor or subsurface horizons respectively.

The used device was specifically designed for shallow surveys up to a water depth of 400m and a sediment penetration of up to 40m depending on the type of sediment and the noise present in its environment. Two different frequency bands are used to penetrate different depths, the primary band ranges from $f = 85\mathrm{s}^{-1}$ to $f = 115\mathrm{s}^{-1}$ and the secondary (low frequency) band from $f = 2\mathrm{s}^{-1}$ to $f = 22\mathrm{s}^{-1}$. The pulse width can be chosen by the user and was differed during the study between $0.07\mathrm{ms}$ and $0.1\mathrm{ms}$ with a ping rate of $50 pings/s$. With these specifications the devise can resolve layers with a thickness of $5\mathrm{cm}$ although this can also vary with sediment type and noise level.

3.3.1 Data Processing

The data were recorded using the program SESWIN and exported from there to be used in the ISE Post-Processing Software. Both programs are made and maintained by Innomar to complement the used device(Innomar Technologie GmbH, 2011). Within the ISE Post-Processing Software the data could be viewed and the first step of processing was done removing the water column from the data. In a lot of cases these devices are used to also track bubbles or fish in the water column but for this study that was not needed as the sole aim was the subsurface information. That made it easy to remove the water column to see the clear image of the subsurface sediments. Further the gain was normalized which made the data more practical to work with. The profiles were then exported as SEG-Y files with trace headers. That way the profiles can be used in a big variety of programs and the header of SEG-Y files makes sure that all the seismic information of the data itself but also the metadata on recording settings are stored together within one file.

All profiles were handled within OpendTect 6.0 (Groot and Bril, 2005) by dGB Earth Sciences and SeiSee 2.22.5 by Dalmorneftegeophysica, both open source software. The aim was to set up a project in OpendTect containing the entire seismic data that were recorded so far in the area and that might be of use for this study. It is a seismic interpretation software that allows for processing, visualization and interpretation of seismic data of any kind in two and three dimensions. SeiSee in contrast is a program designed for mainly the visualization of two-dimensional seismic data of different formats. Consequently it has a lot of options to add band pass filters and an automatic gain control to enhance the visual display of the profiles. In this study it was mainly used to manipulate header information and export data with such specifications that allow it to be used in OpendTect. The ability to edit the text header is the strongest feature of the program and was essential for this study. It was also used to manually add missing metadata to the profiles which was mainly the case for the GSC profiles. Those were produced using different gains and settings while recording, unfortunately without specifying the changes in survey setup. That led to inconsistent profiles containing jumps and breaks within the recordings. As the metadata were missing, they had to be added retrospectively and via visual confirmation regarding the profile images.

OpendTect requires seismic data and their respective headers to have a specific formatting. It uses the UTM coordinate system and the recorded data had to be converted from geographical coordinates. That was done by editing the header data using R (R Core Team, 2015). The header bytes of SEG-Y files are integer fields meaning they cannot store decimal numbers. Hence to store coordinates a field called "coordinate scaling" is required to guarantee a high resolution and no information loss. That way the coordinates can be divided by the scalar number in order to come up with decimal coordinates when importing the data. That field has to be fitted to the edited coordinates in order for the profile to be displayed properly and in its true position. Furthermore OpendTect is not able to recognize the so-called "delay header". That is a field in the SEG-Y header describing how the gain was changed while recording a profile. Programs such as SeiSee recognize this header byte and display the profile in the correct way. Though without this value, the profile will end up containing jumps and edges. For those profiles to be displayed properly in OpendTect, the workaround is a divided import of every single segment that has a different delay while manually adding that delay during import of the segment. That way you end up having to import a lot more files but they will be displayed properly which is the main purpose in this case. Afterwards these segments can be merged using the program and one of its big advantages is the possibility to export these newly merged profiles in a format that not only suits OpendTect but can also be adapted to any style needed, e.g SEG-Y or ASCII. As the GSC profiles were missing the delay header completely, the jumps in those profiles were avoided by the same import procedure as for the other profiles. The only difference was a visual determination of the delay times at the breaks between the segments.

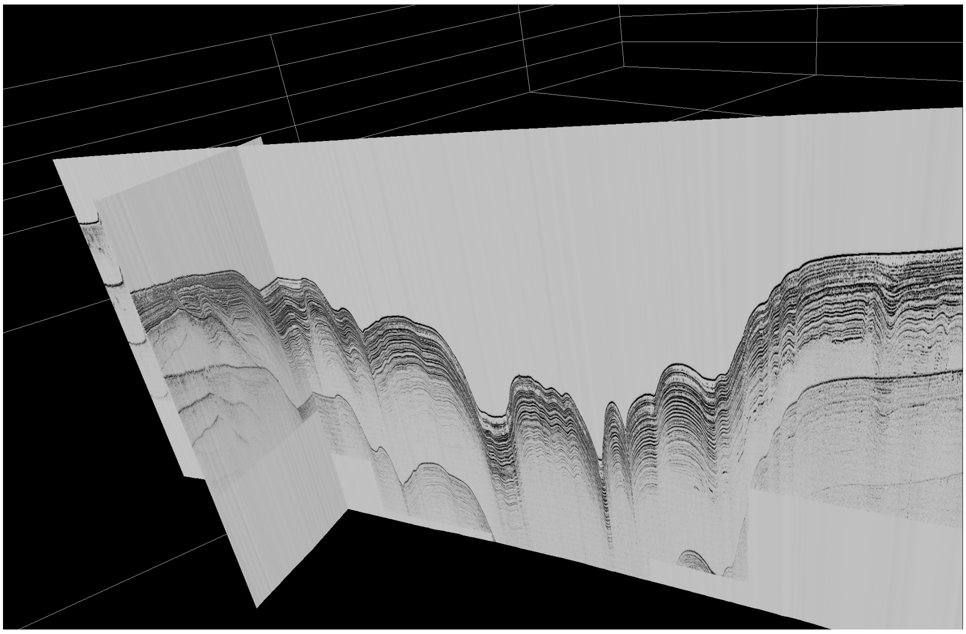


FIGURE 3.4: After the profiles were processed, segments aligned and filters applied, OpendTect made it possible to view the two-dimensional data in a three-dimensional environment. That made interpretation easier as the spatial distribution of features could be easily imagined. In this screenshot the profiles C and L are cross-cutting. The seafloor and other horizons as well as features at the crossing can easily be tracked over both profiles.

That led to aligned profiles but could not solve the issue of a true arrival time as there was no way to tell which arrival time represented the zero-offset value to which the delay time had to be added. After the data have been fitted to match the requirements of OpendTect in the described way, all profiles were imported into a project displaying them altogether in the 3D environment. Before analyzing the profiles, they were manually enhanced to gain the maximum amount of information from them. That was done using preset filters of OpendTect. Mainly frequency filters were used to get better contrasts in the profiles. This enhancement was done visually to create the best possible output for the interpretation of the profiles. It differed from profile to profile evaluating every segments separately.

3.3.2 Data Analysis

For the analysis of the data the graphical interface of OpendTect was used. At that point the program's project contained the two-dimensional seismic profiles visually enhanced by applied filters, the bathymetry of the area as a three-dimensional horizon and the borehole locations with horizon descriptions from their respective logs attached to it. For the interpretation of the seismics, the two-dimensional images of the profiles were used to determine features within every profile. The three-dimensional interface was used whenever there were structures or horizons visible in more than one profile or in the best case in profiles cross-cutting each other as already shown in figure 3.1. Furthermore a visual comparison of the already given bathymetry data and the water depths that were gained from the seismic profiles could be done this way. But for a more enhanced analysis of the seafloor, a specific feature of the software was used. The program allows for manual and automated horizon tracking. Given that, the user can pick a horizon that is clearly visible in one of the profiles. By setting seeds the horizon is identified as such an can be assigned to a distinct corresponding horizon of another profile. The automated tracking tool uses these seeds and follows the horizon along the profile based on its amplitude changes. The user provides a threshold for the divergence from the marked values for the selected horizon and the program creates a 2D horizon from that. In a 3D seismic environment, the tool would track the horizon even over the complete volume. In this study the seafloor was easy to track as it is the first clearly visible horizon in any profile and the automated tracking tool worked very well in interpolating the seafloor horizons across each profile. Afterwards all seafloor profiles were merged to belong to one 3D horizon.

These horizons can then be used to be compared to the 3D bathymetry in the program itself. The export tool also allows for them to converted to different data text formats to be used in programs such as ArcGIS which was done in the study. In ArcGIS the profile lines containing basically only the easting, northing and water depth at each given point along it were used together with the already available bathymetry data. These points and the existing isolines were interpolated to create new 3D horizons of the seafloor of the basin in the area. One drawback of this was the difference in spatial resolution. Along the profiles there is a very high resolution of depth values and the rest of the area is only covered by a more sparse resolution containing isolines based on very few measurements compared to that.

4 Results

4.1 Seafloor Mapping

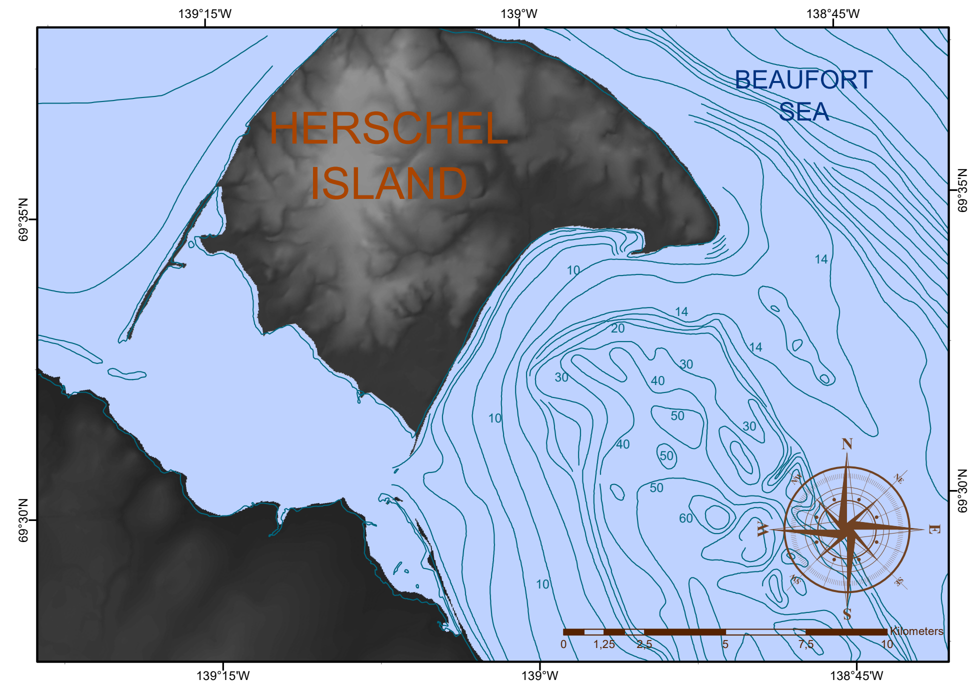


FIGURE 4.1: The Bathymetry map of Basin was updated using depth values from the echosounding profiles. Changes occurred mostly in the area close to Herschel Island where the profiles were located. Smaller structures can be seen in the map now.

Based on the seismic reflection profiles, the seafloor could be derived and horizons were extracted from that. Those profiles were used to enhance the already existing bathymetry for the area that was based mainly on point measurements. The comparison of both the old and new bathymetry data shows a generally concurring image. The big structures were well in accordance. What set the bathymetry won from seismics apart were small structure within the bigger image that were previously hidden due to the lack of resolution. In figure 4.2 that is evidently visible by comparing the echosounding profile and its corresponding seafloor to the horizon of the older bathymetry data cutting the profile. The small components of the seafloor could not be detected by the old bathymetry data but the echosounding profiles are able to resolve those. This is a tremendous improvement for bathymetric maps of the basin. Besides the water depths from the seismic data itself, the point measurements of water depth at the locations of boreholes was used to not only verify depths from the seismic profiles whenever they were located on or in the vicinity of such a profile but were also included in the regenerated bathymetry data that is now available and visible in figure 4.1.

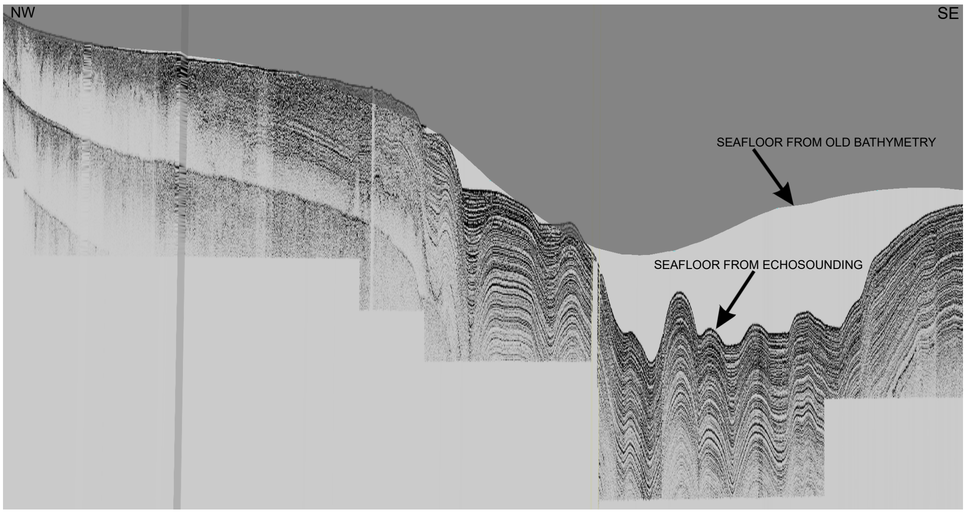


FIGURE 4.2: Profile I is one of the echosounding profiles. Here it is shown compared to the old bathymetry. The bottom line of the dark grey area marks the seafloor extracted from the old bathymetry data. The top black line of the seismic data is the seafloor derived from the profile. The difference is mainly visible where small structures are crowding the seafloor. The overall trend of the bathymetry profiles is basically the same.

4.2 Data Assessment

The reflection profiles are of disparate quality. The 2013 profiles recorded by the AWI have a good signal-to-noise ratio and almost no jumps or breaks. The upper structures as well as the uppermost horizon marking the seafloor are clearly visible. On the contrary the 2006 GSC profiles are very hard to get a hand on as essential metadata were missing from the recordings such as delay times or the used pulse width. That resulted in data containing jumps and being

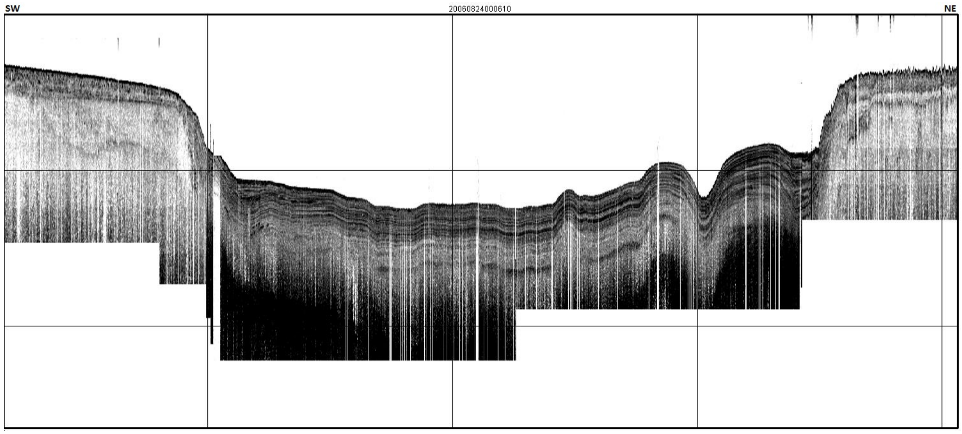


FIGURE 4.3: The echosounding profile 0610 recorded by the GSC is a clear example of poor data quality. The lack of metadata made it hard to process this profile. The jumps could be fixed visually by aligning the profile segments but the subsurface information is evidently lacking quality. Note that there is no scale attached as missing delay times did not allow a determination of the segment representing the zero-offset value.

of only moderate quality regarding the noise level. Furthermore any information about the depth and two-way-travel time of the signals was missing as it was impossible to state which part of a profile represented the original zero-offset segment even after combining the segments to form uniform profiles cleared of such jumps (Figure 4.3). Hence those profiles were mainly used for a qualitative analysis approach trying to identify the structures that can be seen while being attentive about their distinct locations and extents.

4.3 Subsurface Structures

The analysis of the 2D profiles leads to the identification of structures that are characteristic for this basin. Plenty of profiles were recorded in the near shore zone, especially towards Herschel Island in the northwest. These profiles show a similar general shape deepening from the coastline towards the basin centre in a convex shape of the seafloor that is visible in figure 4.5. That shape terminates at a certain depth of about 12m where the seafloor structure gets more irregular. Throughout the study area the profiles show thick layered structures especially in the upper parts. Despite having multiples in almost every profile, some of them show a clear transition horizon

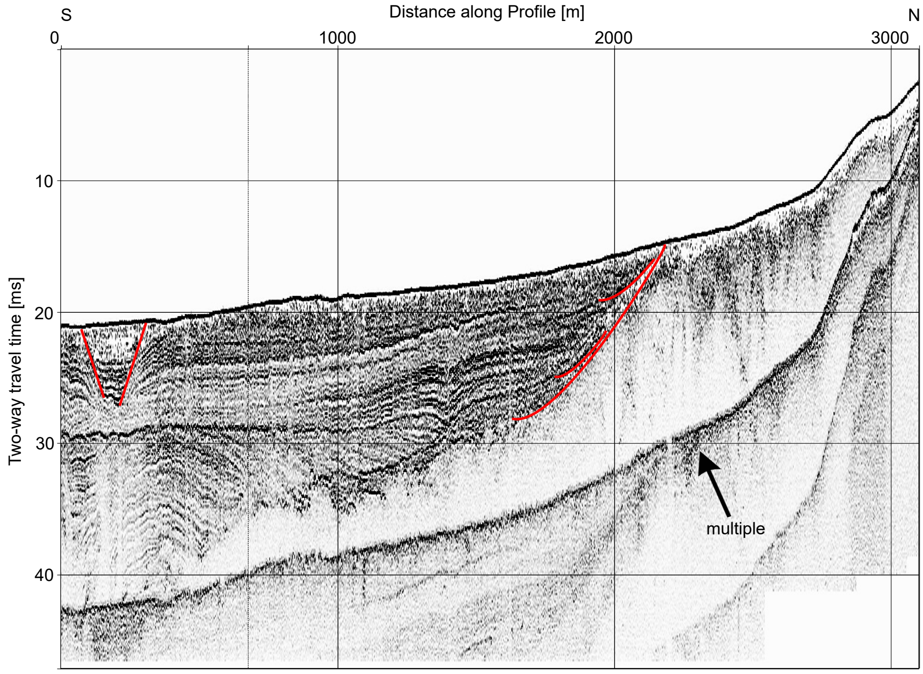


FIGURE 4.4: Echosounding Profile B. The onlaps (red) that can be seen everywhere close to the shoreline with a principle direction towards the coastline are clearly visible in this profile. Some of these onlaps dip towards each other forming a v-shaped area of lamination in between.

between laminated structures on top and non-laminated layer underneath. The most clear of these horizons can be seen in the profile B (Figure 4.4) In most cases this transition is not that clear and more of a fading effect towards the bottom making it impossible to actually locate those horizons of an imaginable stratigraphic alternation.

Onlaps are distributed in several profiles with a principal dipping direction towards the coastline though sometimes showing varying orientations seen in figure 4.4. Some of these onlaps are oriented towards each other confining distinct v- shaped areas with laminated structures in between them that have to be regarded separately as the lamination in between those onlaps can be clearly distinguished from the ones surrounding them. Thus they have to be of different origin or timing providing a reason for the onlaps. In some areas close to the coastline structures are visible that form mounds on the seafloor (Figure 4.6). These very distinct features have a characteristic set-up that is unique to them in this area. Apart from the formed mound on the surface they show no lamination underneath it, hence

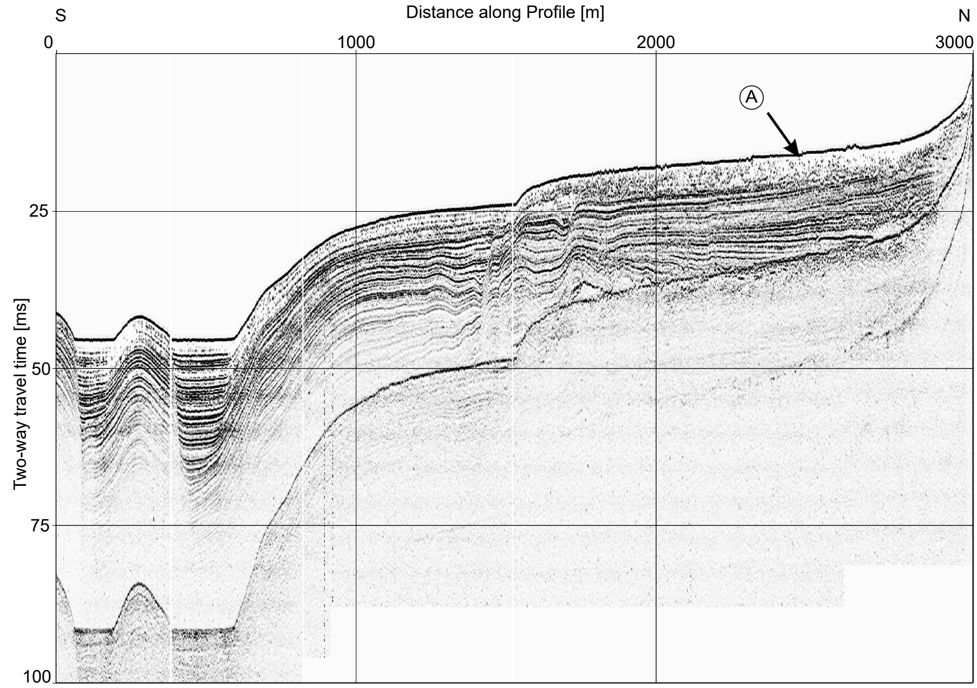


FIGURE 4.5: Echosounding Profile D. This profile was recorded close to the coast of Herschel Island and shows the general convex shape of the profiles in this area as well as an area on non-lamination close to the shore (A).

evidently differing from the rest of the area and being very local features.

Towards the deeper parts of the basin, the picture tends to get dominated more by small-scale features in opposition to the big dominating convex shape of the more near-shore profiles as seen in figure 4.6. It clearly marks a change in possibly history but definitely conditions right now. Here successions of mounds and troughs dominate the seafloor leading to the deepest parts of the basin. Some of the mounds are very pronounced as distinct features that can be localized clearly. Even in these parts the lamination of the subsurface is obvious, extending over the whole area. Nevertheless even in these profiles showing the uppermost thick layers containing laminations, no distinct horizon could be picked that would represent a change in lamination and thus stratigraphy or density contrast. There are only some rather small areas very close to the shore of Hershel Island and in the north of the basin on the Herschel Sill where this lamination seems to be disappearing or missing in the uppermost part (Figure 4.5). The conditions of these area, though very local, must

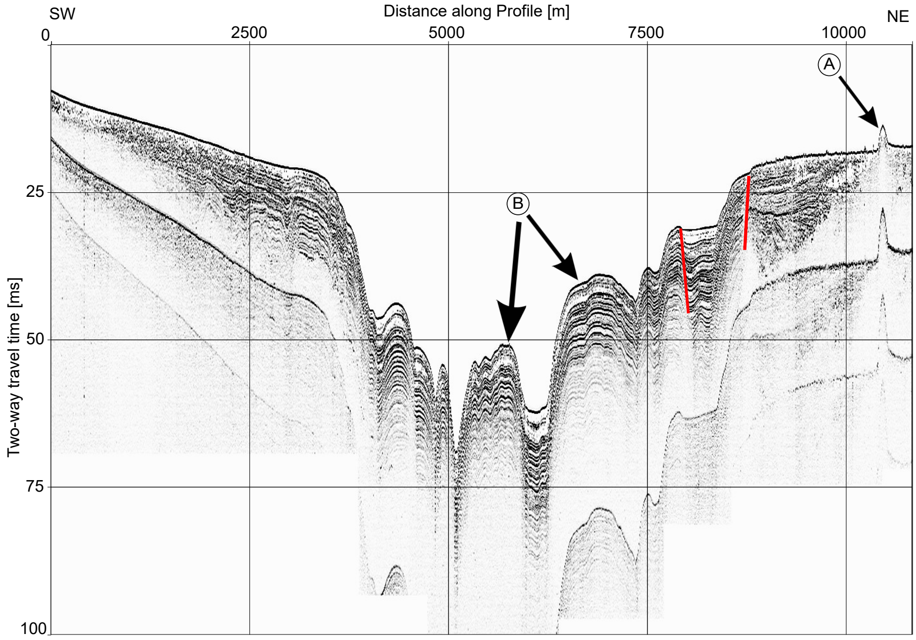


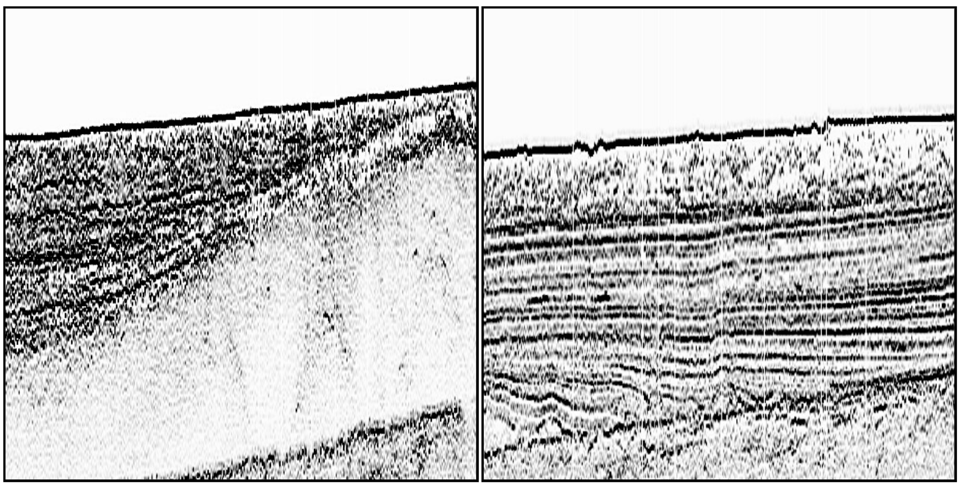
FIGURE 4.6: Echosounding Profile L. The is the longest of the profiles recorded by the AWI in 2013. It shows the deeper parts of the basin. Visible here are the different mounds without (A) and with (B) lamination underneath as well as small linear structures cutting the lamination (red lines).

distinguish from its surroundings. Aside the already mentioned onlaps there are other positions in the profiles where the lamination is interrupted very locally by lineation structures that seem to be deriving from the seafloor cutting downwards (red lines in figure 4.6). These features are visible in several profiles though they do not show the same dipping direction everywhere. That might mean that they are either distributed randomly or part of a complex process varying over time and distance.

5 Discussion

5.1 Structure Interpretation

The pre-existing bathymetry of the Herschel Basin was already quite precise given the fact that it was mainly based on point measurements throughout the area. Nevertheless this new dataset recorded by parametric echo sounding provided a lot more details on smaller structures in the basin that were hidden in the old data due to a lack of resolution. The seafloor structures are considerably irregular within the whole study area though certain features could be tracked throughout the basin. Whether these structures developed right in the beginning contemporarily with the generation of the basin or afterwards will be assessed by interpreting the different structures separately and in the context of the big picture of landscape evolution.



(A) (B)

FIGURE 5.1: The contact between the non-laminated basement and the laminated strata is seen in the left close-up from profile B. The layers terminate in onlaps onto the contact horizon. The right close-up shows an area near the coastline of Herschel Island from profile D. The uppermost part of the subsurface shows no lamination marking an area of deposition as well as erosion.

The convex shaped structure that could be seen in many profiles extending from the coastline a few hundred meters into the basin is part of the Yukon Coastal Shelf known as Thetis Bay in this distinct area. It diminishes further away from the coast at a quite constant depth tracking it in many profiles. It gets replaced by other, smaller structures and steeper slopes. That marks the geomorphological transition between the Shelf and the actual Herschel Basin at a depth of about 12m. This convex shape is a result of sediment being transported from the coast onto the shelf area. It gets into the ocean after being eroded from the coast. Most of the sediment accumulates in the near-shore area with only very little of it being transported further offshore. That explains the convex shape as the most of the sediment is already deposited in the shallow parts of the shelf, especially in areas of low wave energy protected by Herschel Island from the prevailing northwest winds. Throughout the area all profiles show thick layers of sediment (Figure 5.2) especially near the coast supporting that interpretation.

Throughout the whole study area the subsurface shows laminations with very few exemptions that will be dealt with later on. This lamination is mostly parallel to the seafloor with little disturbances stretching to the bottom until it cannot be seen anymore (Figure 5.2). These laminated structures represent the thick layers of sediment that have accumulated in the basin after it was formed. The origin of these sediments is thought to be marine from the borehole data that are available. It consists of mostly clay and silt sometimes interbedded with traces of sand or rarely even gravel. The borehole data to date does not show any sediments of glacial origin up to a depth of around 10m which would mark a transition in sedimentation. In most of the profiles this lamination simply fades towards the bottom due to a lack of penetration depth which is in part because of the soft sediments here. They attenuate the acoustic signal significantly not allowing for deep penetration into the subsurface. But in the north of the basin where the profiles A, B and C were recorded, a discordance between the uppermost laminated part and a non-laminated part is seen. This likely marks the contact to the basement of the basin that was created by the basin formation and thus contemporarily to the creation of Herschel Island (Figure 5.1a). The onlaps between this basement and the sediments support this interpretation as a sign of

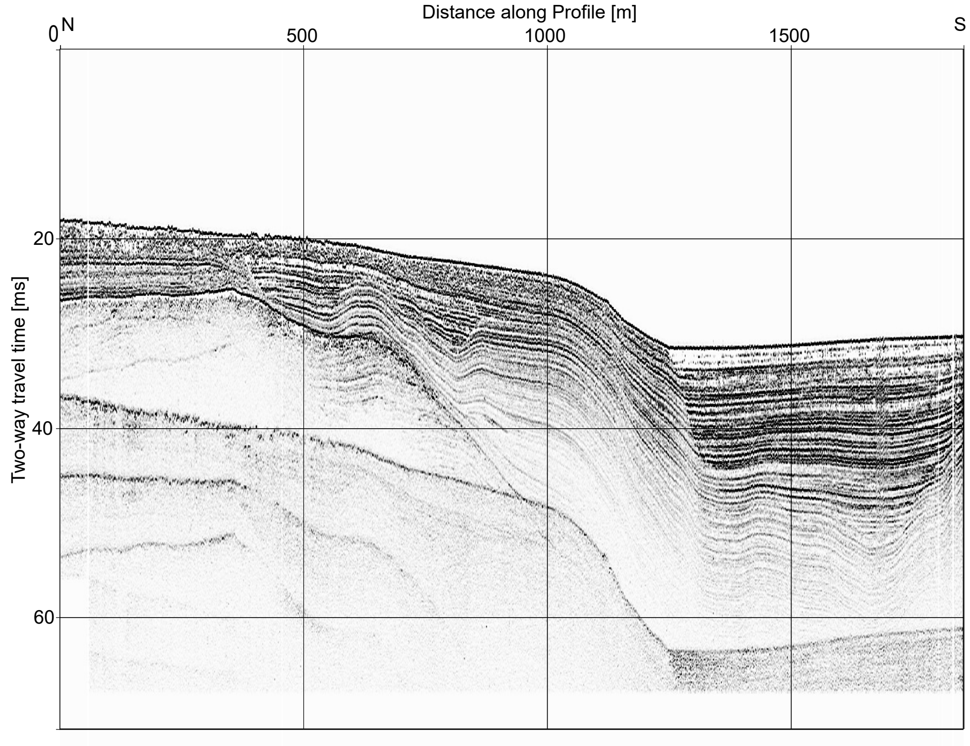
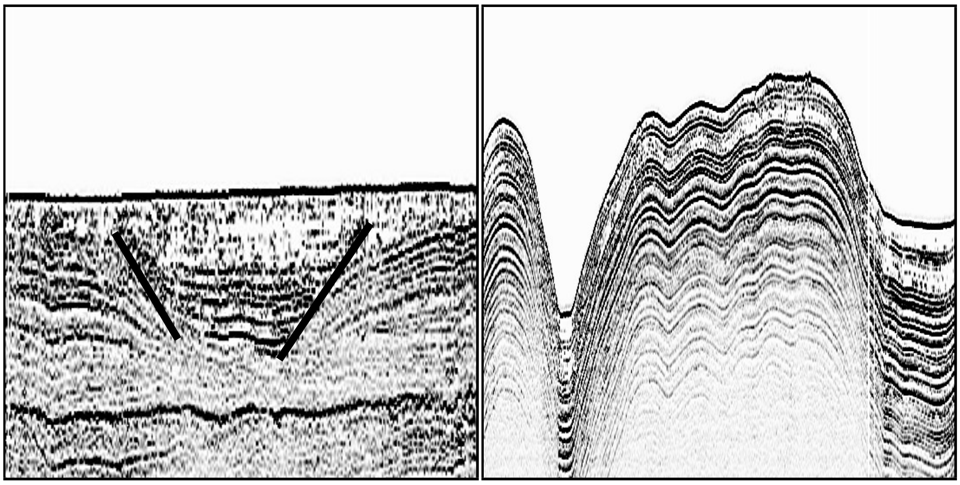


FIGURE 5.2: The echosounding profile C provides a good example for the lamination that covers the whole study area with only few exemptions. Still there are some minor distractions to that rule visible epsecially in the northern part of this profile to the left of the figure.

retrogradation (Catuneanu, 2006; Nichols, 2009). After the deglaciation the basin got filled with sediments as the sea level rose. That process is still continuing to date.

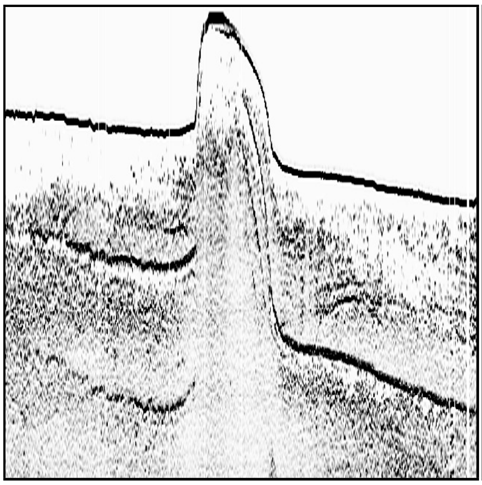
In some profiles at very distinct locations there is no lamination in the uppermost part of the subsurface visible in the close-up figure 5.1b. These parts of the profiles are all situated in very shallow areas on the shelf close to the shoreline of Herschel Island. The subsurface here is still made up of sediments but they might be subject to not only deposition but also erosion depending on winds and therefore underwater current directions. These areas are highly dynamic and very characteristic for this near-coastal area of Herschel Island with a lot of sediment input from coastal erosion but also strong currents that are capable of eroding the surface sediments again. Other highly dynamic areas are represented by the onlaps that are forming v-shaped structures in the upper part of the subsurface a bit further offshore in deeper basin parts (Figure 5.3a). Here these structures are more pronounced. That means erosion has taken place at some point and formed a channel or trough over time as deposition was low or did not even occur. Due to a possible change in current direction this channel no longer got eroded at some point but subject to deposition again. From that point on the sediments transported there started to fill that channel leading to the very distinct feature that is visible today as v-shaped channel that contains laminated sediments and is evident due the sediments in the channel differing from the surrounding layers even though the seafloor got levelled again by the process hiding the channels from bathymetric data.



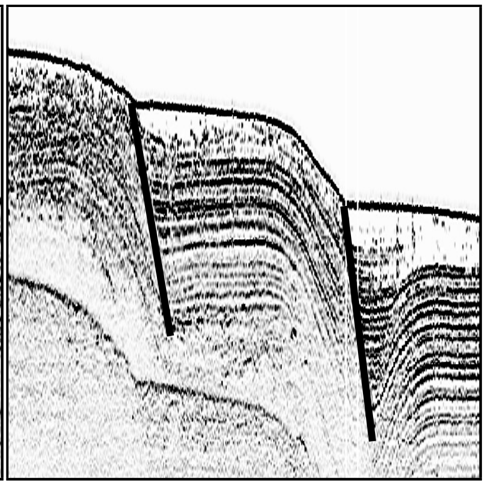
(A) (B)

FIGURE 5.3: This infilled channel can be seen by the onlaps to both its sides cirected towards each other (A). They form a v-shaped structures with laminations in between them. The pingo-like features appear mostly in the deeper basin parts (B). They form a rather big mound on the seafloor that still has lamination visible in the upper layers.

Mounds on the seafloor in rather shallow areas of the shelf close to the shoreline represent a very frequent feature here. These mounds differ considerably from not only the surroundings but also from the laminated mounds in the deeper parts of the basin. They are clearly visible in the close-up of profile L in figure 5.3b. They contain no lamination beneath the surface leading to the conclusion that they might not be made up of sediments. But a likely different explanation is gas masking. The features have a kind of diapiric form masking the lamination by something that is coming from the bottom. This only appears in shallow areas that tend to warm quite substantially in summer time. These warm water masses might thaw a potential subsurface permafrost underneath it by warming it. In this case the permafrost might even be the offshore extension of the present terrestrial permafrost on the coast. Greenhouse gases like methane or carbon dioxide are trapped in the subsurface while frozen but could get released by this process and find their way through small faults or cracks in the sediment up to the seafloor and into the water column. This gas release is then masking the signal recorded by the echo sounder producing a non-laminated area. This possible gas release might be substantial to the local water state and it has to be studied further if this is the signal we can see here. Other features interrupting the lamination are the small faults that can be seen in some profiles (FIgure 5.4b). Even in close distance they do not show a coinciding dipping direction making it hard to draw conclusions from them. The seismicity of the region is very low so that might not be the reason for them. Nevertheless they could be created by post-glacial rebound due to isostasy after deglaciation though that is speculation.



(A)



(B)

FIGURE 5.4: The gas masking features are found everywhere in the basin (A). In most cases they are located quite close to the coastline as in this case in profile E. These faults of profile H are are an example for this characteristic feature that reappears in many profiles not being restricted to distinct areas of the basin

The deeper basin is dominated by smaller structures and shows pingo-like features (PLF). Here the picture of the seafloor and the subsurface looks very irregular apart from the lamination that is seen everywhere even here. The troughs and mounds visible in this part show that this is a very dynamic area that was and might still be subject to many exterior influences in the past. Some of the featured here are very distinctive mounds containing a layering (Figure 5.3b). These fit very well the descriptions of pingo-like features (M.J. O'Connor & Associates Ltd., 1985). They are supposed to be formed by pingos that were generated together with terrestrial permafrost when the area was exposed to the atmosphere(Mackay, 1972) meaning they formed after the glacier retreated but before the basin was flooded. They continue to exist in today's relatively warm waters. Likely they are not frozen inside but consist of sediments. The troughs surrounding these PLFs were probably generated simultaneously simply by not being uplifted. Though water currents might flow along those today making them channels with less deposition explaining why the structures persist.

The discovered structures in the basin can be classified by their time of generation with regard to the basin itself. The contact between the basement and mostly overlying sediments could be found and hints surely to the basement that developed syngenetically with the basin itself. Shortly after the basin formation pingos and terrestrial permafrost must have been present linking that to exposure to the atmosphere. The remnants are visible today as the PLFs in the deeper basin. That was followed by the parallel bedding throughout the entire study area as well as the convex shape of the shelf area close to the coast by sediment input from the shore and from the ocean. The distinct areas of missing lamination in the upper part due to erosion and the discordance between sediments and basement were formed in and after the start of sedimentation. The smallest structures such as channel infillings, gas masking and faults represent the youngest existing features of the basin though their age could not finally be determined by this study.. Channel infilling is an ongoing process still occurring to date as well as the development of the faults. The gas masking could be a very recent feature due to thawing permafrost in the subsurface. It might even get accelerated and multiplied over time as a result of a warming ocean. It is likely though that this might occur more regularly in summer times with warmer waters representing a seasonal variation.

5.2 Basin History

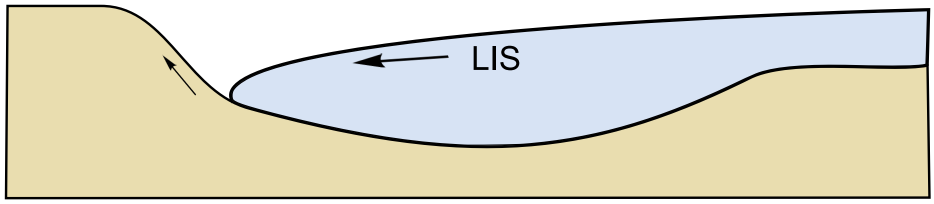


FIGURE 5.5: The first stage of basin evolution is marked by the advance of the LIS. It carved out the basin pushing the material onto an ice push moraine that is known as Herschel Island today. The blue mass is the advancing LIS, the brown town represents today's basement of the Herschel Basin.

The assessment and interpretation of the structures in the study area support the hypothesis that the basin was formed by the advance of the LIS carving it out and pushing the sediments together with other allochthonous material to its margin where Herschel Island was formed as an ice push moraine (Fritz et al., 2012; Mackay, 1959). The geological map (Figure 2.2) shows that the entire area surrounding Herschel Basin consists of basically moraine deposits. This advance formed today's basin basement (Figure 5.5).

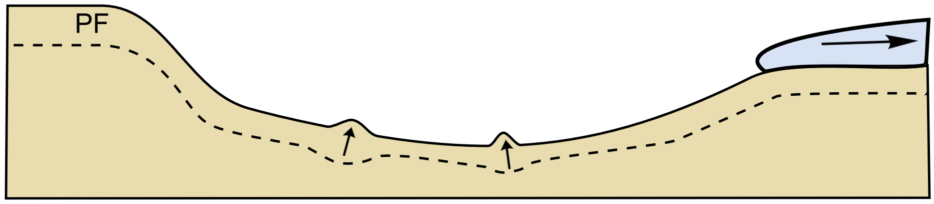


FIGURE 5.6: After the LIS retreated the moraines as well as the basin floor were exposed to the cold atmosphere. Permafrost (dashed line) and corresponding feature like pingos (mounds in the figure) are created. It is likely that permafrost existed even before exposure when the basin floor was covered by the ice sheet. The intake of lacustrine sediments into the basin commenced.

After the retreat of the LIS the basin floor was exposed to the atmosphere and little sedimentation occurred. Terrestrial permafrost was already present then being generated during ice sheet coverage or formed during exposure to the atmosphere with features like pingos that are seen today as PLFs on the seafloor (Figure 5.6). there is no data how deep the permafrost must have been though.

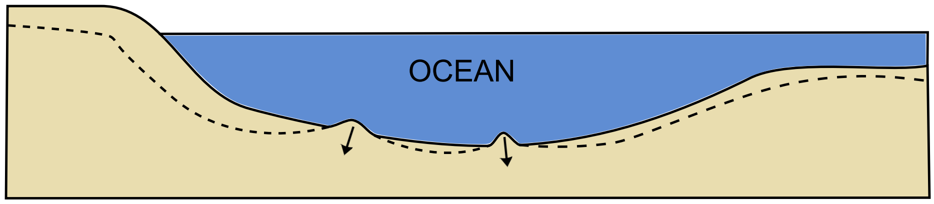


FIGURE 5.7: The basin gets flooded by oceanic water and becomes part of the Beaufort Sea. The thermal energy of the warmer water leads to a thawing of the permafrost and a decline of pingos.

Due to sea-level rise the basin got flooded, possibly around 10 000 years ago (Hill et al., 1985). The thermal energy of the water column initialized thawing of the drowned permafrost. The permafrost layer became thinner and features like the formed pingos retreated over time (Figure 5.7). Already there must have been an input of mainly lacustrine deposits into the basin as rivers were flowing into it. Unfortunately I could not locate these lacustrine deposits in this study.

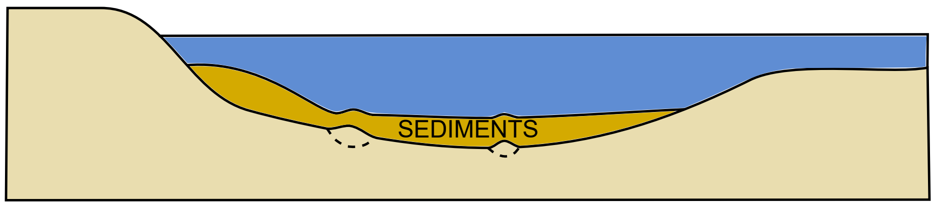


FIGURE 5.8: Marine sediments get deposited on the basin floor covering the pingo-like features and shielding them from the water column. Thus we can still see those features in the deeper parts of the basin today. The sediments form thick layers of clay and silt on the seafloor, the uppermost stratigraphy of the basin today.

Intense sedimentation began and deposited thick layers of mainly marine silt and clay over the basin floor as drawn in figure 5.8. The parallel bedding of this sedimentation can be seen in the entire study area at least in the upper 15 to 20m that were subject to this study (Figure 5.2). In the shelf area this got more complex over time as not only depositional but also erosional elements can be found differing from the deep basin. This part is highly influenced by the exterior conditions like wind and thus current directions. In the deep and shallow parts the oceanic dynamics formed even more multiplex structures such as the gas masking, the channel infillings and the faults discussed before. The permafrost retreated almost completely leaving only small patches of frozen ground that have been discovered in boreholes in a depth of 18 to 20m beneath the seafloor and about 25m underneath present sea-level.

6 Conclusions

6.1 Data Enhancement

The bathymetric dataset was enhanced by this study using the newly obtained data from echosounding though the big image remained largely unchanged. The provided results amount to a vital improvement of the resolution of the data to see smaller structures in the bathymetric maps that could not be resolved before. This study focussed on the upper part of the subsurface showing a variety of different structures that were analyzed. No apparent changes in lithology could be derived. The layered sediments throughout the entire basin mainly consisted of clay and silt after analysis of the borehole data, no prominent horizon of a change in lithology was extracted (Figure 6.1). Changes would probably only be visible in deeper lying parts of the subsurface sediments using a different setup. Apart from that the configuration of the parametric echosounding recordings was sufficient for the study with the tasks on hand and the purposes it was conducted for. But for a more detailed, especially deeper, image of subsurface a slightly different survey would be necessary. Lower frequencies could penetrate deeper, specifically in this area with soft sediments dominating the environment and attenuating the seismic signal significantly. In this way the suggested contacts between marine and lacustrine sediments as well as the glacial till could possibly be extracted. That was not possible with the data on hand.

The already available data from older surveys mainly from the 1970s and 1980s was a useful help as supplemental material in interpreting the newly recorded data. Though the lack of resolution and documentation sometimes made those hard to be used conveniently (EBA Engineering Consultans Ltd., 1984, 1988a,b; Hill et al., 1990; M.J. O'Connor & Associates Ltd., 1985; O'Connor, 1983; Quinn, 1992). The difference was shown when working with the latest digital data, a vast improvement to the old data only available on paper. Programmes such as OpendTect and SeiSee provide powerful tools in processing the digital data using computer and human experience altogether without too big of an effort to fit it to the special needs of every user. In the end that made the interpretation vastly easier and should be considered when using those older datasets as more than just supplemental material. Nevertheless missing metadata and record documentation can produce less convenient datasets and needs an enormous of processing to be enhanced even when working with up-to-date data. That should be a major focus of any future geophysical study.

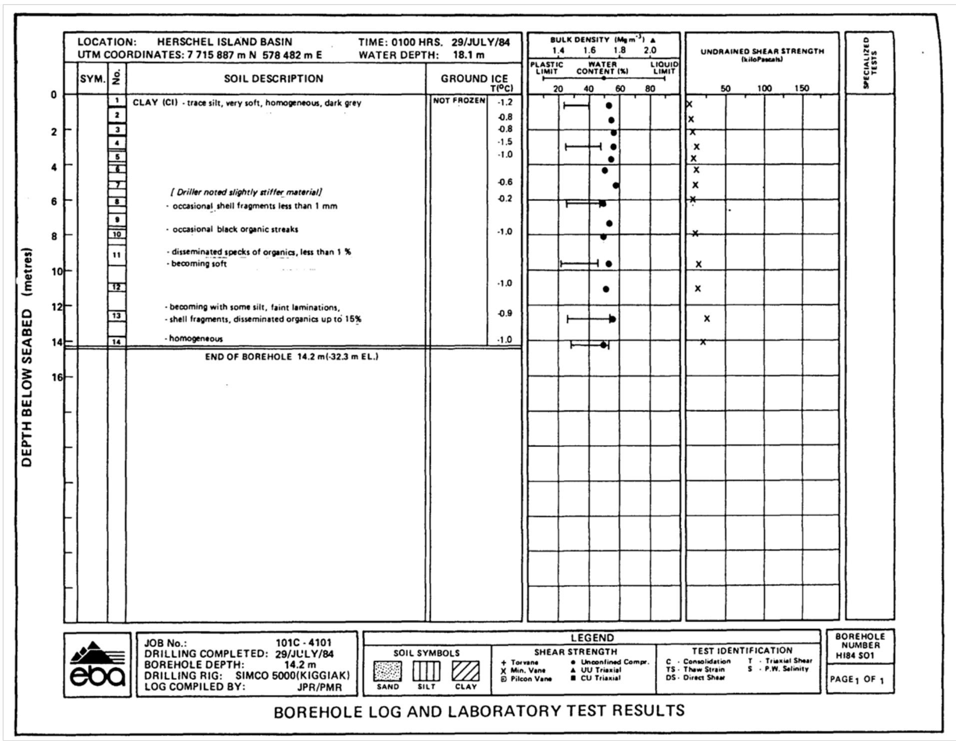


FIGURE 6.1: One of the borehole logs that was used to correlate the data to the seismic profile. It was drilled in a water depth of 18.1m with a core of 14.2m length. The whole core shows no alteration in lithology consisting only of clay with traces of silt. That is very characteristic for the basin. Lithology changes are expected to be discovered deeper into the subsurface.

6.2 Basin Evolution

This study provided insight into the evolution of the Herschel Basin. It showed what structures could be found using this survey. These structures were not only interpreted but also given timing with regard to the creation of the basin itself. It lead to a division of the basin evolution into four main stages (Figure 6.2).

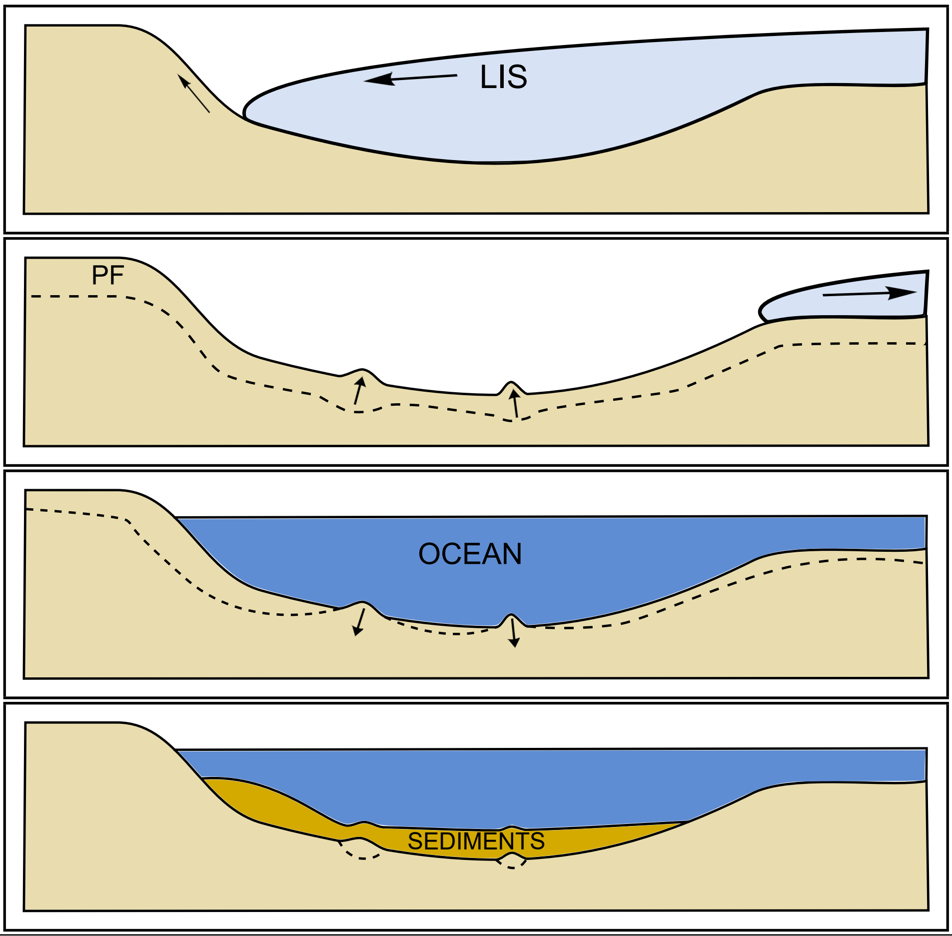


FIGURE 6.2: This schematic overview presents the basin evolution. I divided it into four main stages that were already described more closely in Chapter 5. The main driver for forming of the basin was the LIS. The biggest influence after creation was given by the exterior settings (exposure to the atmosphere and flooding).

That was one of the main notions of this thesis and supported the hypothesis of basin generation by the furthest advance of the LIS during the Late Wisconsian 23,000 to 18,000 years before present (Blasco et al., 1990). Several features formed during or shortly after the creation of the basin in a terrestrial environment like the permafrost features suggesting that the basin floor was exposed to the atmosphere at some point. Though the final proof of discovering the contact between the marine and lacustrine sediments could not be extracted during this study and needs further evidence. I also showed that the Herschel Basin is a highly dynamic environment creating and altering smaller structures on the seafloor such as channels, faults and even gas masking.

6.3 Outlook

The results of this study support the proposed hypothesis for the basin development in total. Though further studies are crucial to gain additional evidence for its evolution. Apriori the whole basin has to be covered by high resolution echosounding data as there is no data for the southeast of it to date. The recorded data needs to contain a proper documentation as well as the necessary metadata needed for processing them sufficiently. Additionally to more echosounding profiles, multibeam data could be collected. That type of data gives no subsurface information without intensive and experienced interpretation but its big advantage is a wide beam that allows for covering not only a profile but also its close surroundings. That way a large area of the basin could be covered in a rather small amount of time using minimal resources. Together with the knowledge from this study, the seafloor structures derived from multibeam imaging could already provide a big knowledge gain of the processes and structures underneath. Furthermore that would make it easier to define areas for future high resolution echosounding surveys providing key areas of interest where structures are found that need further research.

But not only additional geophysical data are needed for a better assessment. More boreholes are essential to gain supplementary subsurface information. An expedition in spring 2016 already retrieved cores from the area in synchronization with the seismic profiles of this study and the analysis of the cores is ongoing with the aim to provide more information about changes in lithology with depth that can be correlated to seismic structures, possibly horizons. The onlaps between the soft sediments and the suggested basin basement provide a further interesting area to drill a borehole as it could provide crucial information on how the basement of basin is structured. The detection of locations of gas masking leaves room for interpretation and needs far more evidence. Water just above the seafloor as well as higher in the column could be sampled there to evaluate the possibility to detect high concentration of gases such as methane that might be released from subsea permafrost there. If high concentrations can be detected, further studies could include atmospheric measurements just above these features to assess if they have a signal releasing greenhouse gases to the atmosphere as suggested for Eastern Siberia (Shakhova et al., 2010). This could be a possible severe feedback mechanism for climate change in the area.

A Echosounding Profiles

This appendix show some of the echosounding profiles that were vital to the Interpretation of seismic structures, though could not be shown in the thesis itself.

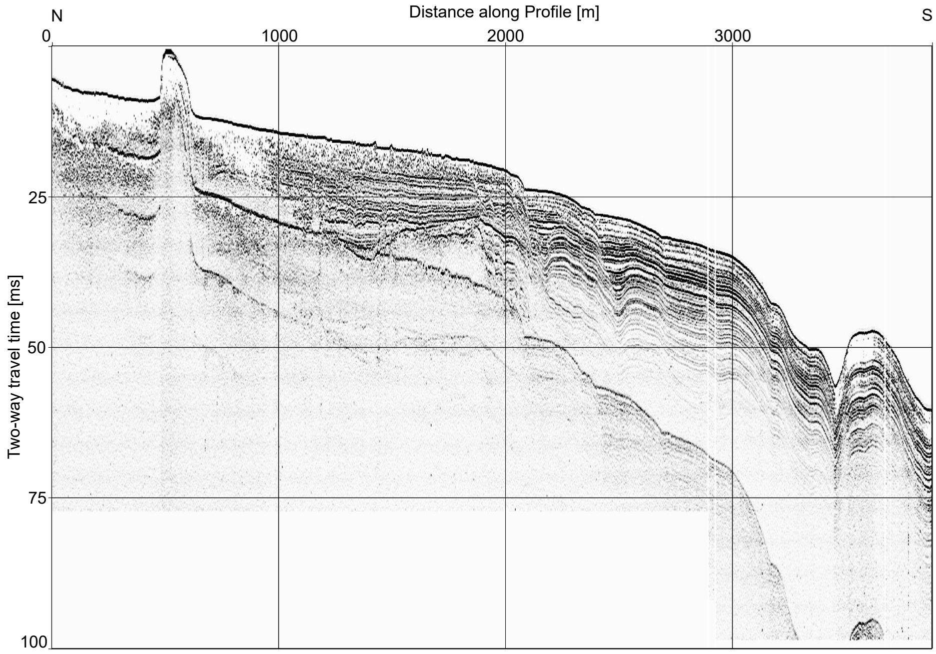


FIGURE A.1: The echosounding profile E shows some feature that were found in other profiles as well. To the north (left in the figure) there is a very distinct mound that formed on the seafloor in a shallow area close to coastline. It contains no lamination in the subsurface separating it clearly from its surroundings as a gas masking feature. Towards the south, the profile shows the characteristic convex shape of near-shore profiles. In the deepest part of the record there is another distinct mound with lamination underneath the surface. This represents a pingo-like feature.

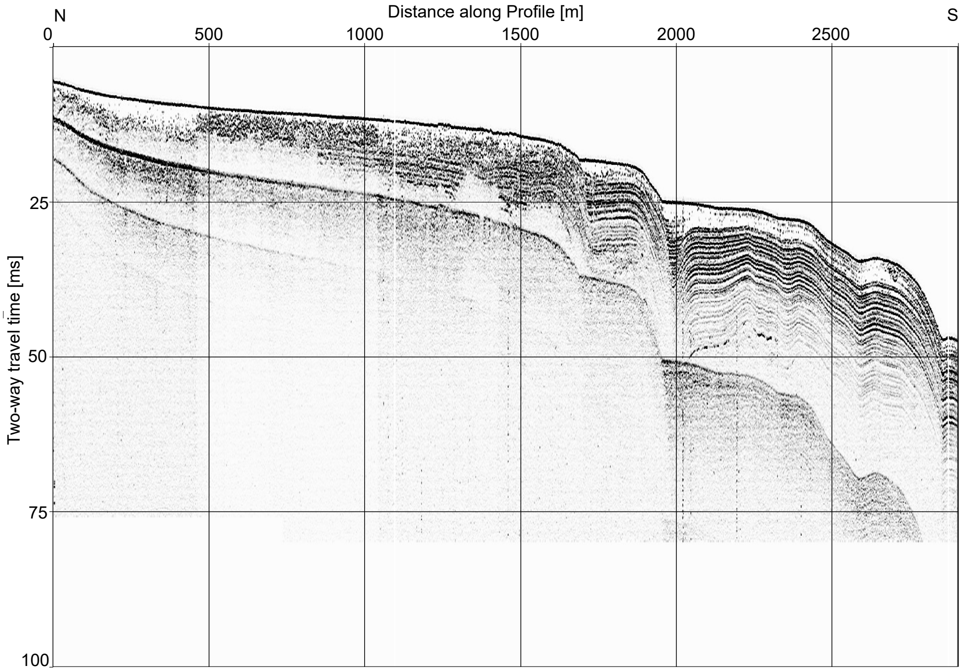


FIGURE A.2: The convex shape of echosounding profile H is again characteristic for the area near the shoreline. Another important structures can be seen at around 2000m distance along the profile. There is a small fault that is stretching from the seafloor down to the non-visible area of no lamination.

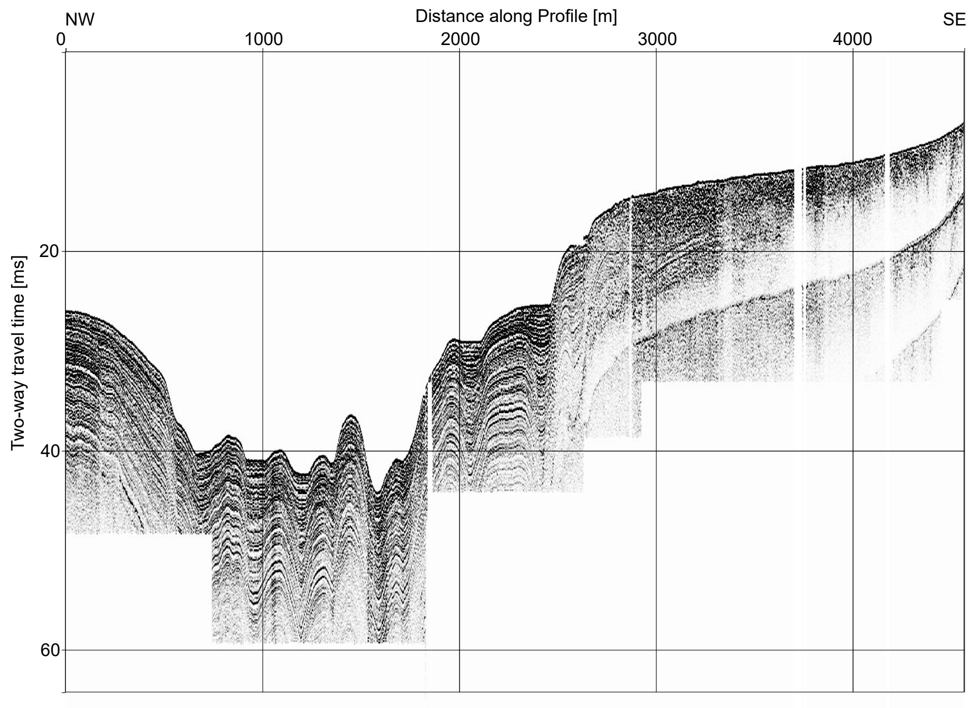


FIGURE A.3: This profile show the very clear transition between the shallow and deep parts of the study area. The shallow area marking the YCS is characterized by a general big convex shape and the deeper parts representing the actual Herschel Basin are much more dominated by small-scale structures of mounds and troughs.

B Borehole Logs

In this part I will show two borehole logs that were used during the analysis of the echosounding profiles. They are characteristic logs for this study and the area.

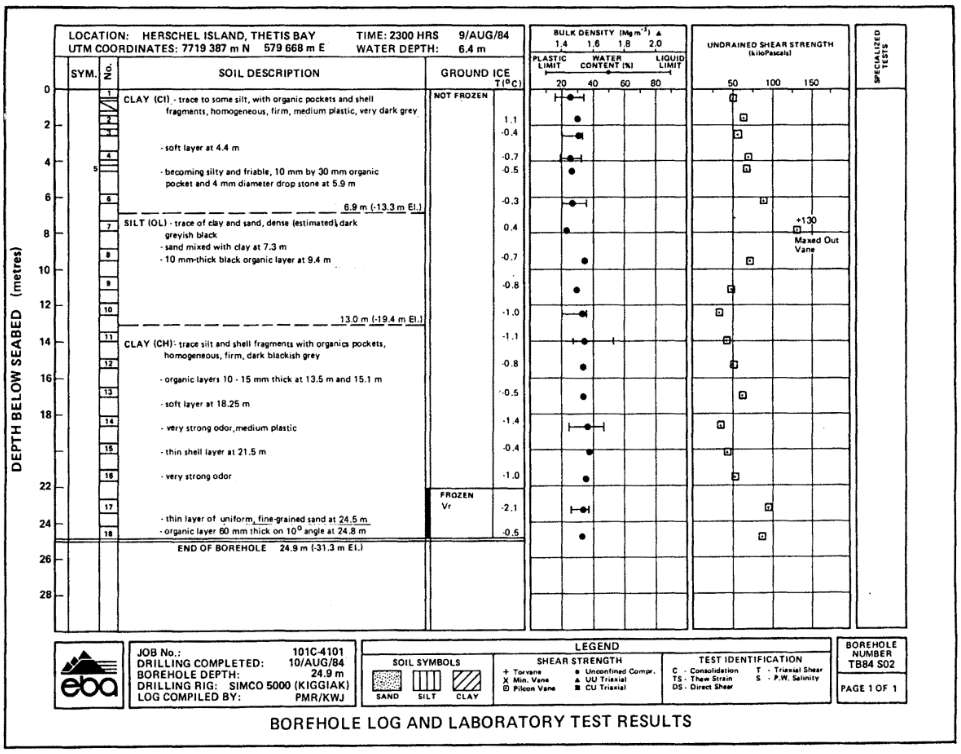


FIGURE B.1: Log for Borehole TB84 S02. This borehole was drilled in a water depth of only 6.4m very close to Herschel Island into the YCS. It shows the characteristic setup of the stratigraphy of the basin with clay and silt layers sometimes interbedded, but dominated by clay. At a depth of around 22m into the borehole (28m below sea-level) frozen material was found of what could be remnants of the terrestrial permafrost that was formed here during atmospheric exposure.

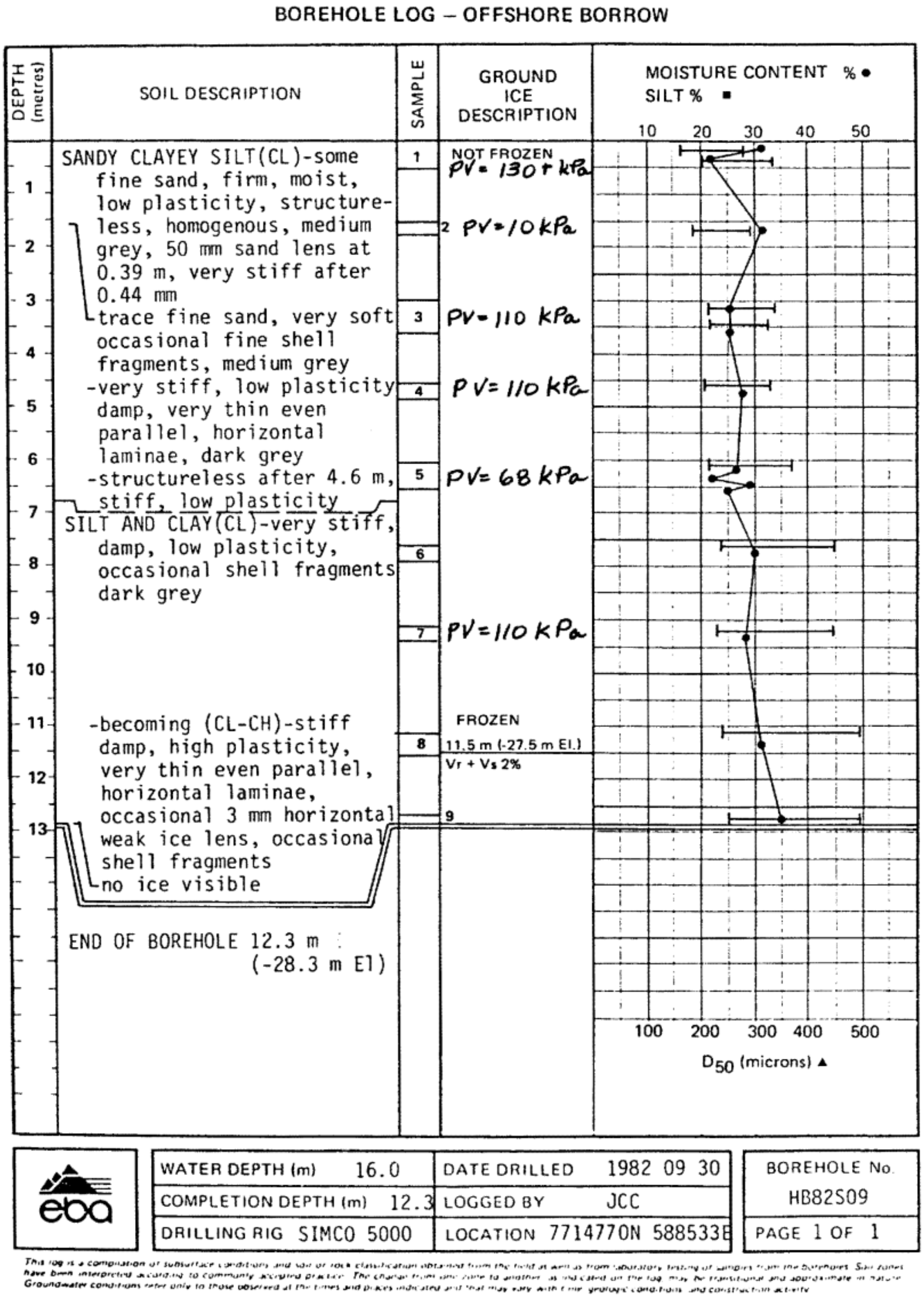


FIGURE B.2: Log for Borehole HB82S09. This borehole was drilled into the Herschel Sill at the margin of the basin itself. the found lithologies are silt and clay as expected. At a depth of abt 11m (27m below sea-level) the ground was frozen, also being a sign of remaining permafrost.

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