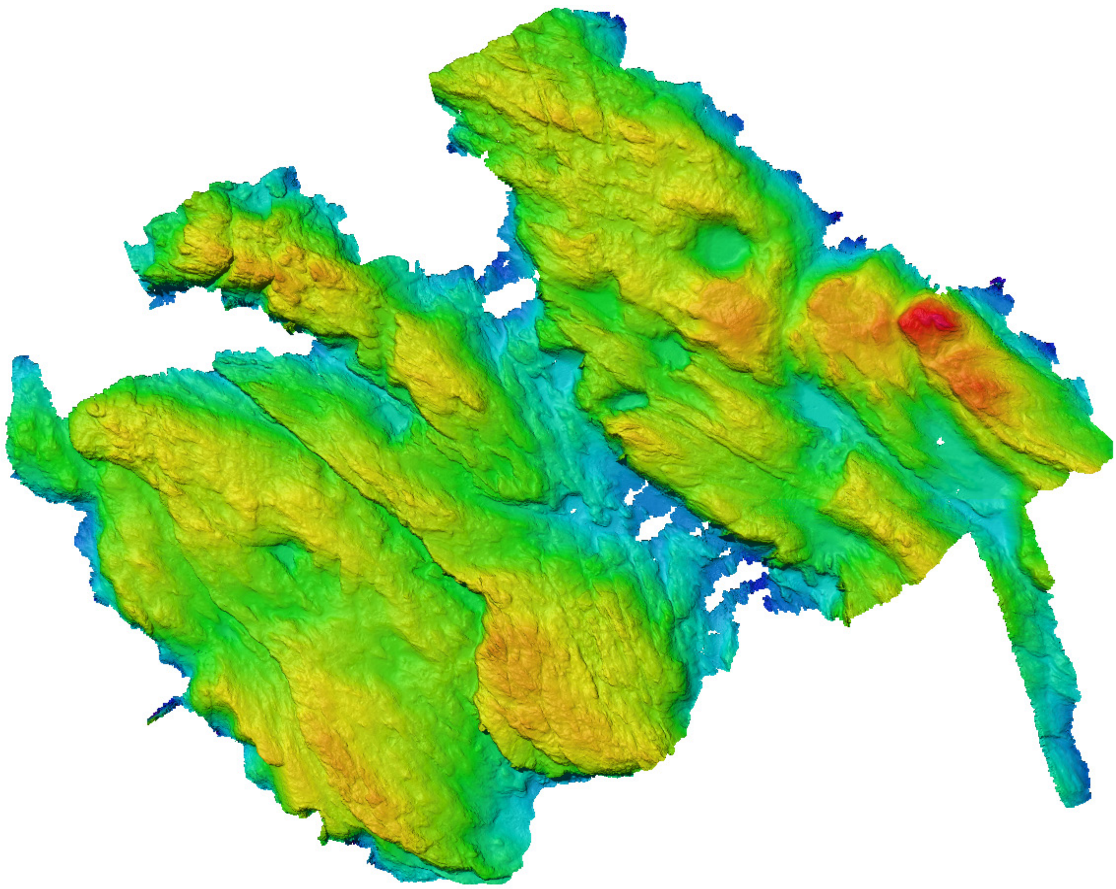
Stockholm University

Bachelor Thesis

Degree Project in
Marine Geology 30 hp

Glacial morphology and bathymetric mapping in Melville Bay, Western Greenland
Multibeam and backscatter mosaic

Caroline Bringensparr



Stockholm 2014

Department of Geological Sciences
Stockholm University
SE-106 91 Stockholm

SAMMANFATTNING

Glacialmorfologi och batymetrisk kartläggning i Melvillebukten, västra Grönland
Multibeam- och backscattermosaik

Under VEGA-expeditionen, som ägde rum i juni 2013, inhämtades reflektivitets- (backscatter) och djupdata med ett multistråligt ekolod över ett cirka 140 km^2 stort område i Melvillebukten utanför kusten av västra Grönland. Ett av expeditionens syften var att söka efter och kartlägga bevis för ett bottenfruset istäcke, vilket troligtvis ska ha nått ut till kontinentalsockelns yttre gräns under det senaste glaciala maximet för cirka 20 000 år sedan. I denna studie sammanställdes den inhämtade djupdatan till en detaljerad karta över batymetrin, vilken användes för att kartlägga utbredningen av morfologiska formationer orsakade av erosion kopplad till istäckets framfart över området. Resultaten visar erosion av berggrunden i form av linjära formationer, smältvattenkanaler och olika typer av fördjupningar. Fördelningen av ytsediment, baserad på reflektivitetsdata, visar att grövre sediment som grus kan hittas i de djupare delarna av undersökningsområdet samt i kanaler och fördjupningar, medan finare sediment såsom silt och lera påträffas generellt över resten av området. Slutsatsen som kan dras är att resultaten starkt pekar på iserosion i detta område, dock är det inte möjligt att avgöra när denna ska ha skett utan åldersbestämning av bottenprover. För att få en mer heltäckande uppfattning av den glaciala historien i Melville- och Baffinbukten krävs fler undersökningar av detta slag.

ABSTRACT

Glacial morphology and bathymetric mapping in Melville Bay, Western Greenland
Multibeam and backscatter mosaic

During the VEGA Expedition, in June 2013, reflectivity (backscatter) and depth data was acquired with a multibeam echosounder from an approximately 140 km^2 large area in Melville Bay, off the coast of Western Greenland. One of the expedition objectives was to search for and map evidences of a grounded ice sheet, which is likely to have reached the edge of the continental shelf during the Last Glacial Maximum, about 20 000 years ago. In this study, the acquired depth data was compiled to a detailed bathymetric map, which was used to map the extension of morphological features caused by the ice sheet's progression over the area. The results show bedrock erosion in the form of linear features, melt-water channels and different types of depressions. The surface sediment distribution, based on the reflectivity data, presents coarser sediment such as gravel in the deeper parts of the survey area as well as in channels and depressions, while finer sediments such as silt and clay can be found generally in the remainder of the area. The conclusion is that the results strongly suggests there have been glacial erosion in this area, however it is not possible to determine when this took place without age determination of bottom samples. For a more comprehensive understanding of the glacial history in Melville and Baffin Bay, more surveys of this kind are necessary.

ACKNOWLEDGEMENTS

A big thank you goes to my supervisor Richard Gyllencreutz and assistant supervisor Martin Jakobsson, for giving me the opportunity to work with this area. The two of you were the ones who inspired me in the first place, during the introductory courses in marine geology, sparking my interest for the marine sciences and for this I cannot thank you enough. Tack! I would also like to thank all of you who have supported me during this time, for your patience and understanding.

TABLE OF CONTENTS

LIST OF FIGURES

APPENDIX

1. INTRODUCTION

Multibeam echosounders are helpful tools for mapping bathymetry, in providing georeferenced high-resolution depth data of the seafloor. This thesis of 30 ECTS was written at the Department of Geological Sciences, Stockholm University and presents how data from multibeam sonars can be used to map and interpret submarine glacial morphology. The data set used in this thesis was acquired by Martin Jakobsson, Stockholm University and Larry Mayer, University of New Hampshire, during the VEGA expedition in June 2013. The survey area is located 25-45 km off Western Greenland, in southern Melville Bay, and covers approximately 140 km^2.

To be able to create a 3-dimensional digital bathymetric model (DBM) from the raw data, certain processing steps were necessary. The first step involved gridding of the data to a resolution suitable to the sounding density and the varying depths of the survey area. The second step consisted of cleaning the raw data from outlier soundings and other artefacts, such as faulty soundings resulting from interference with other on-board instruments. In the third step, additional processing such as backscatter mosaics and Angular Range Analysis were performed. These two methods combined should provide further support to the interpretation of the survey area. The first, backscatter, is a measure of the intensity of the returning sound pulse and is used to estimate the roughness and sediment type of the seafloor. The second, Angular Range Analysis – or ARA for short – is a method used to characterise the surficial sediments of the seafloor and is based on the angular response from the backscatter data.

The DBM was used to map and interpret submarine glacial structures, such as melt-water channels and lineations caused by ice movements. This was done in order to investigate whether the Greenland Ice Sheet have reached this far out from the coast or not, since the Last Glacial Maximum. The backscatter and Angular Range Analysis results were used to map the surface sediment and were in addition to the DBM used for further interpretation of the seafloor and its properties. All together, the data analysed in this thesis gives a good idea of what the seafloor off western Greenland looks like.

1.1. HYPOTHESIS

The bathymetric data from the multibeam sonar survey should provide geomorphological evidence of a Greenland derived grounded ice sheet and/or icebergs. In addition to this, the backscatter and Angular Range Analysis results should provide further information on the different types of seabed in the area, with respect to the surface sediment and/or bedrock.

1.2. THESIS OBJECTIVES

The main focus of this thesis is to investigate evidence of glacial activity on the seafloor, and can be divided into the following objectives and questions to be answered:

- Mapping and interpretation of glacial morphology, landforms and bedrock structures
    - Are there any signs of glacial activity? If so, what are those?
    - Are there similar formations as in the onshore geology?
    - What are the causes of the glacial formations in the area?

- Mapping of surface sediment and/or bedrock
    - Is it possible to define areas of similar surface type from the bathymetry, backscatter and Angular Range Analysis data?

2. Background

Greenland is Earth's largest island and has an area of more than 2 million km^2. Currently, about 80% of this land is covered by the up to 3.4 km thick Greenland Ice Sheet, the only remaining ice sheet in the northern hemisphere (Bennike & Björck, 2002). In north-western Greenland, the ice sheet has mainly marine ice margins, with glaciers and ice-stream outlets in, among others, Melville Bay (Briner et al., 2013). The largest outlet glacier in Western Greenland is Jakobshavn Isbræ, which drains about 6% of the entire ice sheet into the Ilulissat Icefjord, further south of Melville Bay, in Disko Bay. The present ice cover is a remainder of Pleistocene ice ages and has an area of 1.7 million km^2 and an estimated volume of 2.6 million km^3 (Henriksen et al., 2009).

In order to understand former glaciations and ice extent, the seafloor is investigated in the search for glacial structures. The best evidence of grounded ice is streamlined lineations carved into the seafloor sediments and/or bedrock (Polyak et al., 2011). Other indicators can be iceberg plowmarks, scour marks, melt-water channels, ridges, furrows and flutes (eg. Jakobsson et al., 2008; Livingstone et al., 2012a). Other erosional landforms could be of larger scale, such as rock basins, over-deepenings, troughs, rock knobs and roches moutonées (Benn & Evans, 2013). However, the large-scale erosional features, both onshore and offshore, are not necessarily caused by glacial erosion, but can be inherited landforms of earlier origin, caused by other types of erosion and weathering. For example, further south of the survey area, on southern Disko and in Disko Bay, a basement surface has preserved remnants of weathered gneiss and pre-Palaeocene landforms, recently exhumed from Palaeocene basalt (Bonow, 2005).

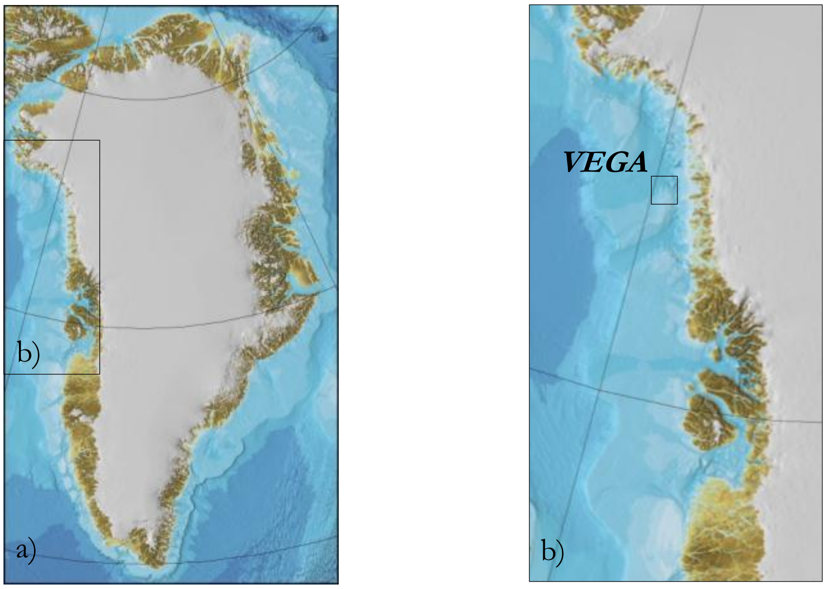


Figure 1 a) Location of survey area for the VEGA expedition, southern Melville Bay, western Greenland. b) Magnification of Melville Bay, with survey area marked out (black rectangle). (IBCAO v 3.0, Jakobsson el al., 2012).

2.1. Setting

The area surveyed during the VEGA expedition is located at 74°25' N, 58°37' W in the southern part of Melville Bay (Figure 1), which in turn is a part of the larger Baffin Bay, off the coast of north-western Greenland. Here, the shelf is narrower than in other parts of Greenland and is characterised by over 500 meters deep areas (Bennike, 2008). The survey area itself consists of two shallower parts, with depths varying between 51 and 628 meters, separated by a deeper trough, where no data collection took place. Earlier investigations of the seafloor in southern Melville Bay and its surroundings have been sparse and the area was not significantly surveyed until 1992. Then, a project named KANUMAS took place under the direction of six oil

Figure 2 Extent of the Greenland Ice Sheet since the last glacial maximum. *White*: current extent, *green*: c. 18 000 years BP, *red*: c. 10 000 years BP; *blue*: major glacier outlet streams. (Henriksen et al., 2009).

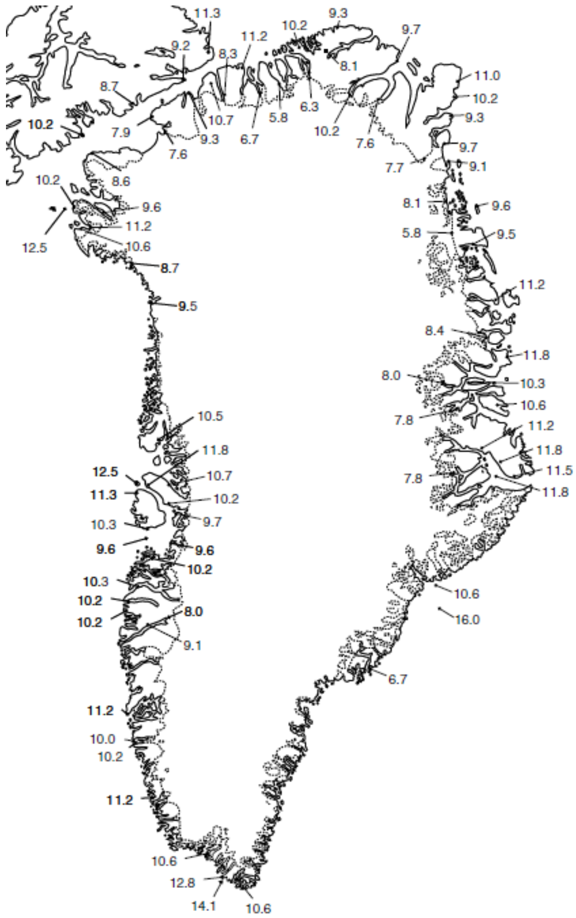


Figure 3 Oldest radiocarbon dates related to the last deglaciation. Dates in cal. kyr BP (calibrated thousand years before present). (Bennike & Björck, 2002).

companies, with state-owned Nunaoil A/S in the lead (Whittaker et al., 1997). During one month they acquired approximately 4 000 km of multichannel reflection data, of which some have been released and included, together with aeromagnetic and gravimetric data, in the 1:2 500 000 geological map of Greenland (Henriksen et al., 2009). Unfortunately the data does not have an even coverage over the entire coastal area or a particularly high resolution, why future surveys of the kind performed during the VEGA expedition is necessary. Neither are there any bedrock analyses available offshore near the survey area, why similarities with the onshore geology have to be assumed. The land areas surrounding Melville and Baffin Bay consists mainly of Archaean and Proterozoic igneous and metamorphic rocks (Whittaker et al., 1997), and the coast due east of the survey area consists of plateau basalt, metasediment, gneiss and granite (Henriksen et al., 2009).

2.2. Late Quaternary glaciation

Greenland was more or less completely ice-covered throughout the better part of the Quaternary and during the Last Glacial Maximum the ice extended out to the edge of the continental shelf in western and south-eastern Greenland (Figure 2, green line), (Bennike & Björck, 2002). The retreat of the ice sheet began about 14 – 10 000 years ago, with a minimum extent about 6 000 years ago, when the ice margin was up to 20 km inside its current position (Henriksen et al., 2009; Briner et al., 2013). During the late Holocene, in a period of cooler climate, some parts of the Greenland Ice Sheet again grew larger (Fleming & Lambeck, 2004).

Not much research have been conducted on the glaciation history of the Melville Bay area, and very little sampling and surveying have been performed there (Bennike, 2008: Fleming & Lambeck, 2004; Briner et al., 2013), this mostly because of severe ice conditions. Furthermore, there is only a narrow strip of bare land between the Greenland Ice Sheet and the ocean, which greatly complicates comprehensive investigations of the area. Some radiocarbon dating is available, though, from a lake on Langesø in central Melville Bugt, where basal gyttja was dated to 9 910 – 9 255 cal yr BP (Bennike, 2008), indicating ice free conditions at the time. In other parts of Greenland, oldest radio carbon dates vary between 12.5 cal kyr BP near Disko to around 6 cal kyr BP in some eastern and northern parts of Greenland (Figure 3). Ice loss was mainly by calving in the marine environment in the earlier stages of the last glaciation, while ablation was the main cause later on and in Melville Bay, the rate of ice loss was likely increased due to the deep trenches that can be found in Baffin Bay (Bennike, 2008).

2.3. MULTIBEAM ECHOSOUNDER

Multibeam echosounders differ from single-beam echosounders in that they consist of, as the name suggests, multiple acoustic wave generating elements called transducers. These convert electric energy to sound and vice versa (Randall, 2008) and transmit a large number of acoustic waves, or beams, which form a fan-like front, covering a wide portion of the sea-floor (Figure 4b). In order to calculate the depth at a location (y, z) from the transducer ([1], [2]), the so called two way travel time *t*, i. e. the time it takes the sound pulse to travel from the ship, down to the seafloor and then back again, is used together with the incident angle θ and the speed of sound in water *c* (Lurton, 2010; Randall, 2008). The latter is affected by salinity, temperature and pressure (LeBas & Huvenne, 2009), why calibrations are necessary for a correct result.

$$y = R\sin\theta = \frac{ct}{2}\sin\theta \quad [1]$$

$$z = R\cos\theta = \frac{ct}{2}\cos\theta \quad [2]$$

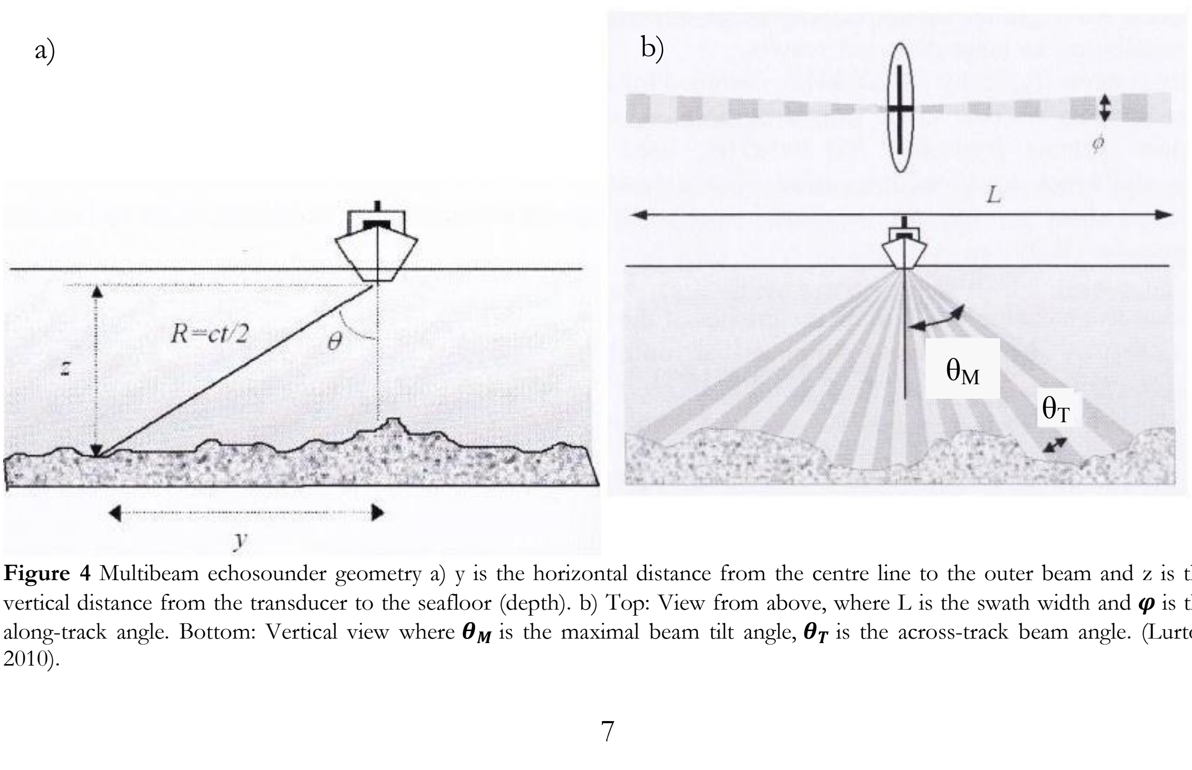


Figure 4 Multibeam echosounder geometry a) y is the horizontal distance from the centre line to the outer beam and z is the vertical distance from the transducer to the seafloor (depth). b) Top: View from above, where L is the swath width and $\boldsymbol{\varphi}$ is the along-track angle. Bottom: Vertical view where $\boldsymbol{\theta_M}$ is the maximal beam tilt angle, $\boldsymbol{\theta_T}$ is the across-track beam angle. (Lurton 2010).

One of the main advantages of a hull-mounted multibeam is that its fixed position makes geographic positioning more accurate than e.g. compared to a towed instrument, such as side scan sonar. Instead of collecting depth data only, a multibeam echo sounder acquires georeferenced depth and reflectivity data simultaneously (Lurton, 2010). The reflectivity data can be used in estimating the nature of the sediments forming the top layer of the seafloor, (see section 2.3.1). Other advantages are better coverage in less time, thanks to the wide swath, and higher resolution of the seafloor, because of the many beams.

2.3.1. Reflectivity measurements

When the wave front from the multibeam reaches the seafloor it will hit it at an angle, causing the individual beams to scatter in different directions (Fonseca & Mayer, 2007). Backscatter is a measure of the intensity of the returning sound pulse and can be used to estimate the roughness and sediment type of the seafloor. The strength of the backscatter varies with absorption in water (range dependent), source power and interaction with the seafloor (both angular dependent), (LeBas & Huvenne, 2009). A rough seafloor, either bedrock or covered with coarser sediment particles, will cause the beams to scatter more than a smoother seafloor (Figure 5).

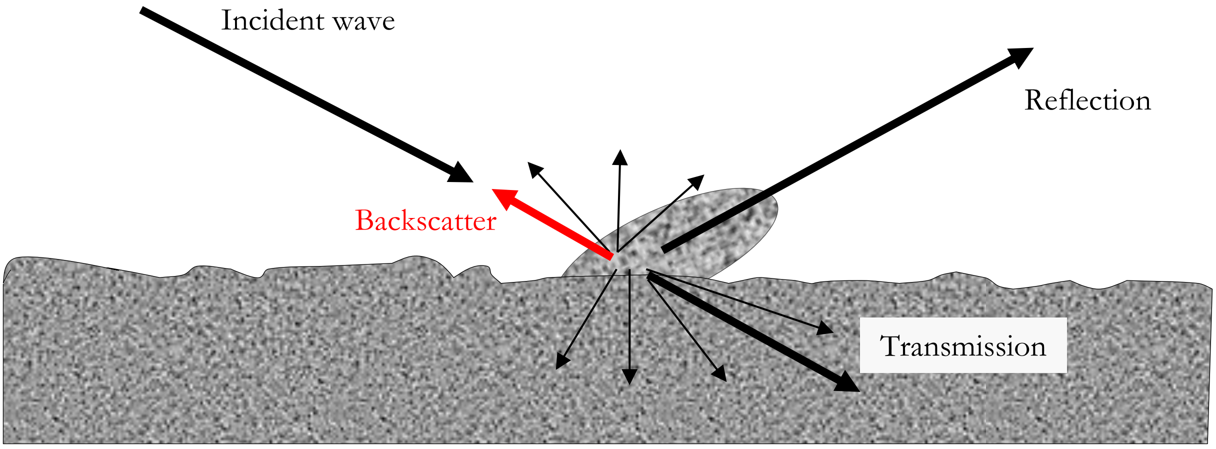


Figure 5 Scatter geometry of an incident acoustic wave. Simplification of the reflection, transmission and scattering of an acoustic wave when it reaches a patch of rough seafloor. Red arrow represents the backscattered signal (after Lurton, 2010).

Angular Range Analysis – or ARA – is a method used to characterise the seafloor by comparison of the actual backscatter angular response to the expected acoustic response based on a mathematical model called the Jackson model (IVS3D Fledermaus, 2011). After processing, the different sediment types of the seafloor are described by different acoustic themes which are presented as different colours in a map. Examples of important acoustical and physical properties of the seafloor that can be estimated based on angular response analyses are grain size, acoustic impedance (product of density and sound speed), acoustic attenuation and the acoustic roughness of the near-surface sediments (Fonseca & Mayer, 2007; Fonseca et al., 2009).

3. METHODS

The VEGA Expedition had three main objectives, of which one is related to this thesis; to map the seafloor for glaciogenic landforms related to the Greenland Ice Sheet. The second objective was to locate possible deep connections as well as barriers between the outer continental shelf and the inner fjord system. The purpose of this was to investigate if warm water could enter the fjords and have an impact on the outlet glaciers. The third objective was to locate the wreck of SS Vega, a ship used by the finno-swedish explorer Adolf Erik Nordenskiöld to sail through the Northeast Passage for the first time. In 1903 the SS Vega sunk somewhere in Melville Bay (Jakobsson, 2013).

All the data was acquired during five days in June 2013 by Martin Jakobsson (Stockholm University) and Larry Mayer (Center for Coastal and Ocean Mapping, University of New Hampshire) on-board the SS Explorer, using a bow-mounted Kongsberg EM2040 1x1 degree single head multibeam echo sounder, with operating frequencies of 200 and 300 kHz (Jakobsson, 2013). The data from the EM2040 was stored as *.all-files in WGS 84. The raw data includes many artefacts due to interference with other instruments on-board the SS Explorer (Figure 6).

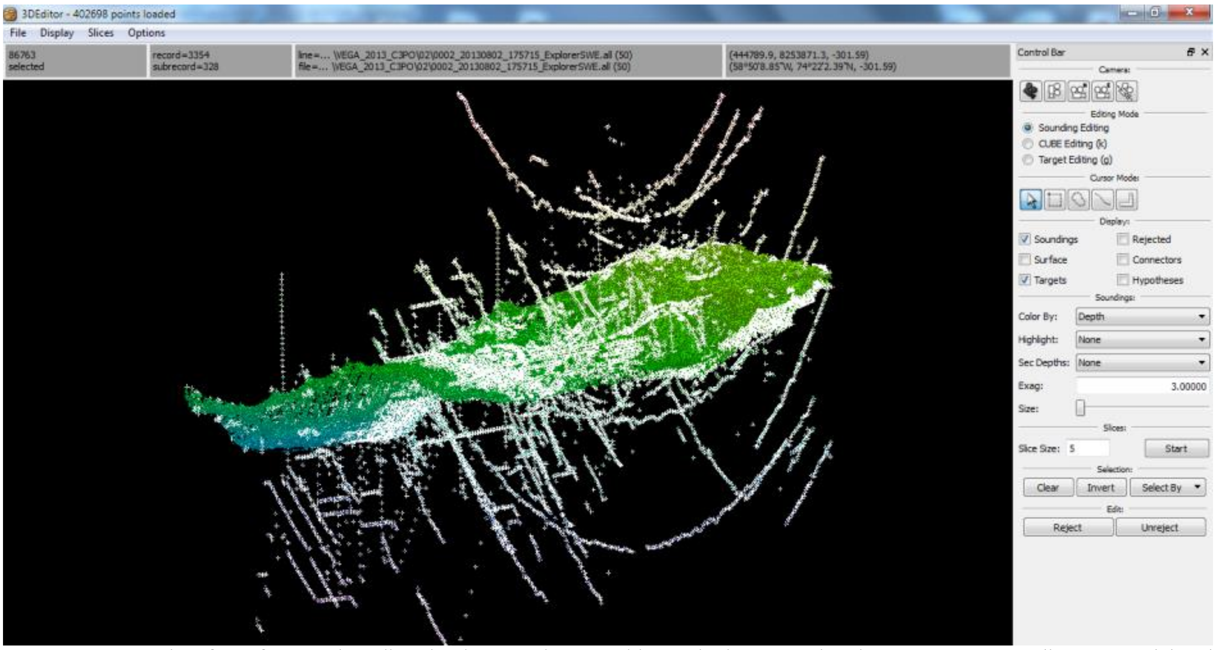


Figure 6 Example of artefacts and outliers in the raw data. In this particular example, almost 90 000 soundings were deleted (highlighted in white). Screen dump, from the 3DEditor in Fledermaus.

3.1. DATA PROCESSING

Data processing was performed using the IVS Fledermaus v. 7. software suite, mainly DMagic (data preparation), Fledermaus (3D exploration, editing and visualisation) and the FM Geocoder Toolbox (backscatter and Angular Range Analysis) (IVS 3D Fledermaus, 2011). All further analyses and preparation of maps were done using ESRI ArcMap v. 10.2.1.

The raw, unedited data was gridded to 5 meters in DMagic, using the gridding algorithm Weighted Moving Average with a weight diameter of 3. PFM:s (file format used for editing) were created using the auto-processing function CUBE, were a bin size of 5 meters was selected and the output coordinate system set to WGS 84, UTM zone 21N. Otherwise the default settings were used. These files were cleaned in Fledermaus from the many artefacts and outliers, using the automatic function “Select outliers” (>2 m away from CUBE surface) as well as manual editing. The cleaned data was exported as *.xyz (ASCII) files and imported to DMagic as gridded data, in order to create new, clean SD-files (DBM:s). These files were then put together to create the bathymetric map of the entire survey area.

Before performing any analyses, the data was filtered using the edited PFM-files from the previous step. Then, the backscatter mosaic and the ARA were built using the Automatic Processing option in FMGT, with a pixel size of 1 meter. Where overlapping of track-lines impaired the result, these lines were deleted and a new image was generated. The only changes made after the backscatter mosaic had been built was editing of the histogram for better interpretability. The results from the ARA were corrected using a beam pattern correction file (*.bpt).

4. RESULTS

The resulting bathymetric map of the survey area presents a good image of the seafloor, although its resolution means no objects smaller than 5 meters are discernable. On the other hand, the features of interest in this study are much larger, so this will not be of any greater importance in the interpretation of the data. The outermost parts of the map will not be discussed in any mentionable extent, mainly because the abundance of artefacts in these areas made distinguishing of the true seafloor difficult. Otherwise the dataset presents an excellent opportunity to interpret the bathymetry and the glacial morphology of the survey area, as will be discussed in the following sections.

4.1. GENERAL DESCRIPTION OF SURVEY AREA

In total, the survey area (Figure 7, with track lines see Appendix: Figure B) covers approximately 140 km^2 of seafloor, with depths varying between 51 and 628 meters below sea level. The general appearance is characterised by a hilly relief (Bonow et al., 2006), with few flat areas, except the interior of some depressions and channels. This is similar to the landforms in Precambrian basement rocks in the Disko Bay, about 600 km south of this survey area, described by Bonow (2005). The entire area bears marks of erosion, although the degree to which different areas have been eroded varies. This dataset can be divided into two halves which are separated by a deep trough were no data could be acquired. The two halves have few similarities apart from some linear features in the shallower parts. Therefore, the general appearance of the halves will be described separately in the following paragraphs.

The most distinctive features of the northern half are the three inclined surfaces ending up in almost vertical cliffs with heights of 40 meters to the west and up to 200 meters to the east. The three cliff edges are aligned in a north-east to south-west direction and have a combined total length of 25 km. The first one from the east, which is the steepest, has its foot in a c. 470 meters deep and c. 500 meters wide trough, with a rather flat surface closest to the cliff. Further away, the seafloor becomes hillier, with flat areas inside some smaller depressions (50-100 meters in width). At the foot of the two other cliffs, to the west, there are areas of up to 100 meters out from the cliff that are more or less flat and that follows the bottom of the cliff from north to south. To the far east there are several larger depressions which are 200-700 meters across and about 100 meters deep. Like the smaller ones, these larger depressions also have completely or almost completely flat interiors. In the mid-southern part there are several incisions, of which some are parallel in a north-south direction and some seem to be more random.

The southern half does not have much in common with the northern half, except from occasional linear features. This area is instead characterised by up to 50 meters deep channels, incised into the bedrock in a meandering network. In particular, there is an almost 10 km long, more or less completely straight channel in a south-east to north-west direction, which in turn is cut by several smaller channels, some of which are perpendicular to the larger one. There are tens of channels with lengths of at least 2 km, 25-150 meters wide and 20-80 meters deep cut into the bedrock in mainly two directions, north-west and almost due north. This half also has a trough, which is smaller than the one in the northern half, and has widths of up to 500 meters and depths of 100-150 meters. Some parts of the trough lack data, but otherwise it presents what seem to be meandering sediment-filled channels. In addition to the already mentioned characteristics there are also several linear features which are particularly apparent in the flatter parts to the east. These range from a couple of hundreds of meters up to 2-3 km and are 10-20 meters deep.

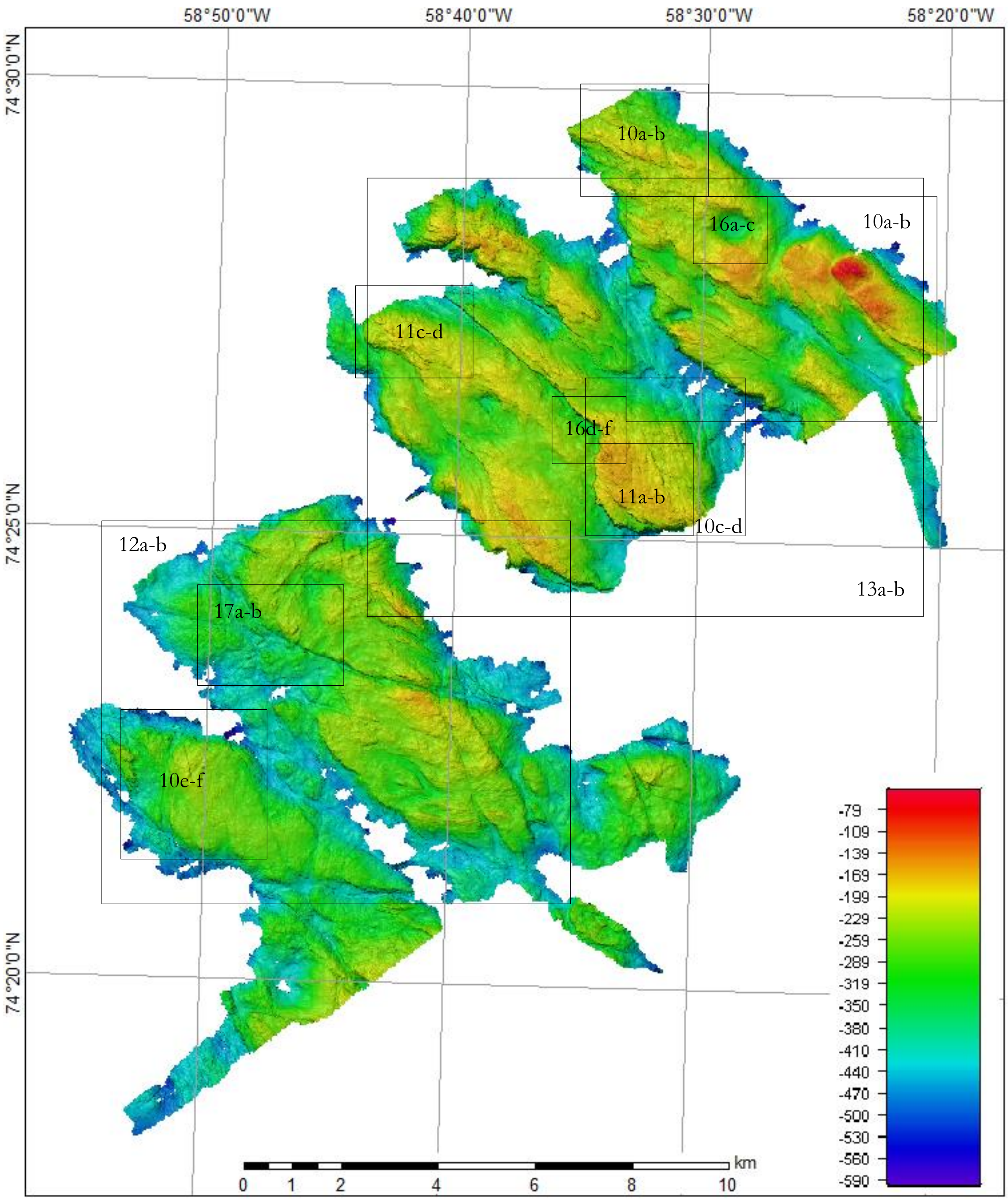


Figure 7 Bathymetry of entire survey area, acquired using a Kongsberg EM2040 multibeam echo sounder, processed, cleaned and visualised in the Fledermaus software suite. Depths in meters. Grid illuminated from the NW. Inset rectangles show discussed features, with corresponding figure numbers.

4.2. Glacial morphology

There are indications of glacial activity all over the survey area, although with varying erosional extent in different areas. There are a wide variety of morphological features of which some seem to have been shaped entirely or in part by glacial erosion. These features can be divided into different categories with similar appearance and likely to have common causes: linear features (4.2.1), melt-water channels (4.2.2) and depressions (4.2.3). Some of these are more distinctive than others and will be discussed further in the following sections, which also will include some smaller features which are likely to be related to the larger ones. For a map with all features see Appendix: Figure C.

4.2.1. LINEAR FEATURES

The flow direction of a grounded ice sheet can be indicated by different linear glaciogenic features, such as ice channels, different types of lineations and streamlined bedrock structures. The most distinctive of the three features are the ice channels, which forms when ice have been concentrated into locally deeper areas and eroded the bedrock into a smooth plastic form. These channels are especially evident in the northern part of the survey area, where their extent is several kilometres and their overall heading is to the north-northwest. Some ice channels are not as easily discernable as others, but instead show only weak signs of erosion. In areas where this is the case, other features will be more prominent.

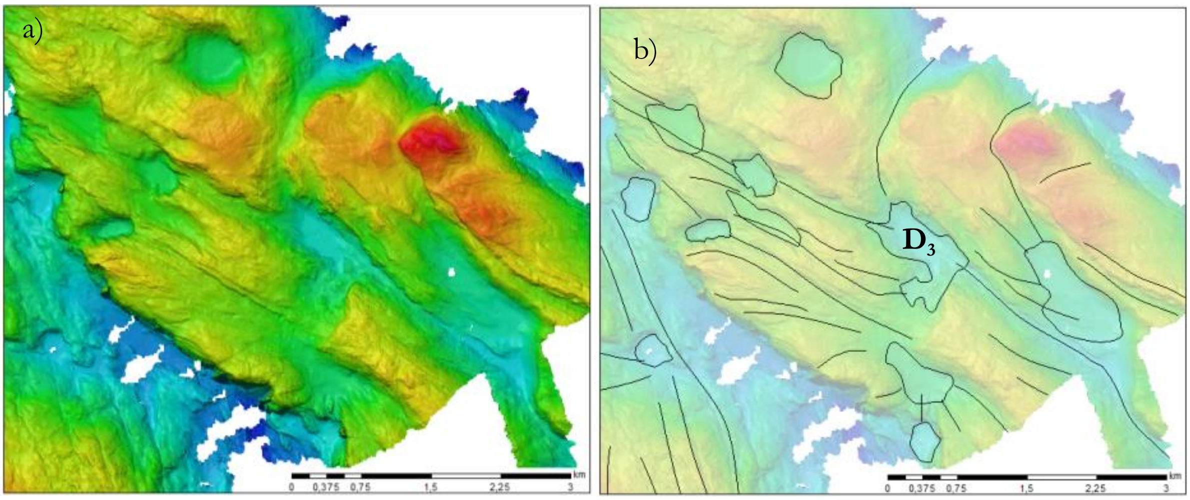


Figure 8 Linear features interpreted as ice channels, in the northern part of the survey area, where a) presents the bathymetry and b) the ice channel and depression features drawn in ArcMap. D_3 is the largest of the depressions within this area.

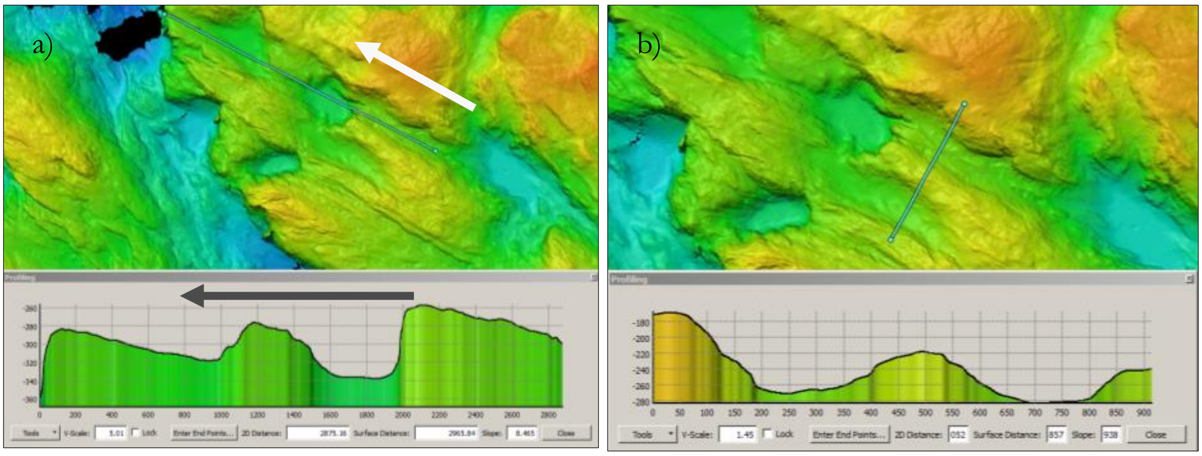


Figure 9 Cross-and length-profile of an ice channel. a) Length-profile showing over-deepened channels, where grey and white arrows indicating an estimated ice-flow direction to the north-west. b) Cross-profile of the same channel showing a smooth u-shape of the channels.

Out of the ice channels present in the northern part of the survey area, the ones with the most distinct form can be seen in Figure 8. There are several shorter channels with lengths varying between 1 and 3 kilometres and a number of depressions (see 4.2.3) in between them. The deeper parts of the channels, as well as the depressions within them, are flat and seem to be covered by a thicker layer of sediment than their surroundings. In some of the flatter parts of the channels there are undulating smaller channels in what seems to be a rather thick layer of sediment. From the deeper depression (D_3) to the north-west (Figure 8), the channel is terraced with over-deepenings of 20-60 meters in each step (Figure 9a). In cross-section, the channels are u-shaped, with flat middle-parts and are steeper to the side where there is a local high (Figure 9b).

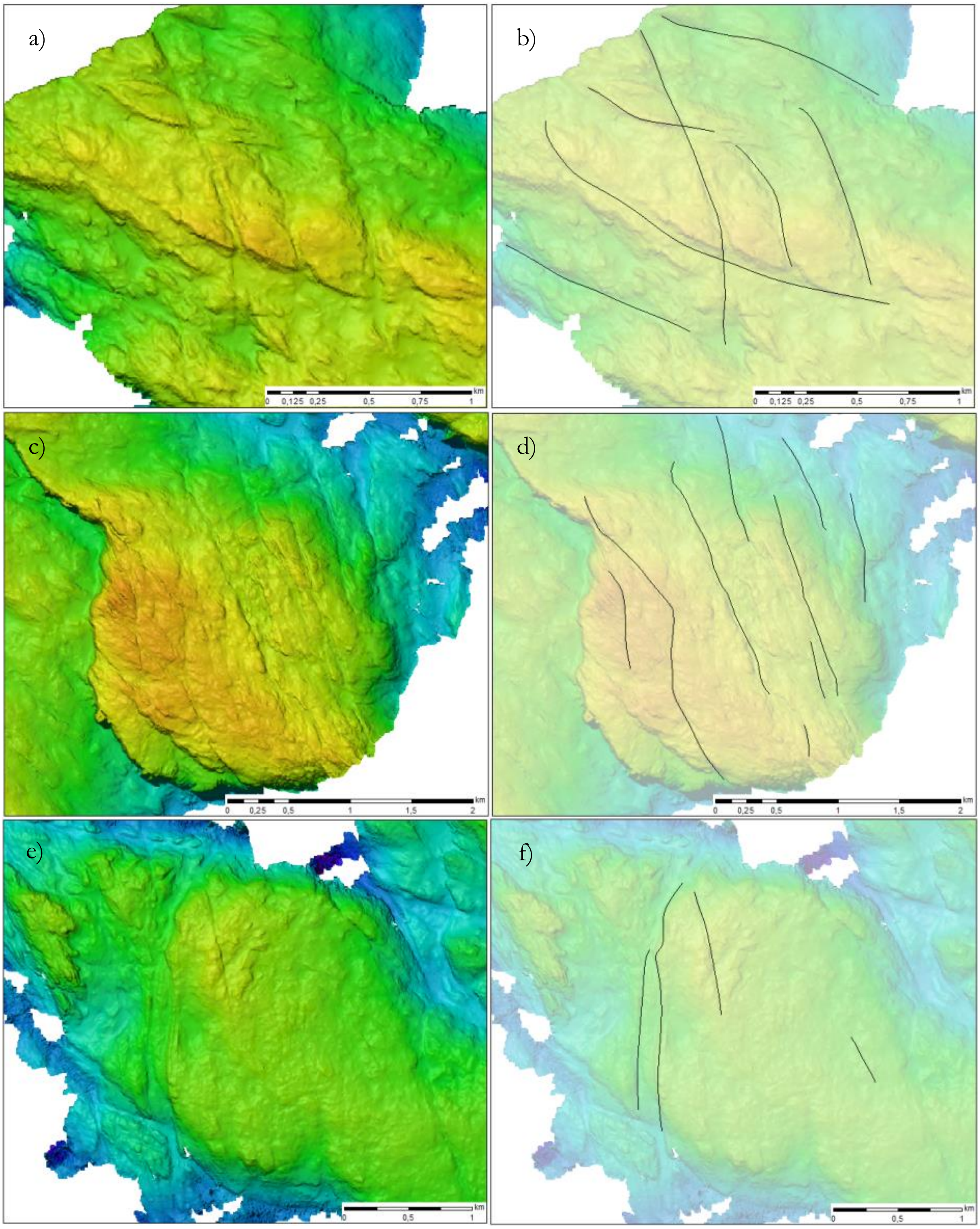


Figure 10 Different types of linear features, in the northern [a)-d)] and the southern part [e)-f)]. V-shaped incisions in a) bathymetry and b) ArcMap features. Lineations in c),e) bathymetry and d),f) ArcMap features.

Linear erosional marks can be found in different shapes, lengths and widths all over the survey area, although they are more abundant in the northern part. The smallest ones are barely discernable while the largest range up to 2-3 kilometres in length, are up to 50 meters across and have depths of 10-20 meters. In general they have a u-shaped cross-section, with either steep or gentle side slopes. Figure 10 presents the most distinctive features, where the four upper images (a-d) are from the northern part of the area and the two at the bottom (e-f) are from the south part. The features from the north are similar in that they are equally narrow, long and have a north-bound heading. They also differ from the southern features in their rougher appearance, while the features in the south are smoother, shallower and wider. On the other hand, their heading seems to be similar to the ones in the north. On the middle "terrace" in the north part, there are some areas where numerous smaller streamlined v-shaped structures can be found. These present similarities with drumlins or crags-and-tails and are all aligned in the same direction. They can be found both in the shallow and deep parts, and seem to line up with the linear erosion mentioned above.

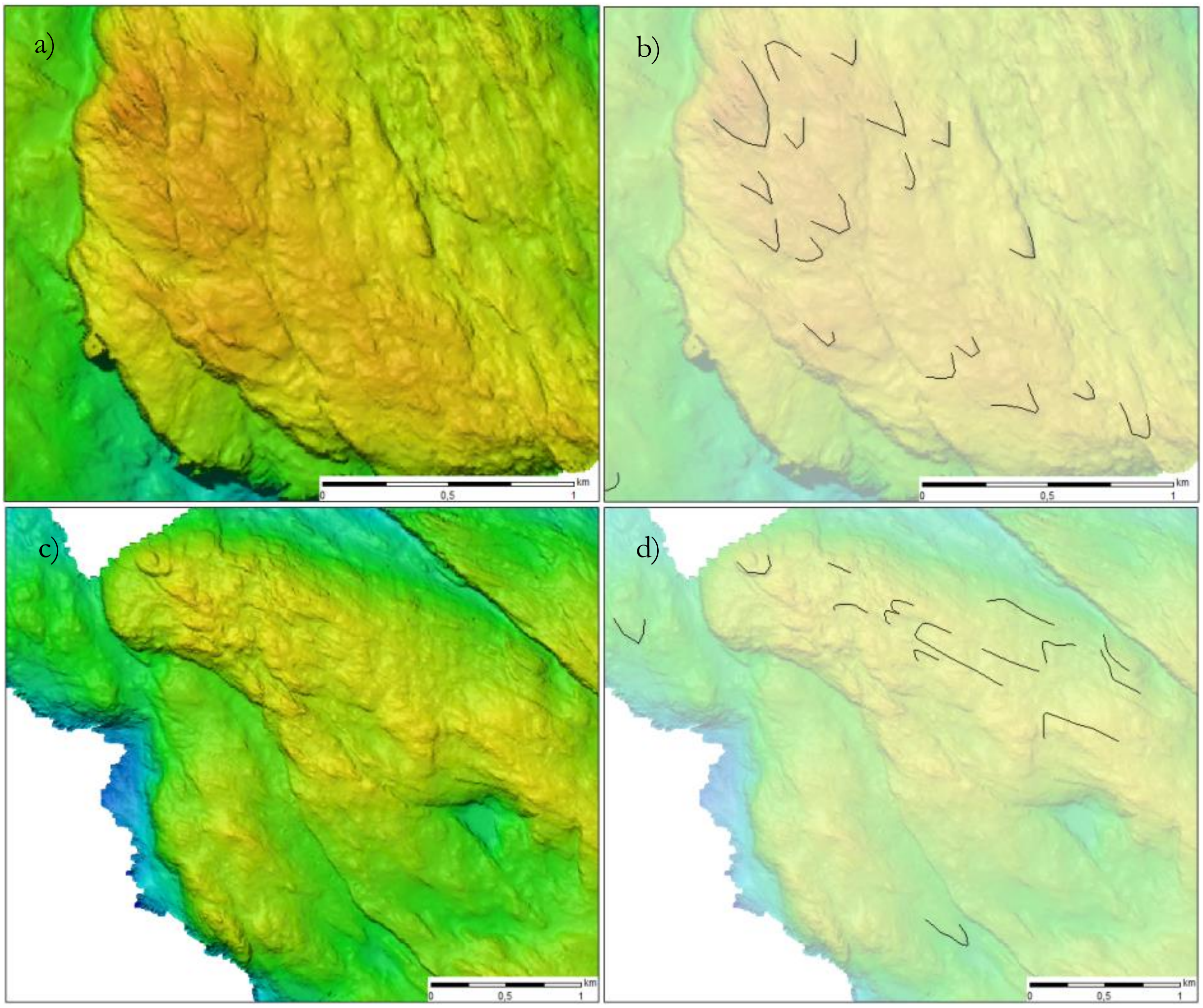


Figure 11 Streamlined features. V- to U-shaped features in a) bathymetry and b) ArcMap features and elongated streamlined features in c) bathymetry and d) ArcMap features.

4.2.2. MELT-WATER CHANNELS

When an ice sheet drains from below the melt-water needs an outlet path and if the bedding is non-permeable, eventually the water and ice, together with debris carried within them, will cut deeper and deeper into the bedrock. This is what seems to have happened in the southern part of the survey area, where there is a network of what appears to be this type of subglacial melt-water channels, cutting the bedrock in numerous places. The channels are present all over the seafloor, except for a flatter part to the south-west. They vary in length and depth and do not seem to have any consistency in their heading, but rather seem to follow local weaknesses in the bedrock. In particular there is one larger channel spanning the entire southern area from east to west. It is at least 8 kilometres long, 50-100 meters wide and up to 50 meters deep, with a smooth u-shaped cross-section and a flat bottom (Figure 12c). In the deeper, flat section of the channel network there seem to have been less erosion, although some channelling tendencies are still visible. This type of shallower and wider channel is also present in the northern part, along the cliff edge bottoms and in the equally flat and deeper section in the middle (Figure 13).

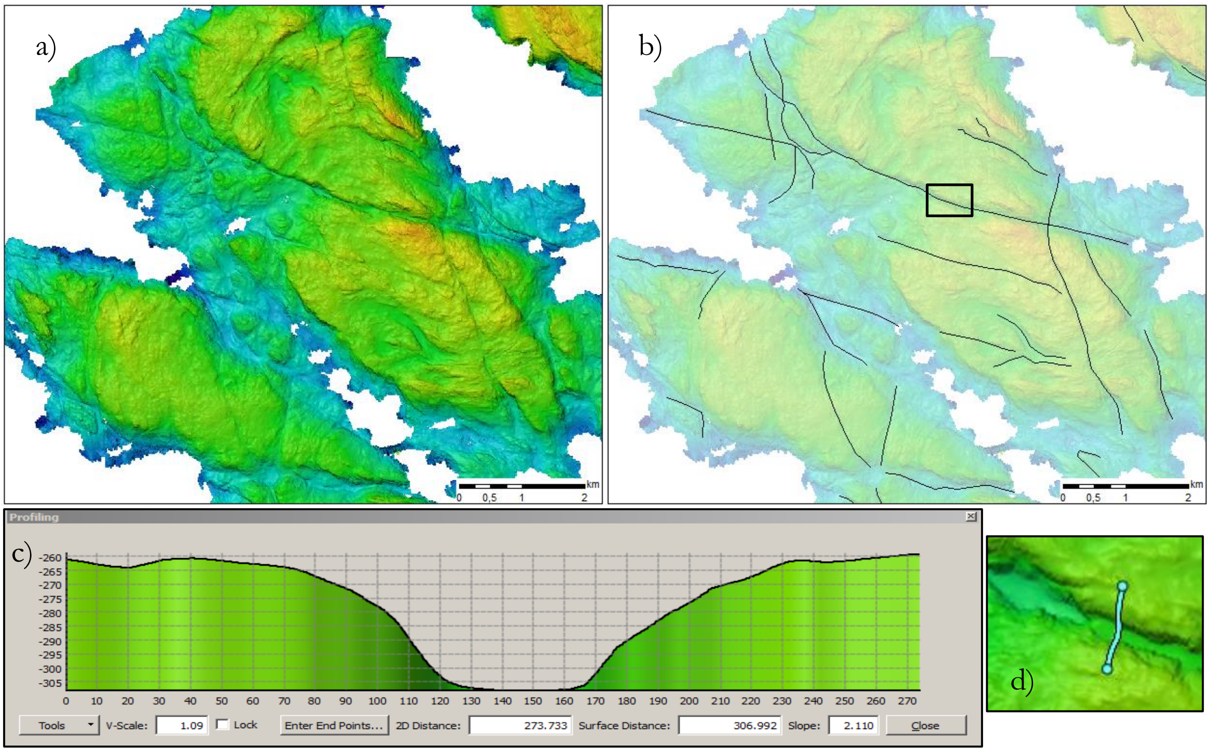


Figure 12 Network of melt-water channels, in a) bathymetry and b) ArcMap features, with the rectangle representing the area containing c) the cross-profile of the largest melt-water channel. d) Magnification of cross-profile in b) and c).

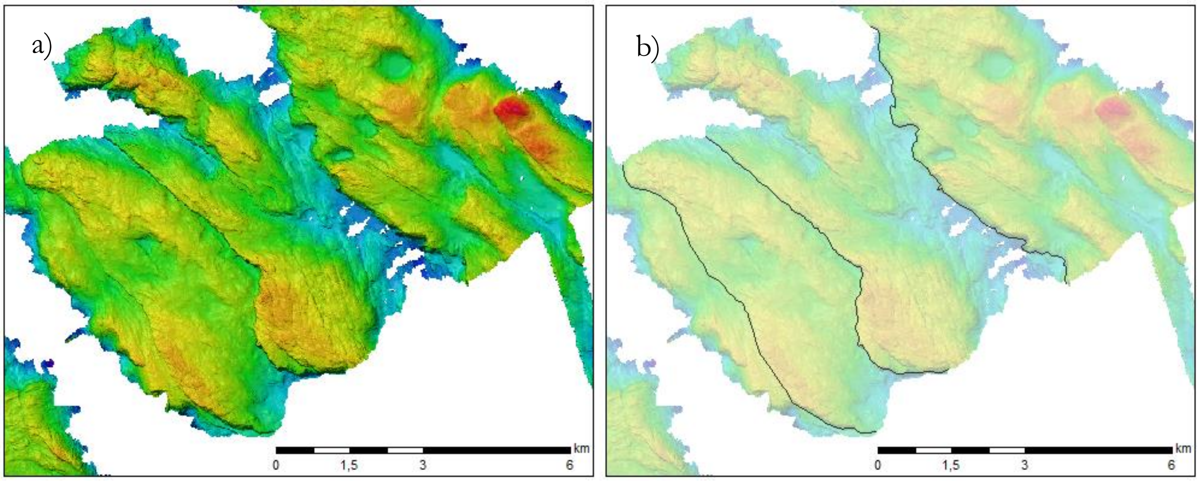


Figure 13 Likely melt-water channels along the cliff edges, in a) bathymetry and b) ArcMap features of the cliff edges.

4.2.3. Depressions

In the northern part of the survey area there are a number of depressions of varying size and shape (Figure 14), mostly concentrated to the interior or the vicinity of the ice channels mentioned earlier. They are present both in the deeper and the shallower areas and some of them have a smooth well-defined edge while others are more rugged and with indistinct shapes. Something they all have in common is that their interiors are completely or almost completely flat, indicating either ice erosion or enough post-glacial sediment deposition to even out any irregularities. They vary in size between a couple of tens of meters and a few hundred meters and the largest one is as wide as 1 000 meters from edge to edge (Figure 15). Depressions D_1 and D_4 are the deepest compared to their surroundings, with depth differences of 100 meters and 60-80 meters respectively.

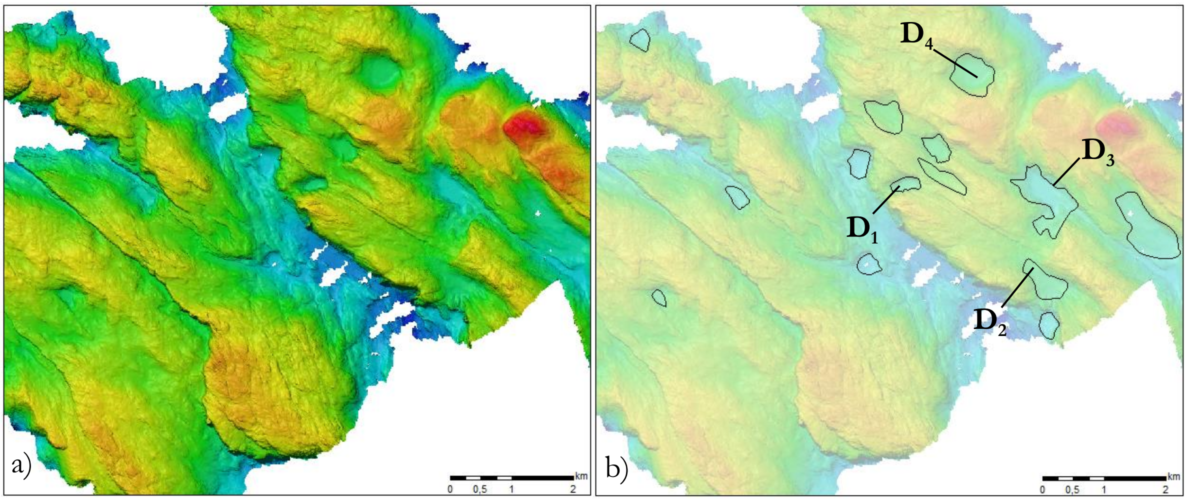


Figure 14 Distribution of depressions, in a) bathymetry and b) ArcMap features. D_1 and D_4 are the deepest, compared to their surroundings, while D_2 and D_3 represents depressions located within the ice channel.

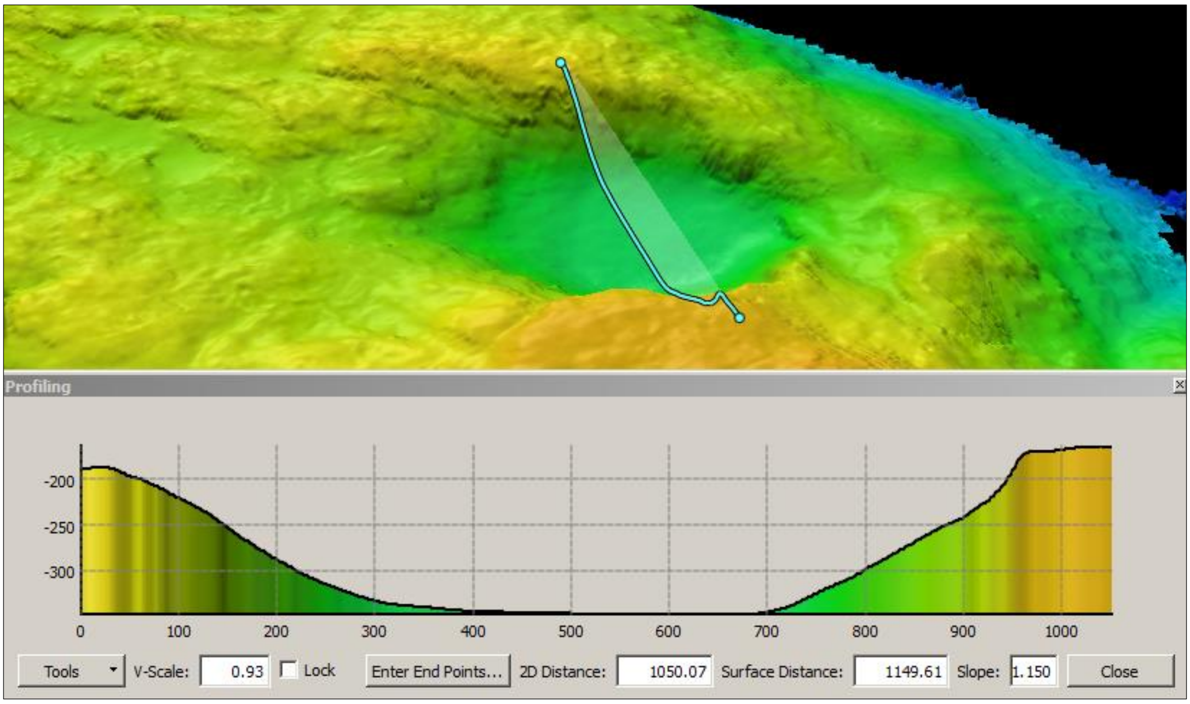


Figure 15 Cross-profile of the largest depression, the up to 1 000 meters wide depression D_4, with a flat interior 300 meters in diameter in this direction.

4.3. Surface sediment

The backscatter data (Appendix: Figure D) provides a good image of the composition of the seafloor, presenting a quite homogenous general appearance at first glance. Upon closer examination, however, it becomes apparent that the irregularities can be easily discernable. The backscatter response seems to be slightly weaker in the northern part of the area compared to the south, indicating a softer and/or smoother seabed. The response is stronger from the depressions, channels and also from below the cliffs and generally is weaker in the flatter areas (Figure 16, Figure 17). Since the ARA is based on the backscatter data, these results are more or less equivalent, with the difference that the ARA also presents sediment grain sizes and that its resolution is lower. The results from the ARA (Appendix: Figure E) divided the survey area into three parts with similar sedimentary composition, where the main grain types were clay, silt and gravel/sand (Figure 18), with the coarser sediments concentrated to the channels, the depressions and along the cliff edges and the finer to be found all over the survey area, mainly in its flatter parts.

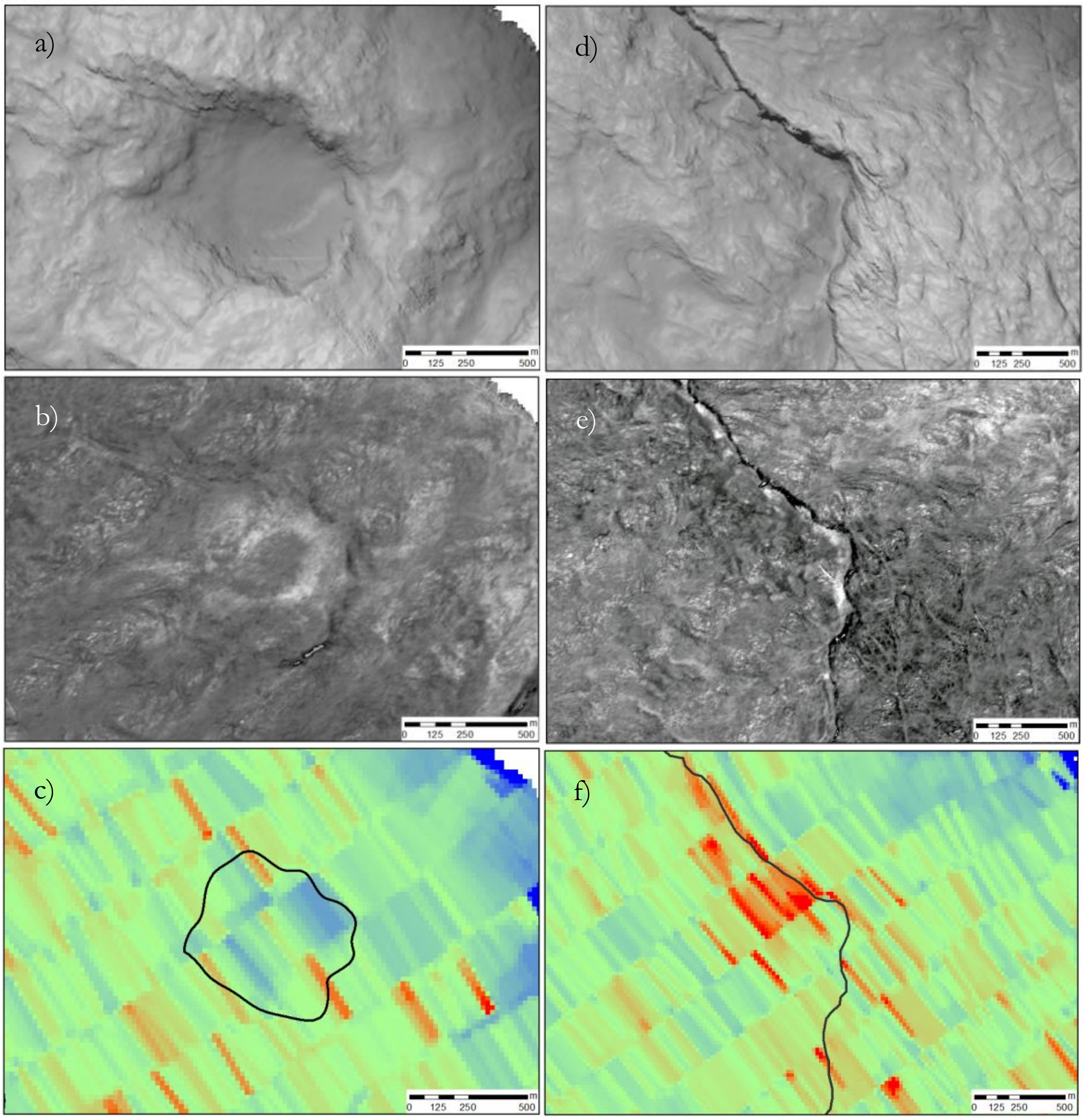


Figure 16 Close-up of depression D_4, in a) bathymetry, b) backscatter and c) ARA-result. In b), a ring of coarser sediments is visible in a lighter colour. Close-up of cliff edge, in d) bathymetry, e) backscatter and f) ARA-result. Both from the northern part of the survey area.

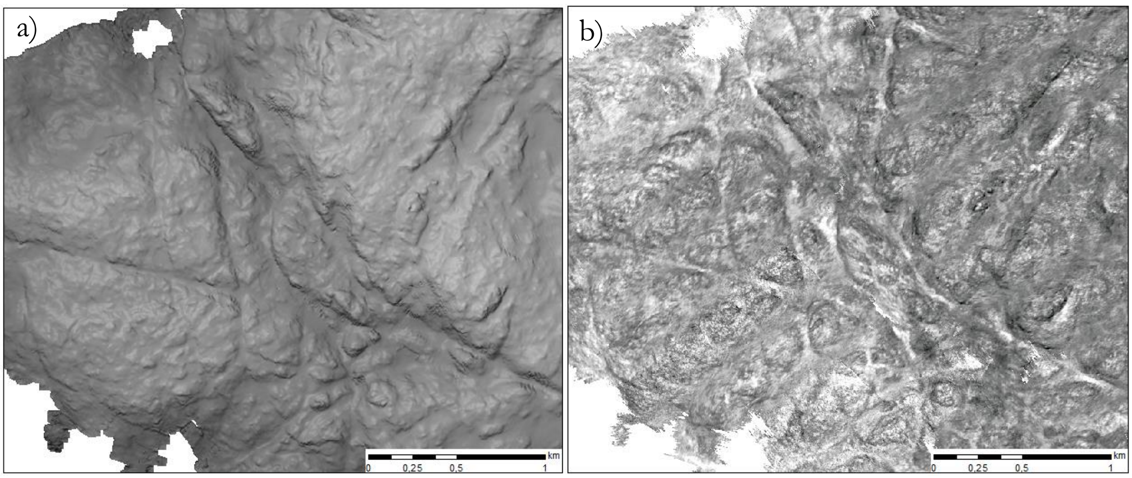


Figure 17 Melt-water channel network, magnification of area to the north-west, in a) bathymetry and b) backscatter. In the latter, the lighter colour of the channels represents a stronger backscattered signal, corresponding to coarser sediments.

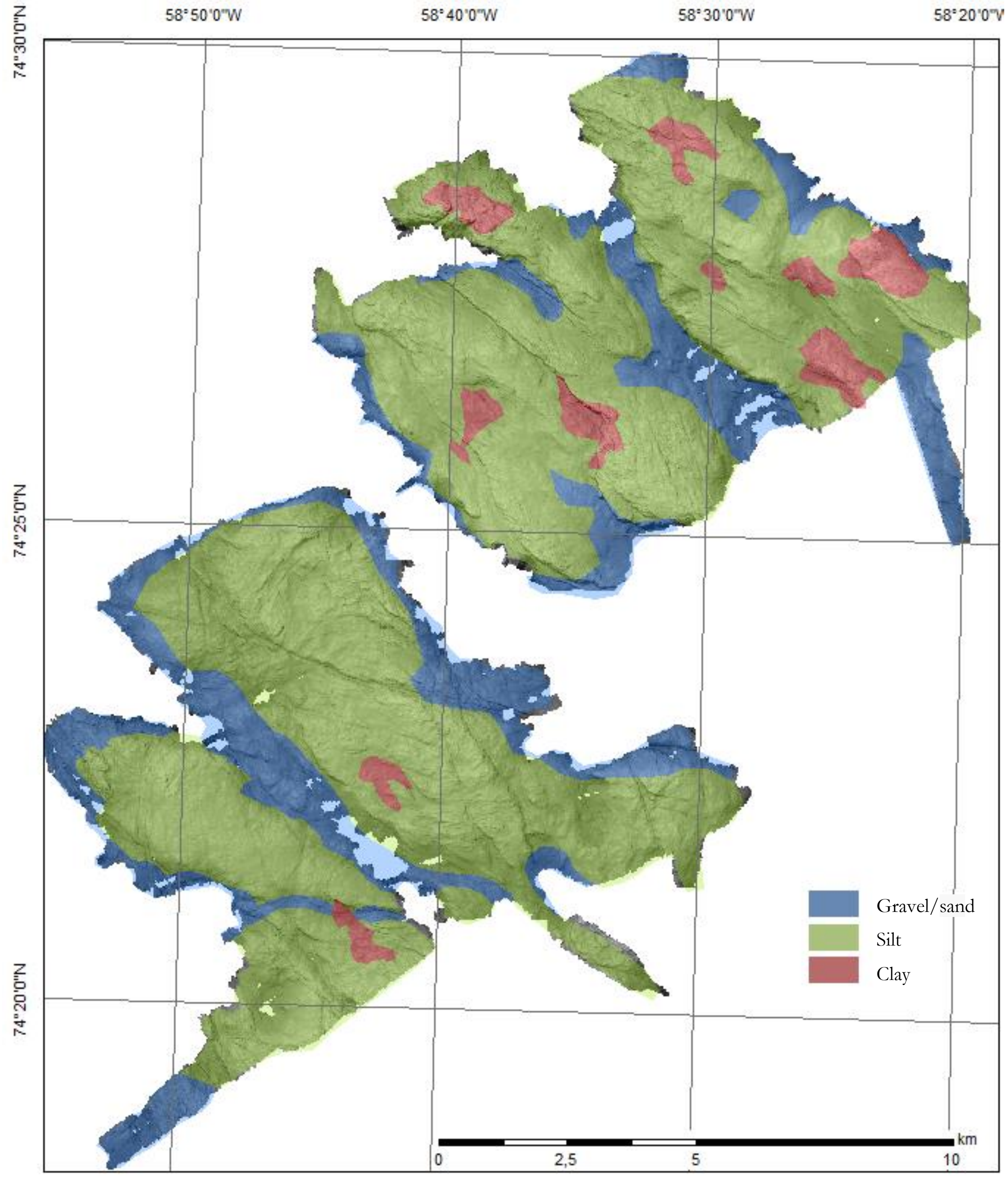


Figure 18 Results from the Angular Range Analysis (ARA), where the backscatter strength is used to estimate surface sediment type. The results presents different areas with similar surface sediment, where blue = gravel/sand, green = silt, red =clay. Drawn in ArcMap, after Figure E (Appendix).

5. DISCUSSION

The main focus of this thesis was to map and interpret the morphology and the surface sediment of the seafloor using swath bathymetry and reflectivity data acquired during the VEGA expedition. The resulting maps provide a good possibility to investigate the glacial landforms and the distribution of different sediment types in the survey area, although the grid size resolution of 5 meters evens out smaller features, making them indiscernible. However, the features of interest in this study are much larger and therefore the grid resolution will not affect the interpretation of the data. The general appearance of the seafloor in the survey area is hilly, and there are few areas that are completely flat. The two parts, northern and southern, are very different compared to each other, with little coherence in their appearance apart from some linear erosional marks. This is especially interesting since they in general have similar depths, and there is only about 10 kilometres between the centres of the two parts. The different appearances of the two halves may be caused by different bedrock composition, with possibly slightly softer bedrock in the northern part, or by different subglacial conditions, as will be further discussed below.

5.1. GLACIAL MORPHOLOGY

Many of the morphological features in the survey area are likely to have been caused by glacial erosion from a grounded ice sheet originating from Greenland. The relatively crude appearance of the features, with a seemingly thin cover of post-glacial sediment, indicates formation, at least to some extent, during the last glacial. However, age determinations of the features will not be possible to perform in this study, because no bottom samples are available. The most distinctive features have a general heading to the north-west, which also seems to be the heading of the closest outlet glacier and of linear glacial erosion onshore (Figure 19). The survey area presents varying rates of erosion, something that is likely to have been affected by different subglacial conditions. These conditions partly depend on bedrock type, where harder bedrock will undergo less transformation than a softer one. The erosion rate also depends on whether the ice is warm- or cold-based, where a warm-based ice sheet will be floating on top of a thin layer of melt-water mixed with sediment, causing more erosion than a cold-based ice sheet. A cold-based ice sheet, on the other hand, would not modify the bedding in any mentionable extent, leaving the pre-glacial structures almost intact. The different signs of glacial activity, where some are more apparent than others, have different causes and can be divided into the following categories, as was mentioned in the previous chapter: 1) linear features, 2) melt-water channels and 3) depressions.

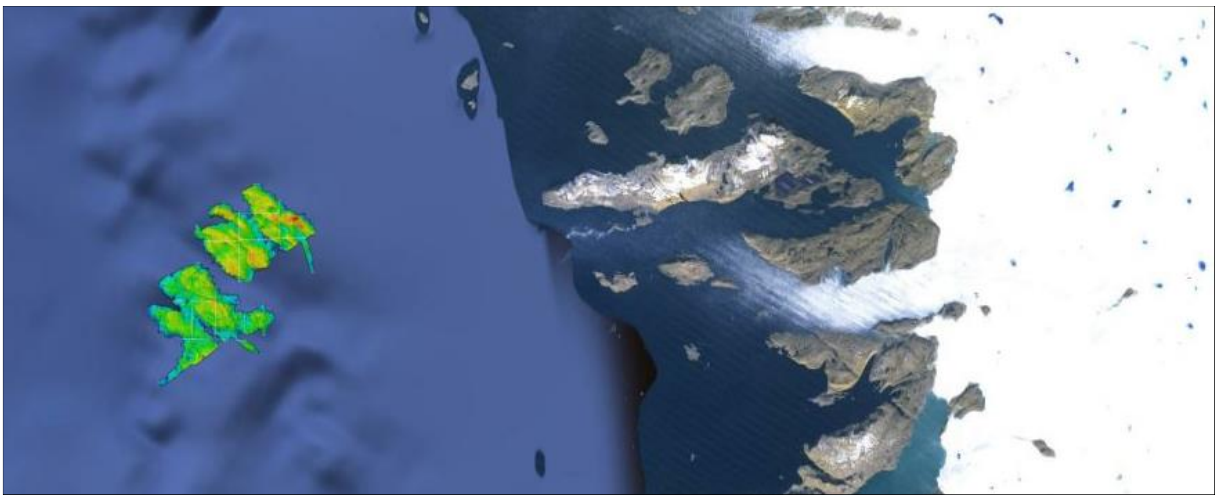


Figure 19 Closest (current) outlet glaciers of the Greenland Ice Sheet, suggesting an ice-flow direction to the west/north-west. Onshore, the exposed bedrock presents similar linear features as in the survey area. (LANDSAT images from Google Earth).

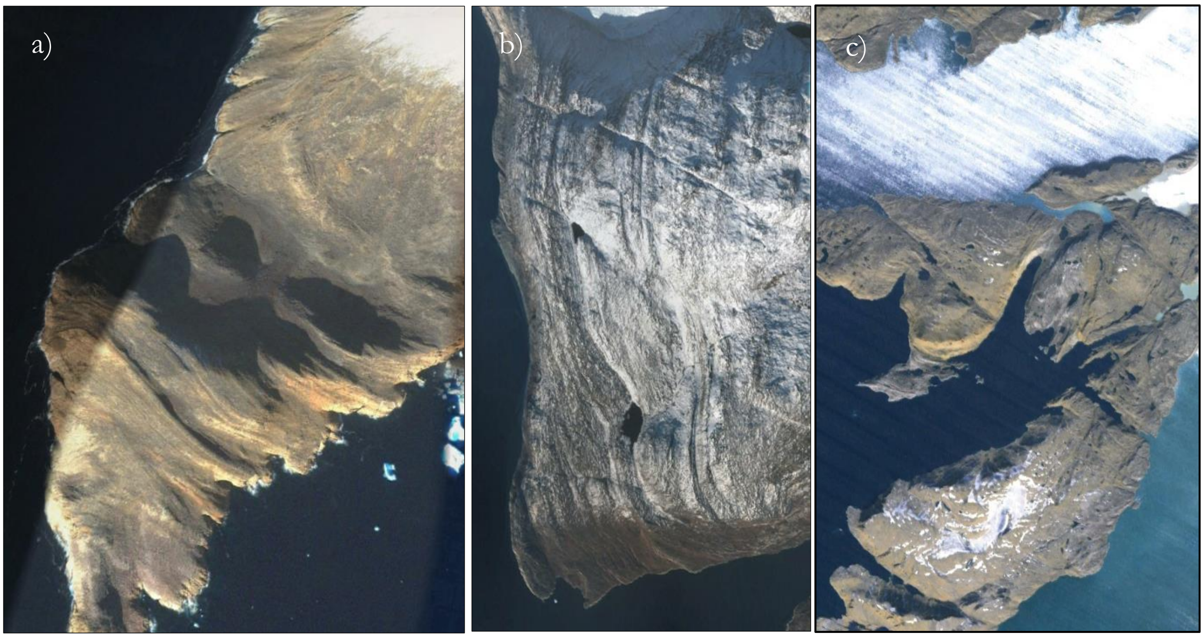


Figure 20 Similar features in the exposed bedrock onshore, due east. a) and b) linear erosion marks and c) deep incision and what appears to be a partly water filled ice channel. As in the offshore morphology, many of the linear features have a heading to the north-west. (LANDSAT images from Google Earth).

5.1.1. LINEAR FEATURES – INTERPRETATION

The linear features are present all over the survey area, with a higher concentration in the northern part. Because of the varying extent of erosion in different areas, it is likely the ice sheet eroding the seafloor have been alternately cold-based and warm-based, causing differing subglacial conditions. This is partly discussed by Livingstone et al (2012b), who mentions that these types of bedforms implies a fast, wet-based ice-flow, which in turn promotes high erosional rates. On the other hand, there are areas where erosion is not as extensive as in other places and this might thus be explained by the fact that the ice sheet has been locally cold-based. Other important factors are the original morphology and the hardness of the outcropping bedrock, the first affecting the paths taken by the ice and the latter affecting the ice's erosional impact on the bedrock.

The most distinctive of the linear features is the ice channel presented in section 4.2.1 (Figure 8), which is smoother than its surroundings and also deeper that the other nearby channels. This is likely because of softer bedding and/or a higher ice-flow rate, causing more erosion. Its interior is filled with lineations, depressions and gouged areas of bedrock. As mentioned earlier, the length-profile in Figure 9 shows a terraced form with over-deepenings in each of the steps. These over-deepenings are typical of glacially eroded bedrock, as the ice's momentum causes increased erosion on the closest part of the lower terrace when the ice flows over the first terrace's edge. The terraced form and over-deepenings of the channel suggests the ice-flow direction is to the north-west. Onshore, there are some morphological similarities, for example the water-filled middle part of Figure 18c, which also is likely to be a former ice channel.

The majority of the different features presented, the narrower lineations and the wider streamlined landforms, also show a general heading to the north-west. Some of the linear features are similar in appearance to those discussed by Hogan et al. (2010) and Livingstone et al. (2012b); (Figure 21). According to the latter, these types of bedforms depend on the structural geology of the bedrock. One important difference is the scale, where the bedforms in Figure 21 are much larger than those discussed in the survey area. Despite this, the crude bedrock forms in Figure 21a have great similarities with the deeper trough areas in the survey area, with rougher outcropping bedrock and possibly a layer of sediment in the deeper parts. Figure 21b on the other hand shows similarities with the shallower flatter parts in the northern area, presented in Figure 10a-d and Figure 11a-d, although the features are less streamlined in the two latter. It is possible these features are caused by a combination of ice sheet abrasion and melt-water erosion.

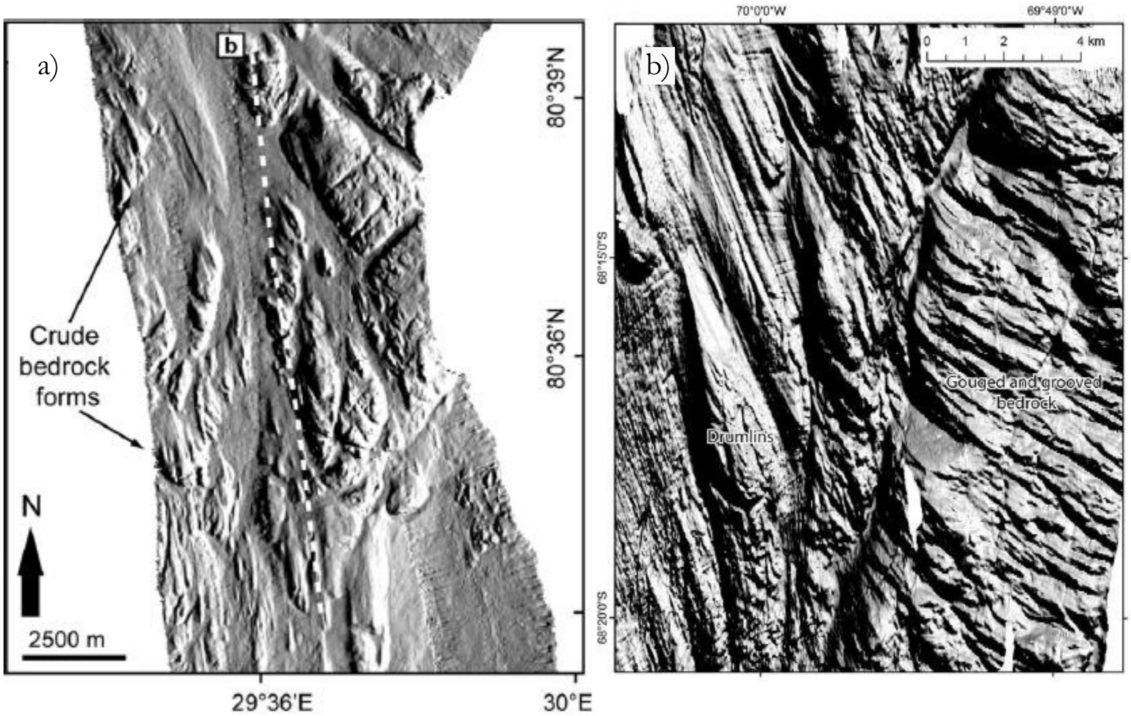


Figure 21 Examples of crude gouged and grooved bedrock forms a) in central Kvitøya Trough, northwestern Barents Sea (Hogan et al., 2010), and b) on the mid-shelf in Marguerite Bay, Antarctica (Livingstone et al., 2012a).

5.1.2. MELT-WATER CHANNELS – INTERPRETATION

The melt-water channels in the survey area can be divided into two categories, of which the first, with its deep incisions into the bedrock, is present mainly in the southern part, and the second can be found in the flat deeper areas in both the northern and southern part. Seemingly the two types have formed under similar conditions, when the need for drainage of the melt-water have become sufficiently great for the water to have a high enough flow rate to erode the underlying bedrock. The incised channels do not have any uniform direction, but rather seem to follow structural weaknesses in the bedding, such as joints, faults or zones with softer bedrock. Similar features can be found onshore, for example see Figure 20c. Considering the flatter channels closest to the cliffs, they follow the local morphology along the cliff edge, where it is possible the ice did not fully reach all the way in, creating a "cavity" were melt-water could flow freely. The difference between the two types of channels is that the first are narrower and deeper, with a seemingly thinner layer of sediment at their bottom, while the second type is wider and shallower, with a sediment layer thick enough to give their interiors a flat appearance. Apart from the melt-water channels, the rest of the southern half does not have many glacial features, but is seems the bedrock is rather untouched by the erosion of the ice sheet. This promotes the idea of a cold-based ice sheet, preceding the formation of the melt-water channels in the southern part of the survey area. This can be referred to as a relict landscape, where one characteristic feature is melt-water channels superimposed on bedrock without any other signs of glacial erosion (Kleman & Hättestrand, 1999).

Melt-water channels of the type where water have eroded the bedrock are discussed by several authors. Hogan et al. (2010) states that this type of channel systems forms due to erosion from pressurised melt-water and that this pressurised water can result in channel sections with different sloping directions. Livingstone et al. (2012b) claims that this type of drainage network can be described as a system of channels and can be incised into ice, sediment or bedrock.

Furthermore, great morphological similarities can be seen between the melt-water channels in this area and those found in the Palmer Deep Outlet Sill, Antarctica, discussed by Livingstone et al. (2012a), (Figure 22).

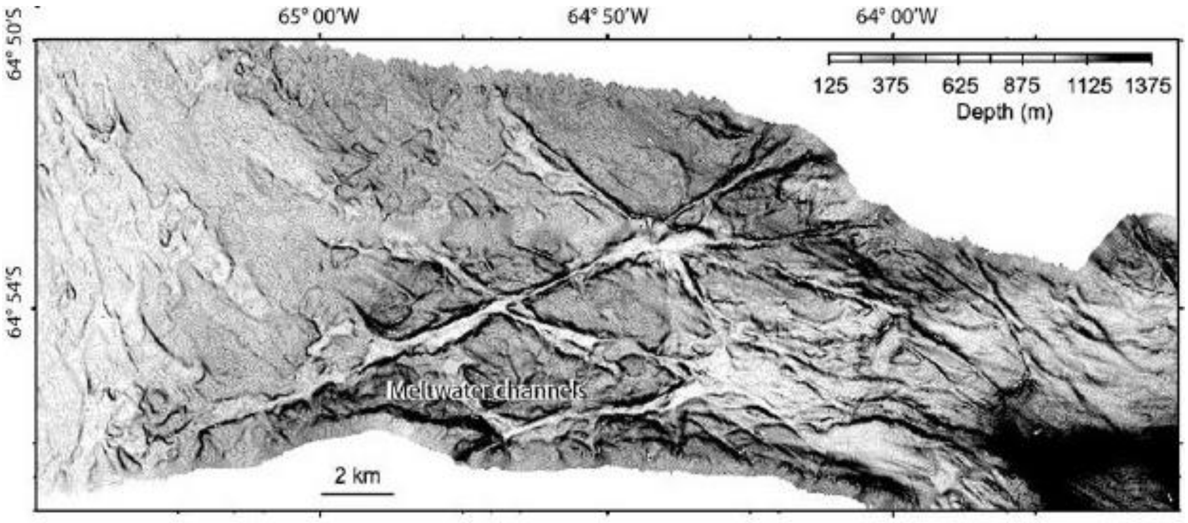


Figure 22 Melt-water channel network cut into bedrock of the Palmer Deep Outlet Sill, Antarctica (Livingstone et al., 2012a).

5.1.3. DEPRESSIONS – INTERPRETATION

The depressions found in the northern part of the survey area can be interpreted as small subglacial lakes or kettle lakes and might have formed, or at least to some extent have been reshaped, beneath the advancing ice sheet. Similarities in the onshore morphology can be found slightly to the south-east of the survey area (Figure 23). The two deepest depressions compared to their surroundings, D_1 and D_4 in Figure 14, are likely to be pre-glacial structures further eroded during the last glaciation. Some of the other depressions, such as D_2 and D_3 which are located within the ice channels, are shallower and may well have been formed by glacial erosion. As have been discussed in the interpretations of the other features, there are several possible explanations to the different erosional extents, such as the original morphology and different bedrock types. In general in this case it is likely that some of the depressions were created during the glaciation and that others were present before.

Figure 23 Onshore depressions of varying size and shape, in part similar to those found in the survey area. (LANDSAT images from Google Earth).

Subglacial lakes are defined as discrete bodies of water that lie at the base of an ice sheet, between the ice and its bedding (Siegert, 2000), and one of the most important factors is the bed topography, with melt-water accumulation in depressions. Unfortunately it is not possible to verify whether water have been trapped in the depressions found in the survey area, but considering the following, there is a possibility this occurred during the last glaciation.

Livingstone et al. (2012b) mentions the similarities between large isolated basins of the innermost shelf and subglacial lakes and discusses different theories as to how these are formed. One of these is the Captured Ice Shelf hypothesis which regards subglacial lakes on land. The hypothesis states that these subglacial lakes can be remnants of pre-glacial depressions where water becomes trapped under the ice sheet as it advances. This might be applicable in submarine conditions as well, assuming the water in the depressions would not be pushed out by the ice sheet, but instead remain trapped beneath it. Livingstone et al. (2012b) further discuss the possibility that glacial erosion itself can form depressions which later becomes subglacial lakes, filling up with melt-water draining from the ice sheet. This could be applicable to the ice channels connected to the depressions, and the smaller undulating channels in the sediments visible within the larger channels. Figure 24 depicts the two different theories, with pre-existing depressions where water gets trapped to the left and depressions formed by ice sheet erosion, and later filled with melt-water to the right.

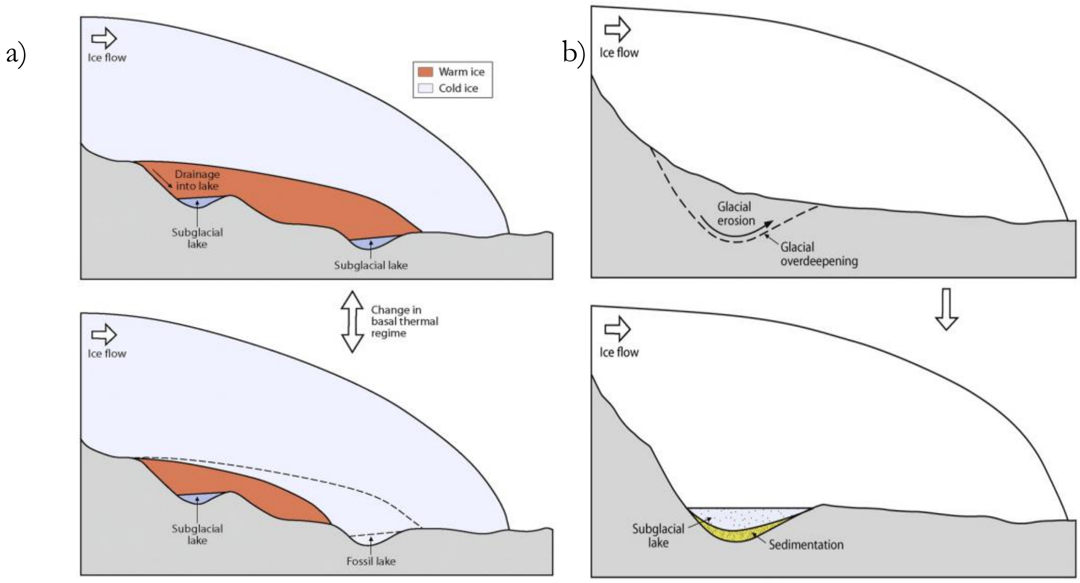


Figure 24 Possible formation causes of the depressions. a) Subglacial lakes forming in pre-existing depression. b) Subglacial lakes formed by glacial erosion, filling up with melt-water draining from the ice sheet. (modified from Livingstone et al., 2012b).

5.2. SURFACE SEDIMENT

The results from the backscatter and ARA provide a decent image of the distribution of different sediment grain sizes in the survey area. However, these results do not provide any information on the types of sediments present, or where they came from. For this to be possible, bottom samples are needed in order to investigate the age, composition and origin of the sediments. Despite the hilly relief seen in the bathymetry, the reflectivity data suggest that the survey area is covered by finer sediments such as clay and silt, with the exception of the deeper troughs, the melt-water channels and the depressions, where coarser sediments are presented. This could be explained by the presence of a sediment layer thick enough to scatter the incident acoustic wave. The concentration of the coarser sediments might be due to either melt-water flow under the ice sheet or to present-day currents following the seafloor topography's deeper areas. Both include higher water velocities, which would allow the currents to carry smaller grains, leaving the largest, such as gravel, behind. Another possibility is that debris carried within the ice was deposited in the melt-water channels if parts of the underside have melted. In one of the larger depressions (D_4), there is a ring of coarser sediment lying in the middle of the flat interior, something that also might have been the result of water currents. It is possible the currents have changed into a circular motion within the depression, concentrating the coarser sediments into the ring shape. The distribution of the finest sediments seems to be concentrated to the local highs, likely because of calmer conditions, allowing the fine sediments to settle.

6. CONCLUSIONS

As the objectives for this thesis was to map and interpret glacial morphology, as well as to investigate the possibility to map and categorise surface sediment, the results have served their purpose. There are several morphological features likely to have been caused by ice and/or melt-water erosion beneath a grounded ice sheet originating from the Greenland Ice Sheet, among others melt-water channels and ice channels. However, without sediment coring samples it is impossible to draw any firm conclusions regarding the timing of these erosional events, although it is likely they occurred during the last glaciation. The features present in the survey area have similarities with formations in the ice-free coastal areas due east. Regarding the second objective, the results from the backscatter and Angular Range Analysis provides a possibility to define areas of similar surface sediment type. According to these results, the survey area is covered by finer sediments in general and has a concentration of coarser sediments in the deeper areas, such as in the different channels and within the depressions. Since no bottom samples are available for correlation with the results from the backscatter and ARA, no certain conclusions can be drawn regarding the sedimentary composition of the survey area.

The results can be summarized as follows:

- The general appearance of the seafloor in the survey area is hilly, with great differences between the northern and southern parts. The erosion extent varies, with wide, smooth features in the north, and narrow, deep and coarse features in the south. These differences are likely to be the result of different erosion rates, caused by different seafloor composition and/or different subglacial conditions. The wider smoother features in the northern part are likely formed under a warm-based ice sheet, while the rougher appearance of the southern part is likely due to a locally cold-based ice sheet, which prevented any significant erosion. However, the melt-water channels are formed under a warm-based ice-sheet, which indicates local differences in subglacial conditions over time.
- The presence of linear features, created by the progression of the ice sheet, indicates a more or less uniform general heading to the north-northwest. Most prominent of the linear features is one of the ice channels, which has over-deepened terraces that strongly suggest an ice-flow in the same direction. Onshore, similar linear features can be found, with headings coinciding with that of the majority of the features in the survey area.
- In the southern part, a network of melt-water channels with deep and elongated incisions in the bedrock can be found. These channels are likely to have formed when the melt-water from the ice sheet needed an outlet path.
- A number of depressions of varying size and shape can be found in the north. These are likely former subglacial lakes and are either pre-glacial landforms not affected to any greater extent by the ice sheet, or were created by glacial erosion beneath the ice sheet.
- The sediment distribution analyses presented coarser sediments in the deeper areas, such as in the channels and troughs, and finer sediments in the shallower, flatter areas. This distribution is likely due to differences in water current strengths, with locally higher water velocities in the deeper areas, and calmer conditions in the shallower.

6.1. FUTURE RESEARCH

In order to fully understand the glaciation history of Melville Bay further research is needed, especially in the form of seismic- and multibeam surveying over larger areas for mapping of the bathymetry and sub-seafloor features. Also, sediment and/or bedrock sampling is essential to determine the composition of the seafloor, and is important for obtaining chronological constrains and for correlation with other areas.

References

Benn, D.I. & Evans, D.J.A., (2013). *Glaciers & glaciation.* 2nd edition. Routledge: Oxon. ISBN 13: 978-0-340-90579-1.

Bennike, O. & Björck, S., (2002). *Chronology of the last recession of the Greenland Ice Sheet.* Journal of Quaternary Science 17(3): 211-219. doi:10.1002/jqs.670.

Bennike, O., (2008). *An Early Holocene whale from Melville Bugt, Greenland.* Quaternary Research 69: 72-76. doi:10.1016/j.yqres.2007.10.004.

Bonow, J.M., (2005). *Re-exposed basement landforms in the Disko region, West Greenland – disregarded data for estimation of glacial erosion and uplift modelling.* Geomorphology 72: 106-127. doi:10.1016/j.geomorph.2005.05.006.

Bonow, J.M., Lidmar-Bergström, K. & Japsen, P., (2006). *Palaeosurfaces in central West Greenland as reference for identification of tectonic movements and estimation of erosion.* Global and Planetary Change 50: 161-183. doi:10.1016/j.gloplacha.2005.12.011.

Briner, J.P., Håkansson, L. & Bennike, O., (2013). *The deglaciation and neoglaciation of Upernavik Isstrom, Greenland.* Quaternary Research 80: 459-467. doi:10.1016/j.yqres.2013.09.008.

Fleming, K. & Lambeck, K., (2004). *Constraints of the Greenland Ice Sheet since the Last Glacial Maximum from sea-level observations and glacial-rebound models.* Quaternary Science Reviews 23: 1053-1077, doi:10.1016/j.quascirev.2003.11.001.

Fonseca, L. & Mayer, L., (2007). *Remote estimation of surficial seafloor properties through the application Angular Range Analysis to multibeam sonar data.* Mar Geophys Res 28: 119-126, doi:10.1007/s11001-007-9019-4.

Fonseca, L., Brown, C., Calder, B., Mayer, L. & Rzhanov, Y., (2009). *Angular Range Analysis of acoustic themes from Stanton Banks Ireland: A link between visual interpretation and multibeam echosounder angular signatures.* Applied Acoustics 70: 1298-1304, doi:10.1016/j.apacoust.2008.09.008.

Henriksen, N., Higgins, A.K., Kalsbeek, F. & Pulvertaft, T.C.R., (2009). *Greenland from Archaean to Quaternary – Descriptive text to the 1995 Geological map of Greenland, 1:2 500 000.* 2nd edition. Geological Survey of Denmark and Greenland (GEUS): Copenhagen. ISBN: 987-87-7871-258-5.

Hogan, K.A, Dowdeswell, J.A., Noormets, R., Evans, J., Ó Cofaigh, C. & Jakobsson, M., (2010). *Submarine landforms and ice sheet flow in the Kvitøya Trough, northwestern Barents Sea.* Quaternary Science Reviews 29: 3545-3562, doi:10.1016/j.quascirev.2010.08.015.

IVS3D Fledermaus, (2011). *Fledermaus Reference Manual* . Version 7.

Jakobsson, M., Polyak, L., Edwards, M., Kleman, J. & Coakley, B., (2008). *Glacial geomorphology of the Central Arctic Ocean: the Chukchi Borderland and the Lomonosov Ridge.* Earth Surface Processes and Landforms 33: 526-545. Doi: 10.1002/esp.1667.

Jakobsson, M., Mayer, L.A., Coakley, B., Dowdeswell, J.A., Forbes, S., Fridman, B., Hodnesdal, H., Noormets, R., Pedersen, R., Rebesco, M., Schenke, H.W., Zarayskaya, Y., Accettella, D., Armstrong, A., Andersom, R.M., Bienhoff, P., Camerlenghi, A., Church, I., Edwards, M., Gardner, J.V., Hall, J.K., Hell, B., Hestvik, O.B., Kristoffersen, Y., Marcussen, C., Mohammad, R., Mosher, D., Nghiem, S.V., Pedrosa, M.T., Travaglini, P.G. & Weatherall, P. (2012). *The International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0.* Geophysical Research Letters 39, L12609, doi: 10.1029/2012GL052219.

Jakobsson, M., (2013). *VEGA 2013: Expedition log.* http://www.geo.su.se/index.php/research/expedition-logs/838-vega-2013-expedition-log. Accessed 2014-04-06.

Kleman, J. & Hättestrand, C., (1999). *Frozen-bed Fennoscandian Laurentide ice sheets during the Last Glacial Maximum.* Nature 402: 63-66.

Le Bas, T.P. & Huvenne, V.A.I., (2009). *Acquisition and processing of backscatter data for habitat mapping – Comparison of multibeam and sidescan systems.* Applied Acoustics 70: 1248-1257, doi:10.1016/j.apacoust.2008.07.010.

Livingstone, S.J., Ó Cofaigh, C., Stokes, C.R., Hillenbrand, C-D., Vieli, A. & Jamieson, S.S.R., (2012a). *Antarctic palaeo-ice streams.* Earth-Science Reviews 111: 90-128. doi:10.1016/j.earscirev.2011.10.003.

Livingstone, S.J., Clark, C.D., Piotrowski, J.A., Tranter, M., Bentley, M.J., Hodson, A., Swift, D.A. & Woodward, J., (2012b). *Theoretical framework and diagnostic criteria for the identification of palaeo-subglacial lakes.* Quaternary Science Reviews 53: 88-110. http://dx.doi.org/10.1016/j.quascirev.2012.08.010.

Lurton, X. (2010). *An Introduction to Underwater Acoustics. Principles and Applications.* Springer-Verlag: Berlin. ISBN: 978-3-540-78480-7.

Polyak, L., Edwards, M.H., Coakley, B.J. & Jakobsson, M., (2011). *Ice shelves in the Pleistocene Arctic Ocean inferred from glaciogenic deep-sea bedforms.* Nature 410: 453-457.

Randall, R.E., (2008). *Elements of Ocean Engineering.* 2nd edition. Society of Naval Architects and Marine Engineers (SNAME). ISBN: 978-0-939773-77-0.

Siegert, M.J., (2000). *Antarctic subglacial lakes.* Earth-Science Reviews 50: 29-50.

Whittaker, R.C., Hamann, N.E. & Pulvertaft, T.C.R., (1997). *A New Frontier Province Offshore Northwest Greenland: Structure, Basin Development, and Petroleum Potential of the Melville Bay Area.* AAPG Bulletin 81: 978-998.

APPENDIX

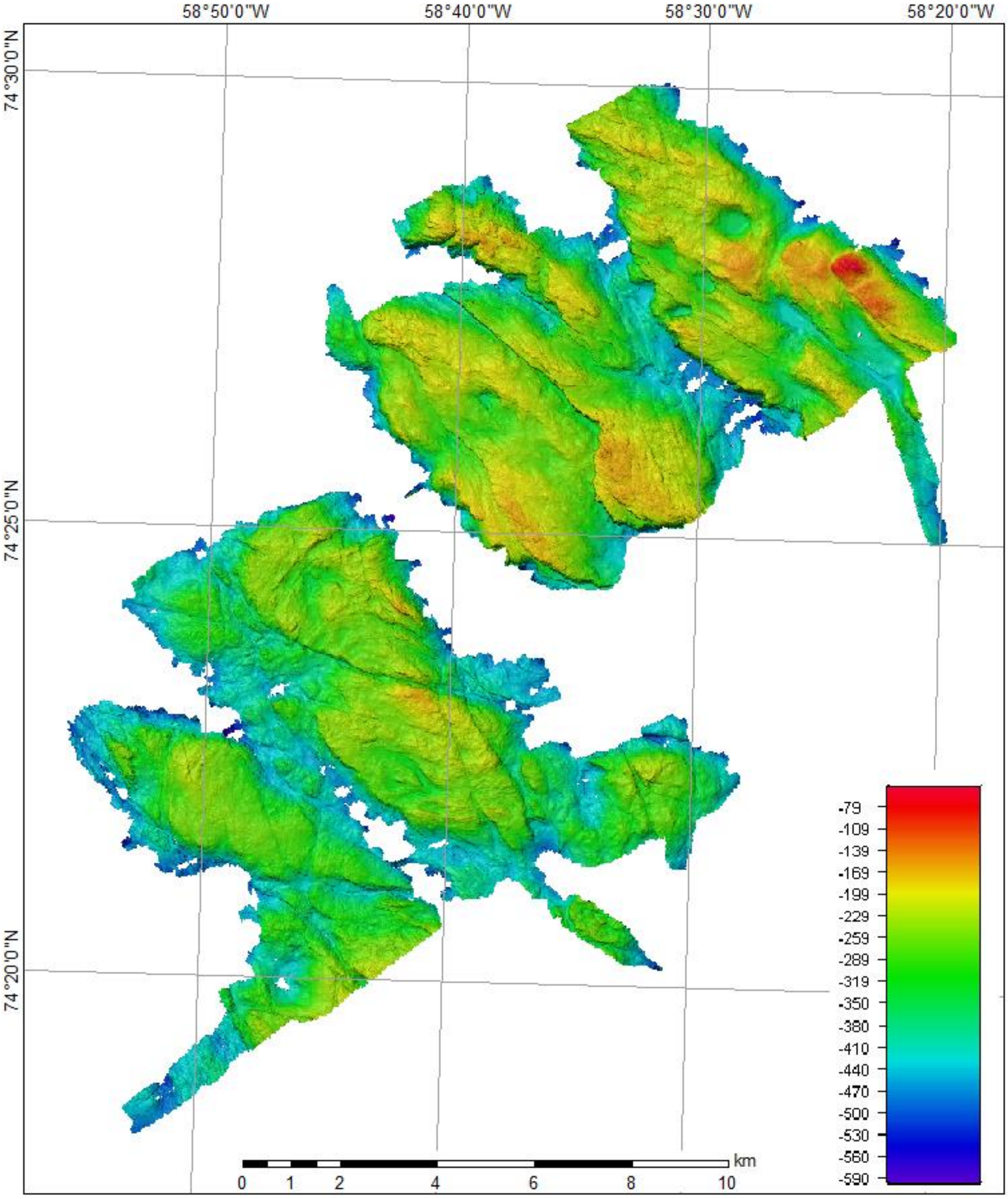


Figure A Bathymetry of survey area.

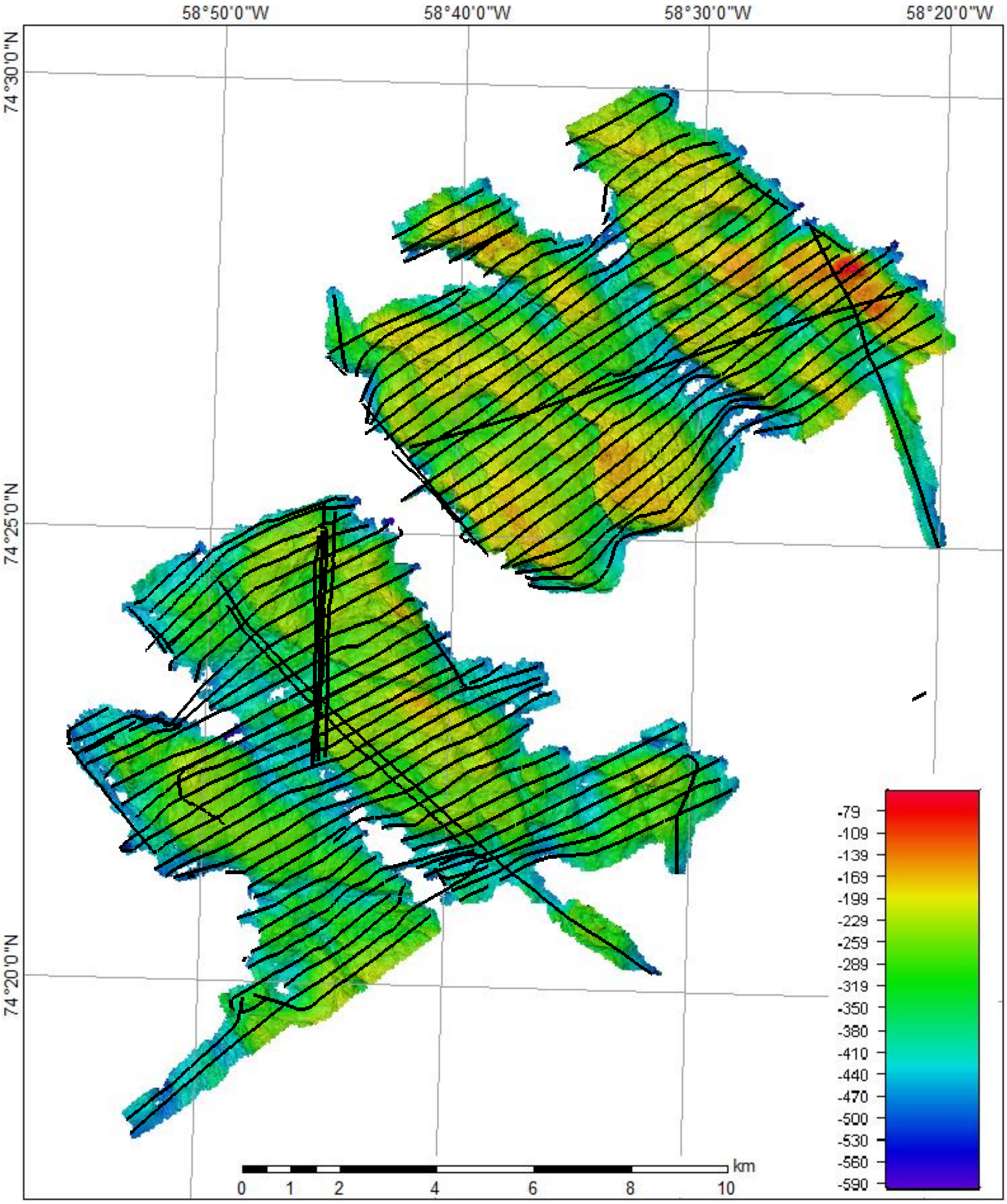


Figure B Survey area with tracklines.

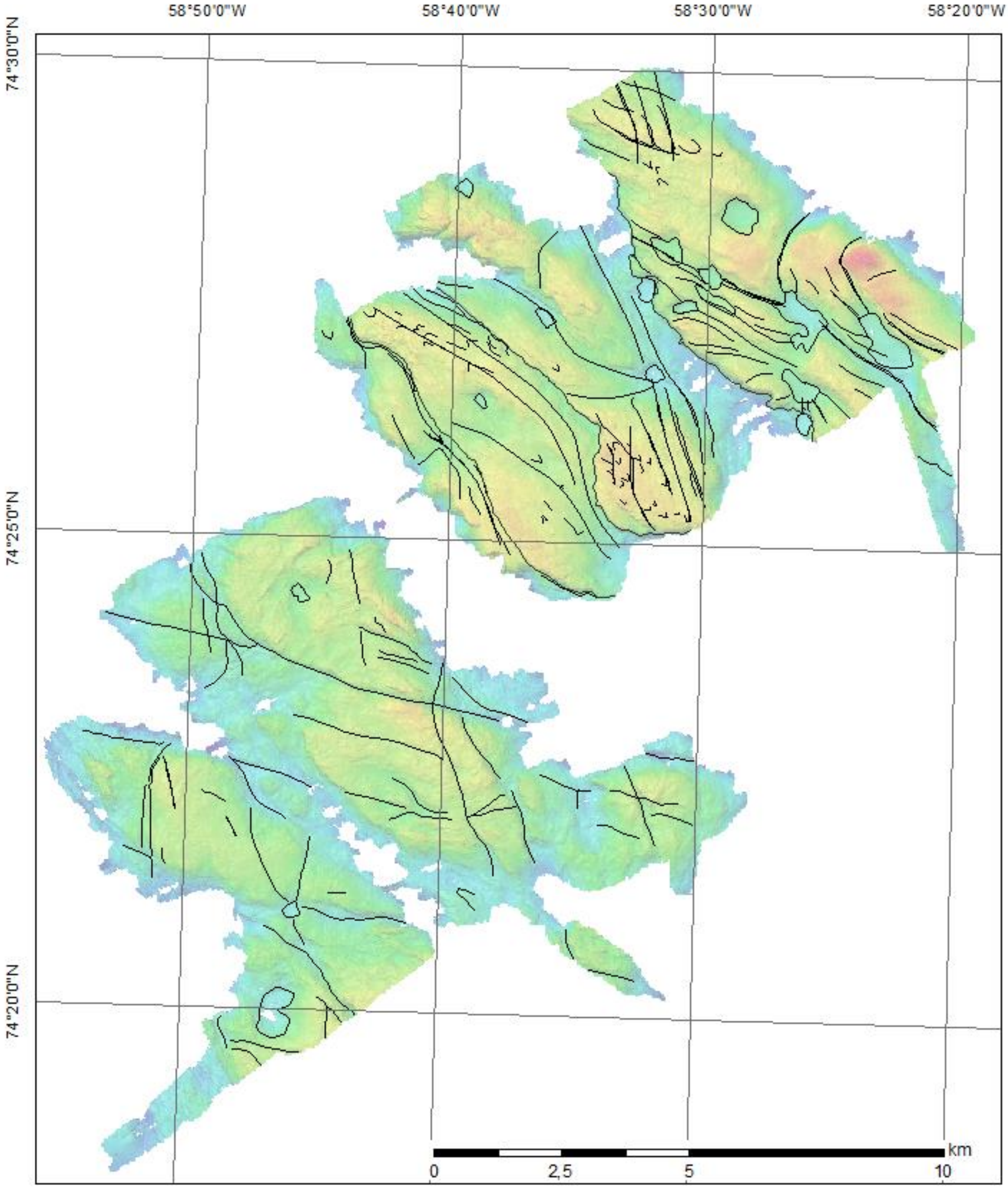


Figure C Survey area with all ArcMap features: ice channels, melt-water channels, linear features and depressions.

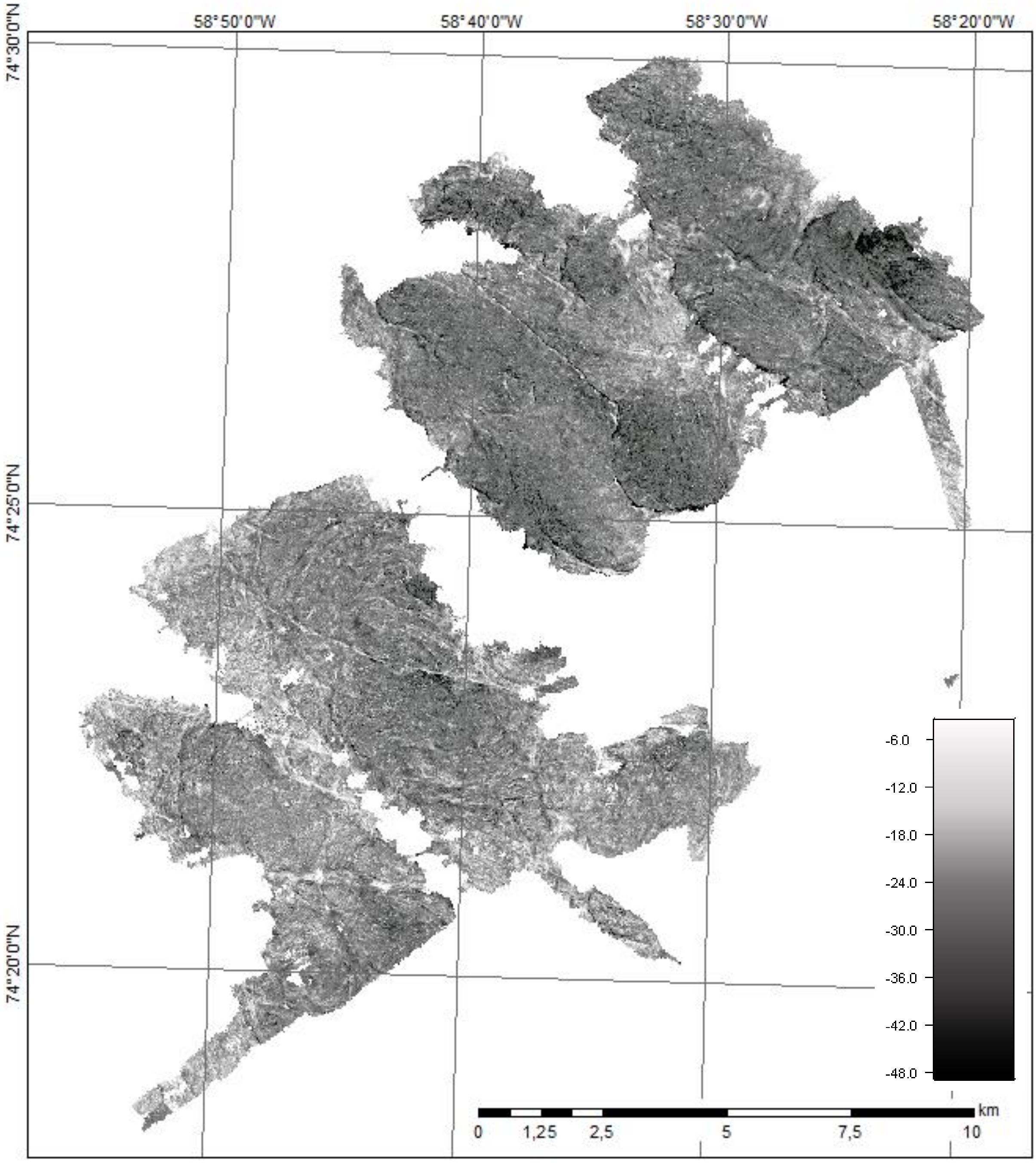


Figure D Survey area with backscatter response.

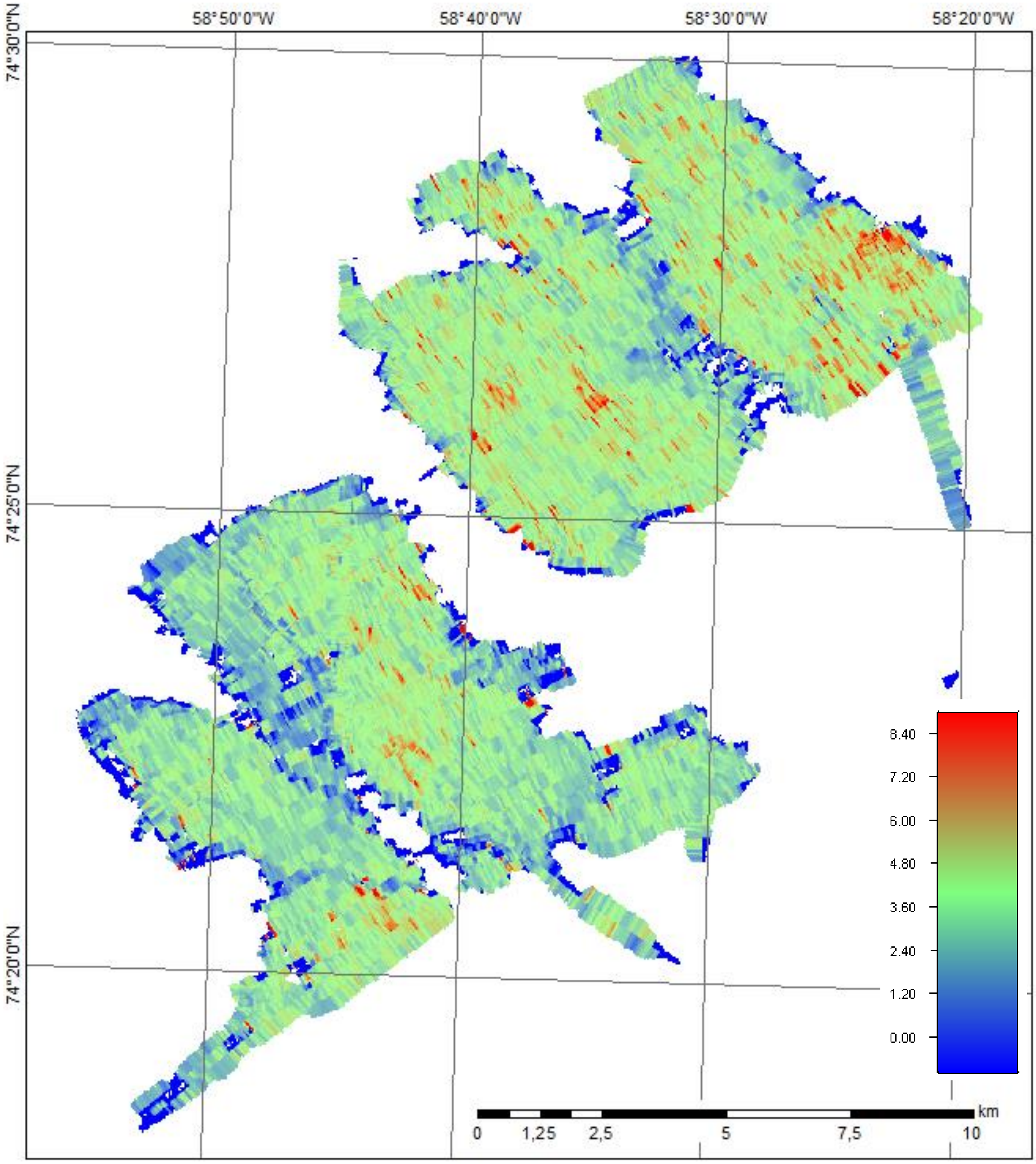


Figure E Survey area with ARA results