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Glacial history and forefield development of Aldegondabreen since the Little Ice Age maximum extent

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Abstract

A geomorphological map has been produced to investigate the glacial history of Aldegondabreen, a small land terminating valley glacier located on the western coast of Spitsbergen. The glacier has changed its dynamic from a tidewater glacier into a land-terminating glacier during the last advance/retreat cycle, and the focus is therefore to reconstruct the glacial history of this cycle.

The map cover the terrestrial glacial forefield and is constructed from field investigations as well as analysis of high-resolution aerial images. Landforms identified in the map have been divided into different categories based on depositional process. These categories are subglacial landforms, supraglacial landforms, glacifluvial landforms and coastal landforms. Each landform mapped in the forefield will be described and interpreted.

The project is also identifying the main units that the forefield is made up of and how the evolution of the forefield have been over time from glacier covered to ice free. A schematic model is made to illustrate how the forefield develop over time and how these main building blocks are deposited relative to each other over time. The results of this study suggest that Aldegondabreen has been dynamic polythermal glacier during the last glacial advance and that the freshly exposed forefield is constantly modified by fluvial erosion which lower the preservation potential of the landform assemblage in the forefield.

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Kristine Ø. Kirkebøen

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1 Introduction

1.1 Motivation

Glaciers are sensitive to climate change, meaning they grow and shrink in response to the climate (Benn and Evans, 2010). In the Arctic the observed temperature change is greater than at lower latitudes, and is consistently exceeding the northern hemisphere average (Miller et al., 2010). By studying the past behavior of glaciers and how they react to the current climate we can get a better understanding of the future development of the glaciers as the climate continues to change. During the Little Ice Age (LIA), most Svalbard glaciers reached their maximum extent due to cooler average temperatures across the region (Hagen et al., 1993). When the LIA terminated around the 1920's, it was followed by the early 20th century warming period (Wood and Overland, 2010), until the 1940s when a cooling trend occurred until the 1960s. From the1960s until the early 2010s, summer temperatures on Svalbard have been increasing (Nuth et al., 2013). Following the termination in approximately the 1920s and the end of the Little Ice Age, the mass balance of Svalbard glaciers has generally been negative (Nuth et al., 2013).

Aldegondabreen is a small land terminating valley glacier, located in Grønfjorden on western Svalbard. As there is little published data regarding this glacier, it presents an interesting case study to investigate landform assemblage, the advance retreat cycle, and how the glacier in general is affected by the climate. This also provides an opportunity to compare Aldegondabreen to other valley glaciers in Svalbard that have been previously studied (Glasser and Hambrey, 2001; Sletten et al., 2001; Christoffersen et al., 2005; Evans et al., 2012; Aradóttir, 2017). In addition, this glacier has undergone significant transformation since the end of the LIA, from a tidewater glacier into a land terminating valley glacier due to rapid retreat of the terminus position. To better understand how these types of glaciers react to the ever changing climate, an investigation of the landform assemblage and the evolution of the forefield will be undertaken. One objective of this study is to understand how the forefield of a land-terminating glacier evolves and changes during glacier retreat. By producing a geomorphological map, it is possible to obtain a time-sensitive snapshot of the forefield, as well as highlight the main glacial processes and the evidence it leaves behind. The geomorphological map can also act as a baseline for further surveys to estimate landscape development (Schomacker and Kjær, 2008). By identifying the main processes, it is possible to investigate how these have previously influenced, and will continue to affect the forefield over time as the glacier continues to retreat.

1.2 Aim and approach

The aim of the project is to produce a terrestrial geomorphological map of the forefield of Aldegondabreen through the use of high resolution aerial images. The aim for the map is to identify key landforms and the surface cover, which was validated with ground-truthing during fieldwork in 2017. In addition, the internal composition of the key landforms in the forefield was investigated. Former ice-marginal positions of Aldegondabreen where reconstructed through historical photos, aerial images and satellite imagery. The geomorphological data obtained in this study is further used to reconstruct the glacier dynamics and thermal regime of the glacier, as well as the evolution of the forefield over time. By also identifying depositional units, characterized as the main building blocks of the glacier forefield, it is possible to investigate the extent to which they affect the evolution of the forefield. This can help us get a better understanding of how a glacier forefield develops during glacier advance and how the forefield will continue to develop and change during glacier retreat. Further, this has implications for the formation and preservation potential of landforms in a forefield of a land-terminating valley glacier. To be able to reconstruct the glacial history and the development of the glacier forefield the study will try and answer the following questions:

- Is the landsystem model approach applicable for identifying glacier type based on the landform assemblage present in the Aldegondabreen forefield?
- What does the landform assemblage in the Aldegondabreen forefield reflect, in terms of glacier dynamics and thermal regime during the last glacial advance/retreat cycle?
- How does the retreat of the glacier affect the preservation potential of landforms in the forefield of Aldegondabreen, what are the main processes affecting this?
- To which extent is the retreat affected by warming climate since Little Ice Age maximum extent?

1.3 Depositional environments

"Glacial sediments can be bewildering in their variety and complexity, reflecting enormous diversity of ways in which debris can travel through glacial systems from source to the place of final deposition" (Benn and Evans, 2010).

By understanding what processes the glacial sediments can express, we can get gain a better understanding of how the glacier has behaved during its active and passive phase. In a glacial system debris is derived either from nunataks and valley sides, or from erosion of the subglacial bed; the debris is then transported by ice flow either supraglacial, englacial or subglacial before being deposited (Boulton, 1978). A figure from Boulton, 1978 nicely illustrates these transport paths of debris in a valley glacier (Figure 1).

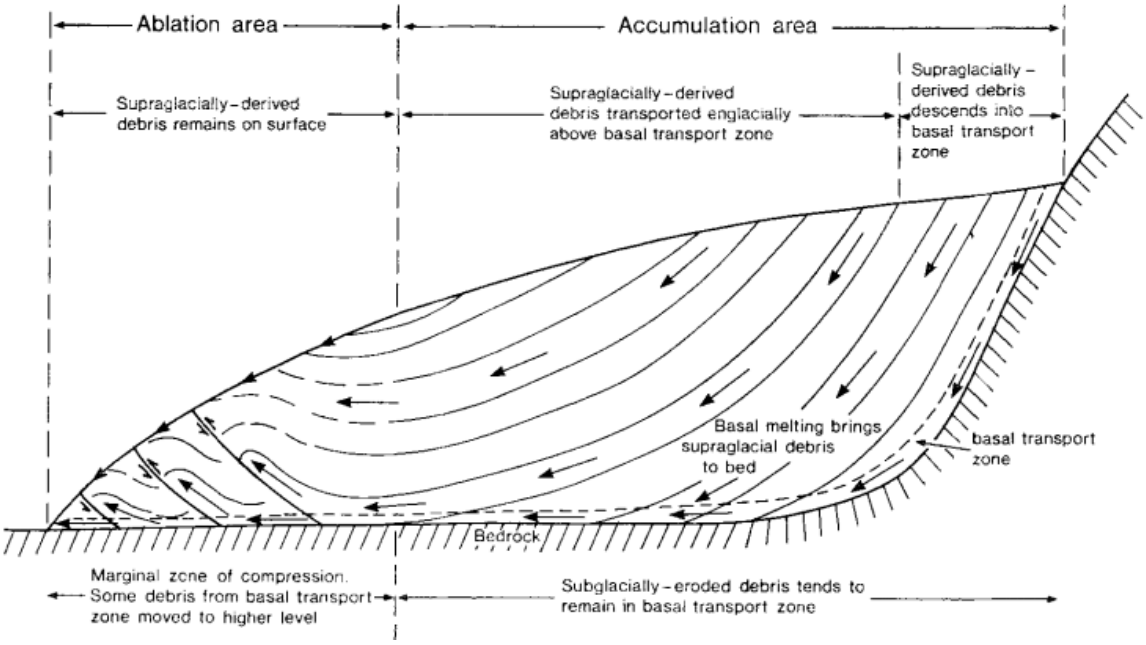

Figure 1: Model from Boulton, 1978. Illustrating transport paths of debris in a cirque glacier or valley glacier with debris derived from a head wall.

To properly understand glacial sediments it is essential to understand the environments they are formed in and which transport processes they have experienced. The stages of source and transport in a glacial system is important for shaping the final product, the sediment that is deposited. The three stages of source, transport and deposition is referred to as the debris cascade system, which is mainly related to the interaction between sediments and the subglacial, supraglacial and proglacial environments (Chorley et al., 1984). Different types of depositional material will result depending on subglacial or englacial transport paths. Subglacial transport can be referred to as the active transport where the transportation occurs at the glacier bed or within the deformable subglacial sediment. The debris carried in englacial or supraglacial can be referred to as the passive transport (Benn and Ballantyne, 1994). The further explain the glacial sediments the focus will be on the subglacial environment, the supraglacial environment and the proglacial environment.

1.3.1 Subglacial environment

In the subglacial environment debris can be derived supraglacially or subglacially. This is also the environment where the active transport of debris occurs. The processes in this environment are difficult to study as the environment is covered by glacier ice. The overlying glacier ice also applies high pressure to the glacier bed, that the pressure melting point of ice can be lowered depending on the thickness of the ice (Benn and Evans, 2010). Processes active at the subglacial bed are dependent on the basal thermal regime: warm-based ice can experience basal sliding, while cold-based ice is frozen to the bed and no sliding will occur (Waller, 2001). Debris that is derived from subglacial environment experience significant reshaping due to friction at the glacier bed and between particles. As debris in glaciers mostly is added at the bed or along the margins of a glacier, the glacial debris load tends to be focused at the bed of the glacier or in close range, within a few meters to the (Benn and Evans, 2010). Sediments deposited at the glacier bed also provide us with information about past and the present ice dynamics and the glaciers thermal regime (Glasser and Hambrey, 2001).

The landform assemblages formed in a subglacial environment can be both longitudinal, transverse and hummocky. The elongated landforms are streamlined features parallel to ice flow often classified as drumlins and flutings (Boulton, 1976; Menzies and Rose, 1989; Glasser and Hambrey, 2001).

1.3.2 Supraglacial environment

Supraglacial sediment is derived from rock fall caused by gravitational processes. The supraglacial environment is therefore characterized by angular material incorporated in the ice by erosion along the sides of the glaciers, or by rockfall onto the ice in the accumulation zone (Boulton, 1978). The material can be transported through the ice passively through the entire transport path, or it can be transported down to the glacier bed and be incorporated into the subglacial debris to be deposited with the subglacial till (Boulton, 1978; Benn and Ballantyne, 1994).

In the accumulation zone of valley glaciers the ice will often contain debris structures that reflect the location where the supraglacial debris was incorporated in the ice (Benn and Evans, 2010). A constant accumulation of supraglacial debris incorporated into the glacier ice can result in longitudinal debris bands where these bands are commonly arranged in longitudinal sets, reflecting the location of persistent debris source and ice flow lines (Hambrey et al., 1999; Glasser and Hambrey, 2001). Other landforms that can be associated with a supraglacial environment include hummocky moraine, kame and kettle hole topography (Benn and Evans, 2010).

1.3.3 Proglacial environment

The proglacial environment recognizes all the processes that occur in the area beyond the ice margin, and is among the most rapidly changing landscapes (Carrivick and Heckmann, 2017). When ice retreats, it exposes land surfaces and sediments to processes that over time will modify glacial landforms and the landscape (Evans, 2003). The most significant processes that occur in these areas are glacifluvial and slope processes (Benn and Evans, 2010). The proglacial channels are seasonally affected and therefore the erosional and depositional effect of the river systems will vary throughout the seasons (Carrivick and Heckmann, 2017). These proglacial channels carry a lot of glacial sediment and bedload which is again deposited in extensive and gently sloping outwash plains; these are typically braided river systems which form due to fluctuating meltwater discharges among other factors (Benn and Evans, 2010).

1.4 Glacial landsystem models

Glacial landsystem models are conceptual models that display the geomorphology of glacier forefields, to help identify certain glacier types. These glacial landsystem models are used as a holistic form of terrain evaluation, where the combination of geomorphology and surface terrain cover in a glacial landscape is related to the process-landform study. Glacial landsystem models are considered a powerful tool for the reconstruction of glacial dynamics and glacial environments (Evans, 2003). These types of conceptual models have been developed for both land-terminating and marine-terminating glaciers but also for surge- and non-surge type glaciers (Evans and Rea, 1999; Glasser and Hambrey, 2003; Plassen et al., 2004; Schomacker et al., 2014). Glacial landsystem models were developed to assist in identifying glacier types by distinguishing the landform-sediment assemblage in a glacier forefield.

Glasser and Hambrey (2003) presented a landsystem model for polythermal glaciated valley systems, based on modern Svalbard glaciers (Figure 2). They suggested a three zoned forefield for a typical receding Svalbard glacier; an outer moraine (1), a moraine-mound complex (2), often draped by supraglacial debris stripes and an inner zone (3) comprising various quantities of foliation-parallel ridges, supraglacial debris stripes, geometrical ridge network, streamlined ridges/flutes and minor moraine mounds.

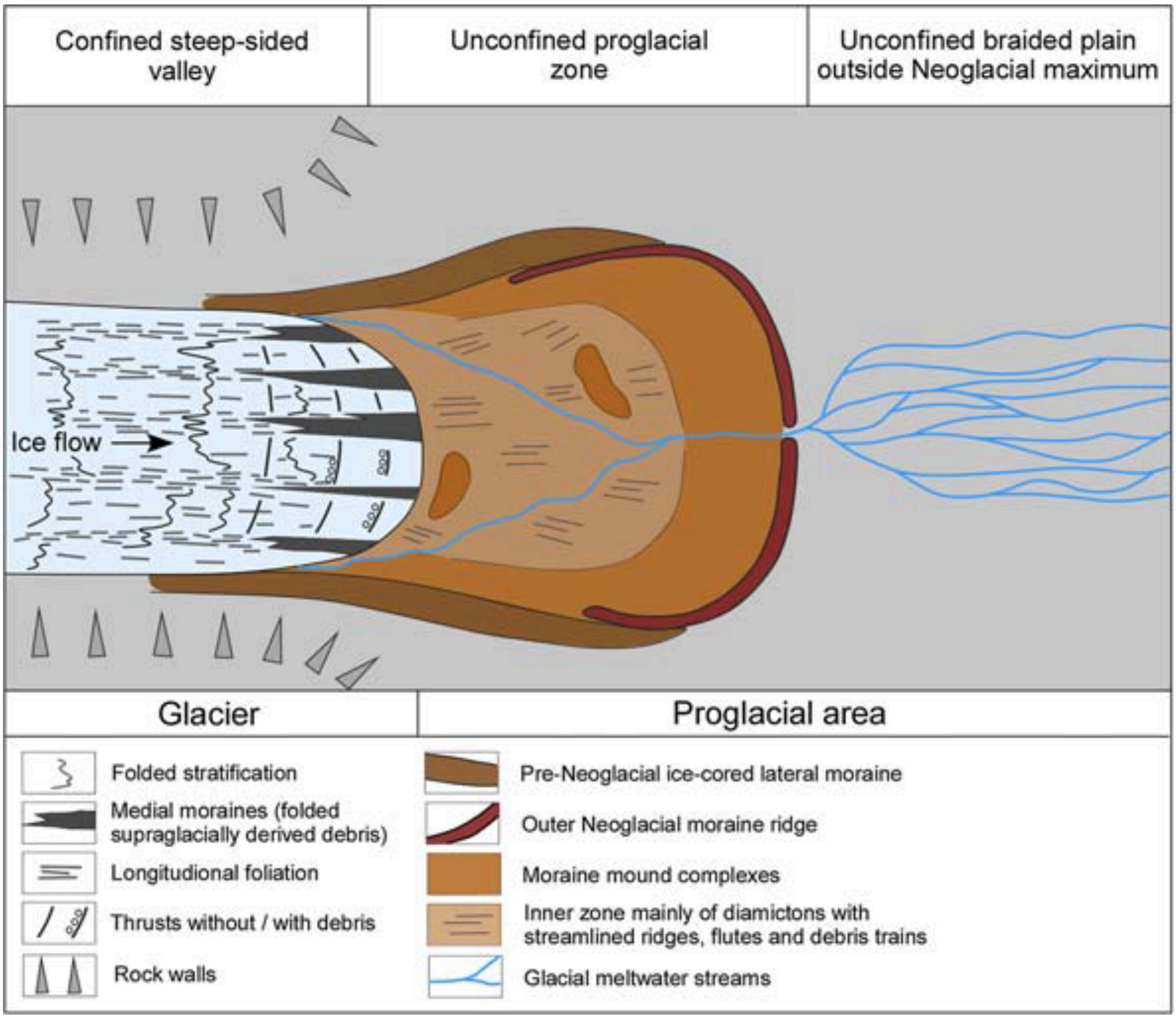

Figure 2: A Landsystem model for terrestrial Svalbard polythermal glaciers from Ingólfsson (2011), modified from Glasser and Hambrey (2003).

The landsystem models for surging glaciers were presented by Evans and Rea (1999, 2003) to differentiate ancient surging margins from other non-surging palaeoglaciers. This model has since been further developed (Figure 3). This model is also composed of a three zoned forefield; the outer zone (A) contains single or multi-crested glacitectonic end moraines consisting of folded and thrusted pre-surge sediments, the intermediate zone (B) is characterized by an active, channeled outwash plain and inactive, pitted outwash deposits on top of stagnant ice. Finally, the inner zone (C) is dominated by subglacial till, flutes, drumlins, crevasse-fill ridges, and concertina eskers (Schomacker et al., 2014).

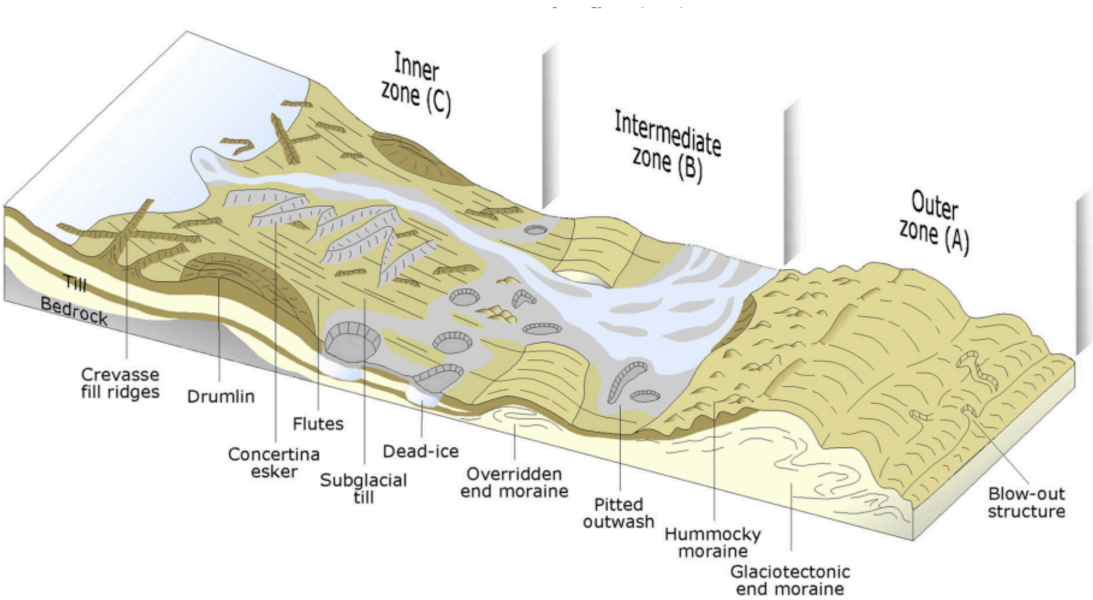

Figure 3: Glacial landsystem model for a terrestrial surging glacier based on Eyjabakkajökull from Schomacker et al. (2014).

2 Setting

2.1 Isfjorden

Isfjorden is the largest fjord system on Spitsbergen, Svalbard. The fjord cuts into the central part of Spitsbergen and is located on the western side of the Spitsbergen island, 78º25'N, 14º78'E. The fjord system opens toward the Arctic Ocean in the west. The Isfjorden system comprises thirteen tributary fjords and bays such as Grønfjorden, Adventfjorden, Sassenfjorden and Billefjorden (Figure 4). In the Isfjorden system there are nine tidewater glaciers terminating into the fjord system (Forwick and Vorren, 2009). The fjord is also surrounded by several large and small land terminating valley glaciers. The fjord is approximately 107 kilometers in length, 11-24 kilometers in width and up to 425 meters deep (Forwick and Vorren, 2010).

Grønfjorden is a tributary fjord located at the outer southern region of the Isfjorden system, between 77 º58' and 78º05'N and 14º19' and 13º57'E. The fjord opens into this system from a line between Festningsodden and Herodden south-southeastwards in the western part of Nordenskiöld Land (Figure 8). Grønfjorden is approximately 16 kilometers long and 2-5 kilometers wide. The depth varies from 50 meters in the southern area to 170 meters in the northern section of the fjord (Zhuravskiy et al., 2012). The Russian mining settlement of Barentsburg is located on the eastern side of Grønfjorden. Five glaciers are located in the fjord today. These are Vardebreen, Vøringbreen, Aldegondabreen, Vestre Grønfjordbreen and Austre Grønfjordbreen. Earlier known names of Grønfjorden used in some older literature include Green Harbour and Green Bay, though several additional versions have been used through history.

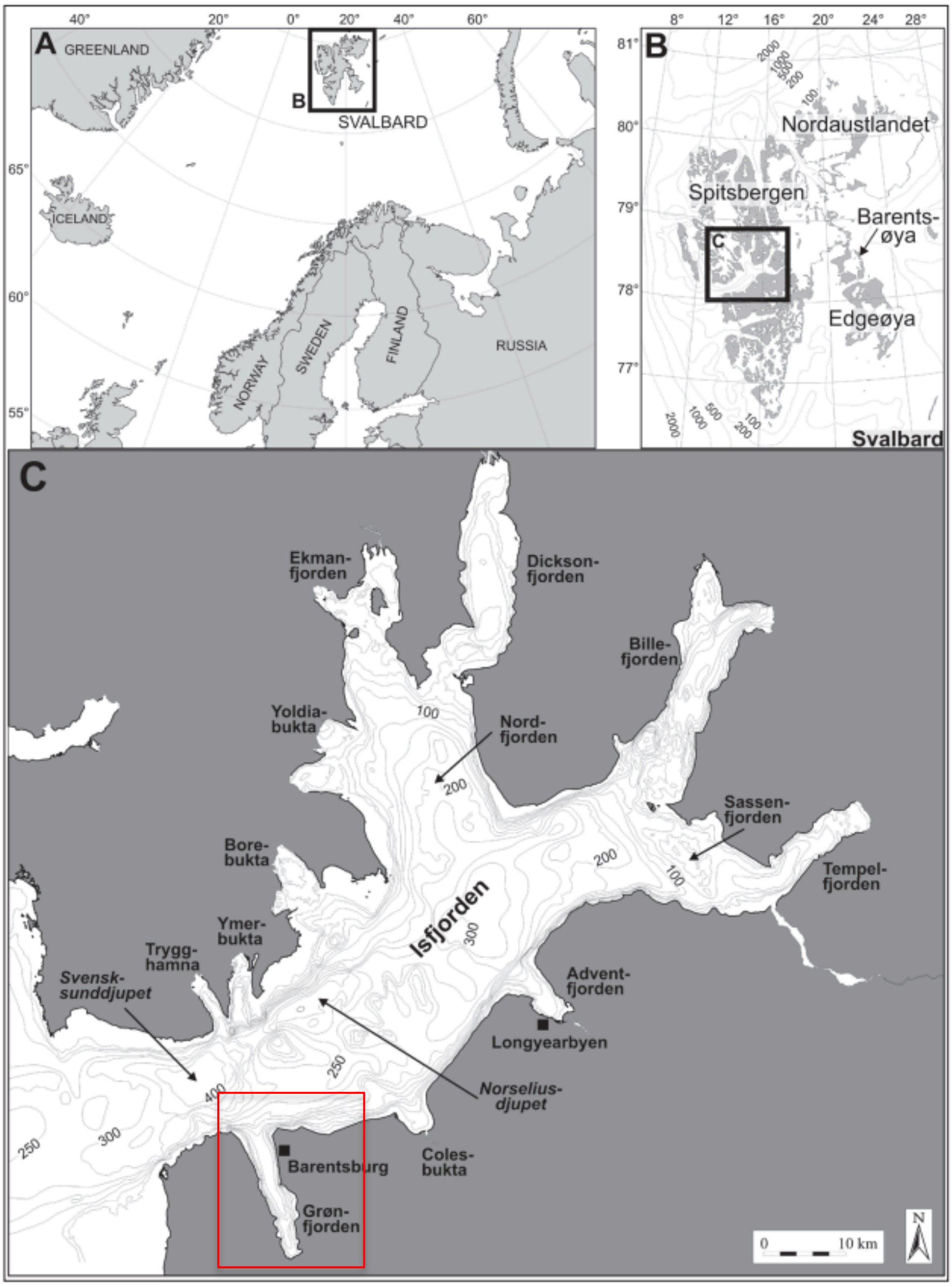

Figure 4: A) Location of Svalbard in the north Atlantic region. B) a map of Svalbard with the location of Isfjorden. C) a map of the Isfjorden area with names of all fjords and bays. Grønfjorden is marked with a red square. Figure modified from Forwick and Vorren (2010)

2.2 Climate

The Arctic surface temperatures increase exceeds those of the northern atmosphere as a whole, a process known as Arctic Amplification; this trend has recently emerged in data relative to the warming trend of the past century (Miller et al., 2010). Due to this process, Svalbard is considered to have a high climatic sensitivity (Førland et al., 1997; Humlum et al., 2007). Several forcing mechanisms are affecting the Svalbard climate, including ocean circulation, atmospheric circulation and the distribution of sea-ice. The warm and cold sea currents play an important role in regulating Svalbard's climate: warm North Atlantic Water flows north along the Norwegian coast and into the Barents-Sea, as well as along the west coast of Spitsbergen (West Spitsbergen Current, WSC). Cold polar water flows south along the east coast of Svalbard (Hanssen-Bauer et al., 1990; Humlum et al., 2007) (Figure 5). In addition, atmospheric circulation patterns transport mild air masses from lower latitudes towards Svalbard. Finally, the fluctuating extension of sea ice causes variations in the weather conditions and therefore affect the climate system in various ways (Førland et al., 1997; Benestad et al., 2002; Humlum et al., 2007; Zhuravskiy et al., 2012). For example, land temperatures are sensitive to the location of the sea-ice edge (Benestad et al., 2002), while snow and ice cover significantly reduce heat and mass exchange between the ocean and atmosphere, again controlling precipitation (Zhuravskiy et al., 2012).

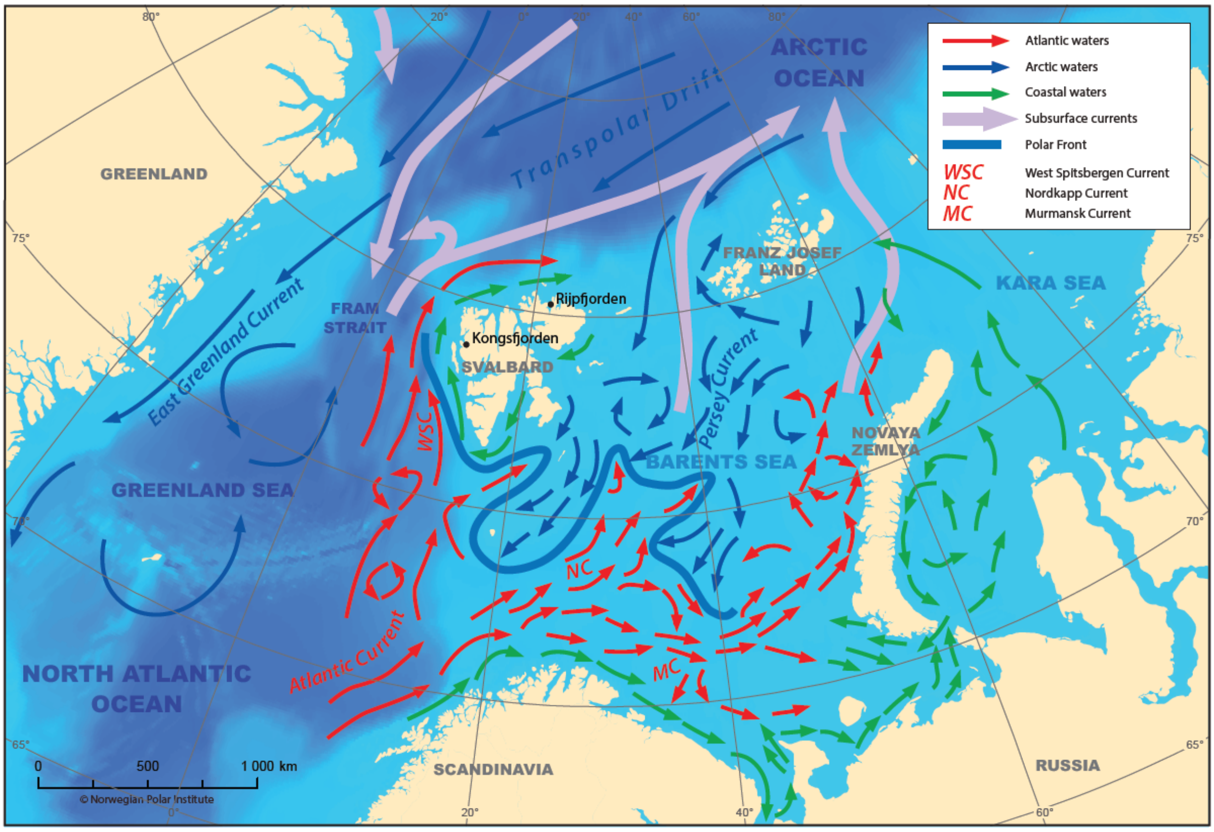

Figure 5: Map of the main ocean currents influencing the ocean climate around Svalbard. The West Spitsbergen current brings warm water along the west coast of Svalbard, and Persey current delivers cold polar water to the east coast (Dallmann, 2015).

The first permanent weather station Svalbard was established in 1911 in Green Harbour (Finneset in Grønfjorden) (Hanssen-Bauer et al., 1990; Nordli, 2010; Førland et al., 2011). Since 1911 the air temperature in the Isfjorden region has been observed continuously at several locations, except for a disruption in measurements during World War II (Nordli, 2010). Significant variations in both temperature and precipitation have been recorded, with positive temperature series trends noted for annual temperature as well as spring, summer and autumn trends (Førland et al., 2011). The measurements show an adjustment from colder temperatures in 1910s to warmer temperatures towards the 1930s. This "event" is referred to as the 20th century warming. After this period of warming there was a decrease in the temperature until the 1960s before an increase in temperature to the present day (Nordli, 2010).

Measurements in Grønfjorden have been carried out since 1911, although gaps exist in the measurements. The Green Harbour measurements were registered from December 1911 to August 1930. In 1933 measurements began in Barentsburg after the weather station was moved from Grumant. Due to WWII there are no measurements from 1941 until they were resumed again in 1947. In 1974 the weather station in Barentsburg was relocated, but since then the station has not been moved, providing consistent measurements until present date in Grønfjorden. (Zhuravskiy et al., 2012).

The long-term measurements compiled from the two stations located in Grønfjorden indicate a warming tendency from 1950 to 2000. Zhuravskiy et al. (2012) looked at the linear regression equations which revealed that from 1950 to 2000 there was an overall warming of approximately 0.3 degrees celsius. For the period 1970 to 2000 the warming trend increased to 1.7 degrees celcius and for the period 1970 to 2007 it had increased to 2.0 degrees celcius. These temperature measurements demonstrate that from at least 1950 Grønfjorden has experienced a continuous warming in air temperature (Figure 6).

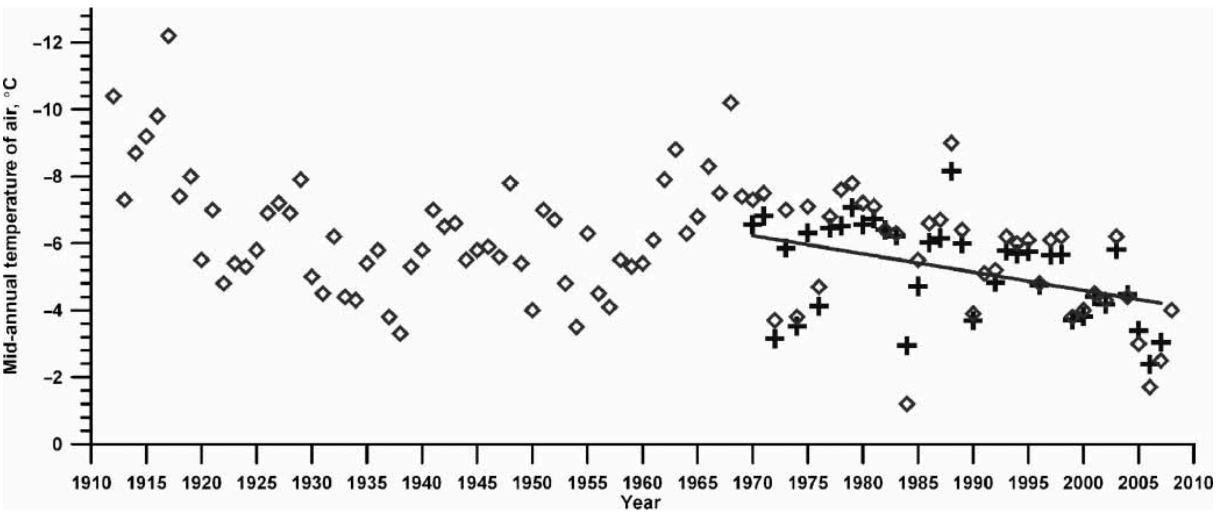

Figure 6: Long term variability of mean annual air temperature in Barentsburg during 1974 to 2007. Annual temperatures for Barentsburg is marked with crosses and mean annual air temperature rise is illustrated with a line. The Svalbard air temperature record from 1912 to 2008 is marked with squares (Zhuravskiy et al., 2012).

2.3 Glacial history

During the Last Glacial Maximum (LGM) around 20 ka BP, Svalbard was in a full glacial mode (Svendsen et al., 2004). Svalbard was covered by the Late Weichelian Svalbard-Barents-Sea ice sheet, and landforms related to ice advance show that the ice margin extended to the shelf break west and north of the Svalbard archipelago (Landvik et al., 1998; Ingólfsson and Landvik, 2013). The large ice sheet was characterized by fast moving ice through larger fjords systems and their adjacent cross-shelf troughs (Ottesen et al., 2007; Ingólfsson and Landvik, 2013) (Figure 7). The regional deglaciation of the ice sheet started around 15 cal. Ka BP, and by 11 cal. ka BP Isfjorden was mostly ice free (Svendsen and Mangerud, 1997; Landvik et al., 1998). The glaciers experienced a substantial retreat during the early-mid Holocene warming (10 000 – 4400 yr BP) resulting in some of the glacier extents being even smaller than today's extents (Svendsen and Mangerud, 1997; Koerner and Fisher, 2002; Mangerud and Landvik, 2007). This warming period in the early Holocene was followed by a cooling period where glaciers re-advanced, referred to as the Neoglacial (Keigwin, 1996; Svendsen and Mangerud, 1997). During the Holocene many Svalbard glaciers reached their maximum extent during the Little Ice Age (LIA) (1900 AD) and their extent can be observed by prominent terminal moraines in front of present day glaciers (Svendsen and Mangerud, 1997). These prominent terminal moraines constrain the glacier forefields that are freshly exposed since the retreat from the LIA maximum extent (Ingólfsson, 2011). Today, Svalbard is in an interglacial mode, with a glacier system dominated by the highland ice fields, ice caps and valley and cirque glaciers (Ingólfsson, 2011). Fingerprints from the Quaternary glaciations record the transition from a full-glacial period to a deglaciation into an interglacial period (Ingólfsson, 2011).

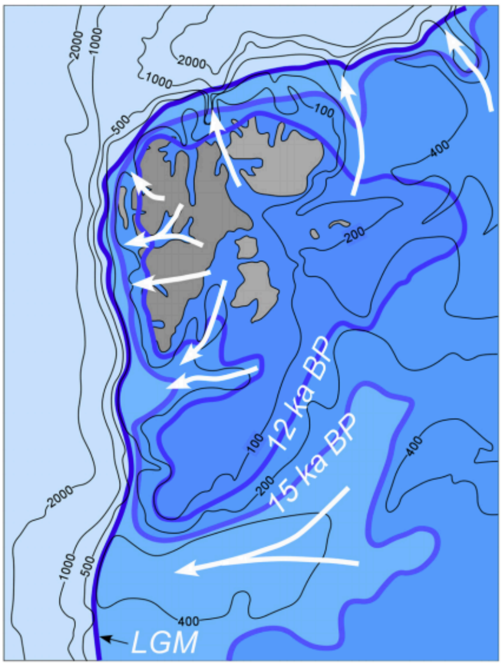

Figure 7: Reconstruction of the margins of the Late Weishelian Svalbard-Barents sea ice sheet from LGM and stages of deglaciation. White arrows are flow lines (ice-streams) (from (Landvik et al., 1998), modified by (Ingólfsson and Landvik, 2013).

2.4 Study site: Aldegondabreen

Aldegondabreen is a small land-terminating valley glacier located on the western side of Grønfjorden, opposite to the Russian settlement of Barentsburg (Figure 8). Historically, this glacier has been known as Aldegonda Gletcher (NPI). Measured last in 1990, this glacier had an area of ~7,6 km^2 (Macheret and Zhuravlev, 1982; Navarro et al., 2005). Aldegondabreen is oriented NE towards the southern part of Grønfjorden. In 1974/75 the glacier was investigated with a helicopter-based radio-echo sounding, revealing a two-layered polythermal structure and a maximum ice thickness of 150 meters (Navarro et al., 2005). These measurements are outdated, and therefore it is difficult to predict the current glacial thermal regime or the maximum ice thickness. The few studies published regarding Aldegondabreen have mainly focused on the hydrology of the glacier or the ice mass itself (Macheret and Zhuravlev, 1982; Navarro et al., 2005). There is no published material on the freshly exposed forefield of Aldegondabreen.

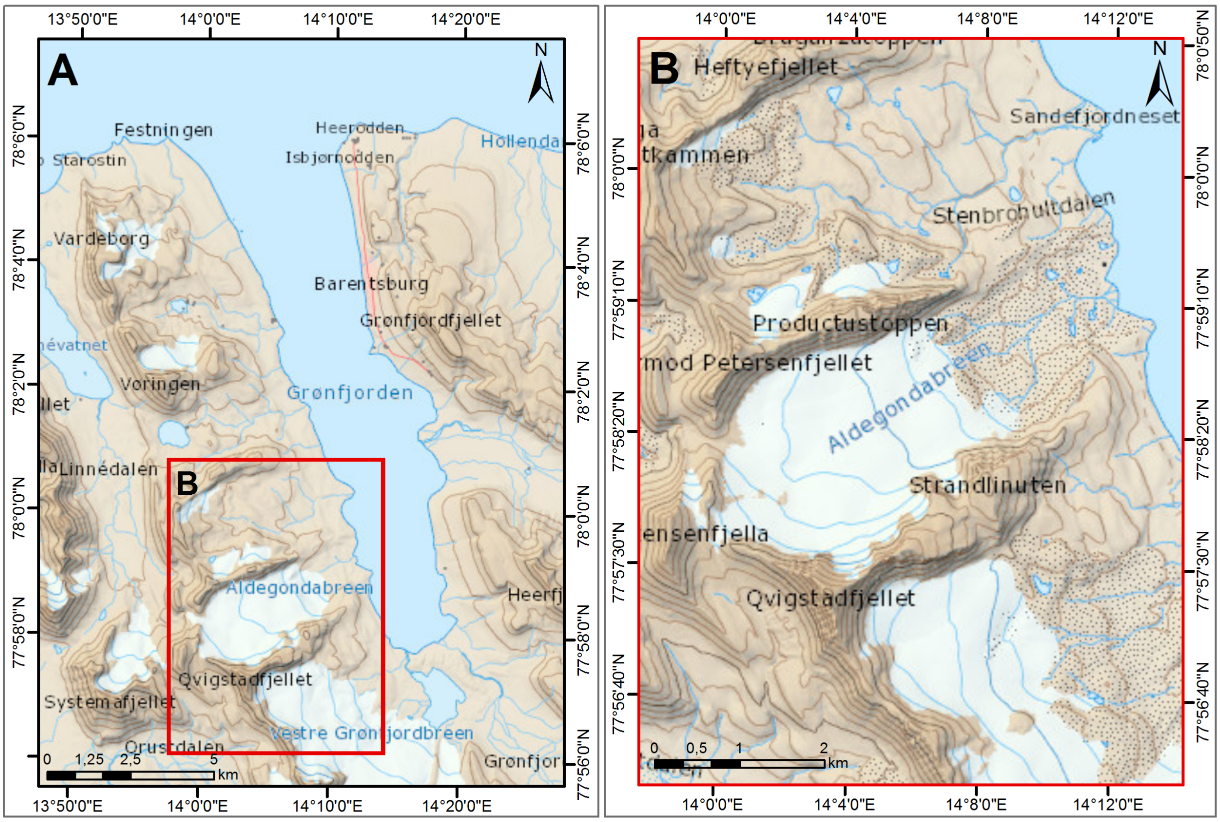

Figure 8. Location map of study area. A) Grønfjorden, red square indicates study area seen in B. B) overview of Aldegondabreen. Source: Norwegian polar institute (NPI).

2.4.1 Bedrock geology

The bedrock geology in the Aldegondabreen area is shown in Figure 9. The area surrounding Aldegondabreen consists of bedrock from upper Paleozoic and Mesozoic time and is within the western fold-belt of Spitsbergen. This has resulted in steeply dipping to vertical beds through faulting and thrusting during the early Eocene (Mørk and Worsley, 2006; Dallmann, 2015). The oldest bedrock surrounding Aldegondabreen are the Carboniferous and Permian layers. Aldegondabreen is currently resting on top of bedrock layers from the Permian (Figure 9). The Carboniferous consist of sandstones, conglomerates which contain plant fossils as well as coal. Permian layers appear as carbonate-rich rocks. From the Triassic period soft shales that weather and erode easily are found. Eastward we find the Tvillingodden formation which is composed of harder siltstone and sandstone. These harder deposits make up thresholds in the forefield of Aldegondabreen crosscutting the forefield NNE-SSW. There are also some beds of calcareous sandstone, which are severely folded and faulted. The uppermost Triassic is dominated by sandstone and siltstones. The Jurassic strata consist of conglomerates overlain by dark grey and black shales, which are soft and easily folded. Cretaceous contains dark shales with an abrupt marked change to sandstones and siltstones found in the Adventalen group (Carolinefjellet Fm., Helvetiafjellet Fm. and Janusfjellet formation) (Hjelle, 1993). As mentioned the area of study lies within the West Spitsbergen fault belt which has resulted in some intense folding and faulting of the bedrock (Dallmann and Elvevold, 2015).

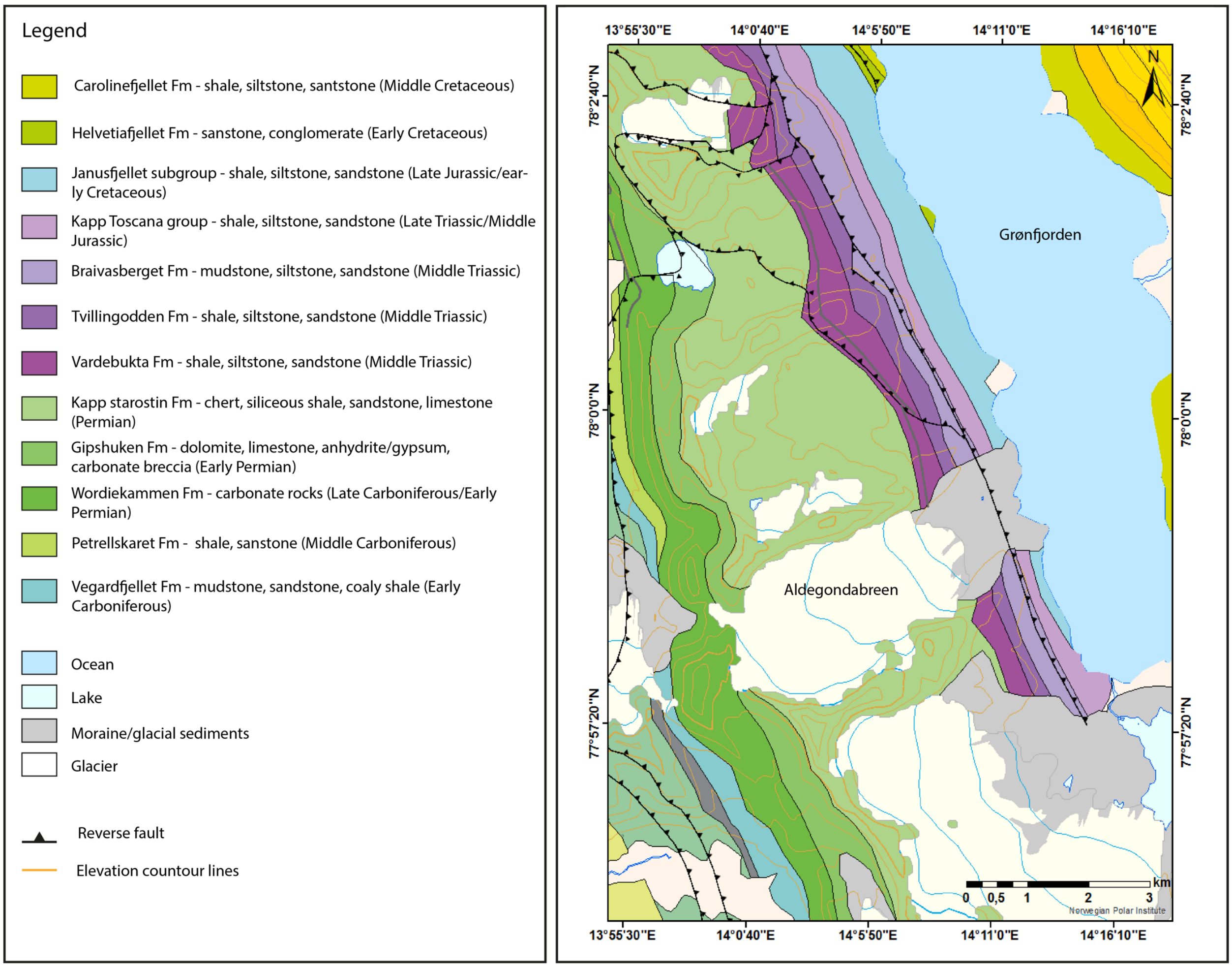

Figure 9. Bedrock map of the western Grønfjorden area surrounding Aldegondabreen. Legend shows youngest to oldest bedrock formations. Source : Norwegian Polar Institute (NPI).

3 Material and methods

3.1 Material

3.1.1 Aerial images

Aerial images from flight campaigns and drone imagery were used to reconstruct former ice-marginal positions of Aldegondabreen. Orthophotos of Aldegondabreen were taken during flight campaigns in 1936, 1951, 2008 and 2010, and were acquired from the Norwegian Polar Institute (NPI). All aerial images are taken vertically except photos taken in 1936 which are oblique. In addition to the aerial images, drone images collected with a Dji Phantom 4 drone during fieldwork in July and August 2017 were used. The 2008 and 2010 NPI images are used in mapping, while drone images collected by Erik Schytt Holmlund are used to further investigate landforms in the forefield.

3.1.2 Digital elevation model (DEM)

Digital elevation model (DEM) from 2008 and 2010 were used to create contour lines in the mapped area. The model is generated from stereo photogrammetry from the 2008 and 2010 aerial images, and is provided by Norwegian Polar Institute. The 5 meter resolution model is used to create a hillshade for the area to use as a background image for the reconstructed ice marginal positions. To create the contour lines for the geomorphological map a 20 meter resolution model was used to avoid excessive noise in the contour lines.

3.1.3 Historical photos

Historical photos from 1910 and 1911 taken by Gunnar Isachsen were used to investigate the previous ice front position and size of Aldegondabreen, and to reconstruct the 1911/1910 ice marginal position. The photos were provided by the Norwegian Polar Institute. Together there are 20 photos available from 1910 and 1911 presenting Aldegondabreen from various angles. Some photos are taken from the opposite side of the fjord looking at Aldegondabreen, while others are taken from the mountain top called Strandlinuten looking down at the glacier. One photo taken by DeGeer in 1908 is also provided by NPI but is not used for reconstructing ice position, as the picture is not suitable for the reconstruction.

3.2 Methods

3.2.1 Geomorphological mapping

A geomorphological map was produced from a three stage process, which consisted of preliminary mapping, field mapping to ground-truth the final mapping. Preliminary mapping was based on the aerial images from the map service Toposvalbard and Svalbardkartet and was used to map the glacigenic landforms with the aim to identify target areas for fieldwork. The final map was produced based on the analysis of aerial images covering the area of Aldegondabreen from 2008 and 2010 and field observations. The map was created in ESRI ArcGIS 10.4. The final scale for the map was in 1:9500 produced for an A3 sheet.

3.2.2 Fieldwork

Fieldwork was carried out during two field campaigns in 2017; the first was a one-day trip 5.July and the second field campaign was a five-day trip 30.August - 2.September. The aim of the fieldwork was to conduct detailed geomorphological mapping with a focus on glacigenic landforms. This was done by collecting observations on the geometry, distributions, ground cover and internal structure of landforms.

The sedimentological investigations of the internal structure of landforms was focused on producing a description of stratigraphy and lithofacies, as more extensive descriptions was not possible due to limited time in the field. Notes and photographs, together with GPS points that mark landforms and data collection points were used to map the surface material. For the depositional sequence, photographs, notes and logs were used to catalog the observations. During every evening a summary of the day was created to note the observations of the day.

3.2.3 Ice-marginal reconstructions

The retreat of Aldegondabreen since 1911 has been reconstructed using historical photos, historical aerial images and orthorectified aerial images and satellite images (Table 1). Historical aerial images and satellite images were georeferenced in ArcMAP to outline the glacier front positions. The historical photos from Isachsen, 1911 were used to obtain an approximate position. As they are taken from the opposite side of the fjord these cannot be georeferenced in ArcMAP. The spatial reference system used is WGS84/UTM 33N. Data were imported into ESRI ArcGIS 10.4 to map the positions on a hillshade produced from the DEM model of 2008/2010.

Table 1: Data utilized to reconstruct ice-marginal positions and for geomorphological mapping. Information given when available.

Date	Source	Type	Resolution/ scale	Number ID
1911	Isachsen, NPI	Photographs	-	-
1936	NPI	Oblique aerial	-	S36_1676
1956	NPI	Vertical aerial	-	-
19.08.1990	USGS	Sattelite image- Landsat 4-5 TM	1898x1063 pixels	LT52170041990231KIS00
2004	NPI	Vertical aerial	-	-
2008	NPI	Vertical aerial (orthorectified)	20 cm resolution	13652
2008	NPI	Digital elevation model (DEM)	5 m resolution	13652
2010	NPI	Vertical aerial (orthorectified)	20 cm resolution	13836
2010	NPI	Digital elevation model	5m resolution	13836
24.082013	USGS	Satellite image – Landsat 8 OLI	2446x1394 pixels	LC82110052013236LGN01
02.08.2016	USGS	Satellite image- Sentinel 2 MSI	2446x1394 pixels	S2A_OPER_MSI_L1C_SGS_20160802T123943_20160802T180556_A005812_T33XVG_N02_04_01
-	NPI	Digital elevation model	20m resolution	-

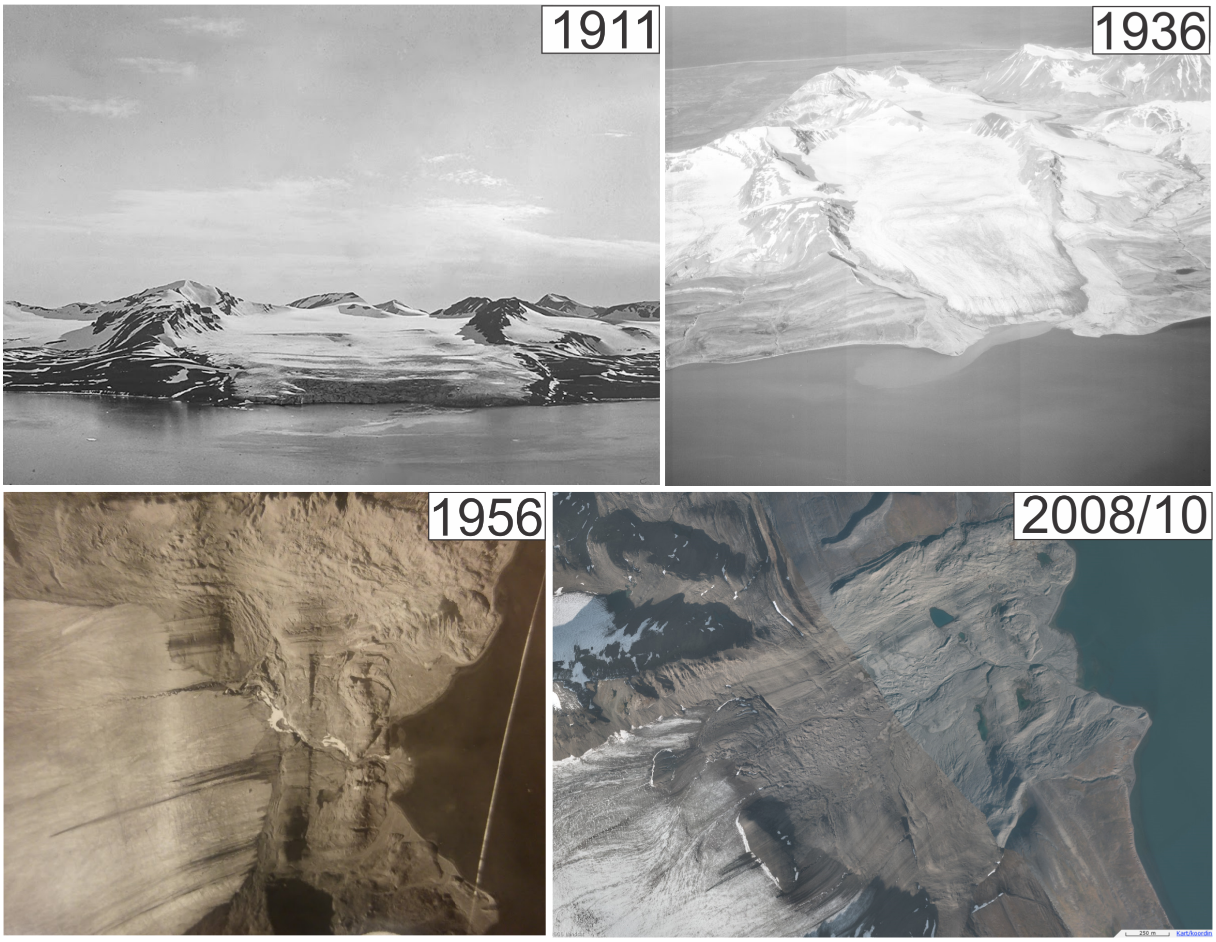

Figure 10: Images used to reconstruct former ice front positions in this study. Photo from 1911 is taken by Gunnar Isachsen, oblique aerial images from 1936, vertical aerial image from 1956 and last the aerial images from the flight campaigns in 2008 and 2010.

3.2.4 Symbols and legend

A legend has been produced to explain the lines and polygons used in the geomorphological map created for the Aldegondabreen forefield (Figure 12). The polygons represent the different surface covers in the area. Polylines represent linear shaped landforms such as channels, transverse ridges, flutes and eskers.

4 Results

A terrestrial geomorphological map covering a total area of ~10 km^2 was produced for the Aldegondabreen glacier forefield. The mapped forefield of Aldegondabreen represents an area of ~3,66 km^2. The map is presented in Figure 12 and the legend for the map is presented in Figure 11. The primary focus was the sediment cover and landform assemblage. A full version of the map with legend is found in Appendix A. Mapped ice marginal positions for Aldegondabreen from 1911 to 2016 can be seen in Figure 25 and are described in Section 4.2.

Figure 11: Legend for geomorphological map of Aldegondabreen presented in Figure 12.

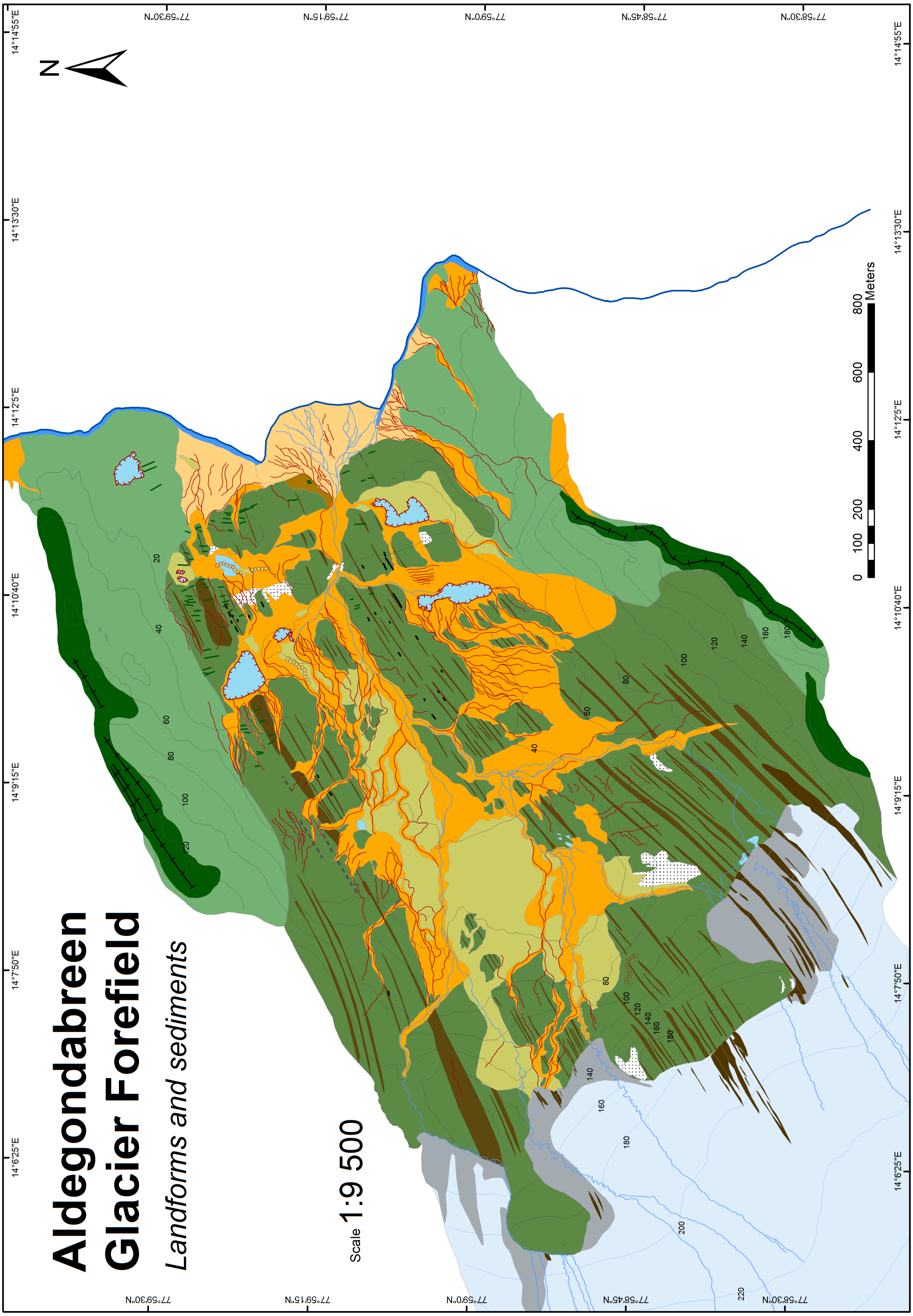

Figure 12: Geomorphological map of Aldegondabreen forefield (2018). Full version can be found in appendix A.

4.1 Geomorphology and internal composition

4.1.1 Subglacial landforms

Subglacial till plain

Description:

The area with this label covers ~1,6 km^2 of the Aldegondabreen forefield. This sediment cover is composed of a clast-rich matrix supported diamict deposited on bedrock. The matrix is medium grained and is firm and difficult to excavate. The clasts in the deposit are subrounded. The surface of the sediment cover is draped with angular clasts in a darker lithology mostly dark shale as well as rounded clasts in a lighter lithology, mainly sandstone. The surface deposit of angular and more rounded clasts occur all over this surface in the forefield. On the northern side of the forefield a larger deposit of the angular material on the deposit is observed. The same subglacial till was observed at the glacier front, covered by glacier ice. A clear section was logged at the glacier front seen in Figure 13.

Interpretation:

The sediment cover is interpreted as subglacial till deposited directly on bedrock and that has not been modified after deposition based on its internal composition (Krüger and Kjær, 1999). The angular and rounded clasts on the surface is interpreted to be supraglacial and subglacial deposits respectively. Freshly exposed subglacial till by the glacier front show the same deposition of subglacial till with rounded clasts on top covered by ice with supraglacial material melting out of the ice. This leads to the conclusion that the sediment cover is a subglacial till produced under the glacier and as the glacier retreats and melts down it leaves supraglacial material on the surface of the subglacial till.

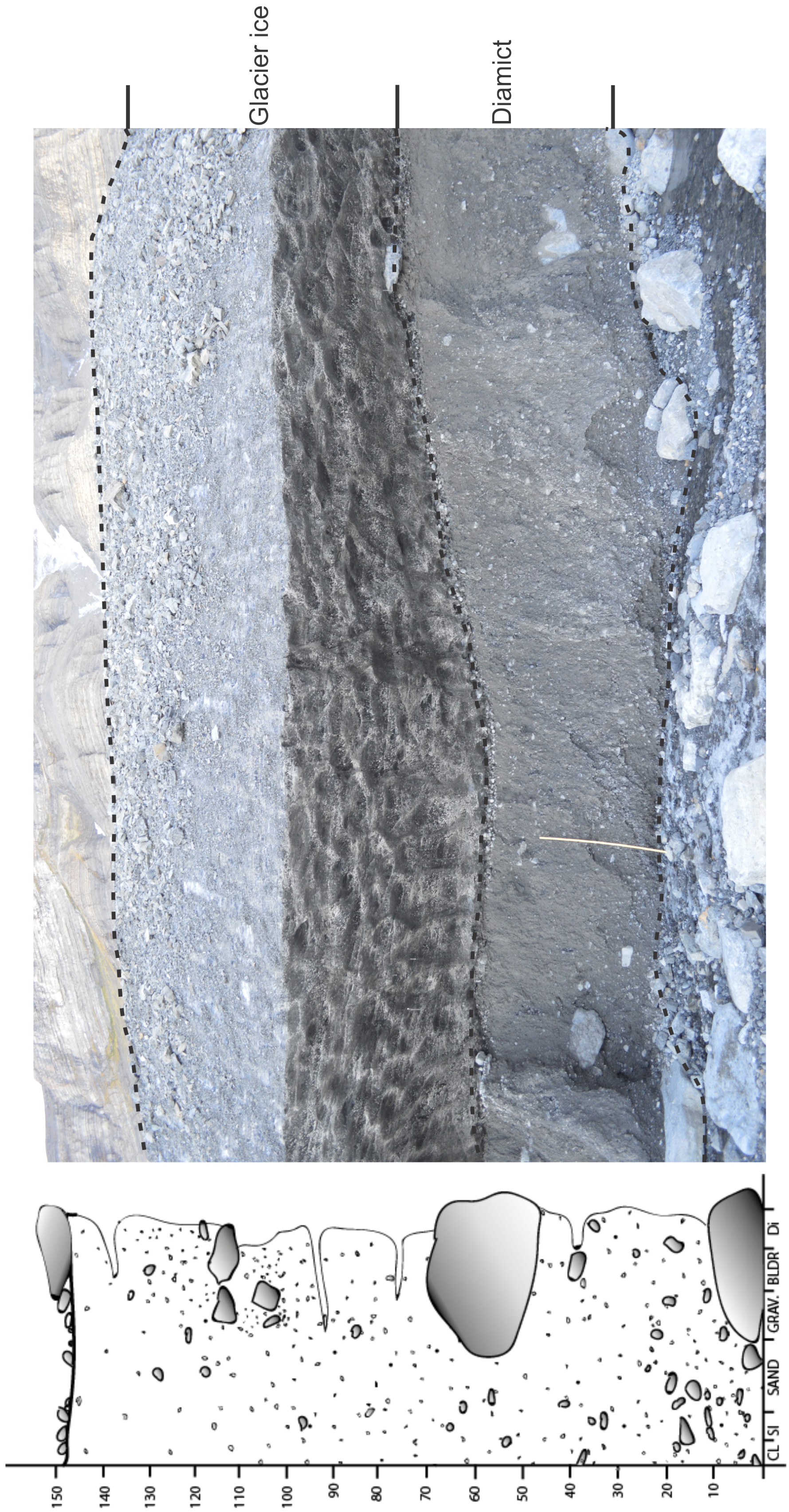

Figure 13: Composite log of the diamict frozen onto the base of the glacier. Picture illustrates the subglacial till, still covered by glacier ice at the glacier front. Supraglacial material is observed melting out on the glacier surface.

Flutes

Description:
In the forefield of Aldegondabreen 26 glacial lineations were observed. Most of the observed lineations begin with one or more boulders in the ice proximal end of the landform (Figure 14 a & b). There is also a small depression observed directly in front of the boulders. The length of the landforms average around 5-6 meters, where the shortest was 2-3 meters and the longest measured 14 meters. The height of the lineations are between 0.2 meters and 0.5 meters and the height of the deposition is similar to the height of the boulder in front of the deposition. The size of the lineations can make them difficult to identify in aerial imagery, though they are easily observed in the field. These landforms only occur in flat surface areas where the subglacial till is identified. The glacial lineations are oriented parallel to former ice flow. The material in the landforms consists of a massive medium grained matrix supported diamict. Angular clasts are observed on the surface of the flute.

Interpretation:
The lineations orientation to past ice, as well as that they initiate with boulders on the ice proximal side and deposition after the boulder, suggests these landforms are flutes (Boulton, 1976; Roberson et al., 2011). Flutes are elongated streamlined ridges of sediment that are aligned parallel to former glacier flow (Boulton, 1976; Gordon et al., 1992). They form when sediment is squeezed into lee side cavities behind obstructions such as a boulder (Benn and Evans, 2010). The flutes described above are small, but they still demonstrate an orientation parallel to the former ice-flow and is only found where the preserved subglacial till is found in the forefield. The angular material on top of the flutes is interpreted as supraglacial material deposited during glacier retreat. The flutes are a result of glacier flow and therefore indicate that the glacier must have been warm-based, as these are the conditions required to create these landforms and also to flow forward and shape the accessible subglacial till.

Bedrock

Description:
Exposed bedrock

In several areas throughout the forefield one can find larger and smaller exposures of bedrock, covering an area of ~0.026 km^2. The mapped bedrock exposures are not covered by any loose material (Figure 14 c & d). They appear most often where fluvial erosion has occurred or on topographic highs. The bedrock is sedimentary rock that has steeply dipping layers, which is very friable and breaks easily up in small pieces. No striated or polished bedrock exposures was observed in the area.

Interpretation:

Historical photos from Isachsen, 1911 show that the entire forefield of Aldegondabreen is covered by glacier ice. This would indicate that the exposed bedrock has been affected by glacier erosion, and/or that the bedrock has been exposed during glacier retreat. During retreat some of the bedrock has also been exposed to fluvial erosion, especially the bedrock exposures found in the channel systems. The exposed bedrock seems to occur in “lines” crossing the forefield. This is due to how the layers of the bedrock are oriented and also affected by the dipping layers. Some of the softer sedimentary bedrock layers are more prone to erosion than the harder sedimentary layers left as bedrock thresholds in the landscape. One of the bedrock thresholds is located by the glacier front, and the other is observed close to the shore.

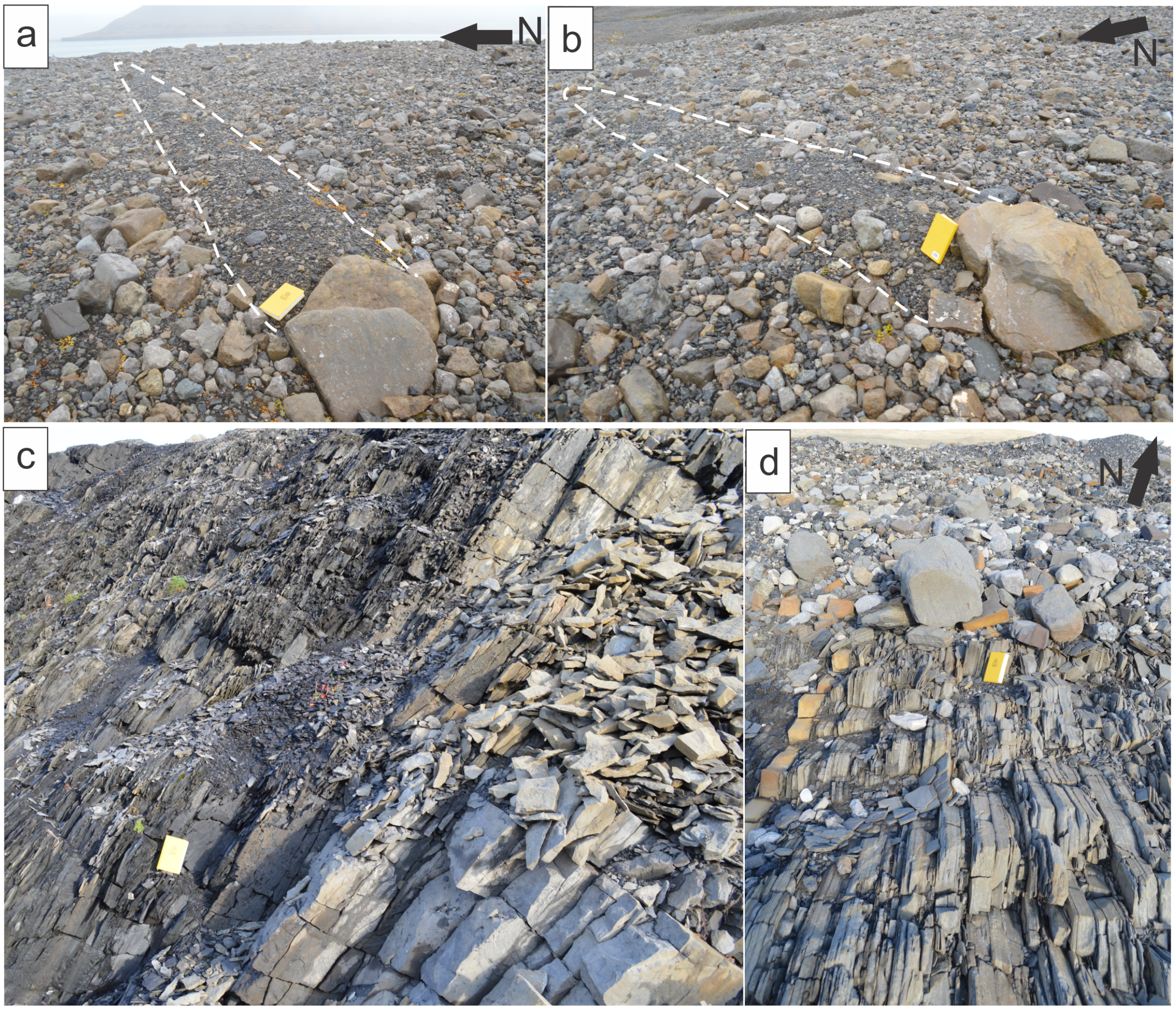

Figure 14: Flutes and bedrock exposures. a) & b) flutes, with an ice proximal boulder and an ice distal tail of sediment. c) exposed bedrock close to active channel. d) exposed bedrock with thin debris cover surrounding the exposure.

4.1.2 Supraglacial landforms

Ablation type medial moraines and supraglacial debris stripes

Description:

Ablation type medial moraines

At the glacier front angular material is observed to melt out of the glacier as the ice thins (Figure 15 c). This angular material emerges as elongated ridges with sorted lithology, usually shale or sandstone. The ridges occur mostly at the southern part of glacier front but also towards the middle part of the glacier front, stretching approximately 400 meters up-glacier from the glacier margin.

Supraglacial debris stripes

In the area of subglacial till cover deposition of angular material of sorted lithology deposited in stripes parallel to former ice flow is observed. The stripes of angular material consist of darker shale or lighter colored sandstone clasts and are therefore very visible both on aerial images as well as in the field (Figure 15 a & b, Figure 16). They are evenly spaced throughout the forefield and are deposited on top of all other observed landforms. The stripes occur as a continuation of the medial moraines melting out of the glacier, and can be traced from the glacier front towards the shore. The stripes draping the terrain do not occur with any marked relief. The concentration of material varies: in some areas, the stripes occur as a line of scattered angular material, but in the northern region of the forefield the deposition of angular material occurs as more of a low-relief sheet of clast supported angular material. These stripes are labelled as "supraglacial debris stripes" in the map.

Interpretation:

The stripes consisting of angular material melting out of the glacier are interpreted as medial moraines melting out as described by (Anderson, 2000; Hambrey and Glasser, 2003). The angular material that composes the debris bands is characteristic of supraglacial or englacial transport (Hambrey and Glasser, 2003). The material has been incorporated in the ice either supraglacially from rockfall or subglacially, and is then transported forward by glacier flow. When the glacier retreats the material melts out by the glacier front. These lines are left in the forefield as linear debris stripes of supraglacial origin and can therefore indicate the past ice flow direction (Hambrey and Glasser, 2003). The sorted debris stripes deposited on the subglacial till plain is interpreted to be supraglacial lineations, also known as longitudinal debris stripes, that have melted out of the glacier and been deposited on the surface of the subglacial till (Hambrey and Glasser, 2003; Evans et al., 2012). These elongated debris stripes provide striking evidence that glaciers have a laminar flow and that the glaciers have been steady in their motion (Anderson and Anderson, 2010). The linear debris stripes are found deposited in the entire forefield, not just along the sides of the forefield. This suggest that the glacier ice holds a lot of material and that glacier must have several sources where material is incorporated into the ice along the glacier margin.

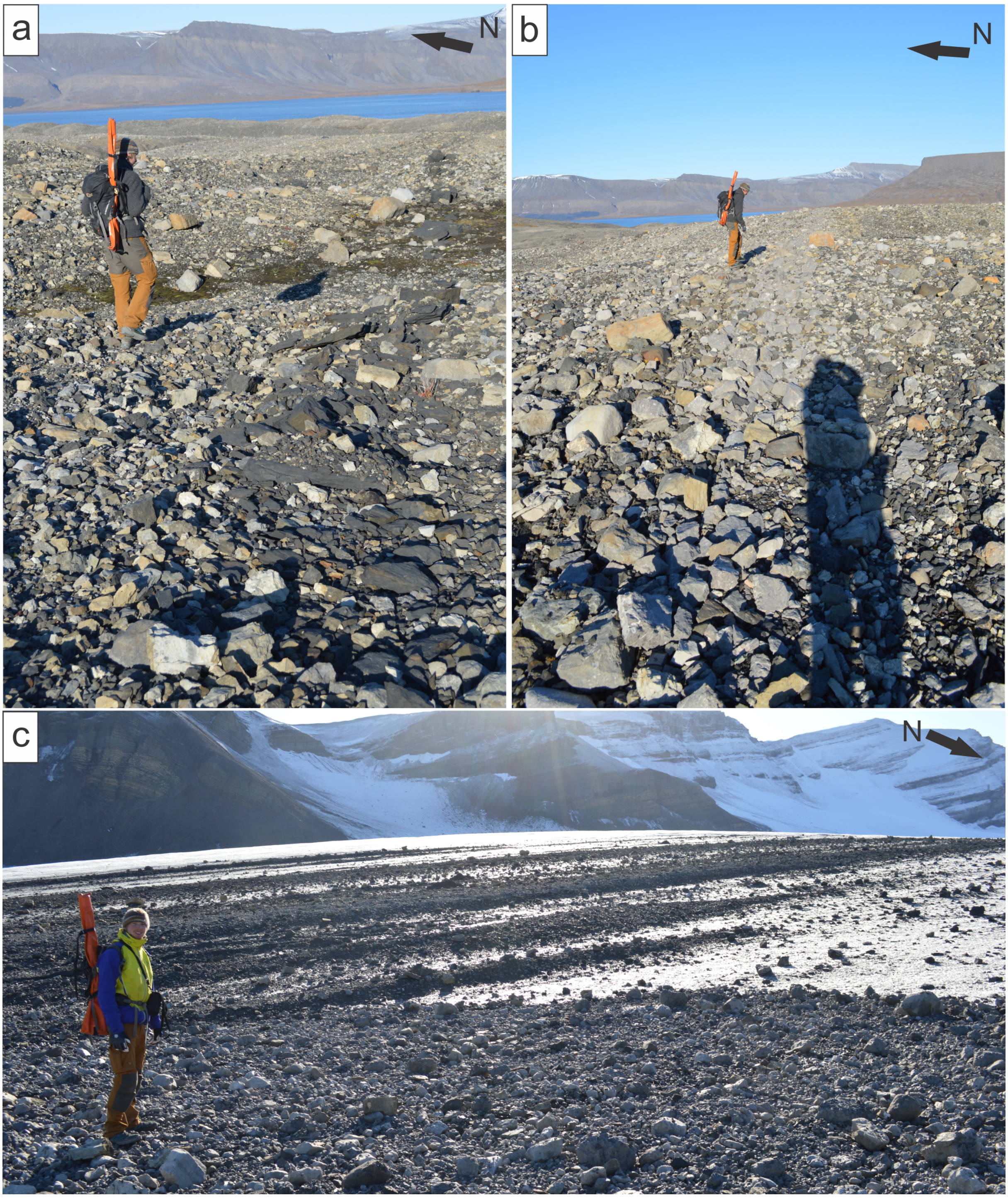

Figure 15: Debris stripes and ablation type medial moraines. a) sorted debris stripes observed in the forefield consisting of dark shale. b) Sorted debris stripe consisting of light colored sandstone. c) Ablation type medial moraines observed at the glacier front. Person for scale.

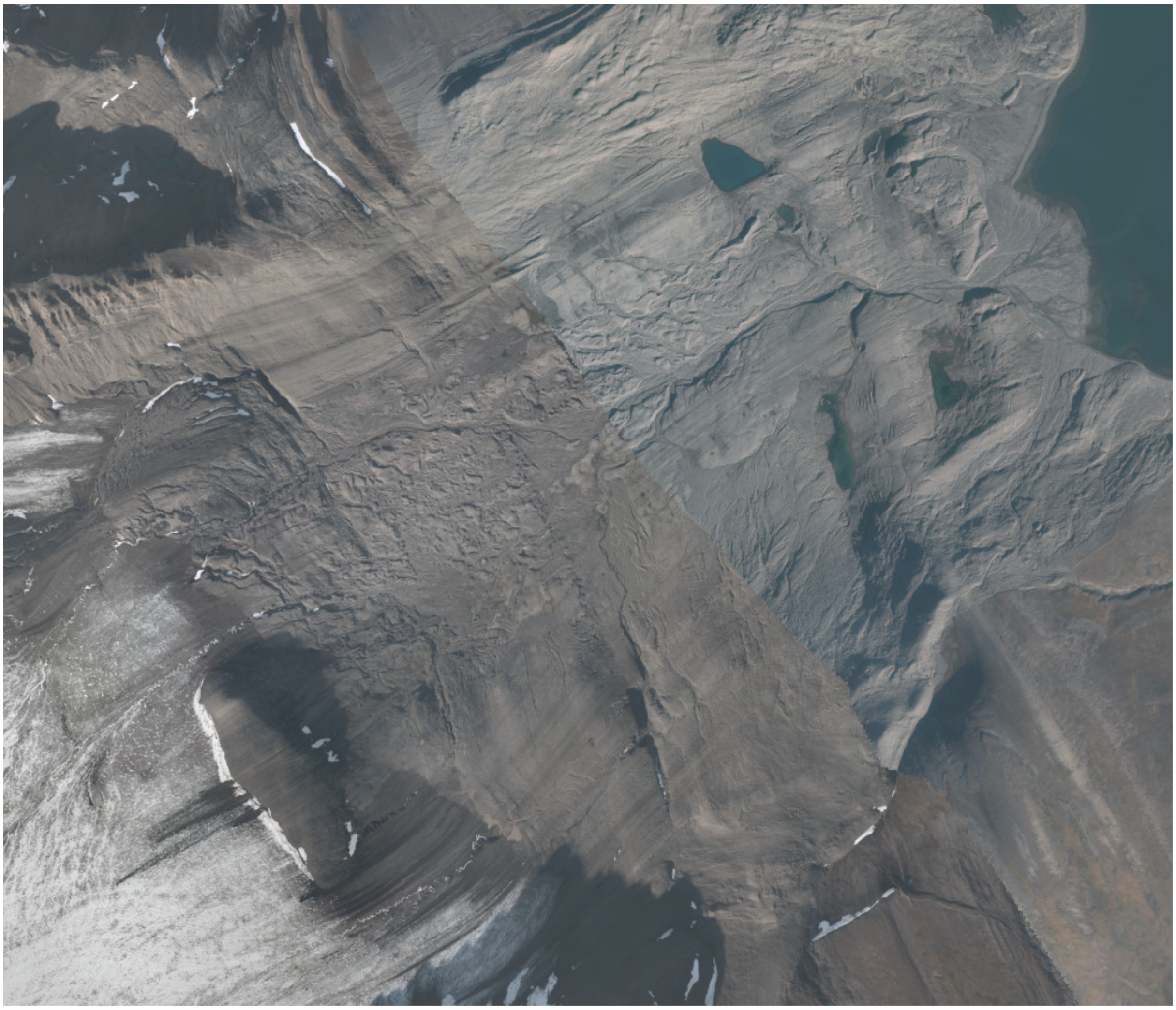

Figure 16: Aerial image from 2008/10 of Aldegondabreen forefield. Debris stripes are the darker stripes visible as dark medial moraines at the glacier front. In the forefield the debris stripes occur as both dark and light colored. These lines can be followed from the glacier front to the shore. Source: NPI, TopoSvalbard.

Small transverse ridge

Description:

On the north-eastern part of the forefield near the shoreline, a number of small transverse to ice flow ridges have been mapped. They occur most commonly on sloping surfaces dipping towards the fjord, but also occur on flat surfaces. The ridges consist of sorted gravel and sand with a higher concentration of a darker shale than the surrounding material, as well as unsorted, loosely-packed material and are visible both on aerial images and in the field (Figure 19a). The transverse ridges are generally small, ranging in size from 3-6 meters long and around 20-50 centimeters in height. Two transverse ridges are observed together with flutes, draping them at a 90-degree angle (Figure 17 a & b).

Interpretation:

A transverse ridge draping a flute is observed. In addition, the existence of sorted sediments in some of the ridges indicate that the material comprises these transverse ridges is not a result of subglacial transport or deposition, but rather a result of melt out of supraglacial and englacial material in combination with fluvial processes. These ridges are found on the lee side of the hills in the forefield, which could suggest that the ridges are a result of crevasse infill from the surface of the glacier. As the glacier moves over an obstacle, extension of the ice on the lee side of the obstacle creates crevasses in the ice where the glacier is flowing downhill. Over time, supraglacial material can slump into the crevasses and result in crevasse infill (Bennett et al., 2000). Meltwater can also be routed into crevasses and deposit glaciofluvial material. The material filling in a scenario like this together could therefore consist of both sorted and unsorted material.

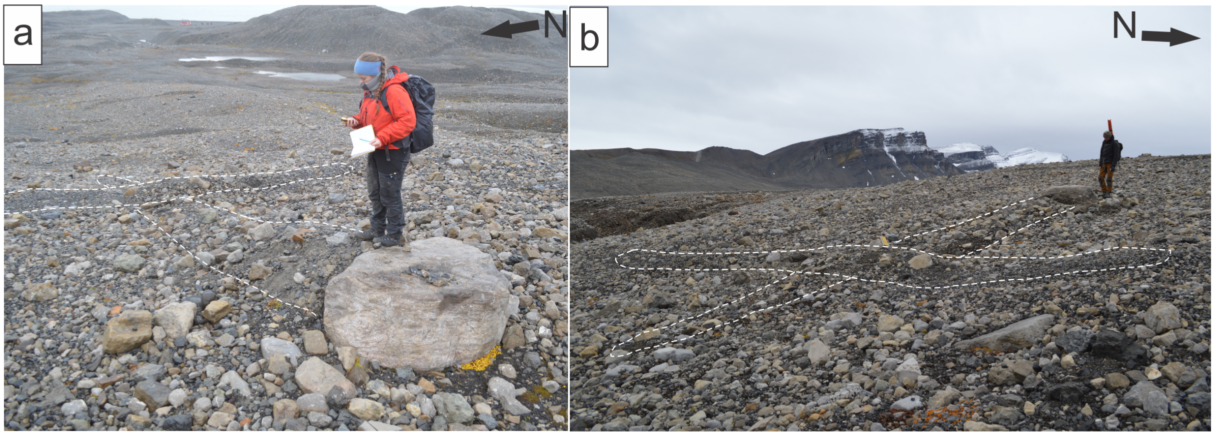

Figure 17: Transverse ridge overlapping flute, oriented perpendicular to each other. Person for scale.

Elongated ridge

Description:

On the northern side of the forefield three elongated ridges are mapped with a grey dashed line. They are easily observed on aerial images as well as in the field, and have an orientation parallel to former ice flow. The ridges are measured to be 241, 149 and 77 meters long and the width is around 10m, though it does fluctuate along the features (Figure 19b). They are surrounded by relict channels and outwash plains that run along the side of the features or transect them. These features consist of a coarse-grained loose diamict, while the surface of the ridges consists of very angular clasts. No striations on the clasts are observed.

Interpretation:

The original size of the ridges is not known as they are surrounded by relict channels; this indicates that fluvial erosion could have influenced the ridge shape. Loosely compacted diamict is not associated with subglacial deposition, as subglacial diamicts usually are more compacted due to high pressure from the glacier ice (Krüger and Kjær, 1999). The diamict composition indicates that the deposition has not been affected by any sorting during transport or deposition. The angular clast and loose compaction suggest that these ridges may be a result of englacial or supraglacial transport. One possible explanation is that these ridges are melt-out medial moraines described by Hambrey and Glasser (2003); Evans et al. (2012); this would explain why the features are oriented parallel to former ice flow.

Kettle hole

Description:

Seven water-filled depressions are observed in the forefield of Aldegondabreen; the outlines of the depressions are included in the map (Figure 12). They occur in areas of the forefield where fluvial erosion is high, but also in the hummocky terrain on the northern side of the forefield. Six of the depressions occur in two "lines" crossing the forefield in an almost N-S direction. The seventh depression occurs in the area mapped as hummocky moraine. The depressions that are mapped are all filled with water, but it was observed during the two field trips that the water limit lowered during the summer season. The depression outlines have various shapes and sizes.

Interpretation:

Due to the occurrence of the depressions in areas of irregular surface topography, these water filled depressions have been interpreted as kettle holes that have formed due to dead-ice degradation (Schomacker, 2008; Benn and Evans, 2010); however, it is unusual that the depressions are all filled nearly to capacity with water, as one would expect water levels to lower over time as the dead-ice disappears. As the water level of these depressions fluctuate, it suggests that they are still fed with water during the melt season. This can be due to snow melt, heavy rainfall or from groundwater in the forefield (personal communication, Andy Hodson).

Hummocky moraine

Description:

The area with this label covers a total of ~0.88 km^2, and is found on both the northern and southern side of the forefield towards the shore. The area is characterized by mounds and depressions, as well as drainage channels and in some areas slumping activity in the northern region (Figure 18). A water-filled kettle hole is located on the northern area near the shore, where slumping activity is still active. The topography of the area is irregular, but overall dips towards the center of the forefield on both sides. This is shown in the map (Figure 12) with 20 meter interval contour lines. Angular clasts are observed on the surface of these two areas.

Interpretation:

The irregular surface that occurs within this area, along with various features such as kettle holes, areas of slumping and drainage channels, indicates this is hummocky moraine (Hambrey et al., 1997; Schomacker, 2008). The surface topography differs from the undisturbed subglacial till in the forefield, which has flatter, undisturbed surface topography. This landform develops and changes over time as trapped dead ice melts, leaving the topography uneven. The slumping activity on the northern area suggests that the moraine might be ice cored.

Figure 18: Slumping activity in the hummocky moraine on the northern area

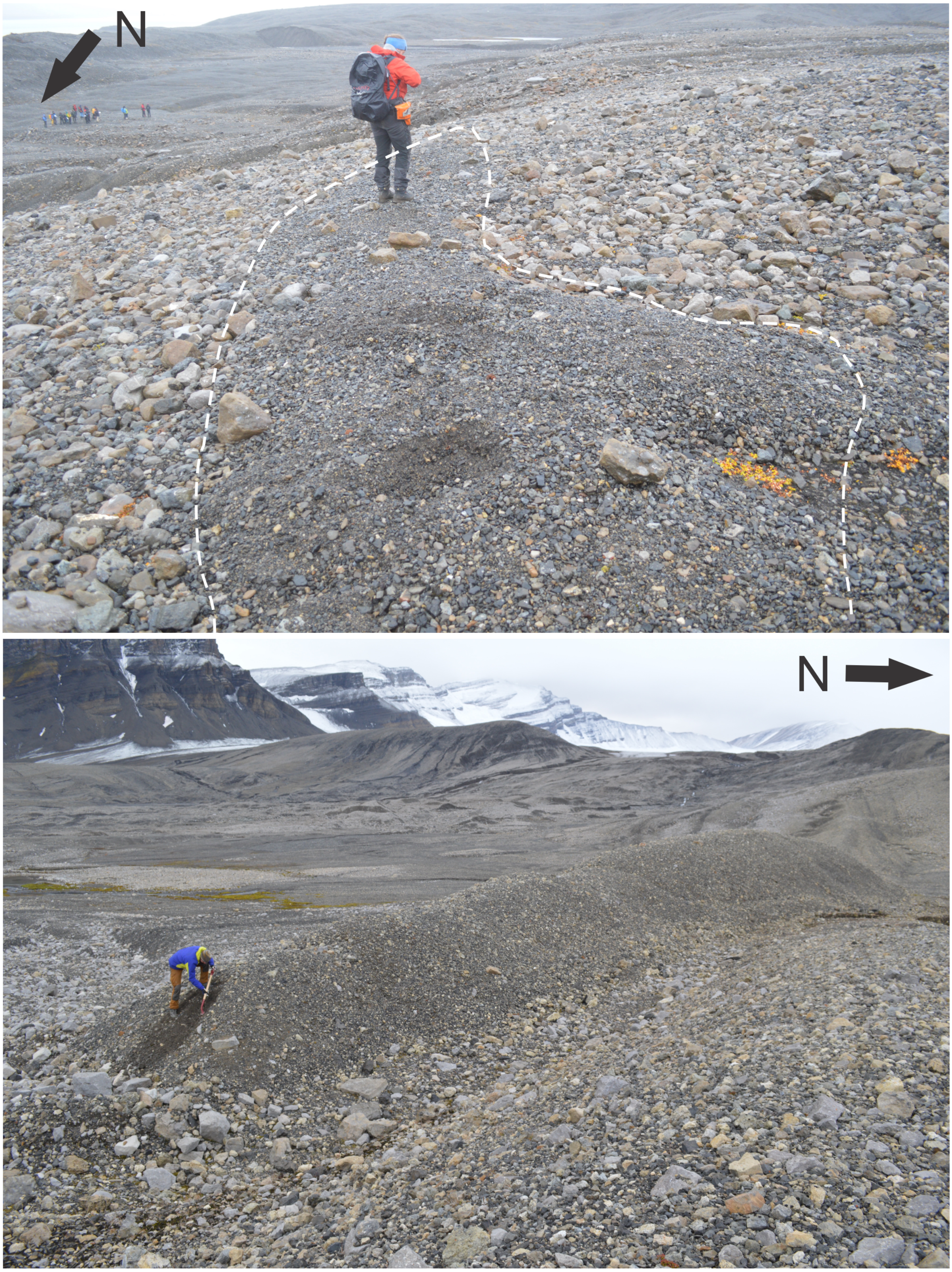

Figure 19: a) Transverse ridge, person for scale, b) Elongated ridge truncated by a channel

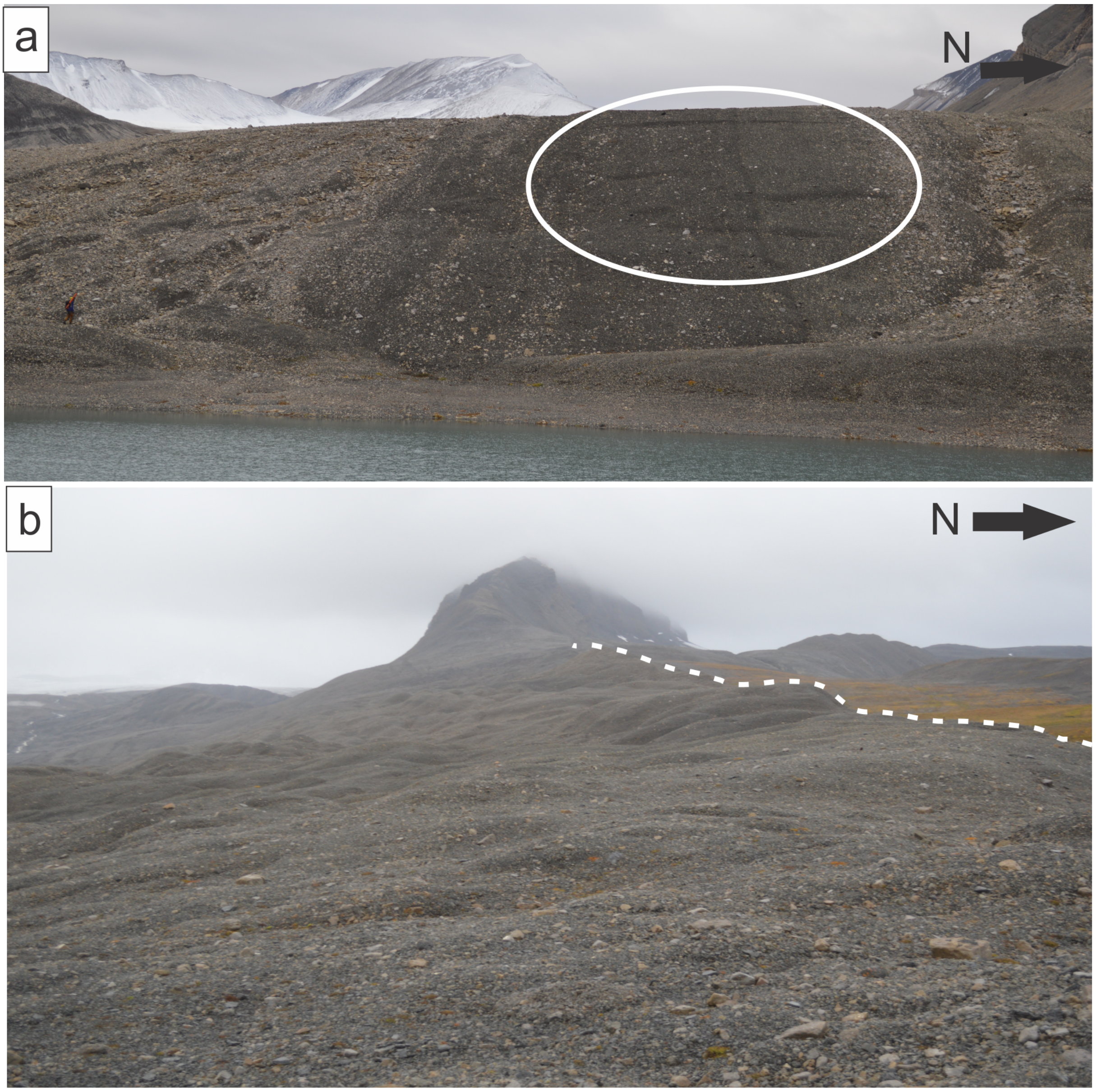

Figure 20: Transverse ridges and hummocky moraine. a) transverse ridges in the forefield or Aldegondabreen. Area where transverse ridges occur is marked with a white circle. Person for scale in the down-left corner. b) Hummocky moraine, northern side of forefield. Outer margin of forefield marked with a dashed line.

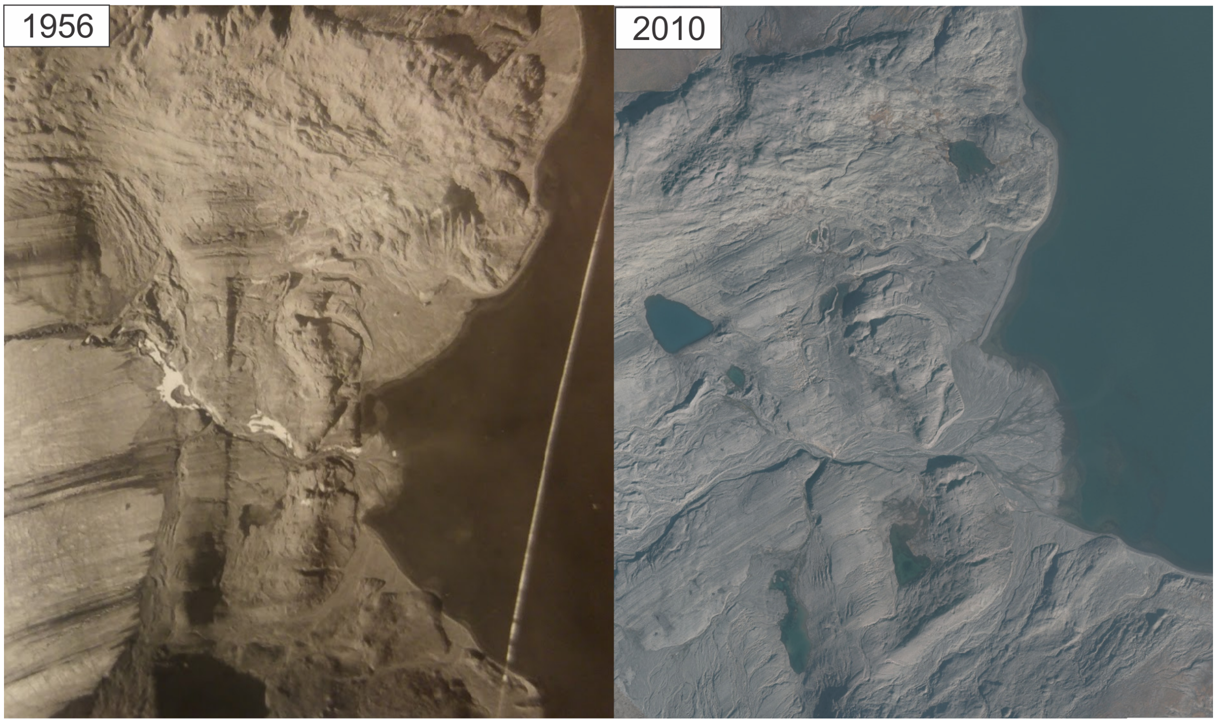

Figure 21: Comparison of landforms in 1956 and 2010. Glacier front is observed in the 1956 aerial image. Changes can be seen at the shoreline with the growing delta, water filled kettle holes have formed after the aerial image in 1956, and grown in size. Transverse ridges are more visible in the 1956 image compared to 2010 image, suggesting weathering of landforms. Source: NPI; TopoSvalbard.

4.1.3 Glacifluvial landforms

Subglacial till plain, incised by channels

Description:

The areas with this label covers ~0,3 km^2, representing areas in the middle of the forefield where the topography is uneven with channel-like depressions. The area is cut by small channels that occur in a complex system, occurring in different topographic levels. The erosional remnants left in this area have the same composition and surface expression as the subglacial till plain described earlier in section 4.1.1. In the channels sorted material consists of gravel and boulders. The channels are relict and no longer active (Figure 22).

Interpretation:

The fluvial erosion has not been extensive enough to classify this area as an outwash plain, as large amounts of the subglacial till plain remains as erosional remnants between the channels. The areas marked by this label are therefore interpreted as a subglacial till plain, incised by channels during glacier retreat. The main material of the erosional remnants is a similar diamict to the areas marked as a subglacial till plain. The area is surrounded by outwash plains and channels which suggest the channel-like depressions in the area are old relict channels, indicating that the area has been affected by running meltwater during glacier retreat. It is therefore suggested that the fluvial erosion stopped before the area developed into an outwash plain where all material is reworked.

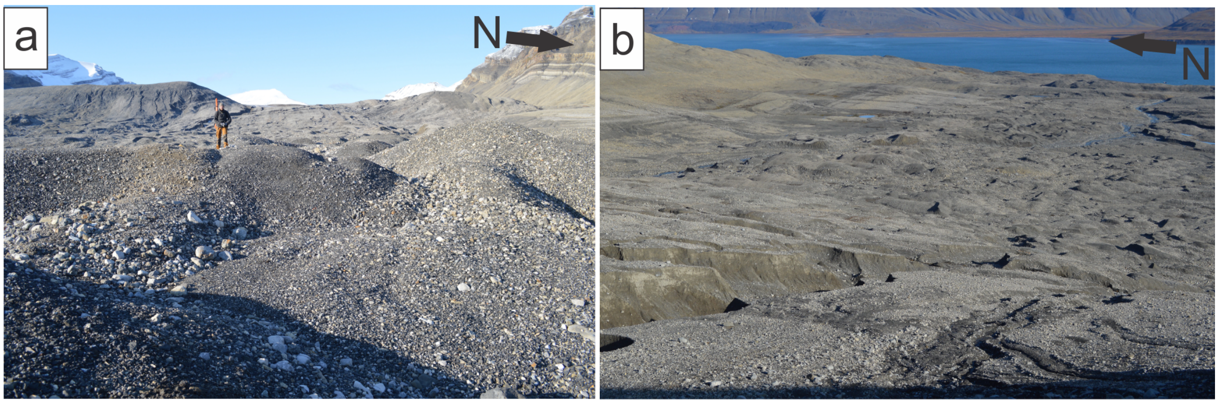

Figure 22: Subglacial till, incised by channels. a) Channel like depressions. Person for scale. b) Overview picture of the area marked as subglacial till, incised by channels. As seen the area has an uneven topography caused by fluvial channel erosion with erosional remnants consisting of subglacial till.

Outwash plain

Description:
These landforms cover an area of ~0.78 km^2 in the forefield of Aldegondabreen. Fans and plains are observed at several locations in the forefield. The surface material is comprised of cobbels, gravel, sand down to fine-grained sand as well as larger blocks in some areas. The material is sorted, and longitudal sandbars appear between channels. There are both active and relict channels streams in these fans and plains, and they occur as braided river systems. Due to the topography of the forefield, most channels lead toward the main meltwater channel system in the center of the forefield, located at the lowest part of the terrain. These braided river systems usually start with a single channel before a plain of channels forms lower in the topography or on flat surfaces. The channels flow towards the lowest point in the topography, leading all channels into a single large river that flows in the center of the forefield all the way to the shore. When the fluvial systems reach the shoreline large fan-shaped plains occurs.

Interpretation:
The sorted material and the braided river systems indicates these areas are outwash plains (Maizels, 1993). The active meltwater channels appear to drain towards the lowest part of the terrain, resulting in channels draining towards the center of the forefield. These outwash plains are created in front of the glacier as it retreats as the river erodes glacial material and transports it towards the shore. As the river systems changes over time, it creates these outwash plains. The intricate system of outwash plains suggests that the glacier has released large amounts of water during retreat at several locations, and several of the channels reflect former glacier front positions during retreat. A modern analog of this is observed at the glacier front. As a result of significant water released by the glacier into the forefield, severe erosion has occurred where the channels have been most active.

Outwash fan at the shoreline

Description:
The areas with this label covers the total of ~0.12 km^2. Five fans have been mapped based on their source and shape. These larger fan-shaped deposits formed in the sea where the glacifluvial channel systems meet the ocean. The surface of all fans are covered in braided river systems, both relict channels and active channels as the outwash plains described above. Sorted material in all grain sizes is found on the surface on all of the fans, ranging from silt to boulders. Four of the five fan systems are no longer active or are seasonally active depending on the source; there were no active channels observed on them during fieldwork. Three of the four inactive systems include beach deposits at the shoreline. The active system is also the largest, and has a number of active channels flowing towards the sea that are actively bringing material to the fjord. There is no beach material observed in front of this fan.

Interpretation:
These fan-shaped landforms are mapped as outwash fans occurring at the shoreline. They are marked with a different label to indicate the difference in depositional environment compared to the outwash plains. These fans build out into the fjord, though their surface expression is the same as outwash plains described above. The main difference is that these fans build out into the fjord as shallow water deltas. Deltas form by fluvial aggradation above water level and progradation of the delta front, as sediments are deposited when channels decelerates on contact with standing water (Benn and Evans, 2010). As the glacier has retreated, meltwater carrying glacifluvial material has created several deltas along the shoreline of Aldegondabreen forefield.

Relict outwash fan

Description:
These deposits are located close to the shoreline and comprise an area of ~0.004 km^2 . The deposits are being eroded by the now-active channels running through this area. In these sections it is possible to observe the internal structure. The deposits consist of alternating sorted layers of gravel in between layers of diamicts, with layers dipping slightly towards the shore. The surface of these deposits are located 6-4 meters above the current sea-level. A seal bone was found buried within the layers. On the surface of the deposit, debris stripes consisting of angular clasts are observed, as well as three small transverse ridges that are partly eroded.

Interpretation:
These deposits are interpreted as delta deposits due to the alternating sorted layers and the slight dipping of layers (Nichols, 2009). They also are interpreted as an older deposit since the layers are found 4-6 meters higher than the present day sea level, making it incompatible with deposition simultaneous to the modern analog described above. It is reasonable to assume that these deposits are remains of an ice-contact delta as diamict layers are present, which can reflect a close proximity of glacier ice (Nemec et al., 1999). Evidence of glacial activity on the surface of these deposits suggest that this fan has likely been overridden, suggesting that the deposits are most likely older, and were deposited before the Little Ice age advance.

Active and relict meltwater channels

Description:
Channels are observed throughout the forefield. The channels are mostly oriented transverse to ice flow before reaching the main meltwater channel which leads directly to the shore. Several of the channels initiate in single apices and spreads out in braided patterns downslope, following the topography. Running water can be traced back to the glacier at several locations.

Interpretation:
The channels are interpreted as meltwater channels (Ashworth and Ferguson, 1986; Schomacker et al., 2012). The number of channels both active and relict suggest a very active meltwater system that mimics the glacier front, but also erodes and reshapes the forefield after glacier retreat. The channel activity migrates according to the meltwater outlet from the glacier, but the topography of the area seems to be the deciding factor controlling channel orientation. The dry channels are interpreted as relict meltwater channels or seasonal channels, active only during spring melt.

Sinuous ridge: Esker

Description:
Three sinuous-shaped ridges in three different locations are observed in the forefield (Figure 23 c & d). They differ in size both in length and height ranging from 50-100 meters long, 2-10 meters wide and 1-4 meters high. Two of the ridges are located in the N-E part of the forefield and the third ridge is located at the glacier front. The two ridges closer to the shore have a smoother, elongated sinuous shape compared to the ridge located by the glacier front, which has a more zigzag-like shape. A section was dug in all three ridges and they all show stratified layers of sand and gravel; angular material was observed on the surface of the ridges (Figure 23e).

Interpretation:
The ridges are interpreted as ridges of glacifluvial origin, also known as eskers based on their sinuous shape and internal composition of sorted sediments (Banerjee and McDonald, 1975). The landforms can be created both through subglacial, englacial or supraglacial deposition. It is difficult to determine the origin of these ridges, but historical photos show no signs of eskers being formed on the surface of the ice where they are positioned. The ridges are deposited by running water carrying material as is flows down-glacier, confined by glacier ice(Banerjee and McDonald, 1975).

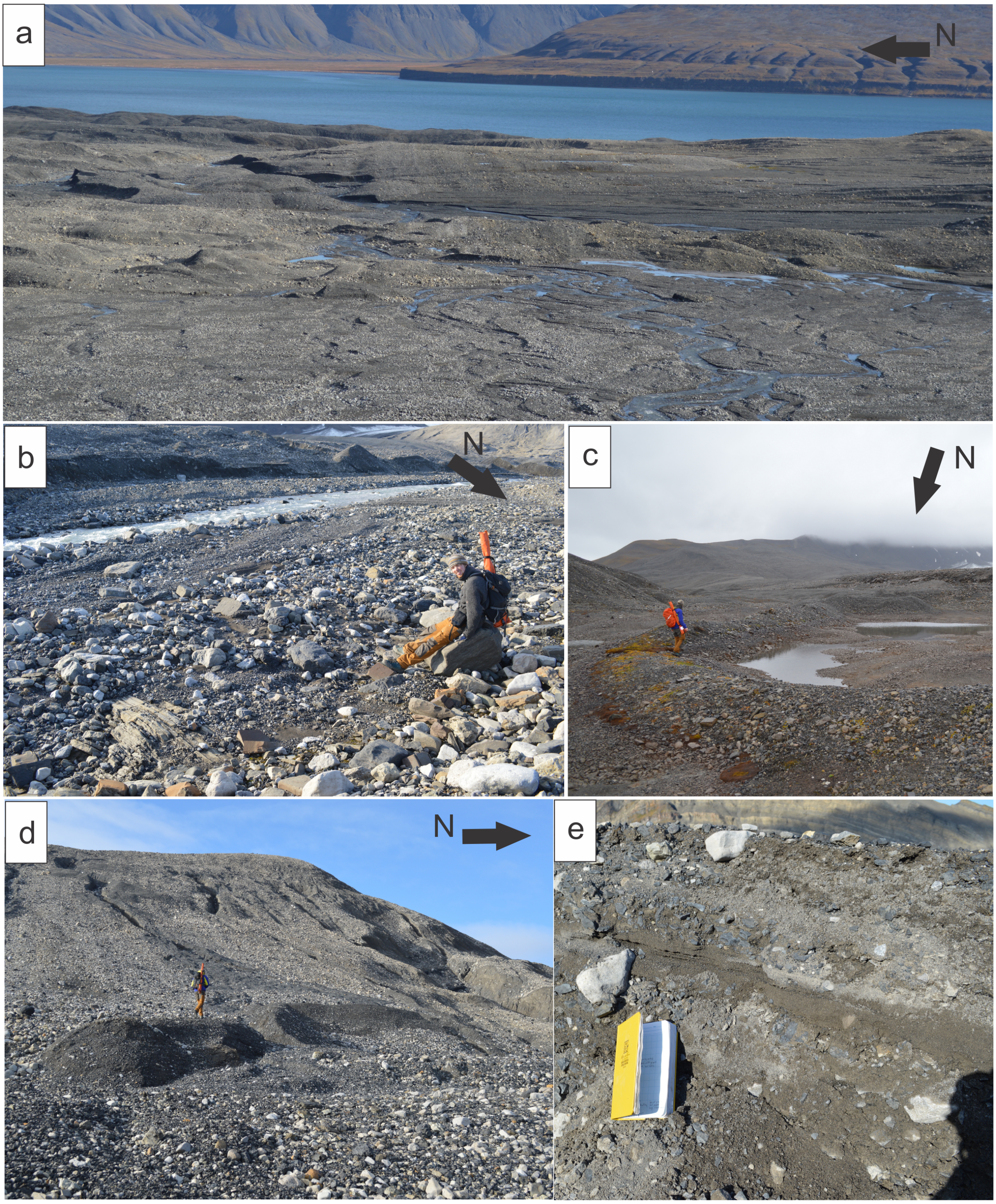

Figure 23: Outwash plain and eskers. a) Overview of an outwash plain on the southern side of the forefield. b) Closer look at the outwash plain. Location is in the center of the forefield. c) Esker, location is east in the forefield close to shore. d)Esker located west side of forefield close to ice margin. e) Section dug in esker seen in Figure 23d. Layers of gravel and sand visible along the side of the esker.

Figure 24: Overview of the outwash fans at the shoreline forming in front of the glacier forefield. In the center of the picture is the largest outwash fan actively depositing out into the fjord.

4.1.4 Coastal landforms

Beaches, modern

Description:

An area of ~0,02 km^2 is mapped as this landform. The landform appears as two continuous bands of sorted material along the shoreline. The two bands are cut by an active delta fan in front of the glacier forefield. The material is sorted gravel and sand with shell and shell fragments. They are confined by storm deposits that are transported to the top of the beach during stormy weather. The deposits are steeply dipping toward the sea.

Interpretation:

Due to the erosional activity by meltwater channels in the forefield, the beach material consists of a mixture of reworked glacial deposits together with shell fragments and other material deposited on the shore by wave action (Hart and Plint, 1989). As the beaches are located at the present day sea level, and the fact that the glacier in 1911 was a tidewater glacier, these beach deposits must be modern, deposited after the glacier had begun retreating and the fan systems became inactive.

4.2 Ice-marginal reconstructions

Eight ice-marginal positions from 1911 to 2016 have been reconstructed using historical aerial images, modern orthorectified aerial images, satellite imagery and historical photos (Figure 27). The approximate measured retreat of the glacier between ice-marginal positions together with the average retreat in meters per year, can be seen in Table 2 and in a time/distance diagram presented in Figure 25. The historical photos from Isachsen, 1911 (Figure 26) are captured from the northern shore of Grønfjorden looking at Aldegondabreen; this created an uncertainty of the exact ice marginal position, and therefore the 1911 ice margin is mapped as a dashed line (which represent an uncertainty). The glacier has retreated a total of ~2.28 km from 1911 to 2016. At the 1911 position, the glacier front was terminating in the fjord and Aldegondabreen was at classified as a tidewater glacier, possibly a calving tidewater glacier. As there is no available bathymetric data in front of Aldegondabreen in Grønfjorden, the exact maximum extent of the glacier during the Little Ice Age and position of the Little Ice Age moraine is unknown. By 1936, the glacier had retreated onto land and the glacier transitioned into a land-terminating glacier. From the historical photos taken in 1911 to the 1936 aerial images, the glacier front seems to have changed significantly from a steep, possibly calving front to a flattened-out glacier front. During this time the glacier had retreated ~0.17 km in 25 years. The transition from a tidewater glacier to a land-terminating glacier implies that the glacier now only loses mass by surface melting, and seems to experience a major mass loss at this time. The average per year increases before decreasing again in the 20_{th} century: presently the average retreat is approximately 18 meters per year. It is important to note that the measurements are taken in a center line on the glacier; the measured retreat between the ice marginal positions various depending on where the measurement is taken. Some areas may be protected against sunlight, or thresholds in the area can affect how the glacier retreats. The protection from sunlight was the deciding reason for choosing an area that would have the most stable exposure throughout time, which was the center of the glacier.

Meltwater channels and outwash fans in the forefield reveal interesting aspect of the retreat history. Several channels outwash fans have repeatedly cut through the landscape transverse to former ice flow and then show a trend of fanning out towards the shore. These channels and outwash fans can reflect several of the reconstructed ice front positions of Aldegondabreen and can help with reconstructing former ice marginal positions (Dyke, 1993). Though they can be helpful and that some of the channels match up with mapped ice front positions, the channels alone are not enough data to be sure of timing of ice position and are therefore not used to reconstruct former ice marginal positions in this study.

Table 2: Measured ice-marginal retreat in kilometers for Aldegondabreen. Measurements are applied along the same line at the center of the glacier. The average retreat in meters is also presented.

	Aldegondabreen							
Year	1911-1936	1936-1956	1956-1990	1990-2004	2004-2008	2008-2013	2013-2016	1911-2016
Retreat in kilometers	~0.17km	~0.32km	~0.77km	~0.5km	~0,36km	~0.11km	~0.05km	~2,28km
Average retreat in meters per year	6.5m/y	16m/y	22.6m/y	35.7m/y	90m/y	22m/y	16m/y	18m/y

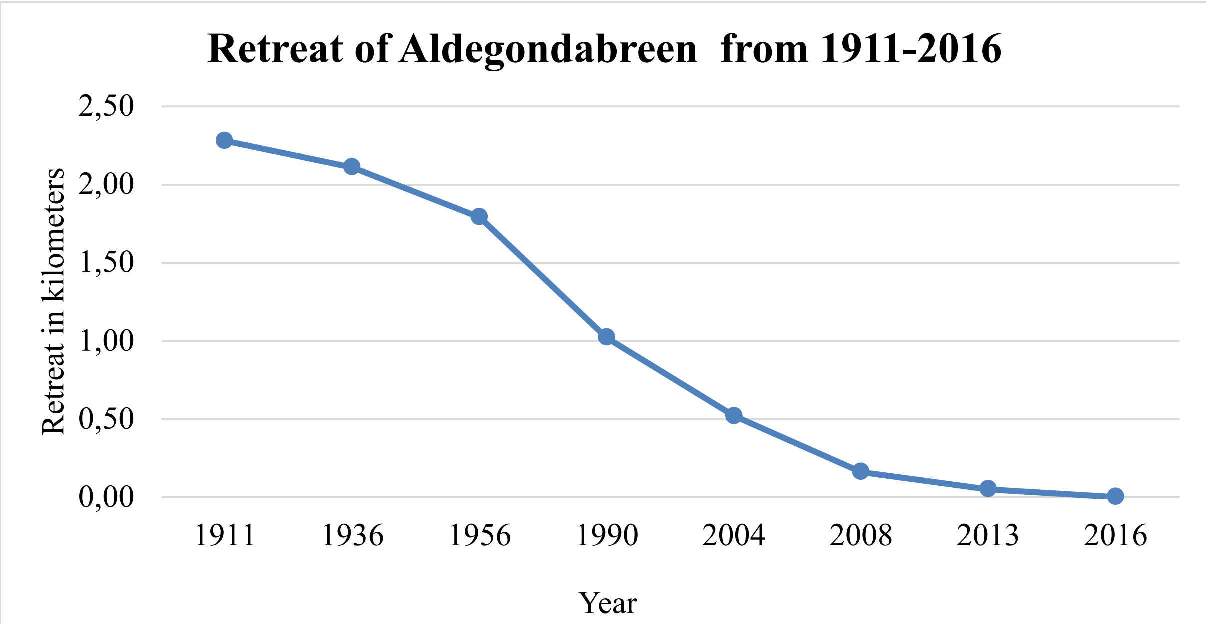

Figure 25: Time/distance diagram for Aldegondabreen glacier retreat. The diagram show the maximum position in 1911, 2.28 kilometers from the 2016 ice marginal position.

Figure 26: DeGeer and Isachsen photos to show when Aldegondabreen still terminating into the fjord compared with a photo taken during fieldwork in 2017. The glacier is almost not visible any more from the fjord in its current state.

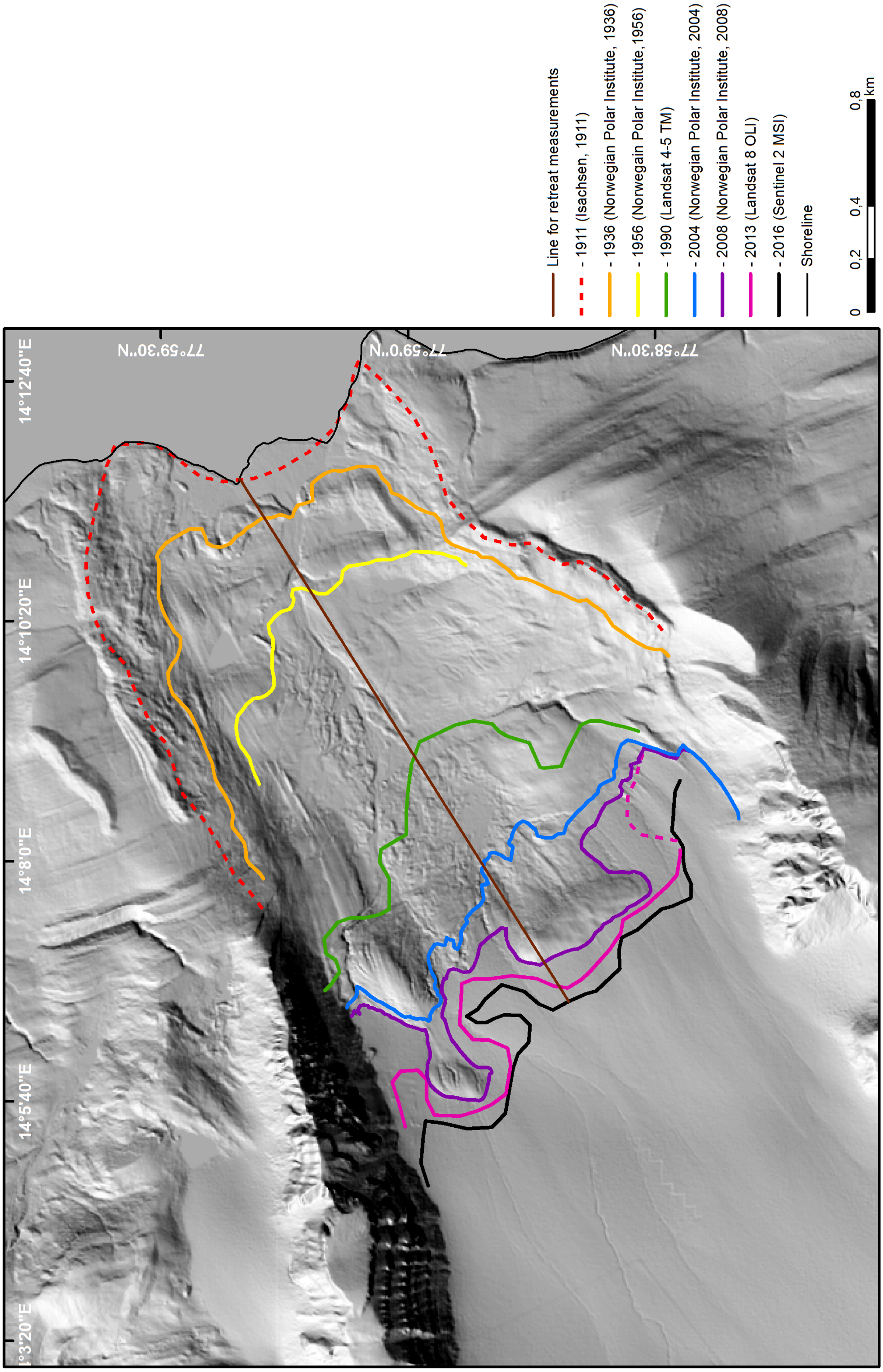

Figure 27: Ice-marginal reconstructions from 1911 to 2016. The lines are based on aerial and satellite images, as well as historical photos. Legend for lines is presented at the top right corner of the figure. Background image is a hillshade created from the DEM provided by NPI.

5 Depositional units of Aldegondabreen

The geomorphological map presented in this study examines the surface features (landforms) of Aldegondabreen. To fully understand the forefield of Aldegondabreen, one objective is to identify the available material in this glacial system: this involves identifying the distribution of materials in the forefield, which strongly controls which landforms can form in a glacial system. By identifying the distribution of materials and how they deposit relative to each other it is possible to use a landsystem approach to identify the glacier type.

In the forefield of Aldegondabreen three main depositional units have been identified: the subglacial, the supraglacial and the glacifluvial material. These three “units” can be regarded as the main building blocks of the forefield of Aldegondabreen. The subglacial and supraglacial material can be directly connected to glacial depositional processes and therefore are unique to glacial environments. Fluvial processes can also be connected to glacial environments, occurring both in front of and on glaciers, such as in subglacial tunnels or on proglacial braided river plains (Benn and Evans, 2010).

A schematic model consisting of 4 steps is shown in Figure 28: this illustrates how the subglacial and supraglacial material is deposited relative to each. The model is based on observations at the glacier front and the forefield of Aldegondabreen.

Step 1: A layer of subglacial till has developed and is actively being deposited at the base of a debris rich glacier, marked as green in Figure 28.1. The glacier ice moves from right to left, transporting englacial material down glacier. The subglacial till is deposited directly on bedrock, marked as a light grey color.

Step 2: The glacier has a negative mass balance, losing mass through surface melt: as a result the ice front is retreating. As the glacier thins, the englacial material melts out of the ice and is visible on the glacier surface, resulting in debris accumulating on the ice surface over time. This scenario is observed at the glacier front of Aldegondabreen today, where a layer of subglacial till is frozen on to the base of debris-rich ice. The ice is overlayered by angular supraglacial debris (Figure 28.2). As the glacier continues to thin out and retreat the supraglacial material is deposited in the forefield of the glacier (Figure 28.3).

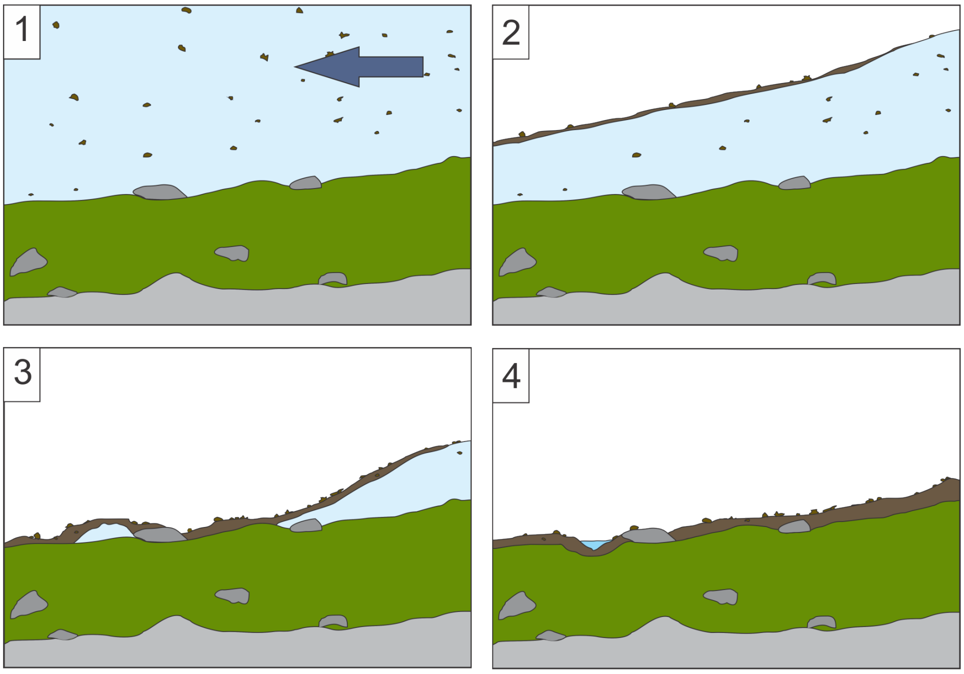

Figure 28: Schematic model showing how the subglacial and supraglacial material is deposited relative to each other from step 1-4. Arrow in step 1 shows ice flow direction.

Step 3: In areas of the forefield where the ice has melted away completely, supraglacial material is deposited directly on top of subglacial material. The extent and thickness of the supraglacial material can differ throughout the forefield depending on how debris is concentrated in the glacier ice and at the glacier surface. The distribution of surface debris on the glacier ice influences ablation rates: a thick cover can "protect" the ice from melting, and ablation rates would decline. This can result in ice covered by debris, or dead ice, remaining in the forefield as illustrated in Figure 28.3. A thin discontinuous debris cover can increase melting and ablation rates and result in a glacier that retreats quickly (Benn and Evans, 2010).

Step 4: In Figure 28.4 the ice has retreated completely. The supraglacial material that was incorporated in the ice as englacial material has melted out and draped the entire forefield. The dead ice previously trapped beneath the supraglacial material has now melted out and resulted in a water-filled depression. As mentioned, the amount of supraglacial material can vary depending in the individual glacier. This model is based on a scenario where the glacier has a debris-rich glacier ice.

The conceptual model illustrated in Figure 28 does not consider the glacifluvial erosion that can occur in the forefield during retreat. How the fluvial processes can modify the landscape and deposit fluvial material is especially noticeable in the Aldegondabreen forefield. The collection of deposits found in the forefield of a retreating glacier is dependent on the processes that occur during glaciation, the retreat and post-retreat. In the forefield of Aldegondabreen the grouping of landforms found is dependent on the extent of supraglacial and subglacial material but also dependent on the fluvial erosion. To illustrate this, a conceptual model of a glacier forefield has been created (Figure 29). The model shows a glacier that is losing mass by surface melt, which eventually deposits supraglacial material as debris stripes. Similar to Aldegondabreen, the glacier in this illustrated scenario is depositing supraglacial material in thin debris stripes as well as in laterally extensive deposits that are parallel to former ice flow. The model also illustrates how the fluvial channels rework the forefield.

Active channels can create large, braided river systems or cut through the landscape in single channels. If there are several single channels carving the landscape, erosional remnants between the channels can remain; in Figure 29 these are illustrated as erosional remnants consisting of subglacial material. If the channel systems are sufficiently active they can erode down to the bedrock, resulting in the deposition as illustrated in Figure 29a; all the subglacial material has been eroded, leaving only fluvial material deposited directly on bedrock. If the channel is less active and only was able to cut through a portion of the subglacial till, a deposition such as Figure 29c would be the case. Subglacial till deposited on bedrock with fluvial material on top. These two types of deposition are seen in areas of Aldegondabreen where the channel systems have truncated the landscape after glacier retreat.

Where the channel system has not yet eroded in the forefield, the prevalent deposition is subglacial till deposited in bedrock, with supraglacial material draping the subglacial till; this depends on the extent of the supraglacial material. The thickness of the supraglacial deposition varies in a forefield, such as that illustrated in Figure 29. This column of deposits is illustrated in Figure 29b. The final column of deposition is the one located near the glacier front (Figure 29d). Here the materials are still in the process of being deposited. This column of units illustrates the ice between the subglacial and supraglacial material; this ice could be trapped as dead ice in the forefield (depending on the thickness of the debris cover), or it could simply melt out and deposit the supraglacial material directly on top of the subglacial material.

It is important to specify that these models don't take all glacial processes into consideration. The models are made to illustrate the main processes building the forefield. The colors of the different units reflect the colors used in the geomorphological map of Aldegondabreen presented in Chapter 4.

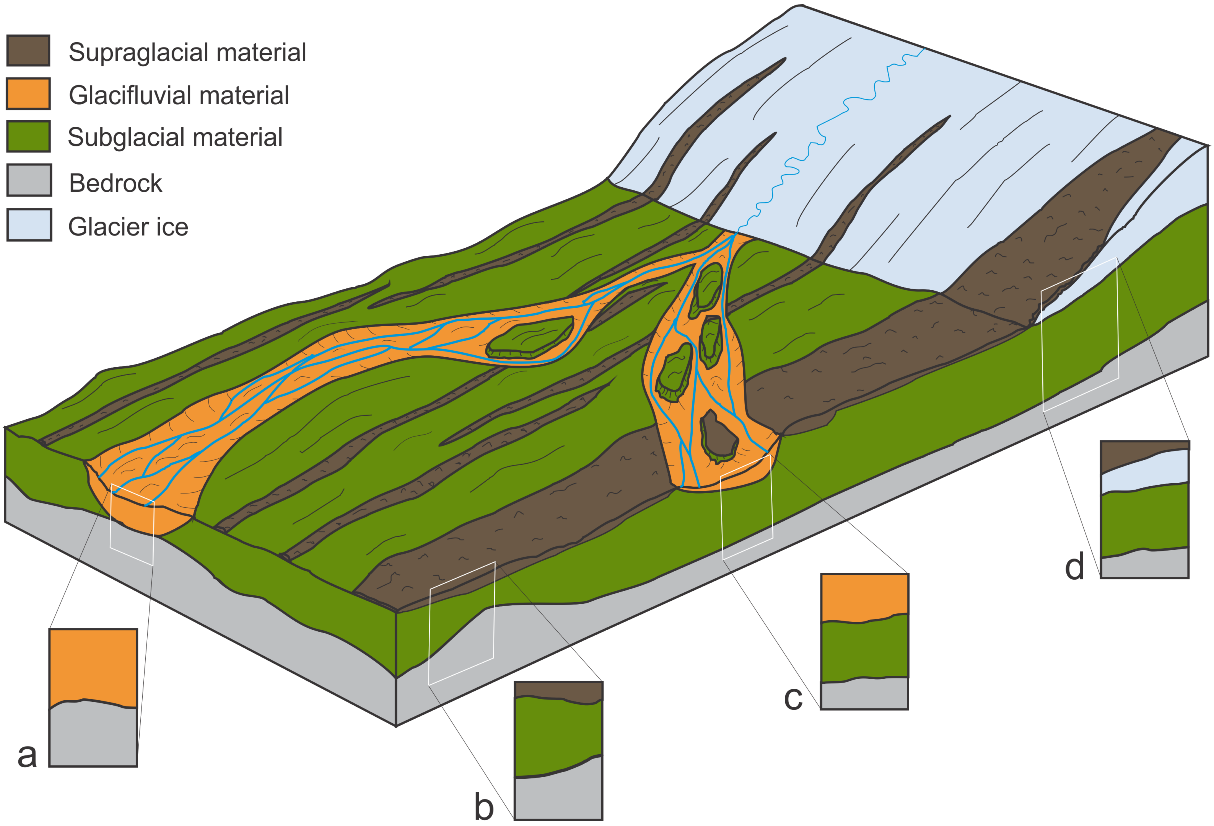

Figure 29: Conceptual model of an active depositional environment in front of a retreating land-terminating glacier that is losing mass by surface melt. The figure illustrates the depositional units that make up an active forefield. The main units consist of subglacial material, supraglacial material and glacifluvial material. Supraglacial material is deposited as debris stripes in the forefield, melting out of the glacier as ablation-type medial moraines. The boxes illustrate a set of units at a location in the forefield marked with white rectangles on the model. a) The fluvial system has reworked all the subglacial till available and redeposited it as fluvial deposits directly on bedrock. b) This box shows the result of a deposition where the supraglacial material is left draping subglacial material. It is not affected by fluvial erosion after deposition. c) This is an area where the fluvial system has eroded away the supraglacial material as well as some of the subglacial material. The box of units therefore consist of subglacial material deposited on bedrock with glacifluvial material on top. d) Final column illustrates the processes happening at the glacier front. Subglacial material is still covered by some ice. The supraglacial material continues to melt out of the glacier and is not yet finished being deposited.

6 Discussion

Following glacier retreat, the forefield of Aldegondabreen has been in constant change. The geomorphological record investigated at Aldegondabreen is from the last glacial advance/retreat cycle, culminating at the Little Ice Age terminal moraine. This section will focus on four main discussion points; 1) How applicable is the glacial landsystem model approach for Aldegondabreen and its glacier forefield, 2) preservation potential of landforms during glacier retreat, 3) ice dynamics and thermal regime and 4) to which extent is Aldegondabreen retreat affected by the warming trend since the end of the Little Ice Age. Suggestions for further research and uncertainties will also be discussed in this chapter.

6.1 Glacial landsystem model approach to identify glacier type?

The glacial landsystem model approach is a method of classifying glaciers based on the landform-sediment assemblage left behind in their forefields. Recent studies on Svalbard have shown that the landsystem model approach is not always applicable. Allaart (2016) and Aradóttir (2017) concluded that the existing glacial landsystem models were too simplified for the complex landform assemblages found both in the terrestrial and marine forefields of studied Svalbard glaciers. Landsystem models are usually based on few glacier observations, resulting in simplified models. The existing landsystem models may not capture the most complex glacier systems, but can be a useful tool for a number of glacier of glacier systems when reconstructing glacier history.

In this study a small land-terminating valley glacier is examined. The results in this study show similarities to parts of the Glasser and Hambrey (2003) glacial landsystem model for polythermal valley glaciers. To compare similarities, the sediment landform assemblage is discussed below.

6.1.1 Landform-sediment assemblage

The depositional units identified in the forefield of Aldegondabreen is the subglacial unit, the supraglacial unit and the glacifluvial unit. The three units are identified as the three main component that composes the forefield of Aldegondabreen. They are identified based on their source, transport and deposition.

The subglacial unit and the supraglacial unit show material available to form landforms. The subglacial unit occurs as subglacial till and is associated with short flutes on the surface of the forefield of Aldegondabreen. The flutes specifically, are an indicator of glacier flow, modification and shaping of the subglacial till under a warm based glacier (Clark, 1999). The supraglacial unit represent a debris-rich glacier that transport debris englacially, which melts out at the surface of the glacier in the ablation zone and drapes the ground during glacier retreat. This is evidenced by the supraglacial material occurring in debris stripes in the forefield, as well as in transverse ridges.

The glacifluvial unit consists of reworked and fluvially-sorted glacial material and occurs in proglacial outwash plains in the forefield of Aldegondabreen and delta deposits at the shoreline. The glacifluvial unit also comprise the eskers found in the forefield. The fluvial activity in the forefield is concluded to be extensive based on the mapped outwash plains and relict and active channels.

When comparing to the glacial landsystem model for typical Svalbard polythermal valley glaciers from Glasser and Hambrey (2003), the most similarities are found in the inner zone of the glacial landsystem model (Figure 2). In this area the subglacial till, flutes and supraglacially-derived debris stripes are the main similarities, together with reworking of material by proglacial streams. The lateral moraines also agree well with the model, though the typical end moraine is missing; this is because at its maximum extent, the glacier was terminating in the fjord. The model also refers to a moraine-mound complex, which is observed along the sides of the forefield.

Transverse ridges observed in a forefield like those discovered in the forefield of Aldegondabreen are usually connected to glacier surge behavior, and the landform is not presented in the glacial landsystem model from Glasser and Hambrey (2003). When compared with the model, this landform is ignored: the reasoning for this, is explained further in the ice dynamics and thermal regime chapter below.

The glacial landsystem model approach may not always work for more complex systems, but in this study there are definite similarities between the glacial landsystem model by Glasser and Hambrey (2003) and the glacier forefield of Aldegondabreen. The reason for this might be that the glacial landsystem studied here is less complex than the recent studies presented above: Aldegondabreen is a small land-terminating valley glacier with one basin, which is not affected by other glacier systems. For this study it is therefore concluded that it is possible to use the glacial landsystem approach to identify glacier type. Aldegondabreen is thus classified as a polythermal glacier landsystem, which, during its active phase is able to produce the sediment-landform assemblage we see freshly exposed in the forefield today.

6.2 Preservation potential of landforms during glacier retreat

One of the main controlling factors of the formation potential of landforms in a glacial system is the sediment availability, and how deformable the beds are in the system (Brynjólfsson et al., 2014). Availability of sediments are not a limiting factor in the Aldegondabreen glacial system. The main limiting factor in the preservation potential of landforms at Aldegondabreen is the continuous erosion by meltwater channels. This fluvial erosion sufficiently lowers the preservation potential of the landforms (Brynjólfsson et al., 2014). The terrestrial glacial environment generally has a low preservation potential due to erosion and periglacial activity (Boulton, 1996; Ottesen et al., 2008). After and during deposition, landforms are exposed to these processes that modify the landscape and the depositional features. Fluvial erosion is extensive in the forefield of Aldegondabreen, which is evidenced by numerous channels and outwash plains in the geomorphological map, and is also illustrated and highlighted in the conceptual model (Figure 27). In some areas of the forefield, the fluvial erosion remove the subglacial material completely, cutting down to the bedrock; in other areas, channels dissect landforms or only incise the upper part of the subglacial material. If we look at low-relief landforms in the area, such as the transverse ridges and flutes, they are highly influenced by surface lowering and degradation by deflation as well as solifluction processes. As these features are small in size, it is believed that they will disappear completely after some time. Comparing older images from 1956 with newer images the small landforms like the transverse ridges, have already shrunk considerably in size over a time span of 50 years (Figure 21).

The preservation of the subglacial and supraglacial unit will depend on various controlling factors, including topography, the amount of meltwater released during glacier retreat, melting of dead ice and seasonal melting of snow. Aldegondabreen forefield is still experiencing constant change and fluvial erosion is believed to continue to reshape the landforms. By having a snapshot of the forefield now – the geomorphological map, the current state of the forefield can be correlated with later studies, shedding light on how the forefield evolves through time and how much it is affected by erosion.

6.3 Ice dynamics and thermal regime

In 1974/75 studies indicated that Aldegondabreen had a polythermal two-layered structure with a maximum thickness of 150 meters (Macheret and Zhuravlev, 1982; Navarro et al., 2005). The polythermal structure fits well with findings from this study as the landform assemblage found in the Aldegondabreen forefield is a result of a warm-based glacier (Boulton, 1976; Clark, 1999; Hambrey and Glasser, 2003). This polythermal – warm based interior and frozen snout structure is also among Svalbard's glaciers (Hagen et al., 1993; Pettersson, 2004). Flutes in the forefield of Aldegondabreen are also indicative of a warm-based glacier (Clark, 1999). It is therefore suggested that Aldegondabreen during glacier advance was a warm-based glacier. The glacier temperature measurements from 1974/74 are out of date, and are not representative for the glacier currently. The glacier has retreated at least 1 kilometer since these studies, with large mass loss due to surface melting. As the glacier is thinning due to surface melt, the glacier also thins in the front, often leading to a front frozen to the bed. Aldegondabreen is likely almost entirely cold based, based on ground penetrating radar data from 2017 that showed only restricted areas of temperate ice in the deeper parts of the glacier (Andy Hodson, personal communication). That a glacial thermal regime can switch from polythermal to a cold based glacier due to mass loss is recognized at other glaciers in Svalbard (Sevestre et al., 2015).

The retreat and advance of glaciers are important factors when understanding the dynamics of the glacier, the glacier's response to climate changes and the evolution of a forefield (Sharp, 1985; Sletten et al., 2001; Barr and Lovell, 2014). The eight reconstructed ice-marginal positions (Figure 27) does not provide the full explanation of Aldegondabreen retreat, as this is a low resolution of the event. This is due to the low frequency of cloud-free satellite images, and the temporal gap between each flight campaign for aerial images. Due to the low number of retreat lines reconstructed, one cannot completely exclude smaller advances of the glacier. But one can argue that small glacier advances would leave push moraines in the forefield (Boulton, 1986), a landform that is not present in the Aldegondabreen forefield today. Therefore it is argued that Aldegondabreen has had an overall rapid retreat since 1911 and the glacier has not had any major advances since then.

The glacier has changed its dynamic behavior from a tidewater glacier to a rapidly retreating land-terminating valley glacier. What is known about the active phase is based on the landform assemblage in the freshly exposed forefield. Flutes are the result of a dynamic wet-based ice formed due to basal sliding (Gordon et al., 1992; Glasser and Hambrey, 2001), and elongated debris stripes are evidence of a glacier with a slow linear flow (Anderson and Anderson, 2010). The landforms found in the forefield are the fingerprints left from the last glacier advance, and this would mean that during the final glacier advance the glacier has most likely had a slow and steady advance during the LIA when reaching its maximum extent. It is unknown if the glacier has exhibited any other type of behavior previous to the last advance.

Many Svalbard glaciers have been classified as surging glaciers, this also includes Aldegondabreen (Sund et al., 2009; Farnsworth et al., 2016). The classification of Aldegondabreen being a surge-type glacier is based on the presence of crevasse squeeze ridges (CSRs) in the forefield. They are classified as CSRs based on observations from aerial images (Farnsworth et al., 2016). In this study these are mapped as transverse ridges and are interpreted as crevasse infill ridges with material infill from melting out of supra- and englacial material. As the CSRs are the only evidence for Aldegondabreen exhibiting a surge behavior, this study concludes that Aldegondabreen has not surged during the last advance based on the landform assemblage. The debris stripes also present in the forefield further support this by suggesting that the glacier had a slow steady laminar flow (Hambrey and Glasser, 2003; Anderson and Anderson, 2010).

The bedrock in this area of study is unique due to its steeply dipping layers crossing the forefield. This has resulted in several bedrock thresholds in the forefield of Aldegondabreen consisting of harder sandstone and siltstones. These thresholds are believed to have acted as pinning points for the glacier during advance and retreat, whereby during advance ice builds up on the proximal side of the bedrock threshold, and is released on the lee side, creating crevasses in the ice (Benn and Evans, 2010).

What will the future look like for Aldegondabreen in terms of ice dynamics? The glacier has experienced rapid retreat, is losing mass by surface melt, and will most likely become completely cold within a few years. The glacier is thinning, and the average retreat the past years indicated that this glacier will most likely completely disappear within a 100-year timespan if the surface melting of the glacier continues at current rate. This glacier's future entirely rest in the climatic development.

6.4 To which extent is Aldegondabreen retreat affected by the warming trend since end of the LIA?

"Glaciers come in many forms, and their sensitivity to climate change depends partly on the physics governing the individual glacier implying that a response can be fast or slow, straight forward or complex, which in sum suggest that not all glaciers are equally suitable for reconstructing past and present climate conditions" (Yde and Paasche, 2010)

Aldegondabreen is located close to the warm West Spitsbergen Current flowing along the coast. The warm waters can also flow into the Isfjorden system, significantly impacting ocean temperatures (Cottier et al., 2007). The study by Zhuravskiy et al. (2012) present data demonstrating an increase in mean annual air and water temperatures in Grønfjorden from 1970 to 2008. They also present a data chart for the Svalbard air temperature record from 1912 to 2008, illustrating an overall warming trend. That Aldegondabreen has responded considerably to the increase in air temperature through visible mass loss and dramatic glacier retreat, as clear when comparing photographs from 1911 and the present day. As inputs for the retreat reconstruction are scarce, it is difficult to discuss Aldegondabreen's retreat in response to temperature change on an annual basis. However, it is possible to consider the larger responses to climate warming: from 1911 to 1936, the glacier did not retreat significantly, but the glacial dynamics underwent considerable change, potentially losing more mass from surface melt. This adjustment in glacial behavior corresponds well with the 20th century warming period. During the cooling period (1940 to 1960), the glacier experienced an average retreat of 16m/year; however, when compared with the late 1950s onward the average rate of retreat increased, agreeing with average summer temperatures. If the temperatures on Svalbard will continue to increase in the same manner as during the last century, it can be expected that Aldegondabreen will disappear within a 100-year timescale.

Aldegondabreen is located close to a mining town, Barentsburg. Meaning that melting rates of ice can be affected by coal dust from the still ongoing coal mining in the area. This is an important factor to take into consideration when studying the glaciers respond to climate, as light-absorbing particles from the coal dust can significantly influence the melting of glaciers and seasonal snow (Khan et al., 2017). Contamination from coal dust can be an important factor controlling increasing melt rates for glacier ice, though it is not the only factor impacting melting, as warmer temperatures also contribute.

While Aldegondabreen is likely reacting to climate change, further investigation into the effect of coal dust in the area and its impact on the melt rates should be undertaken. In this study with the amount of data available, there is a small question mark to if Aldegondabreen actually is suitable for future climate change reconstruction without further investigations contributing with more data, should we take into consideration what Yde and Paasche (2010) stated about the sensitivity to climate change depending partly on the physics governing the individual glacier.

6.5 Further research and uncertainties

This study examined the geomorphology of the forefield of Aldegondabreen and the reconstructed ice margins to reconstruct the glacial history as well as the development of the glacier forefield. However, due to limited time spent in the forefield during fieldwork, there are uncertainties regarding some landforms which can be improved by further reasearch in this area.

The first essential method to gain a better understanding of the genesis of landforms, is to complete a more detailed study of the sedimentology of the landforms in the area. A more detailed study of the internal composition could help determine if the eskers are of subglacial or englacial origin. The elongated ridges also require more detailed investigation to fully comprehend their formation. The age of the older fan deposits near the shore could be determined through radiocarbon dating of the excavated seal bone; this can provide the approximate age of the deposit. Further investigations regarding the glacier should be undertaken, as existing measurements are outdated and therefore not representative at present date. Continious data measurements of the glacier ice could aid in determining average ice loss as supporting data for the retreat and also the current ice thickness of the glacier. Temperature measurements distributed across the glacier could determine the current glacier temperature, and the amount and location of warm remaining within the glacier. Investigation into the impact of coal dust is important for determining if the glacier's mass loss is affected by other physical conditions other than general melt caused by warmer temperatures. A description of hummocky moraines could be enhanced through ERT-measurements to investigate if dead ice is located within the two moraines, along with sedimentological investigations to fully understand their formation. To obtain a position of the glacier's maximum extent, bathymetry data in the fjord in front of the forefield should be collected. This data could also help reveal the LIA terminal moraine.

7 Conclusions

- The imprints of the last glacier advance/retreat cycle is captured in a geomorphological map. The map is a representation of the forefield's current state, and can be used when monitoring the development of the Aldegondabreen forefield.

- The ice-marginal reconstructions reveal that Aldegondabreen has experienced rapid retreat since ~1911, with a total distance of 2,2 kilometers and a calculated average retreat of 18m/y.

- The landform assemblage found in the forefield of Aldegondabreen reveal a debris-rich, warm-based dynamic glacier during last glacier advance, with a slow steady flow. This is supported through the identification of the main components of Aldegondabreen and how they deposit relative to each other.

- With the data collected in this study, Aldegondabreen can be identified as a polythermal valley glacier with the glacial landsystem approach. Identification is based on the glacial landsystem model presented by Glasser and Hambrey (2003).

- The preservation potential of landforms can be very low in areas of the forefield due to heavy erosion by meltwater channels during glacier retreat.

- The glacier has responded to warmer summer temperatures and is continuously retreating today. It is possible to concluded that the glacier is reacting to climate warming, but the effect of coal dust on glacier mass loss should also be examined.

- There are still some uncertainties regarding Aldegondabreen: it is suggested that further sedimentological studies and other glaciological investigations are needed to fully understand the Aldegondabreen glacial system.

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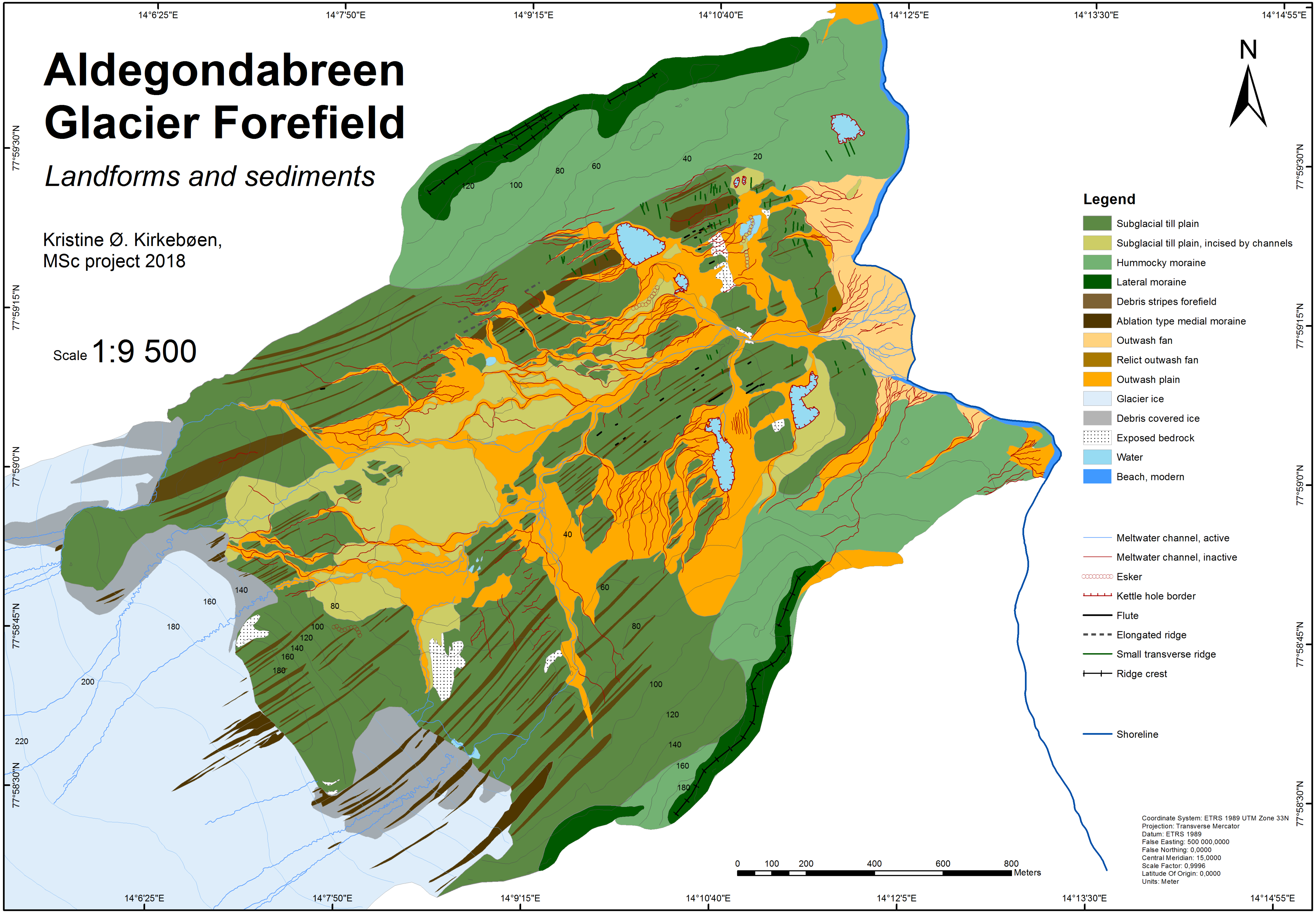
Appendix – A

Geomorpholocial map of Aldegondabreen glacial forefield, 2018


Aldegondabreen
Glacier Forefield
Landforms and sediments
Kristine Ø. Kirkebøen,
MSc project 2018
Scale 1:9 500
N
Legend
Subglacial till plain
Subglacial till plain, incised by channels
Hummocky moraine
Lateral moraine
Debris stripes forefield
Ablation type medial moraine
Outwash fan
Relict outwash fan
Outwash plain
Glacier ice
Debris covered ice
Exposed bedrock
Water
Beach, modern
Meltwater channel, active
Meltwater channel, inactive
Esker
Kettle hole border
Flute
Elongated ridge
Small transverse ridge
Ridge crest
Shoreline
0 100 200 400 600 800 Meters
Coordinate System: ETRS 1989 UTM Zone 33N
Projection: Transverse Mercator
Datum: ETRS 1989
False Easting: 500 000,0000
False Northing: 0,0000
Central Meridian: 15,0000
Scale Factor: 0,9996
Latitude Of Origin: 0,0000
Units: Meter
14°6'25"E
14°7'50"E
14°9'15"E
14°10'40"E
14°12'5"E
14°13'30"E
14°14'55"E
77°59'30"N
77°59'15"N
77°59'0"N
77°58'45"N
77°58'30"N