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Investigating the Glacial Geomorphology of Western Sørkapp Land, Svalbard: Mapping and Developing a Glacial Land System

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Abstract

The Arctic is warming almost four times faster than the rest of the world and will experience numerous changes in both the close and far away future due to global warming and climate change. Many of these changes are human-induced. The changes in the Arctic are intensified by the Arctic amplification. Svalbard, situated between the Greenland Sea and the Barents Sea, is largely affected by global warming as almost 60% of the archipelago is covered by glacial ice, with most glaciers currently retreating. Some Svalbard glaciers are surge type. There are many unknowns regarding surging glaciers and how they are affected by climate change. In Svalbard, many areas are difficult to access and in such areas, the use of remote imagery is particularly useful. Glacial geomorphology can give insight into the behaviour of glaciers and their characteristics. Here it is used to study landforms at the forelands of four glaciers in a north-to-south transect in the region Sørkapp Land in southern Spitsbergen. No detailed geomorphology maps exists of these glacial forelands.

Four glacial geomorphology maps were produced. The maps include landforms and glacial extents. Measurements for glacial retreat were conducted in ArcGIS Pro. A landsystem approach considered all four forelands as polythermal landsystems, with Bungebreen having landforms of both polythermal and surge-type. The landsystems defined the thermal regime of the glaciers and all four glaciers were deemed to be polythermal. Bungebreen is likely a surging polythermal glacier. The glacial geomorphology maps produced in this study were compared to a geomorphological map of the Hornsund region (scale 1: 75 000) published in 1984. Based on that map, geomorphological changes in the forelands of Gåsbreen, Bungebreen and Vitkovskijbreen were identified. The last glacier Belopol’skijbreen was not included in this map. Belopol’skijbreen, the most southern of the studied glaciers, have retreated most. Differences in landforms at the studied glaciers are likely caused by topographic differences, as well as variations in insolation. It appears that the glaciers of the study area are largely conforming with the landsystems of other retreating glaciers in Svalbard, indicated by ice melt-out and slope processes. However, the results of this study confirm the need for a landsystem for polythermal glaciers with tendencies to surge. From this study, it is clear that more research is needed on surging glaciers and how they will be affected by climate change. This study contributes valuable information on the land-based glacier in Sørkapp Land for further studies. Future studies should focus on how they and other glaciers in Svalbard respond to current climate change and how they will be affected by regional changes.

Sammendrag

Arktis varmes opp nesten fire ganger raskere enn resten av verden og vil oppleve mange endringer i både nær og fjern fremtid på grunn av global oppvarming og klimaendringer. Mange av disse endringene er menneskeskapte. Endringene i Arktis forsterkes av den arktiske forsterkningen. Svalbard ligger mellom Grønlandshavet og Barentshavet og er i stor grad påvirket av global oppvarming ettersom nesten 60 % av øygruppen er dekket av is, og her trekker de fleste breene seg tilbake. Et kjennetegn ved noen isbreer på Svalbard er at de er av *surge-type*. Det er ukjent hvor mange det er av denne bretypen og hvordan de påvirkes av klimaendringer. På Svalbard er det mange områder som er utilgjengelige og i slike områder er bruk av fjernbilder spesielt nyttig. Videre, siden isbregeomorfologi gir innsikt til hvordan isbreer utvikler seg og deres egenskaper, brukes det her til å undersøke områdene foran fire isbreer i et nord-til-sør-transekt i det sørlige Spitsbergen. Det finnes ingen detaljerte geomorfologiske kart over forlandene til disse isbreene.

Det har blitt produsert fire glasiale geomorfologikart i denne studien. Kartene inkluderer landformer og breutstrekninger. Målinger av isbreenes tilbaketrekninger ble utført i ArcGIS Pro. Ut fra en landsystemtilnærming ble de fire forlandene definert som polytermiske landsystemer, med Bungebreen definert som både polytermisk og *surge-type*. Landsystemene definerte det termiske regimet til isbreene, og alle fire isbreene ble ansett for å være polytermiske. Bungebreen er sannsynligvis en *surging* polytermisk isbre. De glasiale geomorfologikartene produsert i denne studien ble sammenlignet med et geomorfologisk kart over Hornsundregionen (skala 1: 75 000) publisert i 1984. Basert på dette kartet ble geomorfologiske endringer ved forlandene til Gåsbreen, Bungebreen og Vitkovskijbreen identifisert. Den siste isbreen Belopol'skijbreen var ikke inkludert på dette kartet. Belopol'skijbreen, den sørligste av de studerte isbreene, har trukket seg tilbake mest. Forskjeller i landformer ved de studerte isbreene er sannsynligvis forårsaket av topografiske forskjeller, samt variasjoner i solinnstråling. Det fremstår som at isbreene i studieområdet i stor grad samsvarer med landsystemene til andre tilbaketrekkende isbreer på Svalbard, hvor issmelting og skredprosesser er vanlig. Resultatene fra denne studien bekrefter behovet for et landsystem for polytermiske isbreer med tendenser til *surges*. Denne studien viser at det er et tydelig behov for mer forskning på *surging* isbreer og hvordan de vil bli påvirket av klimaendringer. Denne studien bidrar med verdifull informasjon om de landbaserte isbreene i Sørkapp Land for videre studier. Fremtidige studier bør fokusere på hvordan de og andre isbreer på Svalbard reagerer på dagens klimaendringer og hvordan de vil bli påvirket av regionale endringer.

Acknowledgements

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Thank you to Kjersti Mølmann and the Norwegian Geological Survey (NGU) for sending me files with symbology for mapping in ArcGIS Pro. Many thanks to my supervisor Danni Pearce for all support and encouragement, and for the opportunity to write about Svalbard and geomorphology.

I was fortunate to travel to Svalbard last year for two courses at the University Centre in Svalbard (UNIS). I was even able to see the study area of this thesis on the flight to Longyearbyen, which was very special to me. The time spent at UNIS gave me a new understanding of climate change in the Arctic. I am very grateful for what I learned there, and for all the people I met who had so much enthusiasm for environmental issues. Your passion fueled me with excitement for my master's project, and for this, I thank you.

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Ås, May 2023
Margrethe Johnsen Otnes

Sørkapp Land from the air on 31st of May 2022 (photo by Margrethe J. Otnes)

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1 Introduction

1.1 Global climate change

Climate change is defined as changes in the climate state apparent by fluctuations in the properties of climate (IPCC, 2018). The changes follow variations in natural internal processes or external forcings such as solar cycles, volcanic eruption and anthropogenic alterations of the atmosphere composition or land use (IPCC, 2018). Since about 1750 the global climate state has been altered by human activities (Masson-Delmotte et al., 2021). One of the most widespread changes is the increase in temperature. The global surface temperature from 2001-2020 was 0.99 °C higher than the reference temperature from 1850-1900 (Figure 1). The palaeo-proxy record shows that this increase occurred faster from the 1970s until 2020, than at any point during the last 2000 years (Masson-Delmotte et al., 2021). Furthermore, when comparing with the most recent warm period, the Mid-Holocene ca. 6500 years ago (when the global average temperatures reached ca. 0.6-0.7 °C warmer than the 19th century global average (Kaufman et al., 2020)), the observed temperatures in the last decade (2011- 2020) are much higher (Masson-Delmotte et al., 2021). A direct consequence of global climate change is the documented melting and subsequent retreat of glaciers and ice sheets (Barry, 2006; Masson-Delmotte et al., 2021; Roe et al., 2017; Ziaja, 2004). The global glacial recession rate, observed since the 1950s, has not been recorded in almost 2000 years (Masson-Delmotte et al., 2021) and the rapidity of this change is of great concern (Arimitsu et al., 2016).

There are uncertainties regarding the impact of global climate change due to the complexity of internal and external feedback mechanisms, with many being centred around the Arctic climate (Box et al., 2019). Since the Arctic is increasingly less covered in snow, ice and sea ice due to global warming (Box et al., 2019) the Arctic receives more solar radiation because of the albedo effect, which further affects temperature and precipitation, increasing its sensitivity to climate change (Serreze & Barry, 2011) (positive feedback mechanism). However, impacting the natural variation in climate is also the burden of anthropogenic activities (Figure 1b). Moreover, human influence has been documented as the major contributor to the glaciers retreating since the 1990s (Masson-Delmotte et al., 2021). It is projected that glaciers will continue to melt in the decades and centuries to come (Masson-Delmotte et al., 2021; Möller et al., 2016) as many regions will continue to experience glacial decline even if the climate were to become stable (Zemp et al., 2015). Whilst communities which rely on smaller glaciers as water sources will experience increased difficulties in receiving enough water, the continued glacial recession and the contribution of meltwater will lead to eustatic changes in sea level.

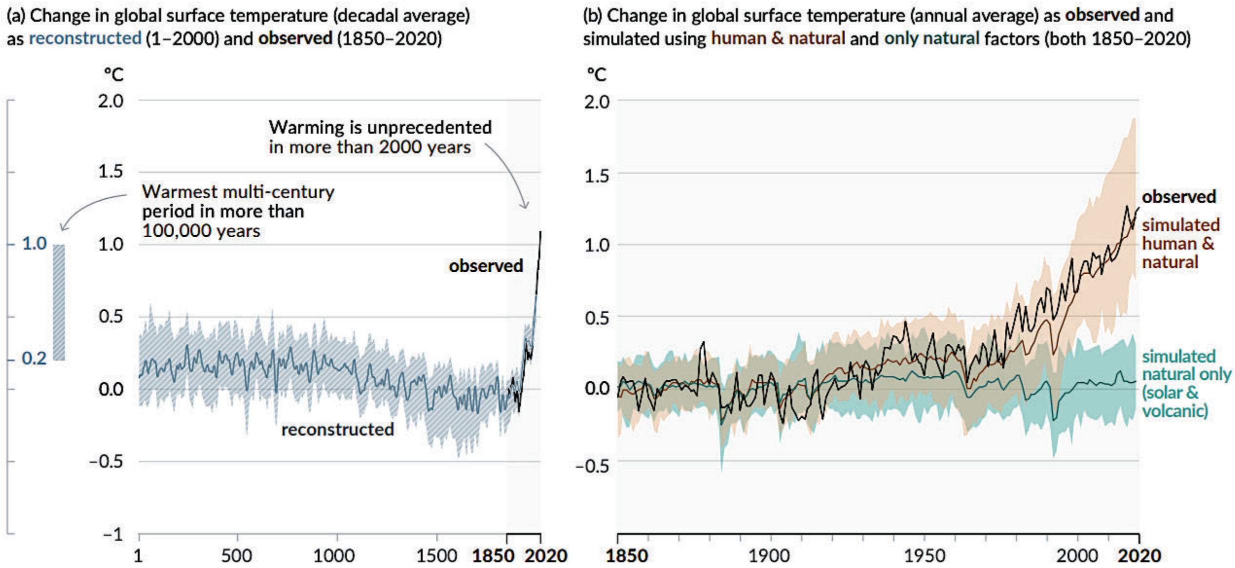


Figure 1: Global surface temperature changes from the last 2000 years, from Masson-Delmotte et al. (2021). ***a) the changes of global surface temperature with averages of a decade*** *during the past 2000 years relative to 1850-1900. For year 1-2000 the data is based on paleoclimatic reconstructions (grey line, average). For the years 1850-2020 the data is from direct observations (black line). The grey shadowed area is uncertainties which becomes reduced after the initiation of instrumental data. There is a significant increase after ca. 1900 of ca. 1°C. This amount of change has not been observed in the last 2000 years. The estimated temperature change from the warmest multi-century period (ca. 6500 years ago) in the last 100 000 years is presented in the vertical bar on the left.* ***b) the change in global surface temperature with annual averages*** *from 1850-2020 relative to 1850-1900. The black line is observed data. The brown line (average) and brown shadowed area (uncertainties) refer to simulated global surface temperatures with human and natural factors. The green line (average) and green shadowed area (uncertainties) refer to simulated global surface temperatures with natural factors. The effect of anthropogenic influence is clearly illustrated.*

Sea level rise (SLR) is estimated as one of the biggest concerns when considering the future climate (Bamber et al., 2018). Predictions of the future SLR is depending on reliable estimates of the sea level in the past. Therefore, the past sea level must be examined according to the principle that processes that happened in the past are the same in present times. The global mean sea level has increased faster since 1900 than in the last 3000 years (Masson-Delmotte et al., 2021). Melting ice from the Greenland Ice Sheet (GrIS) and glaciers in the Arctic contributes more to the global sea level rise than the mass loss from Antarctica Ice Sheet (AMAP, 2021). Within these, a major contributor to the global sea-level rise is the land-based glaciers of the Arctic (AMAP, 2021), due to glaciers and ice caps of the world being more sensitive to external forcing than ice sheets on a short timescale and the mass loss of GrIS has increased rapidly since 1995 (Bamber et al., 2018). Below are descriptions of the changes in the Arctic following the increasing glacial recession.

1.2 Changes in the Arctic

Climate change can negatively affect human life including, food security, water resources, infrastructure and they threaten Indigenous people in addition to the threat against their culture (Pörtner et al., 2019). Currently, approximately 4 million people permanently reside in the Arctic and 10% of these are Indigenous people and they are strongly dependent on nature to live (Pörtner et al., 2019). People's food and water security are at a higher risk, in addition to the risk of infrastructure being damaged due to the thawing of permafrost. However, there are some impacts that some consider as positive, such as higher possibilities of marine shipping, tourism and access to important resources due to a lengthening of the open water season in the Arctic Ocean (Previdi et al., 2021). Many of these effects follow changes occurring in the cryosphere.

Global warming has over the last decades affected the cryosphere by shrinking and reducing the ice mass of ice sheets and glaciers, decreasing the snow cover, diminishing the extent and thickness of the Arctic Sea ice and increasing the temperature of the permafrost (Pörtner et al., 2019). The Arctic is considerably more affected by small shifts in temperature and precipitation compared to the lower latitudes, due to the effect termed Arctic amplification (Pithan & Mauritsen, 2014; Previdi et al., 2021), leading the Arctic to warm up to four times faster than the rest of the world (Rantanen et al., 2022). It has been observed that the temperature has increased the most during fall and winter, in contrast to the Artic summer which has not experienced such a large increase (Previdi et al., 2021). From 1971-2019 the average annual near surface air temperature in the Arctic increased by 3.1°C (AMAP, 2021). Furthermore, sea level rise, extreme sea levels and the changes in the cryosphere influence coastal environments and polar areas (Pörtner et al., 2019).

The sensitivity of the Arctic affects the rate of geomorphology processes and landforms (Allaart et al., 2021). Glacial, periglacial and coastal environments respond to the aforementioned warming by exposing land due to glacial retreat (Allaart et al., 2021). When the land is no longer protected by the glacier it gets exposed to the climate and can then be affected by processes such as weathering and re-sedimentation (Allaart et al., 2021). Processes working on the re-sedimentation can for example be fluvial, alluvial and slope processes.

The mass loss from Arctic ice not only contributes to eustatic sea level rise but has been documented to affect the meridional ocean overturning circulation (e.g. the Atlantic Ocean currents) by weakening it with increased freshwater input (besides the increase of precipitation and ocean warming) (Previdi et al., 2021). Other changes include the thawing of permafrost which increases the amount of carbon in the atmosphere and leads to changes to the Arctic carbon cycle which in turn affects the global carbon cycle (Previdi et al., 2021). In addition to glacial recession, the extent of sea ice is being reduced. Between 1979 – 2019 the sea ice extent in the Arctic in September decreased by 43%. However, the extent and area covered by sea ice have declined over the entire Arctic throughout the whole year (except for the Bering Sea) and the sea ice is getting thinner and younger (AMAP, 2021). The reduction is largely believed to be owned to warm, saline Atlantic Water mixing with cold, Arctic Water because of more wind (Hanssen-Bauer et al., 2019). For example, it has been observed that the sea ice in the fjords of the west coast of Svalbard has almost disappeared during winter. In fact, the whole of Barents Sea is now ice-free during most of the summer and autumn (Hanssen-Bauer et al., 2019). Thus, the above highlights that changes that occur in the Arctic have worldwide implications (Previdi et al., 2021).

However, the Arctic does not hold the largest ice mass on Earth. The Antarctica Ice Sheet is the largest single ice mass on Earth. Much of the ice mass there terminates by the sea, however most of the ice mass covers land. The main uncertainty connected to predictions of the future climate are the behaviour of ice sheets. The uncertainties come from limited observations, inadequate model representation of ice sheet processes, and how little is understood about the complexity of atmosphere-ocean-ice interactions. Since a collapse of the Antarctica ice sheet likely will lead to a major rise in sea level, it is imperative to study glaciology (Pörtner et al., 2019). Another uncertainty for future projections is the contribution of Arctic land-based and marine terminating glaciers to sea-level rise. As both of these types exits on Svalbard, it is an ideal place for studying glacier behaviour, geomorphology and more.

2 Background

The following chapter includes background information on Svalbard such as the climate, its geological setting and how the archipelago has been affected by glaciations. Furthermore, the study area in Sørkapp Land is put in a regional setting by examining previous studies and describing the regional geomorphology.

2.1 Svalbard

Svalbard is an archipelago situated below the North Pole between the Arctic Sea, Greenland Sea and the Barents Sea (Figure 11) from 74° to 81°N and 10° to 35°E (Zwoliński et al., 2013). Thus Svalbard has a high Arctic climate setting (Gilbert et al., 2018). Figure 2 illustrates the seasonal cycle of Svalbard represented by air temperature and the coldest month in average in Svalbard is recognized to be February (Hanssen-Bauer et al., 2019). The lowest temperature reached -24°C in 2021 at Svalbard Airport (Norsk Klimaservicesenter, n.d.). In average the warmest month is July (Hanssen-Bauer et al., 2019) with the maximum temperature reaching 12.4°C in 2021 at Svalbard Airport (Norsk Klimaservicesenter, n.d.). Most of the meteorological stations in this dataset are places with low altitude and a coastal climate due to accessibility (Hanssen-Bauer et al., 2019). This skews the data towards such areas and are not necessarily very representative for areas with high altitudes or non-coastal areas. Generally, the air temperature on Svalbard increased by 3-5 °C from 1971 to 2017 (Hanssen-Bauer et al., 2019). The air temperature increased less in the southern regions and more in the inner fjords (Hanssen-Bauer et al., 2019). The highest increase was seen in winter, and the least increase was observed in summer (Hanssen-Bauer et al., 2019). The focus on summer temperatures vs. winter temperatures is important because it is linked to the potential of glacier growth. For example, unfavourable conditions for glacier growth are cold winters but very warm summers. Glacier growth particularly depends on precipitation, however there are many unknowns on how the precipitation is at present and how precipitation has fluctuated in the past.

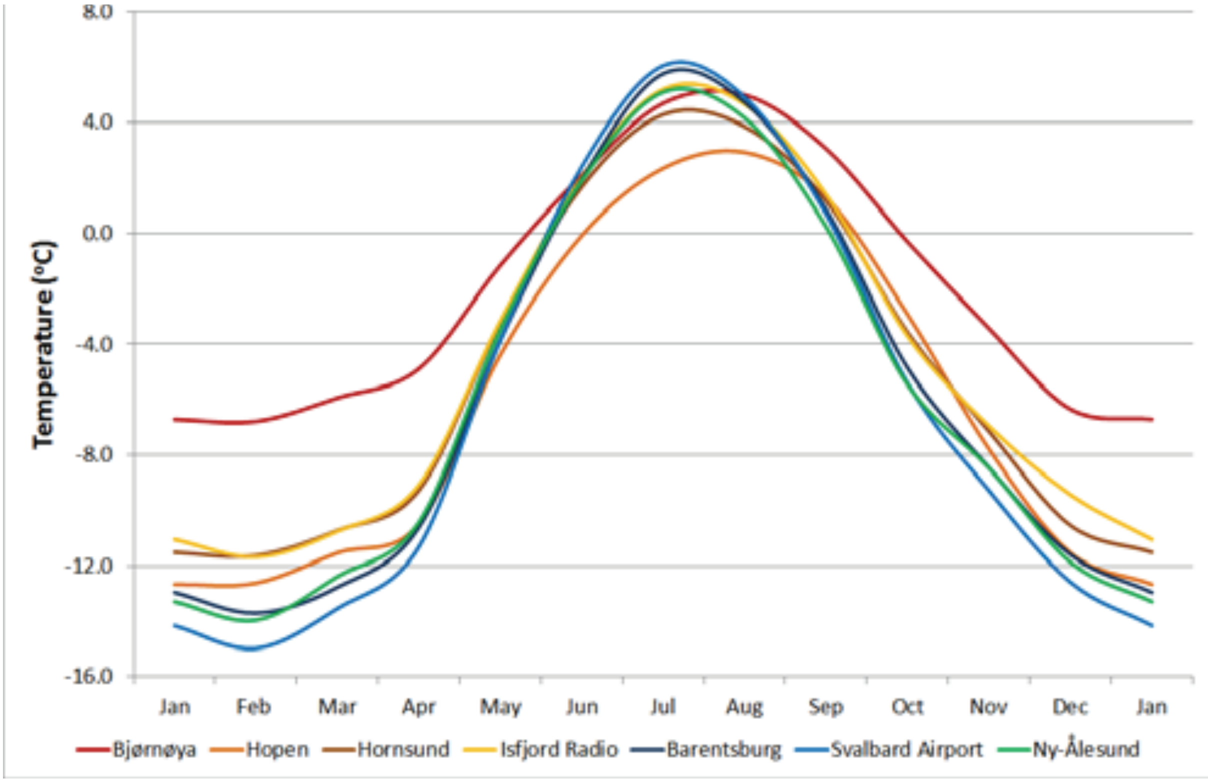


*Figure 2: Measured air temperature in °C on some weather stations in Svalbard showing the average in the period of 1971-2000 from January to January to show a seasonal cycle. Figure from Hanssen-Bauer et al. (2019). *Note the quality of the image is as in the original publication.*

Because of the high Arctic climate setting Svalbard has a continuous permafrost cover in at least 90% of the land area (Gilbert et al., 2018). The permafrost cover varies in thickness, with the thinnest areas close to the sea and the thickest areas in mountain regions (Atakan et al., 2015). Due to Svalbard's position in the Arctic Ocean, it gets both cold Arctic air from the North and mild maritime air from the South, which ensures a rather high weather activity over the land, particularly in winter. Northeasterly winds dominate, but locally the winds are more controlled by the local topography (Hanssen-Bauer et al., 2019). Another effect due to Svalbard's Arctic location is that the climate of the archipelago is largely affected by the ocean currents surrounding it (Figure 8) (e.g. Allaart et al., 2021). The West Spitsbergen Current brings warm ocean water from the North Atlantic and interacts with the cold ocean water brought by the East Spitsbergen Current (Allaart et al., 2021; Hanssen-Bauer et al., 2019). Together, the air and water masses control the amount of precipitation delivered to the archipelago. In Svalbard the mean annual precipitation varies greatly as seen in Figure 3, from 196 mm at Longyearbyen to 581 mm by Barentsburg (Hanssen-Bauer et al., 2019).

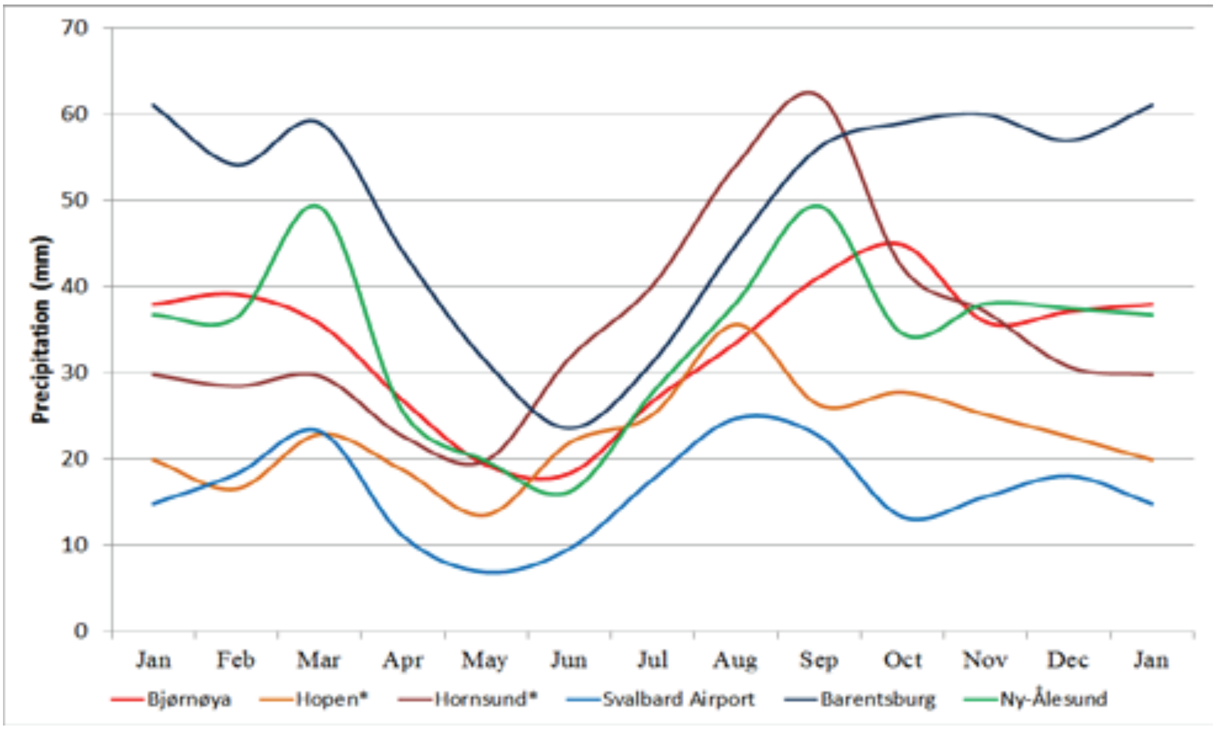


*Figure 3: Measured annual precipitation on average in the period 1971-2000 from January to January showing a seasonal cycle in mm for some of the meteorological stations in Svalbard. Figure from Hanssen-Bauer et al. (2019). *Note the quality of the image is as in the original publication.*

The landscape of Svalbard includes a range of landforms including coastal plains, valleys, moraines and distinctive types of mountain areas (Atakan et al., 2015). The landforms are mostly created by glaciers, glacial runoff, post-glacial land uplift, freezing and thawing processes in permafrost and weathering processes (Atakan et al., 2015). The underlying bedrock exerts control over the appearance of some of the landforms even as they are greatly formed by glacial and periglacial processes.

2.1.1 Geology of Svalbard

Svalbard is famous for its diversity in bedrock as there exist traces of rock types from all of the Earth's principal periods (Barr & Thuesen, 2022). This includes rocks of Pre-Cambrian age which can be found in selected areas at Nordaustlandet and Spitsbergen, rocks of Permian and Silurian age in the west and south, sedimentary beds from Triassic, Jurassic and Cretaceous, and sedimentary deposits from the Neogene that is found in the central and southern Spitsbergen (Barr & Thuesen, 2022). The sedimentary rocks are rich in plant and animal fossils, and this is what makes the foundation for the coal industry on Svalbard (Barr & Thuesen, 2022). Figure 4 is an overview map of the most prominent rock types on Svalbard made by NPI (the Norwegian Polar Institute) (Atakan et al., 2015). The map is only an indication of the actual rock types because of the scale (1:2 million). Most of the sedimentary rocks are younger than the Late Silurian (Atakan et al., 2015). However, in eastern Svalbard there is occurrence of some older sedimentary rocks from Neoproterozoic and Early Paleozoic which still have their original sedimentary characteristics preserved (Atakan et al., 2015). There are also some sedimentary rocks in parts of western and southern Svalbard of Early Paleozoic age that is in a stage of transition between sedimentary and metamorphic, but on the map, they are grouped together under sedimentary rocks (Atakan et al., 2015). There are a few instances of ingenious rocks in Svalbard (Atakan et al., 2015). Most of them can be found on the eastern side of Svalbard and on Nordaustlandet (Atakan et al., 2015). However the presence of Gabbro can be found on various places on Spitsbergen (Atakan et al., 2015). The rock type Dolerite from the Early Cretaceous is intruded between sedimentary layers and can be found in many different places in Svalbard. Metamorphic rocks appear in large quantities areas along the Pre-Caledonian basements of Svalbard (Atakan et al., 2015).

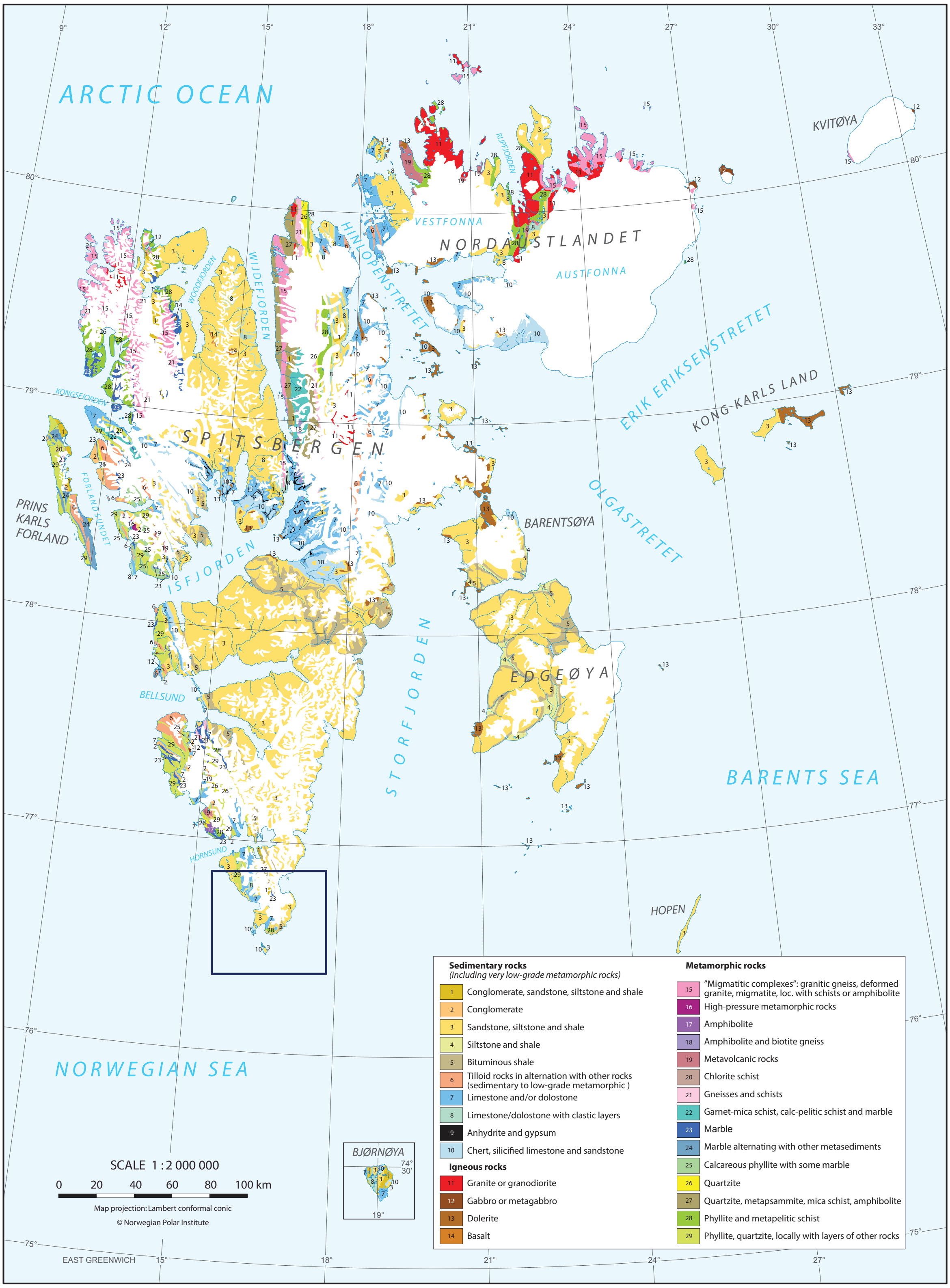


Figure 4: An overview of the geology of Svalbard. The different types of bedrock are divided by their origin process in the legend. Figure from Atakan et al. (2015). The black box indicates Sørkapp Land where the study area is located.

Above was a brief summary of Svalbard's geological history. Since the placement of Svalbard came to be where it is today, it has been influenced by many glaciations over the last 2.6 million years.

2.1.2 Glaciation of Svalbard

On Svalbard there are more than 1000 glaciers (ca. 35 528 km^2) covering about 59% of the total of land area (Figure 9) (Atakan et al., 2015). Glacier types including cirque glaciers, ice fields, valley glaciers and ice caps are spread across the archipelago (Atakan et al., 2015). The amount of glaciation is determined by the topography and the local climate. Spitsbergen's topography is mostly consisting of mountain terrain where glaciers are separated by mountain ridges and nunataks (Atakan et al., 2015). On the main island of Spitsbergen there are three main groups of interconnected ice fields, and they are located in the northwest, northeast and the southeast, separated by less glaciated areas (Atakan et al., 2015). The large islands of Edgeøya, Barentsøya and Nordaustlandet has a flatter topography, therefore these islands consist of lower elevation ice caps. These three islands account for 40% of Svalbard's glaciated area, with Nordaustlandet having the two largest ice caps (Austfonna and Vestfonna) (Atakan et al., 2015). The glaciers found on Svalbard are of both of land-terminating and tidewater glacier types. However, the tidewater glaciers account for over two-thirds of the glaciated area of Svalbard (Atakan et al., 2015). Most of the glaciers are polythermal, meaning they consists of both cold and temperate ice (Atakan et al., 2015), however many of the smaller and middle-sized glaciers can also be cold based (Nuth et al., 2013). Svalbard is also known for an abundance of surging glaciers (Atakan et al., 2015) with an occurrence somewhere between 13-90% (Farnsworth et al., 2016). During the present geological time period, the Quaternary (2.6 Ma to 11 700 years ago), Svalbard has experienced different stages of glaciation.

Svalbard has been covered by an ice sheet known as the Svalbard-Barents Sea Ice Sheet (SBSIS) several times during glaciations over the last 2.6 Ma (Atakan et al., 2015). SBSIS has covered Novaya Zemlya, the Svalbard archipelago in addition to Bjørnøya and Franz Josef Land (Ingólfsson & Landvik, 2013). The Last Glacial Maximum (LGM) has been defined for Svalbard to be around 24 000 years ago (Atakan et al., 2015). The ice started to retreat from the outer shelf around 20 500 years ago towards the inner shelf (Atakan et al., 2015). However, it was not until the Bølling interstadial around 15 100 – 14 200 years ago that the ice retreated from the inner shelf in the west towards the fjords. It has been indicated that this was a rather rapid retreat (decadal to centennial) (Atakan et al., 2015). By contrast, the eastern side of Svalbard did not become ice free until about 10 000 years ago (Atakan et al., 2015). It is important to remember this is only the broad strokes of the Svalbard glacial history, there are local variations and quite many parts of the glacial history are not well constrained (Farnsworth et al., 2020).

During the Holocene, proxy evidence points to an early general warming of the area with July temperatures of 10 500 – 9000 years ago to be 4-5 °C higher than today (Atakan et al., 2015). Some of this time falls under the Holocene Thermal Maximum which lasted from 10 000 to 5000 years ago. During this time the Svalbard glaciers were smaller than what they were in most of the 20th century (Atakan et al., 2015). Actually, most of the glaciers in Svalbard disappeared around ca. 9700 years ago (Hanssen-Bauer et al., 2019). Then there was a change in around the Late Holocene, around 4000 years ago when the glaciers advanced in bursts as is recorded by several moraines (Atakan et al., 2015). This advance climaxed in about 2500 years ago (Atakan et al., 2015), at the beginning of a period called the Neoglacial (Farnsworth et al., 2020). There were still some glacial fluctuations within this period, where some glaciers may have retreated beyond the current glacier front, but most glaciers had an advance during the cooling period named the Little Ice Age (LIA, ca. 1250-1920) (Atakan et al., 2015; Farnsworth et al., 2020).

The Little Ice Age

It is disputed how and when the onset of the LIA was initiated, but a consensus seems to be that the LIA began in an already began period of cooling (the Neoglacial, above) (Farnsworth et al., 2020; Miller et al., 2012), following a decrease in summer insolation (Farnsworth et al., 2020). As observational data were not available until the start of the 20th century (Atakan et al., 2015) one has had to rely on proxies to infer climatic data from previous times. For example, there has been found evidence of sulphur loadings, from around 1275-1300 AD, in ice cores from the Arctic and Antarctica (Gao et al., 2008) indicating explosive volcanic events (Miller et al., 2012), leading to a decrease in insolation due to aerosol cover, favouring glacial growth. 1275 AD has therefore been proposed as the start of the LIA (Miller et al., 2012). The persistent cooling of the Artic following the volcanic events were likely due to feedback mechanisms between the ocean and sea ice (Miller et al., 2012). Furthermore, transport pathways of Arctic sea ice has been found in marine archives to have a large impact on the Arctic climate, and have been suggested as a possible trigger for the LIA (Miles et al., 2020). At Svalbard, chironomid assemblages in lake sediments indicated a decrease in July temperatures from 200-1750 AD (Atakan et al., 2015). Evidence from ice-cores in Svalbard also points to a cooling trend in winter temperatures after 800 AD and indicate that the temperature began to rise after 1850 (Atakan et al., 2015). Regardless, it appears that the Svalbard glaciers seemed to reach their maximum extent around the 1930s (Błaszczyk et al., 2009), with a glaciated area of ca. 38 871 km^2 (Martín-Moreno et al., 2017), before they started to retreat when summer temperatures started to increase dramatically (Atakan et al., 2015). The maximum comes later than the cooling trend because glaciers have a rather long response time to changes in climate.

Recently, it has been discussed whether the LIA was when most glaciers on Svalbard had their maxima during the Holocene. This is because some earlier Neoglacial ice margins have been identified, and these are some places found tens of meters outside of what is believed to be LIA ice-margins (Farnsworth et al., 2020). This is supported by different dating methods, where some conclude that the LIA is in fact not the largest recent glacial event in most locations. Additionally, it has been discovered recently that most glacier re-advances during the Late Holocene have been dated to have happened between 1.0-0.5 ka BP, not in the late LIA, which has been the accepted theory (Farnsworth et al., 2020). Furthermore, many of the re-advances of glaciers during the period between the Neoglacial and LIA have been identified to belong to surges, in particular the most extensive glacier deposits from the Late Holocene (Farnsworth et al., 2020). Nevertheless, the glaciers of Svalbard have experienced a consistent and sometimes rapid shrinking since the mid 19th century and the termination of the Little Ice Age (Geyman et al., 2022; Martín-Moreno et al., 2017).

Recent glacier fluctuations

The shrinking and ice mass loss the Svalbard glaciers are experiencing follows a large increase in temperature (Chapter 1.1). Observations made on front positions on the Svalbard glaciers implies a general retreat since the observations started in the 1930s (Błaszczyk et al., 2009). In the period between 1961 to the 2000s the glaciated area was reduced by 7% in all regions (Hanssen-Bauer et al., 2019). Such intense mass loss leads to great changes in the surrounding landscape and also causes the Svalbard glaciers contribution to sea level to increase (Hanssen-Bauer et al., 2019). Most of the glacial reduction in later years has been contributed to the ice mass loss from tidewater glaciers, but glaciers terminating on land have also experienced a significant retreat (Martín-Moreno et al., 2017). While comparing older aerial photos from the end of the 1930s with modern aerial images and satellite imagery, the retreat rate of Svalbard glaciers has been found to be ca. 0-100 m/year, with an average of 30-40 m/year (Atakan et al., 2015). Yet, the glaciers in Svalbard have not only experienced a great recession but they are also thinning (decrease in elevation) (Zwoliński et al., 2013). In the western and southern regions, the retreat rates have generally increased (Atakan et al., 2015). Evidence of glacier fluctuations can be found in the landforms left behind after the glaciers retreat. Both older landforms and newly revealed ones can give information about glacial behaviour, thermal regime and more, therefore it is important to study geomorphology.

Since the southern region is one of those with an increase in retreat rates, four land-based glaciers there were selected as the study area for this thesis. Below follows an introduction to the region of Sørkapp Land.

2.2 Sørkapp Land

Sørkapp Land is a peninsula of ca. 1300 km^2 (Ziaja & Ostafin, 2015) located in the south part of Svalbard and is defined here as extending from 76.88°N in the west to 76.97°N in the east

(Figure 11). The area is difficult to access due to wide shallows off the shore and many submerged rocks (Ziaja, 2016). The nearest research station is the Stanisław Siedlecki Polish Polar Station in Hornsund (Hornsund polar station) which requires an extended boat journey from Longyearbyen (Figure 11) (Zwoliński et al., 2013). There is a weather station at Sørkappøya (ca. 6 km from the southern edge of Sørkapp Land) but it has only temperature data for a few years and no data of precipitation (Norsk Klimaservicesenter, n.d.), meaning the data may not be completely reliable. However they may give an indication therefore some of the data are presented here. The minimum temperature for 2011-2022 (no data for 2017-2019) ranges from -29.3°C (2020) to -16.1°C (2016). The maximum temperature in the same period (except 2017-2019) ranges from 6.5°C (2011) to 9.2°C (2016). 2016 appears to have been the warmest year measured at Sørkappøya, however the data is only from 2011 to 2022.

Lacking meteorological data from Sørkapp Land can be solved by using data from the meteorological station in Hornsund (ca. 10 km away) (Figure 11) as they have been found to be comparable with meteorological observations from several locations in western Sørkapp Land during some summers in the 20^{th} century (Ziaja, 2016). The weather station in Hornsund is situated at a low altitude and close to the coast. Since the study area is also close to the coast and on low altitude it can be presumed that the glaciers in the study area is influenced by similar weather as in Hornsund and therefore have a related climate (Hanssen-Bauer et al., 2019). Hornsund is seen to have the next coldest summer temperature and the third warmest winter temperatures (Figure 2). The annual average precipitation measured at the Hornsund weather station (Figure 3) was in the period of 1961-1990, 405 mm, and in the period of 1971-2000, 428 mm (Hanssen-Bauer et al., 2019). The mean annual temperature by the Hornsund meteorological station has been measured to have increased by almost 2°C (Ziaja, 2016). An increase in precipitation at the Hornsund meteorological station has been observed since the 1980s. The increase is in total precipitation, intensity and frequency of rainfall (Ziaja, 2016).

2.2.1 Previous studies in Sørkapp Land

As studies for geomorphological research tend to be done by nearby research stations (such as the one in mentioned above, Figure 11) because it makes for easier access to the landscape (Allaart et al., 2021) studies in southern Spitsbergen have been concentrated near the Hornsund Polar Station. The studies from Hornsund about the nearby tidewater glaciers and are mainly from Polish researchers. The limited studies on the land-based glaciers in Sørkapp Land is largely due to accessibility issues. Therefore the few studies that has been conducted have centered around the western part of the peninsula because the lack of glaciers there make it easier to access from Hornsund, also there is a former trapper station there where a few people can stay (Ziaja, 2016). The work centred on western Sørkapp Land has focused on the deglaciated area and the forelands of the glaciers Gåsbreen and Bungebreen and were mostly based on several expeditions to western Sørkapp Land during the 1980s by Polish researchers. These investigations were done on the de-glaciated landscape of western Sørkapp Land, and they resulted in a map which apparently showed the natural environment in the area (Ziaja, 2016). However, this map was not found during this investigation and thus cannot be presented. Below follows descriptions of some of the work that has been conducted in or near the study area (Chapter 2.4).

The Polish geographer Wieslaw Ziaja has conducted much research in the de-glaciated parts of western Sørkapp Land (Ziaja, 2016). The research focused on landscape transformation from field excursions in the 1980s and an excursion in 2008 and both glacial landforms and vegetation changes were described (Ziaja, 2016). Additionally, the extents of the glaciers and their marginal zones were measured. The natural environment and landscape were found to have gone through rapid changes, such as expansion of glacial forelands and some changes of the coast, since the 1990s (Ziaja, 2016). The reasons for the changes were believed to be climate warming and the redevelopment of fauna (Ziaja, 2016). Maps of the landscape changes, elevation changes and vegetation cover were created after the 2008 investigation (Ziaja, 2016). However, many of the maps and articles that were produced are not available. Furthermore, there have been created detailed maps by other researchers of western Sørkapp Land (Ziaja, 2016), however they are not accessible.

Studies have looked into whether parts of Sørkapp Lands had been covered by the SBSIS. There are erratics at a mountain peak (Kovaleskifjellet) at 640 m a.s.l. and surrounding this mountain there are wide valleys and moraine ridges indicating that the western area of Sørkapp Land was likely covered by the SBSIS during the Pleistocene (Ziaja, 2016). Klysz and Lindner (1982) came to a similar conclusion based on evidence of roches moutonnées, smooth massifs, ancient moraine sediments present at over 300 m a.s.l. and ancient ground moraine observed at a sea cliff ca. 1.5 km outside the terminal moraine of Bungebreen, which made them believe the region had been covered by a larger glacier that during Weichsel and the Early Holocene. A different study in western Sørkapp Land investigated the deglaciation in this area by using radiocarbon dating on materials found in raised beaches (Salvigsen & Elgersma, 1993). These dates also indicated that the area had been totally glaciated at least once in the Quaternary, probably during the Late Weichselian, by a glacier based in Hornsund that was able to grow and later cover Sørkapp Land (Salvigsen & Elgersma, 1993). Sediments that are probably pre– Late Weichselian age in the north-western part (Gåshamnøyra) was also found (Salvigsen & Elgersma, 1993).

Further, the dated beaches indicated that Sørkapp Land was deglaciated before 11 000 BP (Salvigsen & Elgersma, 1993). There was found no evidence of any readvances during the Younger Dryas, contrary to the deglaciation in Norway (Salvigsen & Elgersma, 1993). The marine limit was found to be ca. 42 m a.s.l. for the whole of Sørkapp Land (Salvigsen & Elgersma, 1993). Sørkapp Land experienced a rapid land uplift after the deglaciation (Salvigsen & Elgersma, 1993). This was followed by a transgression of the sea, which resulted in a large beach ridge which is present for most of the western coast (Salvigsen & Elgersma, 1993). From 5000 BP and onwards there was a slow regression of the sea down to the present sea level (Salvigsen & Elgersma, 1993).

In a study from 2017 it was found that in the basin of Sørkapp Land, that also included parts of Wedel Jarlsberg Land and Torell Land, the glaciers had retreated a total of 16.5% since the termination of the LIA at the end of the 19th century (Martín-Moreno et al., 2017). The basin was in 2017 covered by 1917 km^2 of ice (Martín-Moreno et al., 2017). The tidewater glaciers were found to have had retreated the most with Hornbreen having the biggest recession of 13 km (Martín-Moreno et al., 2017). The study had mapped the maximum glacier extent of the LIA in all of Svalbard (Figure 5). The glaciers in Sørkapp Land (blue box) are presented to have had their largest LIA extent with their terminal moraine complexes. This is the case for Bungebreen, where pebbles from a marine terrace were observed within sediments covering the ice-cored moraines and at outwash fans (Klysz & Lindner, 1982). The inclusion of these pebbles into glacial sediments is evidence of a Bungebreen advancing during the Late Holocene, likely during the LIA (Klysz & Lindner, 1982).

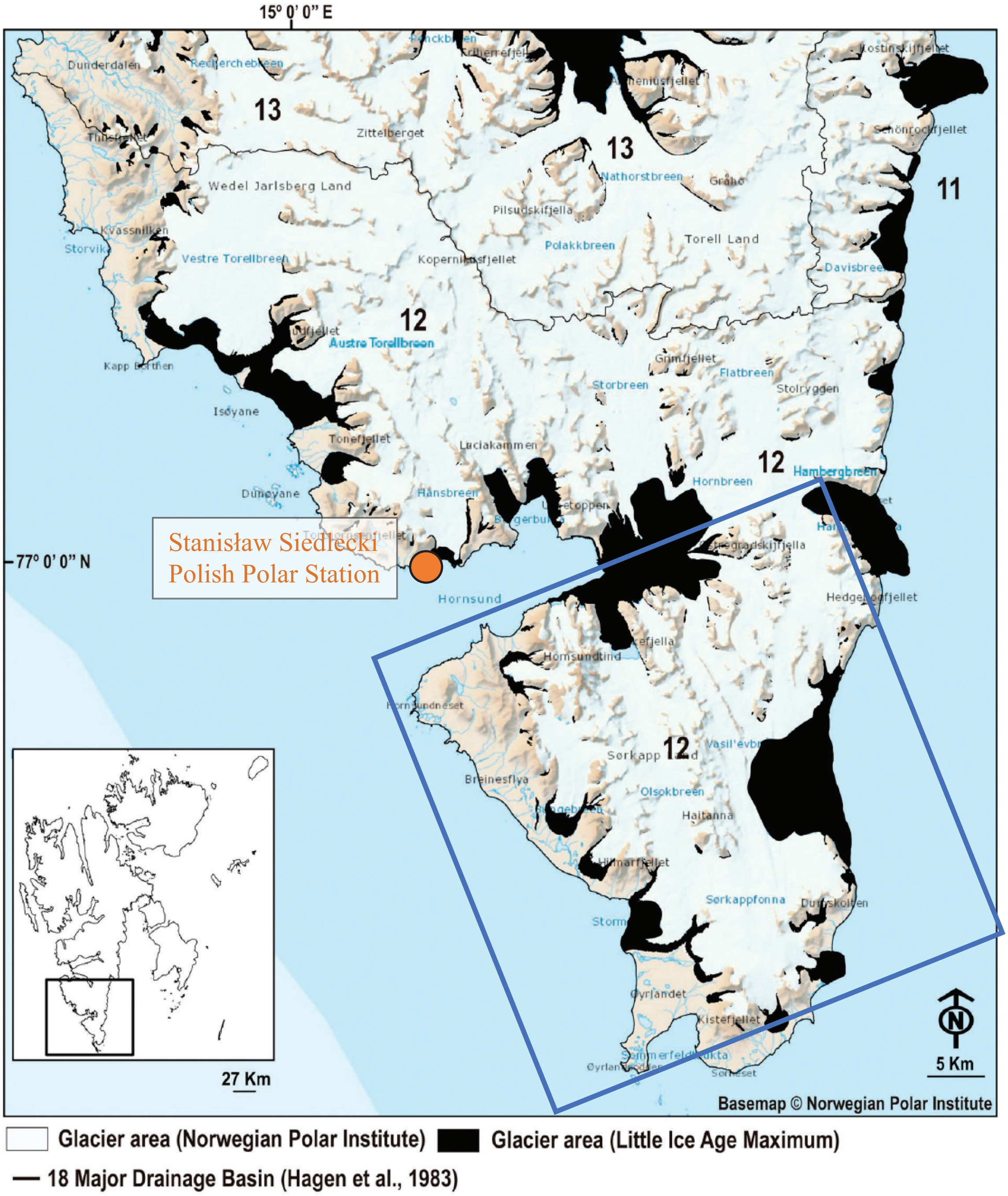


*Figure 5: Overview of the maximum glacial extent during the LIA for Sørkapp Land and parts of Wedel Jarlsberg Land and Torell Land from the study of Martín-Moreno et al. (2017). Blue box indicates Sørkapp Land. Orange circle indicates the Hornsund polar station (Stanislaw Siedlecki Polish Polar Station). *Note the quality of the image is as in the original publication.*

The following chapter describes the geomorphology of the study area (Chapter 2.4) in detail based on previous work.

2.2.2 Geomorphology of Sørkapp Land

Common landscape features in Sørkapp Land are moraine fields, sandurs and coastal lowlands with some well-devolved raised beaches (Atakan et al., 2015). The landscape is clearly affected by glaciers, both past and present, as there are both alpine mountains and some rounded mountains to the west (Atakan et al., 2015), with plateaus in some places. Some of the alpine mountains come up as nunataks between glacial ice. The Sørkapp Land geology mostly consists of sandstones, siltstones and limestones (Figure 4). None of the bedrock complexes at Sørkapp Land have a horizontal direction and all are cut through by faults (Ziaja, 2016). The oldest rocks (Middle Proterozoic) can dip up to more than 90°, while the younger rocks have smaller dips (10-25°) (Ziaja, 2016). The glaciations the area has undergone by past and the current glaciers, has led to the formation of glacial landforms and Quaternary deposits, such as marine sediments. However, there are no Quaternary deposits on the steep mountain slopes due to erosion and since they were deglaciated, they have largely been affected by slope processes which has led to the formation of many talus fans that can be up to 10-20 m thick (Ziaja, 2016). Most of the glacial sediments are from the late Holocene, mostly from during and after the LIA. It is rare to find sediments from the end of the Pleistocene in this area (Ziaja, 2016).

Many glaciers of Sørkapp Land have extensive marginal zones (e.g. Gåsbreen, Bungebreen and Vitkovskibreen), and these have the most various geomorphology in the area (Zwoliński et al., 2013). The moraines and the glaciofluvial deposits can be up to several metres in some places. However, the unconsolidated Quaternary deposits are not continuous (Ziaja, 2016). The coastal lowlands, from Gåshamnøyra to Olsokbreen, are characterized by sequences of marine terraces, that were unglaciated throughout the Holocene (Ziaja, 2016; Zwoliński et al., 2013) and are therefore well developed. Evidence of isostatic uplift is found in the area with the presence of marine terraces at great height above the present sea level (Zwoliński et al., 2013). These coastal plains were formed as shallow offshore seabed's during the Pleistocene and the Holocene (Ziaja, 2016). The wide coastal plain below Bungebreen, Breinesflya, is the largest of the Sørkapp Land lowlands with a width of 3-4 km (Ziaja, 2016). Breinesflya goes into the narrower coastal plain, Tørrflya, between Bungebreen and Vitkovskijbreen and reaches all the way to Olsokbreen (Ziaja, 2016).

The western side of the peninsula is different from both other areas on Sørkapp Land and in Spitsbergen in general because most of it has not been glaciated since before the Holocene (Ziaja, 2016). Additionally, the northern part of western Sørkapp Land has non-glacial rivers and lakes that make up important elements of the landscape, in contrast to the rest of Sørkapp Land (Ziaja, 2016). The mountains in the northwest Sørkapp Land are exposed to relative warm and dry eastern foehn winds and these melts the snow cover during winter (Ziaja, 2016). This has been found to have occurred since the beginning of the Holocene, not only today, meaning there are both geological and geomorphological evidence that prove that lack of glaciers (Ziaja, 2016). Because of the retreat of the glaciers the boundary between the two different regions are slowly shifting towards the east (Ziaja, 2016). In the period from 1980-2008, the recession of the glaciers in western Sørkapp Land accelerated (Ziaja, 2016). One reason for this is because the glaciers in the area were not in equilibrium with the contemporary climate, particularly air temperature, meaning that the glaciers will still experience recession even if there were an end to the current climate warming period (Ziaja, 2016). This means the de-glaciated area of Sørkapp Land is affected by other processes than glacial, such as weathering and slope processes, which coincidently may destroy evidence from previous glaciations.

In the summer of 1959, Jewtuchowicz (1965) observed landforms such as eskers and kames in the foreland of Gåsbreen and Bungebreen. At the time, it was observed that the eskers and kames in proximity to the two glaciers occurred in different environments, at Gåsbreen they were in a deglaciated area, while at Bungebreen they were in an area still covered by ice (Jewtuchowicz, 1965). In the foreland of Gåsbreen it was observed that large amounts of meltwater was continuously destroying the landforms ahead of the glacier and covering them with sediments, resulting in the Gåshamnøyra outwash plain (Jewtuchowicz, 1965). Regardless of the meltwater destroying some landforms and depositing sediments, eskers and other landforms such as end moraines and channels could still be observed in 1959 (Jewtuchowicz, 1965). At the time, the eskers observed in the foreland of Gåsbreen was in front of the terminal moraine in the Gåshamnøyra plain, and the two longest (the largest was 186 m long) eskers were sinuous, while two short ones (the smallest was 32 m long) were straight (Jewtuchowicz, 1965). While, in the foreland of Bungebreen, a straight esker was emerging 4 m above the glacier near the western lateral moraine (Jewtuchowicz, 1965).

The observed kames were found in close proximity to the eskers. In Gåshamnøyra the kames were found in groups and one of the kames was mound formed and was just below 2 m high and had a diameter of 6 m (Jewtuchowicz, 1965). The kames were mostly made up of sand and gravel (Jewtuchowicz, 1965), similarly to the eskers. As was the case for the esker, mounded kames were emerging from the Bungebreen glacier front with only the upper part of the kames being visible rising 3 m above the ice surface (Jewtuchowicz, 1965). Jewtuchowicz (1965) concluded, based on morphological evidence and analysis of the structures of the landforms, that the eskers and kames of Gåshamnøyra and Bungebreen were formed subglacially.

In 1980, Klysz and Lindner (1982) conducted fieldwork in the foreland of Bungebreen with the aim to reconstruct the glacial history of Bungebreen from Weichsel until the Holocene. It was then observed that the marginal zone has changed considerably since the first investigations of Jewtuchowicz in 1959. The changes in the foreland were assigned to the substantial retreat of the glacier (Klysz & Lindner, 1982). In 1980 the glacier front was located ca. 700-800 m from the terminal moraine (Klysz & Lindner, 1982). Between the glacier and the terminal moraine there was a several dozen metres wide area with ablation moraine (Klysz & Lindner, 1982). A distinct feature of the area west of the medial moraine was an outwash plain, this was also the case east for the medial moraine (Klysz & Lindner, 1982). Both the eastern and western side of the medial moraine included an ice-dammed lake, however the lake west of the medial moraine was smaller (Klysz & Lindner, 1982).

The terminal moraine was up to 60 m high and was part of many parallel elevations, as was considered typical for ice-cored moraines and has been considered as an effect of the glacier having multiple retreat phases (Klysz & Lindner, 1982). The terminal moraine was deemed degraded, and the melting of the ice-core led the terminal moraine to flatten and to form vast depressions that were infilled with silty-sand sediments (Klysz & Lindner, 1982). Close to the western lateral moraine there are some individual accumulations of sand and gravel that had a great variety of lithology and grain size, and in few instances they were found in the formation of gravel-boulder islands at the surface of the glacier margin (Klysz & Lindner, 1982). These formations were apparently the same ones that Jewtuchowicz (1965) analysed to be eskers, however Klysz and Lindner (1982) did not attribute them to be eskers because the formations were found to be ice-cored and did not have any sediment bedding.

During the fieldwork in 1980 there were observed two meltwater gorges across the terminal moraine complex of Bungebreen, one referred to as the western gorge and a southern gorge (Klysz & Lindner, 1982). Two distinct fans were formed below the two gorges (Klysz & Lindner, 1982). This led Klysz and Lindner (1982) to discover a trend in the marginal zones of some of the land-based glaciers in Spitsbergen (Bungebreen, Werenskioldbreen and Nannbreen) where the glaciers had two distinct outwash tracts connecting to gorges of the ice-cored terminal moraine complex where one is referred to as the western gorge and the other as the southern gorge. A trend observed in the 15 years prior to 1980 was that the western gorges were abandoned which led to the formation of the southern gorge (Klysz & Lindner, 1982). It was believed that the trend was due to the southern and south-east parts of the glacier melting faster since they received more insolation than other parts of the glacier (Klysz & Lindner, 1982).

The retreat of Bungebreen at the end of the 19th century started with the marginal parts of the glacier becoming lower which resulted in an influx of meltwater channels that cut through the outwash plains both inside and outside of the terminal moraine complex (Klysz & Lindner, 1982). The recession of the glaciers expanded the marginal zones and sediments appeared around the glacier tongues and eventually new mountain ridges or ranges will appear (Ziaja, 2016). The marginal zones developed from ice-cored frontal moraine ridges into large complexes of different landforms, including intramarginal sandurs with proglacial rivers beds, kettle holes, kames, eskers and small ridges of fluted moraines (Ziaja, 2016). Later, the landforms can be transformed into other types of landforms, by for example slope processes and the thawing of dead ice that leads to geomorphological changes of the debris covering the dead ice, resulting in kettles holes and tongues from minor landslides (Ziaja, 2016). The described landscape changes in western Sørkapp Land is mostly the result of effects due to glacial retreat, and this has led to the appearance of a new landscape (Ziaja, 2016). A longer summer season and less persistence of snow patches has affected geomorphic and hydrologic processes in the whole peninsula (Ziaja, 2016). These changes is seen in debris-flows becoming more common and fluvial processes becoming more extensive (Ziaja, 2016).

Based on this detailed summary of the known geomorphology in the Sørkapp Land region and the studied literature, the following knowledge gaps was formed.

2.3 Knowledge gap

Geomorphology

Zwoliński et al. (2013) has in their report of geomorphological settings of Polish research areas on Spitsbergen published the fragment of a geomorphological map of Hornsund (scale 1:75 000), where the north-western part of Sørkapp Land can be seen (Karczewski et al., 1984) (Figure 6). The original map covers the entire Hornsund region (larger area than in Figure 6), however since the fragment shows the whole area of Sørkapp Land that is included in the original map and has the best quality it is included here, while a scan of the original map is found in Appendix A and a larger figure of the fragmented map can be seen in Appendix B. There exists no detailed geomorphological map of Sørkapp Land as whole. The legend from the original map is presented in Figure 7. Based on the fact that this geomorphology map is from the 1980s and that the landscape has changed drastically since then (Chapter 2.2.2), a more detailed geomorphology map of the altered Sørkapp Land region is needed.

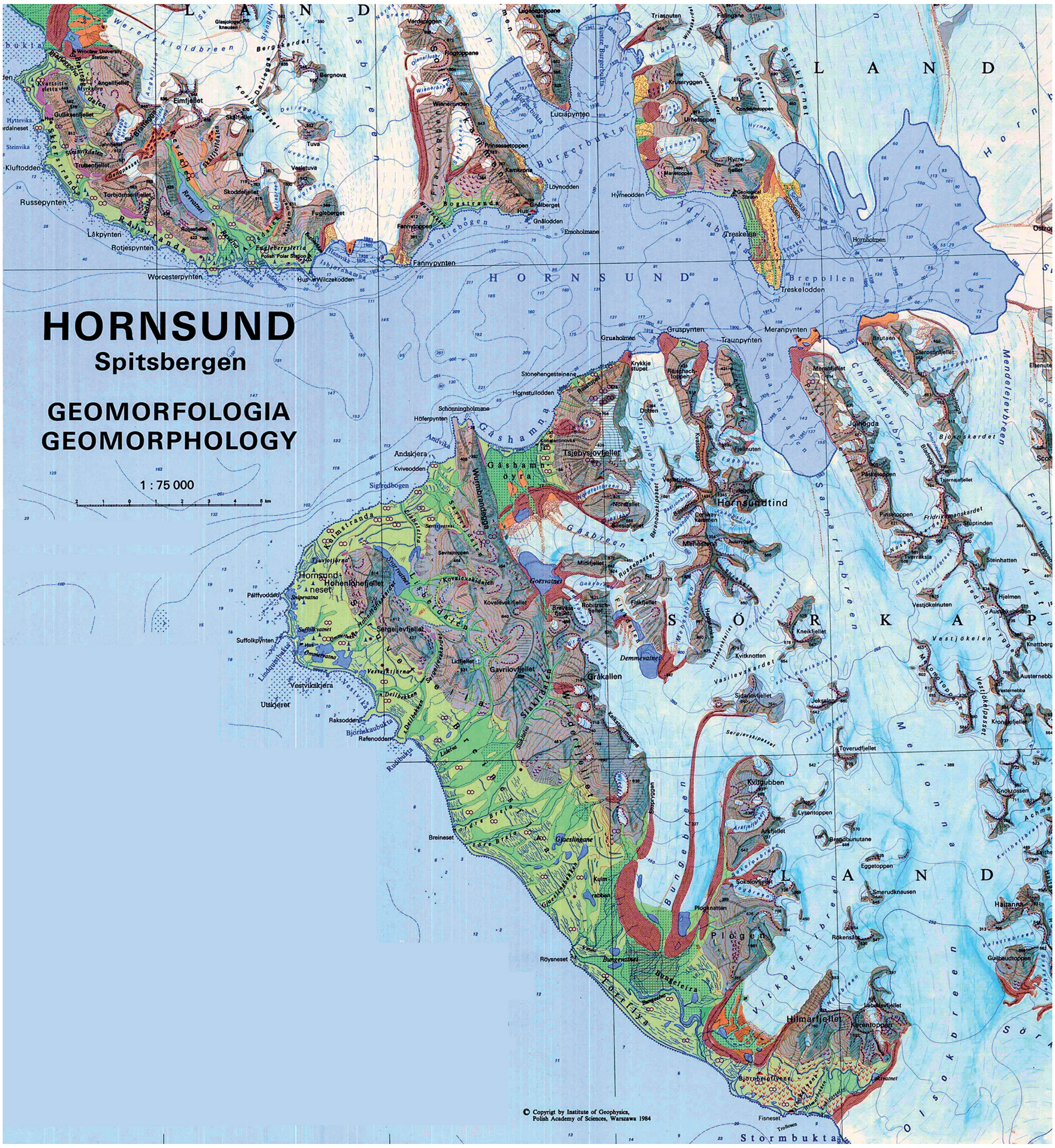


Figure 6: Fragment of geomorphological map of Hornsund found in Zwoliński et al. (2013). Copyright by Institute of Geophysics, Polish Academy of Sciences, Warszawa, 1984.

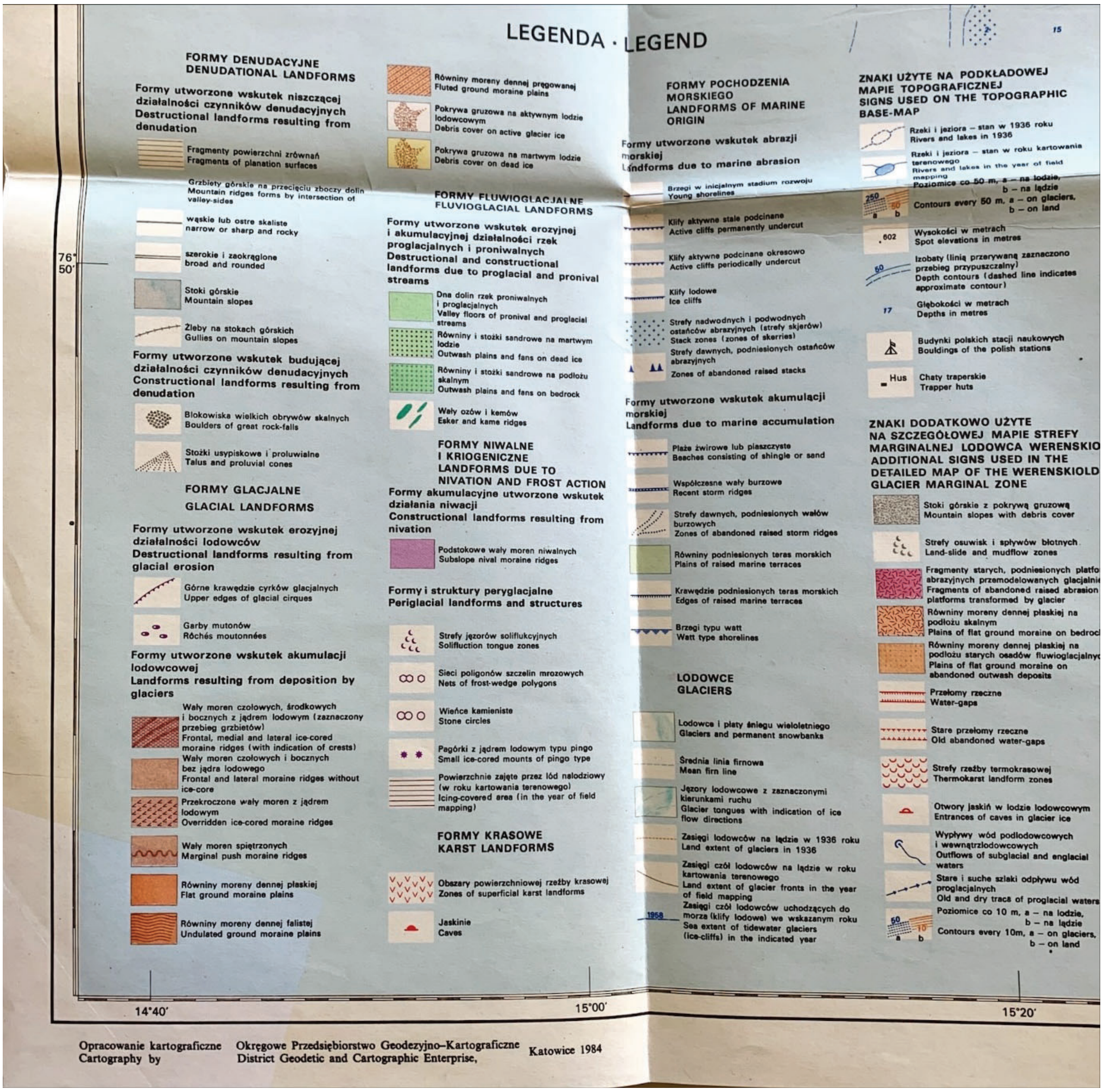


Figure 7: Scan of legend belonging to the original geomorphology map of the Hornsund region by Karczewski et al. (1984).

NPI has geomorphology maps of Svalbard, but they only show the larger landforms and therefore does not have the details one wants for the geomorphology map of an area. There are generally few produced geomorphological maps of Svalbard (Figure 8). As such maps make for a base line for the current conditions of the landscape, they make for something to compare latter changes with, which is why it is important to make such maps (Allaart et al., 2021). The maps make for a better understanding of landforms, how they are connected to each other and their development process (Allaart et al., 2021). In view of the lack of these maps, it is imperative to continue researching and producing maps where there doesn't exist any. From the research for this thesis, it has not been uncovered any high-resolution geomorphology maps for the glaciers in the study area (Chapter 2.4).

Figure 8: Map of Svalbard. a) where there exists maps of general geomorphology and maps of glacier forelands. b) the main ocean currents surrounding Svalbard. WSC: West Spitsbergen Current, ESC: East Spitsbergen Current, EGC: East Greenland Current, NAC: North Atlantic Current, NCC: North Cape Current. Warm currents in red, cold currents in blue. From Allaart et al. (2021)

<u>Geomorphology of the land-based glaciers in Sørkapp Land</u>

Most of the published work with close proximity to the Sørkapp Land region has been conducted in Hornsund (Figure 11) and has focused on the tidewater glaciers. Most of the research has investigated why the tidewater glaciers are retreating (Błaszczyk et al., 2009; Strzelecki et al., 2020). Furthermore, most of the work conducted in the Sørkapp Land region and nearby regions such as Hornsund has been focusing on glaciology and not on geomorphology. Nor has the focus been on the land-based glaciers in the region. The land-based glaciers in Sørkapp Land have therefore not received much attention, except from some

Polish researchers (Ostafin et al., 2016; Ziaja, 2016; Zwoliński et al., 2013) that have mostly studied how the landscape has transformed. In particular there have not been done much research in the area of Vitkovskijbreen and Belopol'skijbreen as the chapters above (2.2 and 2.2.1) indicates. Therefore, this study chose to focus on the geomorphology of the forelands of the land-based glaciers in western Sørkapp Land.

Surge-type glaciers

Even though surge-type glaciers are in abundance in Svalbard (Chapter 2.1.2), there is still a lack of knowledge about the ones in Svalbard. The question is both how many there are, and which ones are of this type. The estimated number of glaciers of surge-type ranges from 13-90% (Aradóttir et al., 2019; Sund et al., 2009). The reason for the uncertainties has been assigned to the fact that surging glaciers were more common during the LIA (Aradóttir et al., 2019; Farnsworth et al., 2020). This could perhaps be because of the temperatures being lower during the period up to and during the LIA than at present (Chapter 2.1.2), and if the accumulation was large on for example cold based glaciers then that might have caused them to surge (since cold based glaciers are frozen too the ground they will often surge if the accumulation gets too large). However, this is not certain as some glaciers on Svalbard have been observed to show surge behaviour in the beginning of the 21st century, even though the ice mass of Svalbard is getting smaller (Farnsworth et al., 2020). This assessment show that there needs more knowledge on how surging glaciers respond to a changing climate. However, there have been studies focused on the number of surging glaciers in Svalbard.

Farnsworth et al. (2016) did a study on all glacier forelands on Svalbard where they used the presence of crevasse squeeze ridges (CSR) to identify surge-type glaciers that had not been documented earlier (Figure 9). The study used high-resolution aerial imagery and added 431 glaciers to the existing 277 glaciers that had previously been documented to demonstrate surge-type behaviour (Farnsworth et al., 2016). Lovell and Boston (2017) did a similar study (both used aerial imagery), but they investigated composite ridge systems in relation to surge-type behaviour and concluded with that at least 32.6% of all the glaciers on Svalbard are probable to be of surge type (Figure 10). Contrary, Sund et al. (2009) concluded that it is likely that the majority, with as much as 90% of the glaciers in Svalbard are of surge-type by studying the geometric changes of the glaciers. It has been suggested that the increasing melting from glaciers may trigger surges. This is important since surges influence the ice discharge and therefore have the potential to increase these glaciers contribution to sea level rise (Hanssen-Bauer et al., 2019; Schuler et al., 2020).

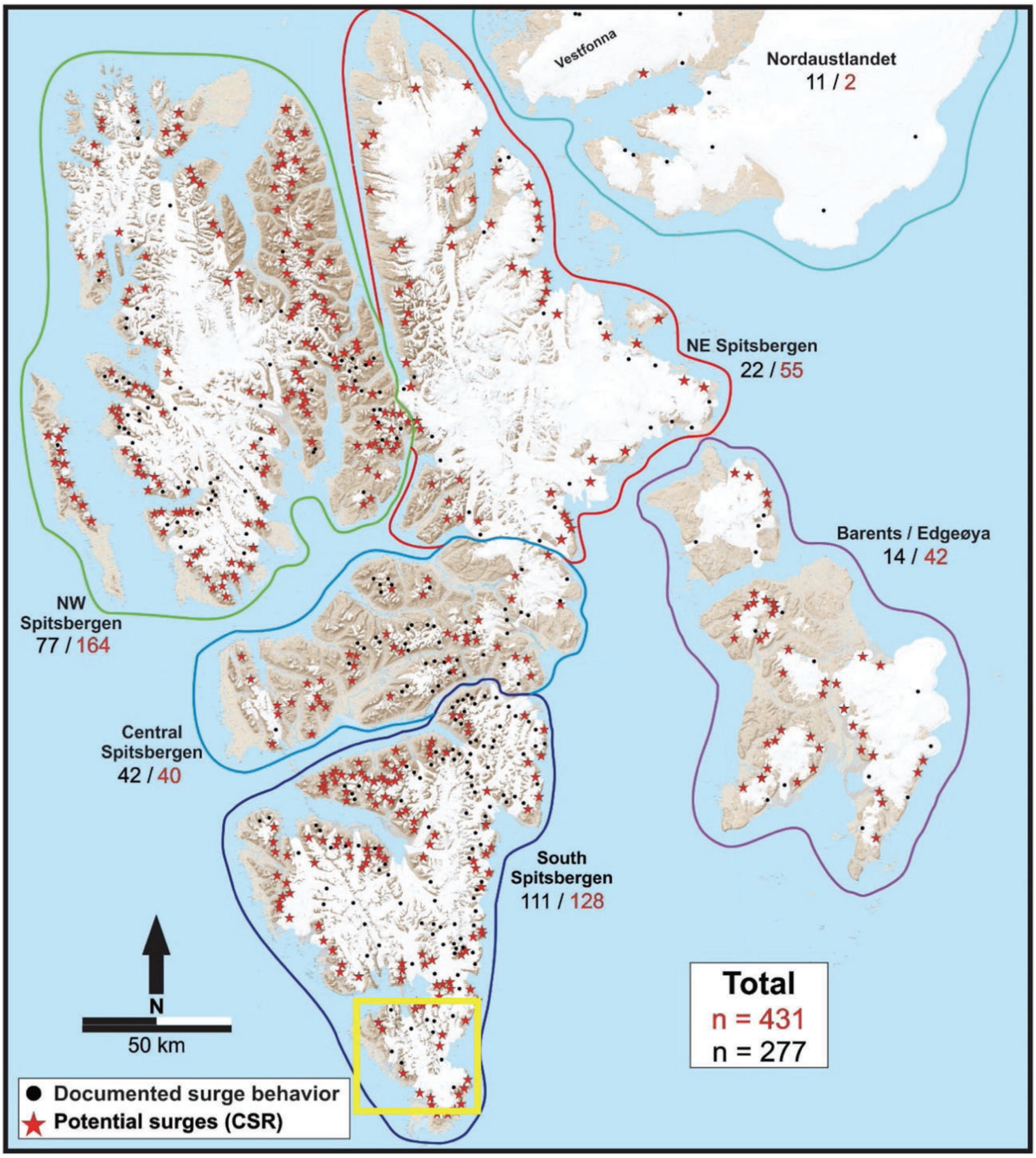


Figure 9: Glaciers documented to have surged (black dots) and glaciers that have potentially surged in the past based on the evidence from CSRs (red stars) divided by their subregions. Figure from Farnsworth et al. (2016). Yellow box indicates the Sørkapp Land.

On Sørkapp Land Farnsworth et al. (2016) documented 37 surge-type glaciers (both tidewater and land-based glaciers), it is not clear from Lovell and Boston (2017) how many they assign to Sørkapp Land, but they documented only 9 with composite ridge network on the whole of South Spitsbergen (Figure 10). Because of the divergence regarding the number of surge-type glaciers on Svalbard (including Sørkapp Land) the glaciers in Sørkapp Land should be investigated to examine if there are any other evidence for surge-type behaviour than CSRs and composite ridge networks. Here, the land-based glaciers are particularly interesting to study as they have been scarcely studied previously.

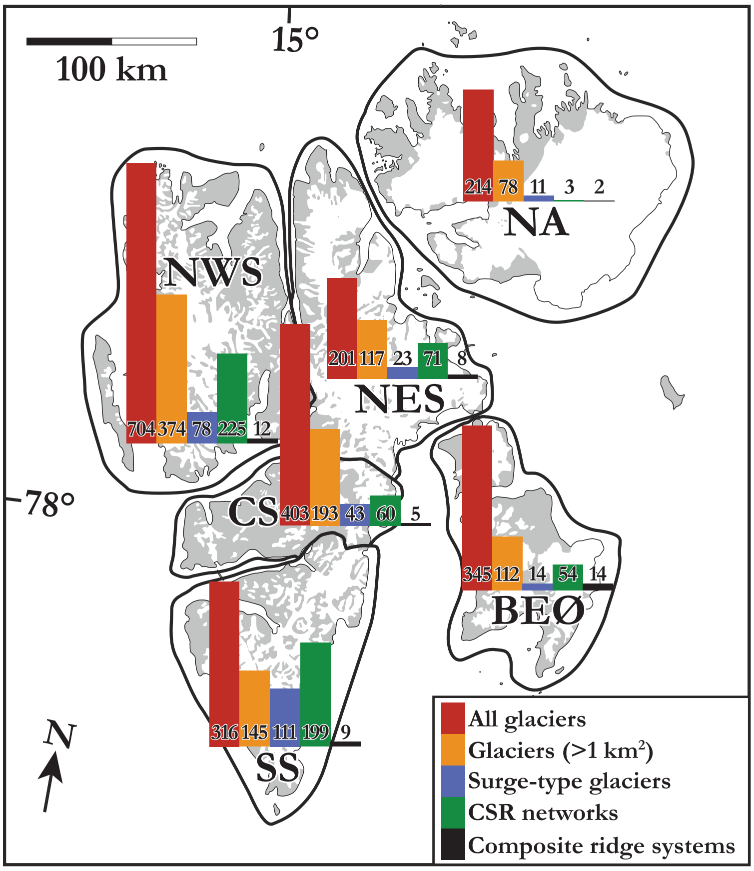


Figure 10: Overview of Svalbard and the numbers of glaciers that Lovell and Boston (2017) studied according to their regions (red column). The glaciers observed with CSR networks are the ones from Farnsworth et al. (2016) (green column). The glaciers with composite ridge system are the Lovell and Boston study. NA: Nordaustlandet, NWS: Northwest Spitsbergen, NES: Northeast Spitsbergen, CS: Central Spitsbergen, SS: South Spitsbergen, BEØ: Barentsøya and Edgeøya.

Sund et al. (2009) suggests that some glaciers may start to show evidence of the beginnings of a surge (the glacier elevation changes, there is an increase of crevasses, and the glacier front thickens) but later on does not surge, referred to as a partial surge. It was found that the glaciers that exhibit this partial surge rarely leave evidence of this in the geomorphological record (Sund et al., 2009). This means that some glaciers with tendencies to surge (perhaps some glaciers only experiencing these partial surges) have not left any evidence of such behind, in terms of landforms. This further adds to the difficulties of classifying surging glaciers.

<u>Few published dates</u>

There exists few published dates from the Sørkapp Land region. One publication is the already mentioned dates from Salvigsen and Elgersma (1993). There are some thermoluminescence dates by Butrym et al. (1987), however their results were criticised by Salvigsen and Elgersma (1993) of being confusing as Butrym et al. (1987) have much higher ages of raised beaches than the radiocarbon dates found in Salvigsen and Elgersma (1993). Whilst this cannot be addressed within the scope of this study, it does represent a clear knowledge gap and is therefore highlighted here.

2.4 Study area

This thesis will focus on four land-based glaciers in Sørkapp Land. Sørkapp Land is the most southern part of the main island of Svalbard, Spitsbergen (Figure 11). There are about 80 glaciers (Ziaja, 2016) covering ca. 55% of the area (Nuth et al., 2013). The largest glacier is the Sørkappfonna ice cap covering ca. 265 km^2 (Hagen et al., 1993) (likely less now that the surrounding glaciers have retreated since the time these measurements was made). There is a rather large difference in the amount of glaciation between the western and the eastern side of the peninsula, where the western side is less glaciated due to the presence of the warm West Spitsbergen current (Figure 8) (Ziaja, 2016). The west side is dominated by some quite wide coastal plains in some places, while the eastern side is dominated by mountain cliffs that only have narrow coastal plains or where the mountains go directly into the ocean (Ziaja, 2016).

As this study will focus on glacial geomorphology the investigation focuses on forelands in front of the glaciers: Gåsbreen, Bungebreen, Vitkovskijbreen (previously Vitkovskibreen) and Belopol'skijbreen (previously Bjelopolskibreen) (Figure 11). The glaciers are located in a north-to-south transect. Gåsbreen, Bungebreen and Vitkovskijbreen are located in the north-west part of Sørkapp Land, while Belopol'skijbreen is located in the south-west part. The marginal zones of Gåsbreen, Bungebreen and Vitkovskijbreen have gotten substantially wider since the 1980s (Ziaja, 2016). Below is a brief description of these outlets.

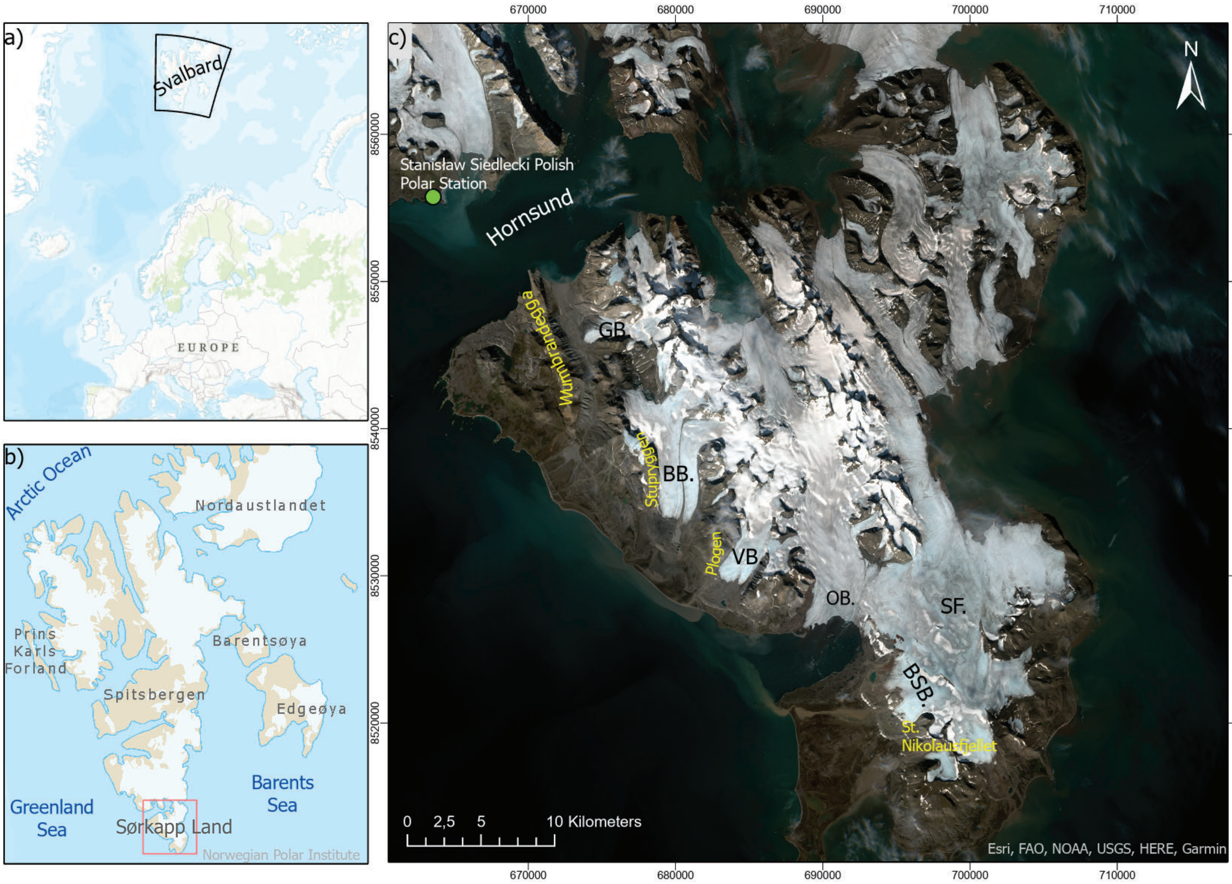


Figure 11: Overview map of the study area. a) Svalbard in relation to Europe. b) Map over Svalbard and surrounding seas. Sørkapp Land is indicated by a red box. Map from NPI. c) Overview of Sørkapp Land and Hornsund with the Hornsund Polar station indicated by green circle. Background image is Sentinel-2A from Earth Explorer USGS (https://earthexplorer.usgs.gov/) from July 31st 2020. Glaciers (in black text): GB. – Gåsbreen, BB. – Bungebreen, VB. – Vitkovskijbreen, OB. – Olsokbreen, SF. – Sørkappfonna, BSB. – Belopol'skijbreen. Mountains and mountain ranges in yellow. From north to south: Wurmbrandegga, Stupryggen, Plogen and St. Nikolausfjellet.

Gåsbreen (Figure 11) is an east-west oriented valley glacier that in 1980 covered an area of 14.3 km^2 and had a length of 7.3 km (Hagen et al., 1993). The front had an expanded foot in 1980 where a lobe formed at the lower portion of the glacier when it left the confining wall Wurmbrandegga and extended on a less restricted and more level surface (Hagen et al., 1993). It is the only land-based glacier in Sørkapp Land that terminates south of Hornsund (Zwoliński et al., 2013). In 1980 it had only had a slight retreat compared to the 1936 aerial photos (by NPI). From the 1980s to 2008 Gåsbreen became thinner, and the front retreated 750 m (Ziaja, 2016). It has a terminal moraine, lateral moraines and annual moraines (Hagen et al., 1993). A large change happened in the valley above the lowest part of Gåsbreen between 2001-2004 because of glacial recession (Ziaja, 2016). In 2000 there was an ice-dammed lake (Goësvatnet, Goës Lake) between Gåsbreen and Goësbreen, but in 2005 the lake was gone, and the area had begun to transform into a more fluvial landscape (Ziaja, 2016). Gåsbreen has the longest monitoring programs of glacial changes in Svalbard because of observations done by De Geer in 1899. The investigations made by De Geer resulted in the production of a map (Ziaja, 2016), however it is not available.

The front of Gåsbreen has a gentle slope (Zwoliński et al., 2013). There is a bed of dead ice covered by a course clastic ground moraine or sandur between the glacier front and the terminal moraine (Zwoliński et al., 2013). Water from meltwater channels gather at the centre of the ice-cored terminal moraine and flows into Gåshamnøyra plain from a notch in the moraine (Zwoliński et al., 2013). Proglacial waters from Gåsbreen has formed an extensive extramarginal sandur, Gåshamnøyra, seen as a flat and wide plain below the glacier (Ziaja, 2016). The Gåshamnøyra plain consists of a large, braided water system that flows into the Gåshamna bay (Zwoliński et al., 2013). The substrate in the middle part of the Gåshamnøyra plain is ground moraine, however the majority of the plain consists of large and flat sandur fans (Zwoliński et al., 2013). A river flowing from the nearby glacier Goësbreen runs through a glacial lake and the terminal moraine of the foreland of Gåsbreen and further to the sea.

Bungebreen (Figure 11) is a north-south oriented valley glacier that in 1980 covered an area of 54.5 km^2 and had a length of 12 km (Hagen et al., 1993). It has a terminal moraine, lateral moraine and annual moraines, in addition to a medial moraine (Hagen et al., 1993). The terminal moraine has two gorges from which sandurs have formed in front of the terminal complex (Zwoliński et al., 2013). Its lateral moraine was in contact with the glacier in 1980 (Hagen et al., 1993). It had a marked retreat from the 1936 aerial photos (by NPI) to 1980 (Hagen et al., 1993). Between the 1960s and the 1980s the snout of Bungebreen flattened and the glacier retreated several 100 metres during this 20-year period (Klysz & Lindner, 1982), before it had another significant retreat (almost 1 km) after the 1980s, even with a surge that happened after 1990 (Ziaja, 2016). The foreland of Bungebreen has changed significantly due to the disappearance of a previous large though rather short river, Vinda, following the glacial recession (Ziaja, 2016). In 2008 there were only small streams left that sometimes flowed in the incised riverbed (Ziaja, 2016). On the other side of the foreland, the river Bungeelva, has become large (at least in summer) due to the lake it flows from has also become larger following an increase in meltwater (Ziaja, 2016). From the terminal moraine to the shoreline there is a distance of 2 km and within those there are seven raised marine terraces (Zwoliński et al., 2013). The lowest terrace is ca. 6-8 m a.s.l. and the highest is ca. 100-130 m a.s.l. (Zwoliński et al., 2013). This area is dominated by beach sediments, and marine sediments from close to the nearby river Bungeelva was dated to an age of ca. 10 985 ^{14}C years (Salvigsen & Elgersma, 1993).

Vitkovskijbreen (Figure 11) is a mostly north-south oriented valley glacier (Hagen et al., 1993) which in 1980 covered an area of 20 km^2 and was 9.0 km long (Hagen et al., 1993). The lateral moraine was in contact with the glacier in 1980, however it had already then had a marked frontal retreat since the 1936 aerial photos (by NPI) (Hagen et al., 1993). From 1990 to 2008 it had retreated 300-400 m and the thickness had been slightly reduced (Ziaja, 2016). Downstream there are a terminal moraine, parts of lateral moraines and annual moraines (Hagen et al., 1993). The terminal moraine is only ca. 500 m from the present-day sea level and is the terminal moraine complex closest to the sea out of the four glaciers in the study area. The area below the terminal moraine complex is dominated by raised beaches (Zwoliński et al., 2013). There are two relatively small sandurs below the terminal moraine complex. These sandurs have been made from two gorges that divide the terminal moraine complex, formed by glacial meltwater (Zwoliński et al., 2013). Gorges in the terminal complexes are from when the glaciers were closer, and meltwater flowed over the terminal moraine directly in front of the glacier. This is evident from the 1936 aerial photos (by NPI).

Belopol'skijbreen (Figure 11) is a mostly east-west oriented outlet glacier of Sørkappfonna. In an inventory by Hagen et al. (1993) it was classified as valley glacier where the catchment area is difficult to determine. However, it was in 1980 estimated to cover an area of 26.4 km^2 and was 6.7 km long (Hagen et al., 1993). The glacier front consists of two merged tongues and they were deemed to have been stationary between the 1936/38 aerial photos and 1980 (Hagen et al., 1993). The moraine system was classified to be made up of terminal moraine, lateral moraine and terminal moraines (Hagen et al., 1993). This glacier is the least known of the four glaciers studied in this thesis. It was not studied by the Polish researchers in Ziaja (2016) and is only briefly mentioned in (Wójcik & Ziaja, 1993). It is not mentioned in any other studies obtained during the work of this investigation.

On the western side of Belopol'skijbreen is the tidewater glacier, Olsokbreen (Figure 11), the only tidewater glacier on Sørkapp Land's west coast (Ziaja, 2016). The eastern lateral moraine of Olsokbreen used to be in contact with the terminal moraine of Belopol'skijbreen on its north-west side. Additionally, Olsokbreen's marginal zone is on the coastal plain below Belopol'skijbreen. During the LIA, Olsokbreen was much larger and thicker than today (Ziaja, 2016). In front of Olsokbreen is the bay Stormbukta, covering ca. 5x4 km, which did not exist at the end of the LIA in 1900 (Ziaja, 2016). It was created when Olsokbreen retreated later and within its lateral moraines there are now wide marginal zones and new coastlines has appeared (Ziaja, 2016). Olsokbreen has retreated 1-2 km since 1990 (Ziaja, 2016).

2.5 Aim and objectives

To be able to close knowledge gaps, more data is needed. Areas that are difficult to reach are encouraged to use satellites and other technologies (AMAP, 2021). Therefore, remote sensing is an appropriate option for conducting research in Sørkapp Land. Moreover, Sørkapp Land is suitable for a remote study of glacial geomorphology due to the extensive forelands of the glaciers, in addition to the glacial and periglacial landscape being untouched (Ziaja, 2016). Furthermore, the mentioned glaciers and their forelands all exhibit diverse features, which makes them interesting to investigate. Additionally, the area is interesting in a climate change perspective because the glaciers seem to have reacted differently to climatic changes in the past. Furthermore, no one has studied these exact glaciers together and been able to draw comparisons or note the differences between them. Since it is a remote area, the use of high-quality satellite imagery makes it possible to study the geomorphology of the forelands of the mentioned glaciers. As there is a lack of recent glacial geomorphology, it means changes in the forelands following increasing global climate change has not been observed. And areas where glaciers and coastlines meet has been encouraged to be studied within the context of the ongoing climate change and glacial recession (Strzelecki et al., 2020). Since the greatest geomorphological variations are in the marginal zones of land-terminating glaciers (Zwoliński et al., 2013) this study will focus on this area for the four aforementioned glaciers.

As previously stated, glacial geomorphology gives valuable knowledge about glacial processes and the creation of landforms. Such knowledge can be used to make stronger models of future climate. Following the statement above, the aim of this research is to identify and map the glacial geomorphology of four land-based glaciers at Sørkapp Land in Svalbard. The investigation involves working with remote sensing by using satellite images, DEMs, maps and Geographical Information Systems (GIS). This aim will be achieved through six objectives:

1. Examine previous studies concerning the geomorphology, glacial history, processes and dynamics, and glacial landsystems on Sørkapp Land and in nearby areas such as Hornsund to identify knowledge gaps.
2. Collect information about the Sørkapp Land landsystem and the thermal regime of the glaciers in this area.
3. Study the relation between landforms (e.g. crevasse squeeze ridges) and surge-type glaciers and establish if these are present at the forelands of the land-based glaciers in Sørkapp Land.
4. Develop a chronology for the landsystem at Sørkapp Land through published numerical datings together with the results from this study.
5. Create a revised model of the landsystem at Sørkapp Land.
6. Produce geomorphological maps in ArcGIS Pro.

3 Methods

Methods used in this thesis include geomorphological mapping based on sentinel imagery, and aerial photos following a mapping method developed by the Norwegian Geological Survey (NGU). Additional analysis of glacial movement was conducted. Below is an introduction to geomorphological studies. Following are descriptions of the methods used and their limits.

3.1 Geomorphology studies

Even though much glaciology and geomorphology research has been conducted, both in the Arctic in general and on Svalbard, there are still uncertainties connected to how glaciers respond to climate change and how that affects the glacial dynamic. To make better models for the future climate it is important that as much knowledge as possible is uncovered. Studying the dynamics and processes of glaciers will contribute to this goal. Furthermore, investigating glacial geomorphology can lead to a better understanding of the responses of glaciers and ice sheets to climate change, as the landforms provide empirical evidence of former ice extent and glacial dynamics. This is possible because geomorphology can be seen as a record of the processes that happen beneath the ice mass as landforms are exposed by the retreating ice margin.

Chandler et al. (2018) details the importance of geomorphological mapping as a method for studying earth surface processes and landscape evolution in glacial and palaeoglacial studies. The approach provides an essential geomorphological framework for palaeoglaciological reconstructions which can help establish glacial chronologies (Chandler et al., 2018). A lot of the development in this field of study in recent decades comes from technical developments, especially within remote sensing and GIS (Chandler et al., 2018). A large amount of high-quality remotely sensed datasets is available, with many services being free e.g. Earth Explorer (https://earthexplorer.usgs.gov/). As it now exists a well-covered network of satellites and therefore a good satellite cover of the Earth, every glacier can be observed. Yet, as the timescale is quite short (in a geological sense) the observational use of glacial change is limited to changes on a decadal scale (Geyman et al., 2022). However, if historical aerial photos are available one can study glacier changes on a marginally longer timescale (Geyman et al., 2022).

On the other hand, within the area of Digital Elevation Models (DEMs), the more frequent use of an unmanned aerial vehicle (UAV) has changed the scale and quality of DEMs and has made it possible to get very high-quality aerial images (Chandler et al., 2018). However, traditional field mapping methods are still held in high regard within the research community of geomorphology (Chandler et al., 2018). An approach with both remote sensing and field mapping is recommended by Chandler et al. (2018). Furthermore, to be able to interpret the glacial landforms and landscapes correctly, chronological and/or sedimentological evidence should also be included in the research to get a holistic view of the glacier system (Chandler et al., 2018). Nevertheless, since the study area of Sørkapp Land is quite remote, this investigation will have to rely solely on remote methods.

3.2 Geomorphological mapping

Mapping was done in ArcGIS Pro version 3.0.2. The geomorphology mapping is largely based on the orthophoto produced by NPI (also available at toposvalbard.npolar.no) (Norwegian Polar Institute, n.d.-b). The orthophoto is a dynamic tiled WMS map service (on request it returns images that consist of active map layers, map extents and zoom levels) that was added as a layer in ArcGIS Pro. The orthophoto is made from aerial photos taken between 2008 and 2011, depending on their location. The ones of Sørkapp Land are from 2010 (Norwegian Polar Institute, n.d.-b). The orthophoto was chosen as a data source based on its high quality compared to sentinel imagery where it is difficult to see details and smaller features. Orthophotos from over 10 years ago can still be used since the landscape does not change too much during such a short period and large landscape changes can be detected by sentinel imagery. The geomorphological maps were prepared in ArcGIS Pro.

Sentinel imagery

Sentinel imagery are satellite images, here used to map glacier extent from 2020 and to compare large-scale landforms with the orthophoto from NPI. The sentinel imagery was downloaded from Earth Explorer (https://earthexplorer.usgs.gov/) on September 14th, 2022. This study has made use of imagery from Sentinel-2. This program consists of two satellites (Sentinel-2A and Sentinel-2B) (Andreassen et al., 2021). The image used is from July 31st 2020 taken by Sentinel 2B. Further, the image had a cloud cover between 0-20%. The image with the least cloud cover was chosen, to get the best view of the glaciers. Sentinel-2 images on Earth Explorer are no longer available but can be found at Copernicus Open Access Hub (https://scihub.copernicus.eu/). Mapping of the glacier extent from 2010 and 2020 is to show the changes the glacier has gone through in the ten-year period. The reason for using 2020 sentinel imagery over images from 2022, is that the 2020 imagery has the best quality, and the glacier extent has not changed very much in just two years (it is practically the same). The sentinel imagery was not used for mapping detailed geomorphology because the imagery is very dark and of poor quality when zoomed to the level needed for such mapping. However major landscape changes can be detected. Large-scale landscape changes are therefore described in the text. Darkness is a large issue on sentinel imagery, even with manipulations to brightness and contrasts. For example, the quality is not good enough to see if flutes are still present.

Images from the Landsat (Landsat 7 and Landsat 8-9) program was reviewed in Earth Explorer (https://earthexplorer.usgs.gov/) on March 23rd, 2023 to detect when a new landform appeared in front of Bungebreen. Images from 2011-2015 was reviewed, however not all years had applicable data and darkness was an issue.

Google Earth Pro and Arctic DEM

Google Earth Pro was used to detect height differences and get a visual representation of the glaciers and forelands. The imagery was of various quality, for Belopol'skijbreen there was only good quality imagery during winter. Elevation exaggeration was set to 3 (the highest possible) to get an overview of the steepness and thickness of terminal moraines, medio moraines and mountain sides. Arctic DEM (https://www.pgc.umn.edu/data/arcticdem/) was used to look at the heights of the moraine complexes for reference, in addition to visual representation.

DTM and contour lines

A digital terrain model (DTM) from NPI was downloaded from https://data.npolar.no/dataset/dce53a47-c726-4845-85c3-a65b46fe2fea (Norwegian Polar Institute, 2014). This terrain model is from 2010 (Norwegian Polar Institute, 2014). A sub model with a 5 m resolution (model 13826) including Sørkapp Land was downloaded. Contour lines with 100 m intervals were made from the DTM by using the contour function in ArcGIS Pro. A shaded relief raster layer was made from the 5 m resolution DTM to use as base map for the geomorphological maps.

Aerial photos

On the website TopoSvalbard (toposvalbard.npolar.no), aerial photos taken in 1936 and 1938 are available from the NPI. Such photos have been used for reference and for a different view of the moraine complexes for all the glaciers in this study. However, the aerial photos of Belopol'skijbreen have an extensive cloud cover and has therefore not been used. These older aerial photos was in the end of 2022 made into a map service layer in TopoSvalbard based on the work done by Geyman et al. (2022). This map service was added in ArcGIS Pro and was used as reference to compare the current landforms with, not for any mapping.

Figure 12: Screenshot of the interface of an aerial photo from 1936 found at [TopoSvalbard](). The glacier to the left is Bungebreen and the glacier to the right is Vitkovskijbreen.

<u>NGU standard</u>

The mapping was conducted by following a standard from the Geological Survey of Norway (Norges Geologiske Undersøkelse [NGU]). This methodology will hereafter be referred to as the NGU standard. The NGU has among other responsibilities, the responsibility for making geomorphology maps on the mainland of Norway. Similar standard has previously been used on Svalbard, e.g. Allaart et al. (2021), Larsen et al. (2018) and Rubensdotter et al. (2015). A zip file with the feature classes was received from the IT department at NGU with instructions on how to add the files into ArcGIS Pro, on 20th September 2022, along with some explanations on how to use the layers. The NGU standard is based on instructions from The Norwegian Mapping Authority (Kartverket) and the NGU standard (SOSI) is explained here: https://kartverket.no/globalassets/geodataarbeid/standardisering/standarder/sosi-del-2-generell-objektkatalog/losmassegeologi-4.0-sosi-generell-objektkatalog.pdf (The Norwegian mapping authority, 2006).

The instructions (SOSI) includes descriptions of the different landforms and features, normally found within previously glaciated areas. However, not all features found in currently glaciated areas are described in the SOSI (or found in the NGU layers). If a feature found in the study area was not included in the NGU standard a new feature class was made, see Table 1. The table also includes other features that were created, not only those of geomorphology. The fluted moraine feature class was made following descriptions of such moraines by Larsen et al. (2006) at the glacier Elisebreen in North-west Spitsbergen, as the glacier has a very similar moraine system as Vitkovskijbreen and Belopol'skijbreen.

Table 1: Feature classes made in ArcGIS Pro as additions to the NGU standard.

Feature class name	Feature
Hummocky moraine	Polygon
Medial moraine	Polygon
Fluted moraine	Polygon
Ice	Polygon
Crevasse fill ridges	Line
Crevasses	Line
Glacier extent	Polygon and line
Lake	Polygon
River	Line
Snow	Polygon

Application of mapping

Mapping was conducted at 1:10 000, but to map detailed features zooming in was necessary. Zoom in was also used to be able to adjust the vertices of polygons and lines. Landforms with snow cover were generally not included in mapping. However, where it was possible to infer the extent of the landform they were included. Similar deduction had to be used for mapping of glacier extent. Below are some explanations for choices made for the most prominent features.

According to a report by NGU the feature class "terminal moraine" include lateral moraines (Christoffersen et al., 2021). Following the NGU standard each moraine complex is therefore here mapped as one polygon. The lateral moraines of Vitkovskijbreen and Belopol'skijbreen are in shadowed areas, which make them difficult to map and the accuracy is therefore lower in those areas. However, when the sentinel imagery has had good enough quality, features such as lines on the eastern lateral moraine of Vitkovskijbreen have been mapped by using the 2020 imagery. Similarly, landforms covered by snow cannot easily be mapped accurately, they are therefore mostly not included in landform polygons, but in its own polygon (Table 1). The terminal moraine polygon can according to the SOSI sometimes be together with better sorted glaciofluvial sediments (The Norwegian mapping authority, 2006). Therefore the line between the terminal moraine and the connected glaciofluvial sediments are somewhat intertwined in certain places.

Moraine material that does not appear as hummocky moraine, fluted moraine or part of the terminal moraine has been mapped as the feature class called "unspecified moraine material", which refers to ground moraine (not specified in the NGU standard). There are other options in the NGU standard, but they are based on the thickness of the sediments and since there are few data available on the thickness of the sediments in the area, those layers could not be used in this study. However, limiting the use of this feature class was aimed since it is imprecise. Some studies have mapped hummocky moraines with lines in addition to a polygon. That has not been done here due to the map would become very cluttered, instead hummocky moraines are represented with a dotted polygon.

Sandurs and outwash plain have both been mapped as the feature class "glacial fluvial deposits" as the feature class is described in the NGU standard as deposits transported and deposited by glacial rivers (The Norwegian mapping authority, 2006). Flutes are mapped as lines. Because some flutes are quite interconnected, the most obvious ones are mapped when the prominent landscape form is fluted moraine. Some flutes go across water bodies and other features, sometimes it was possible to map them across such features. There was no suitable feature class for crevasse fill ridges, so such a feature class was created (Table 1). There is a line feature class in the NGU standard for terminal moraines (has no description). This feature class has been used to represent annual moraines which are distinct linear features and has been used on both lateral moraines and terminal moraine complexes.

Both active meltwater channels and relict meltwater channels (the most prominent ones) have been mapped. In the NGU standard there is no distinction between those two. It was not always easy to see if they are connected or not, therefore some are shorter than others. The NGU standard differentiates between the direction of meltwater channels (left or right), but those have not been used here as it was not easy to determine which direction the meltwater channels went. Meltwater channels from rivers that are not of glacial origin (e.g. beside Gåsbreen) have not been mapped.

For landslide material, a layer from the NGU standard named "landslide material, not classified according to thickness" has been used since the thickness of the material is unknown. There are specific types of landslides in the NGU standard. However, since the exact nature for the landslides in the study area are often unknown or have not been able to be detected on the imagery those cannot be used.

3.3 Glacial extent

The retreat and advance of the four glaciers were measured using the distance and area tool in ArcGIS Pro (Figure 13). The measurements were conducted on a sentinel imagery from 2020. All measurements were done between previous mapped glacial extent from the 2009 orthophoto from NPI and sentinel imagery from 2020 (see above). On the smaller glaciers, Vitkovskijbreen and Gåsbreen, four measurements were done, on each side of the glacier. As Bungebreen is larger and has both retreated and advanced, five measurements were done there. Considering the shape of Belopol'skijbreen, seven measurements were done there. An average was then calculated from the measurements.

Figure 13: Screenshot of the ArcGIS Pro interface with an example of distance measurements to calculate average retreat at Gåsbreen.

<u>Glacier outline</u>

Glacier outlines from 1936-1972, 1990 and 2001-2010 were downloaded from the NPI from https://geodata.npolar.no/arcgis/rest/services/Temadata/I_Isbreer_Overflatetyper_og_utstrekning_Svalbard/MapServer/21 (Norwegian Polar Institute, n.d.-a). The layer with glacier outline from 2001-2010 is used to show the extent of the glaciers in 2009, as it fits good with the 2009 orthophoto on the maps. However, since it is from several years there are some areas where the glacier extent does not exactly match with the glacier extent line from 2009, there are therefore some gaps within the glacier extent line from 2009.

3.4 Limitations and assumptions

Since the investigation is based on satellite images, orthophotos, aerial photos and DEMs it has only been possible to map the land surface. It cannot be disregarded that there may be other sediments underneath the sediments that are not seen from remote imagery. Therefore, this geomorphological investigation is restricted to the main sediment types on the surface. For example there may exist alluvial sediments around or beneath glaciofluvial sediments. As there is a lack of sedimentology records available, the depth of all sediments is mostly unknown. The mapping boundaries have been set within the extent of the main terminal moraine complex due to time limitations and for the mapping to be consistent. If one were to map outside of that boundary it would be difficult to map consistently when the glaciers are as different as they are, especially the topography surrounding the glaciers is quite different. Important areas outside the terminal moraine complexes are mentioned in the text.

As with any remote study there is likely to be some errors with the identification of landforms. This is a known and acceptable approach when ground truthing is not possible. This study has been cautious, and some features will be uncategorized so not to mistakenly map features. Additionally, some features are difficult to discern from one another, e.g. annual moraines which may lead to some features being mapped wrongly. Similarly, in areas where there are many of the same features that nearly go into each other e.g. old crevasses or meltwater channels, not all have been mapped because then the map would become overcrowded with features. Some feature classes are size-dependent, e.g. kettle holes (small or large). As there is no explanation in the NGU standard on the size of each category, this becomes a subjective matter according to the mapper. In this study, one has aimed for consistency but that may not always have accomplished. As much of the investigated forelands are recently deglaciated there is still water in most of the kettle holes. When it has been difficult to see the difference between shadows and kettle holes, kettle holes have not been mapped as that could lead to errors. In the orthophoto, darker areas may appear flatter than they actually are, and brighter areas may appear steeper than they actually are. A similar effect makes it difficult to differentiate bedrock with e.g. brighter sediments and large blocks. On the 2009 orthophoto from NPI it is difficult to discern between landslides scarps and trimlines. Here Google Earth Pro has been used to determine which they are. Furthermore it is quite difficult to differentiate between the landslide material and hummocky moraine as they look quite similar on aerial photos.

No fieldwork was conducted during the work for this thesis. This has been both favourable and disadvantageous. An advantage is the opportunity to research a larger number of glaciers than what would be possible if one were to conduct fieldwork in the limited time a thesis has available. The possibility of studying several glaciers at the same time is great for a first look. Further, this type of study can be useful for others that will later conduct research in the same area. If so, they can compare their findings with this study and possibly confirm or rebut this study’s findings. A weakness of not conducting fieldwork is that the uncertainties become larger, when one cannot study the build-up of the sediments. The best approach is of course to use both remote investigations and fieldwork as presented by Chandler et al. (2018). However, when one does not have the opportunity to do so that does not mean the work is not valuable.

4 Results

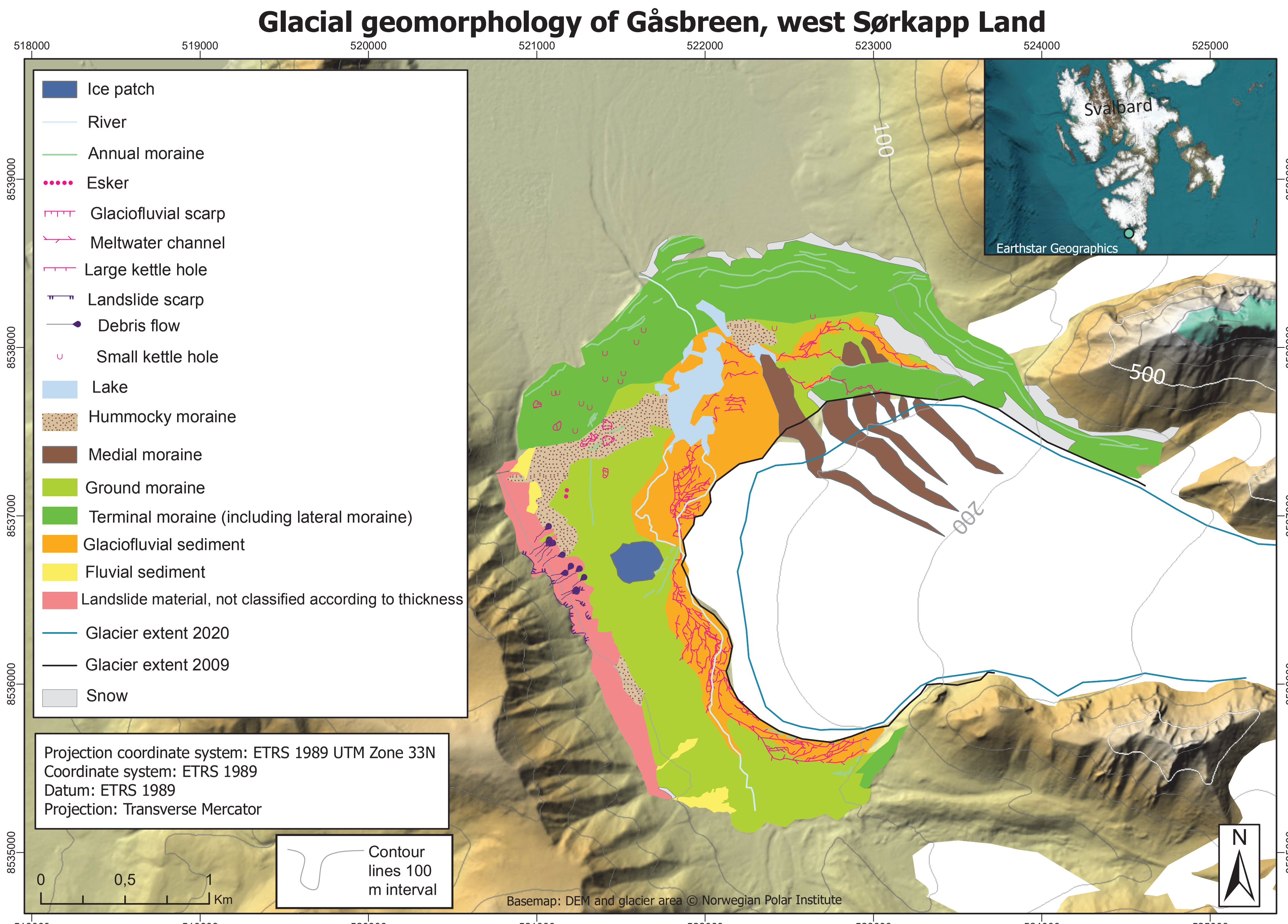
The following chapter includes geomorphological maps for the forelands of Gåsbreen, Bungebreen, Vitkovskijbreen and Belopol'skijbreen and includes descriptions of selected landforms. This chapter demonstrates that objective 6 is achieved.

4.1 Gåsbreen

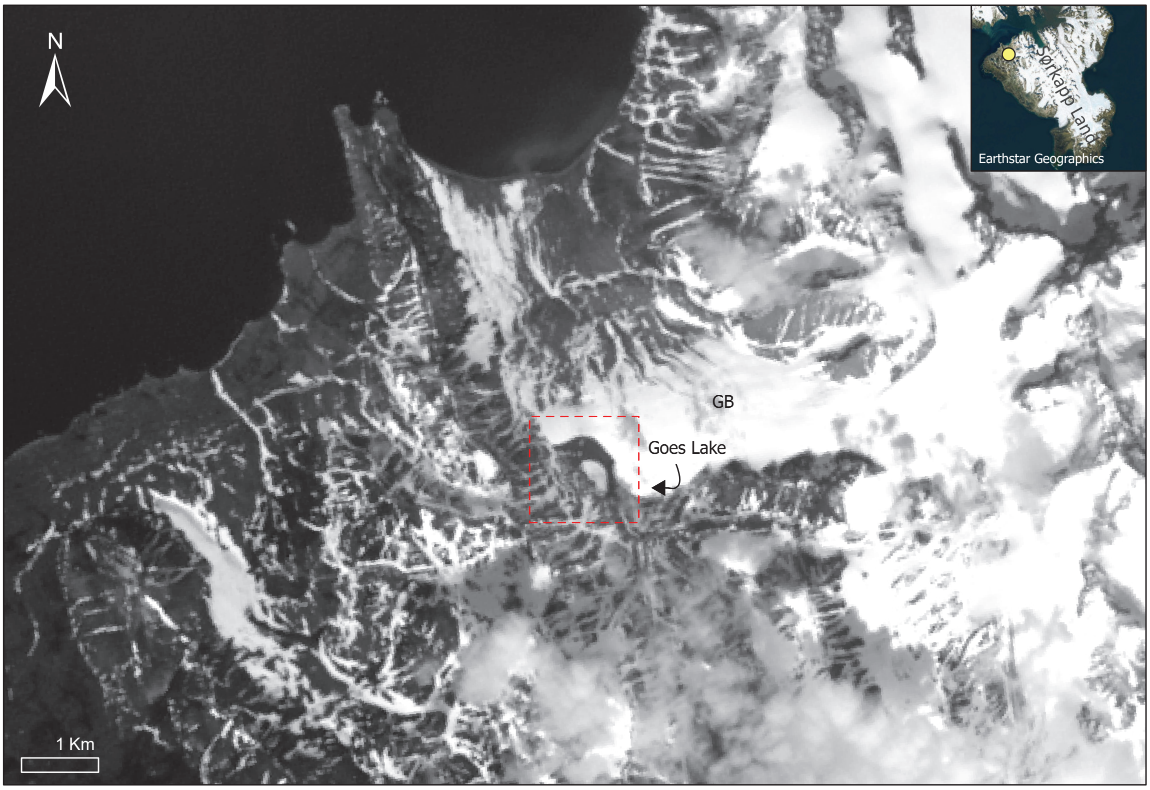
The following descriptions resulted in a geomorphology map of the foreland of Gåsbreen (Map 1).

Gåsbreen is the most western valley glacier on Sørkapp Land. It is located between Silesiafjellet and Midifjellet at 76.9°N, 15.9°E (Figure 11). The glacier is confined by a mountain ridge, Wurmbrandegga, to the west. The length of the glacier is ca. 6.06 km. The glacier has retreated ca. 174.5 m from 2009 to 2020. Gåsbreen has considerable debris cover, compared to the other glaciers in the study area. The debris consists of a coarse clastic ablation moraine (Zwoliński et al., 2013). Since the cover is quite extensive it was difficult to determine the exact 2020 glacier extent. In the 2020 imagery there are some changes compared to the 2009 orthophoto. Namely, the meltwater system has changed routes and the medial moraines by the glacial front are more pronounced (due to thinning of the glacier).

The 1936 aerial photos available on TopoSvalbard (Chapter 3.2) does not have clear views of Gåsbreen because they are either taken from outside of the coast or behind the mountains next to Gåsbreen. However, Gåsbreen can be seen on the pictures taken from the coast, where the glacier front appears to be very close to its terminal moraine. Dudek et al. (Submitted) mapped Gåsbreen to reach the nearby mountain Wurmbrandegga in 1938. As stated in Chapter 2.4 there has been an ice-dammed lake near Gåsbreen. In 2002 some parts of the glacier was still reaching Wurmbrandegga and dammed up Göes Lake (Figure 14). The lake has been observed from 1985 (Dudek et al., Submitted), before it disappeared at some point before 2005 (Ziaja, 2016). However, on the orthophoto from 2009 and the satellite imagery from 2022, there has not been found plausible evidence of glaciofluvial sediments in the area the lake used to be.



Map 1: Glacial geomorphology map over the foreland of Gåsbreen



Basemap: Landsat 7 ETM © EarthExplorer

Figure 14: View of Gåsbreen (GB) and Göes Lake on a satellite image from 2002. The lobe adjoining the glacier to the nearby mountain range Wurmbrandegga can be seen directly above the glacial-dammed lake.

<u>Terminal moraine complex</u>

The terminal and lateral moraines in front of Gåsbreen are ice cored (Ostafin et al., 2016; Zwoliński et al., 2013) (Figure 15 B and C). There are evidence of annual moraines along the terminal and lateral moraines (Figure 15B). Annual moraines represent stages in the glacier recession where the glacier had a stand-still. The terminal moraine complex consists of a terminal moraine and two lateral moraines, one north of the glacier and the other south of the glacier (Figure 15C). The lateral moraine to the North starts below Silesiafjellet and reaches a height up to 60 m (Zwoliński et al., 2013). The lateral moraine to the south below Wurmbrandegga is greatly degraded, except for close to Midifjellet. The lateral moraine to the south falls under shadow in the orthophoto by NPI which made it more difficult to map (Figure 15C). In front of the glacier there is a minor end moraine mapped following Dudek et al. (Submitted) (Figure 15D). There are some kettle holes present on the west side of the complex (Figure 15A). There are two small moraines of the terminal moraine extending outside of the complex, these have been mapped as terminal moraines following Dudek et al. (Submitted). There has not been found evidence from old crevasses or crevasse fill ridges on the lateral moraines. The terminal moraine complex has hummocky characteristics some places, but these have not been mapped as the main landform is terminal moraine. Additionally, there are hummocky moraine in three places in the foreland, such as a large area northwest of Gåsbreen near Wurmbrandegga (Figure 15A). Furthermore, a large portion of the foreland is made up by ground moraine.

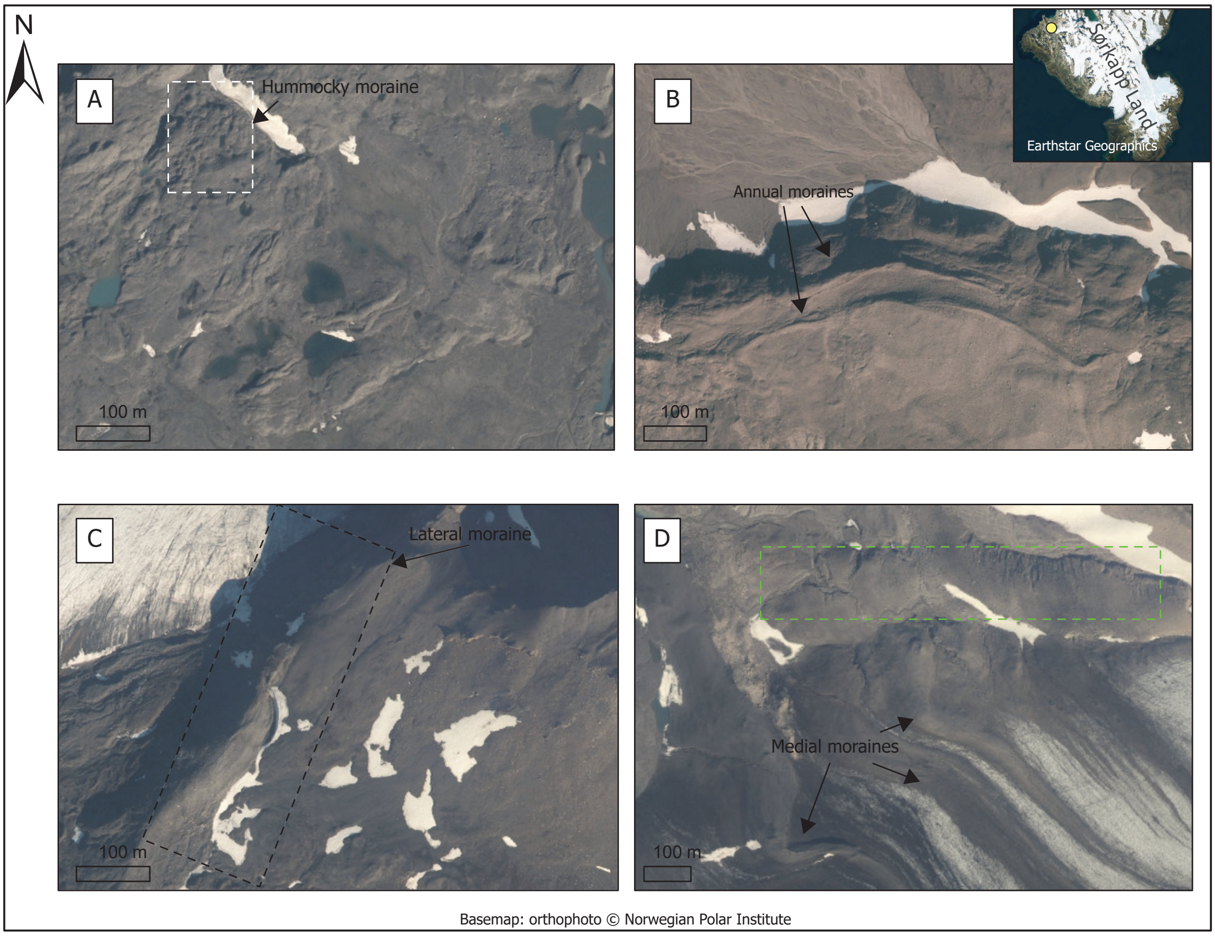


Figure 15: Landforms on the foreland of Gåsbreen. A: Kettle holes and hummocky moraine (white box). B: Annual moraines on the terminal moraine. C: The southern lateral moraine. D: Medial moraines at the end of the glacier. The green box indicates an ice-cored annual moraine.

<u>Medial moraines</u>

There are distinct medial moraines close to the terminus that continue on to the glacier (Figure 15D and Figure 16). Two smaller medial moraines continue over the small terminal moraine near the glacier front (Figure 15D and Figure 16). These two small medial moraines do not appear to continue on to the glacier. The biggest and middle medial moraines were likely ice-cored because in the imagery from 2020 they appear to have lowered.

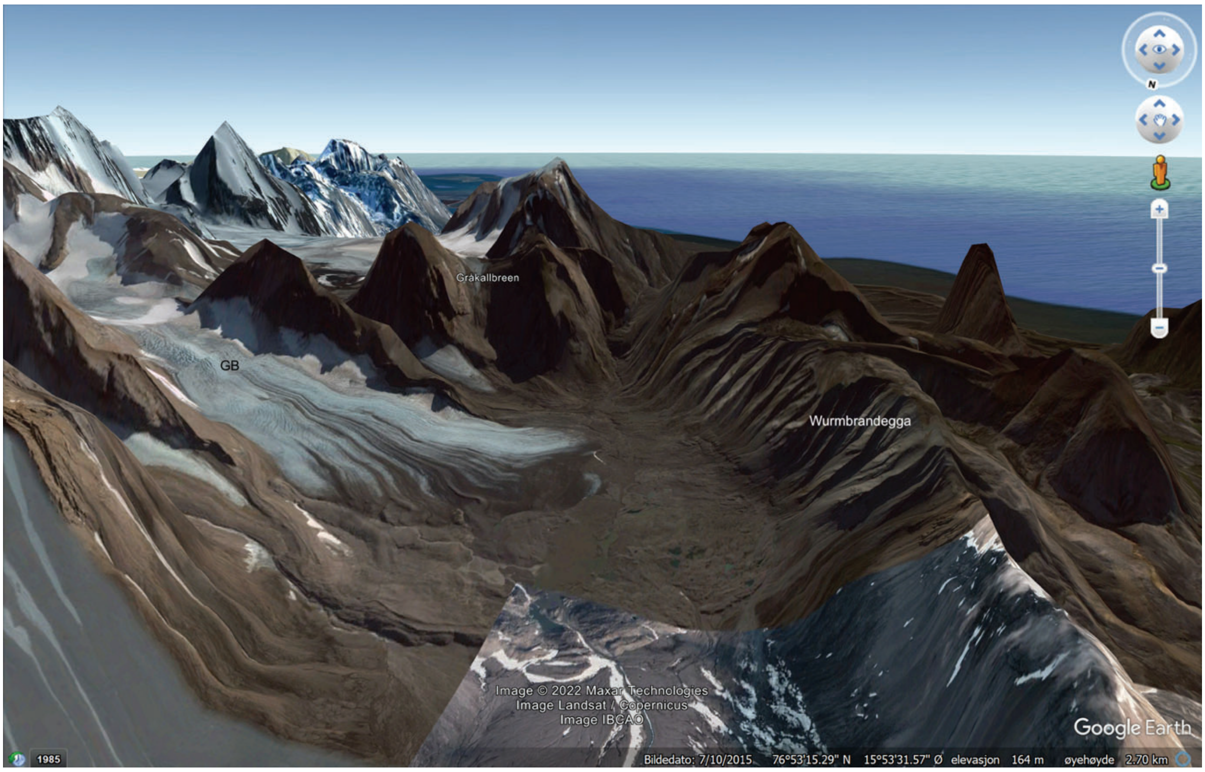


Figure 16: Imagery of the foreland of Gåsbreen (GB) from Google Earth Pro from October 2015. The medial moraines and debris cover on the glacier are clearly seen by the glacier front. Note that north is in the left-bottom of the image and the older imagery in the bottom of the imagery. Exaggeration level: 3.

<u>Sediments near Wurmbrandegga</u>

On the mountainside of Wurmbrandegga there are several landslide scarps, debris flows and sediments of landslide material (talus fans) (Figure 17). Debris flows and talus fans are common in recently deglaciated areas (Ziaja, 2016). The debris flows on the mountain side can be difficult to map since the imagery is flattened. Furthermore, the slopes appear to be affected by other processes, such as snow avalanches and fluvial processes (Figure 17C). Some of the older debris flows are challenging to map as newer debris flows may have overrun them (Figure 17A). The hummocky moraines surrounding the slopes also make it problematic to map the debris flows. There is a possibility that the landslides scarps actually are trimlines from when the glacier was directly on the mountain slope (Figure 17B). Near the last slope of Wurmbrandegga close to the terminal moraine there are fluvial sediments, mapped as such because of the lack of glaciers in the catchment area (Figure 17C). Additional fluvial sediments are on the other end of the ridge. There is a patch of remnant ice between Wurmbrandegga and the glacier on the western side, following the mapping of Dudek et al. (Submitted) (Figure 17D). Next to the ice remnant there are four annual moraines. These were mapped as eskers in Dudek et al. (Submitted). The ice remnant appears to have disappeared in the sentinel imagery from 2022. Between the glacier and the landslide material near Wurmbrandegga, there are a large cover of ground moraine.

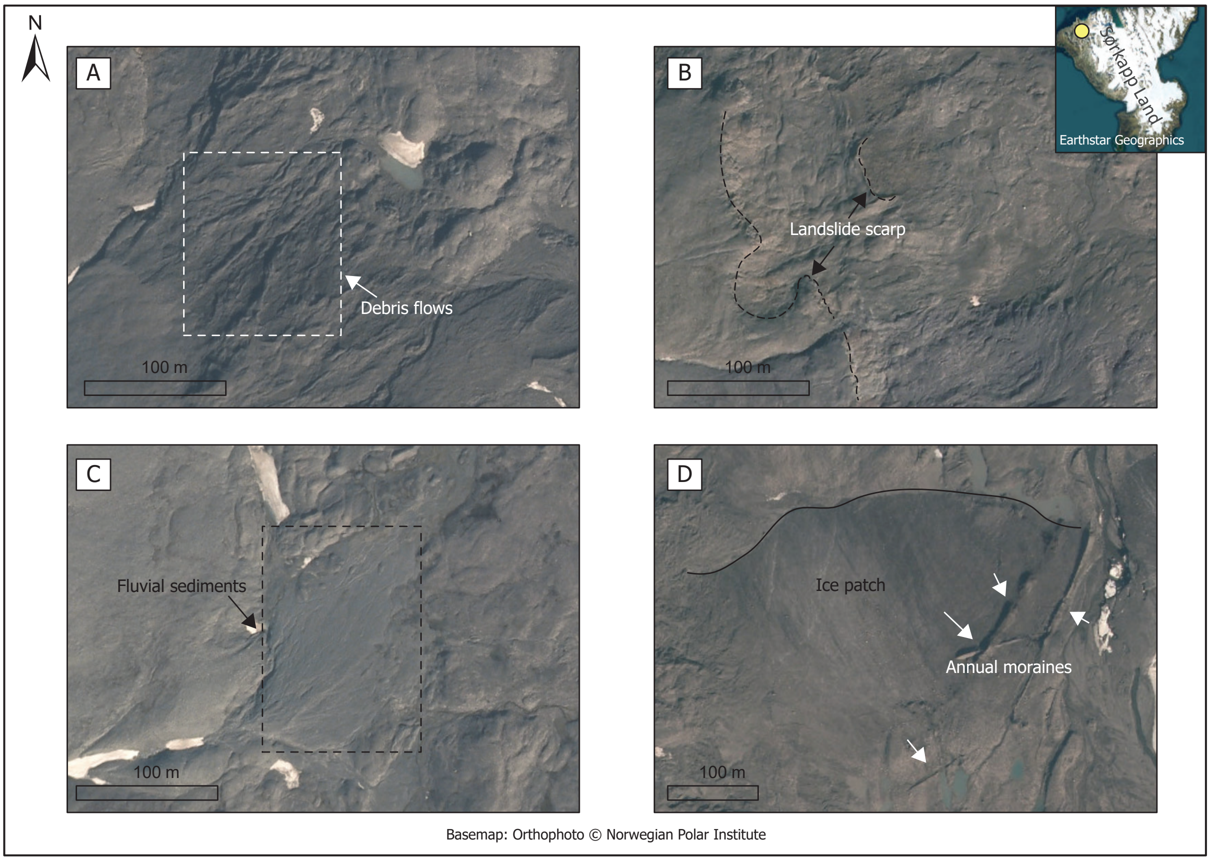


Figure 17: Landforms between Gåsbreen and the mountain ridge Wurmbrandegga. A: Debris flows indicated by white box. Hummocky moraines can be seen to the right of the white box. B: The left black dashed line indicates trimline or landslide scarp. Small black dashed line indicates landslide scarp. C: Fluvial sediments below Wurmbrandegga indicated by black box. D: Ice patch (inside black line) with annual moraines across it (indicated with white arrows).

<u>Glaciofluvial sediments</u>

A considerable amount of glaciofluvial sediments are found along the edge of the glacier, particularly in the southern area (Figure 18A). Much of the glaciofluvial sediments are likely from meltwater of Gåsbreen as well as from the nearby Goësbreen. Furthermore, there are glaciofluvial sediments near the present lake, in addition to a small area on the east side of the lake. Meltwater channels and rivers can create cuts in sediments, here referred to as glaciofluvial scarps (Figure 18A). Most of the glaciofluvial scarps are found near the glacial river on the southern side of the glacier where it cuts into glaciofluvial sediments. There are both new and older meltwater channels present (Figure 18B). Relict meltwater channels appear as darker coloured on the imagery, and new and active meltwater channels appear in brighter colours. However, it is important to note that meltwater channels are one of the most active and changing elements in glacial forelands.

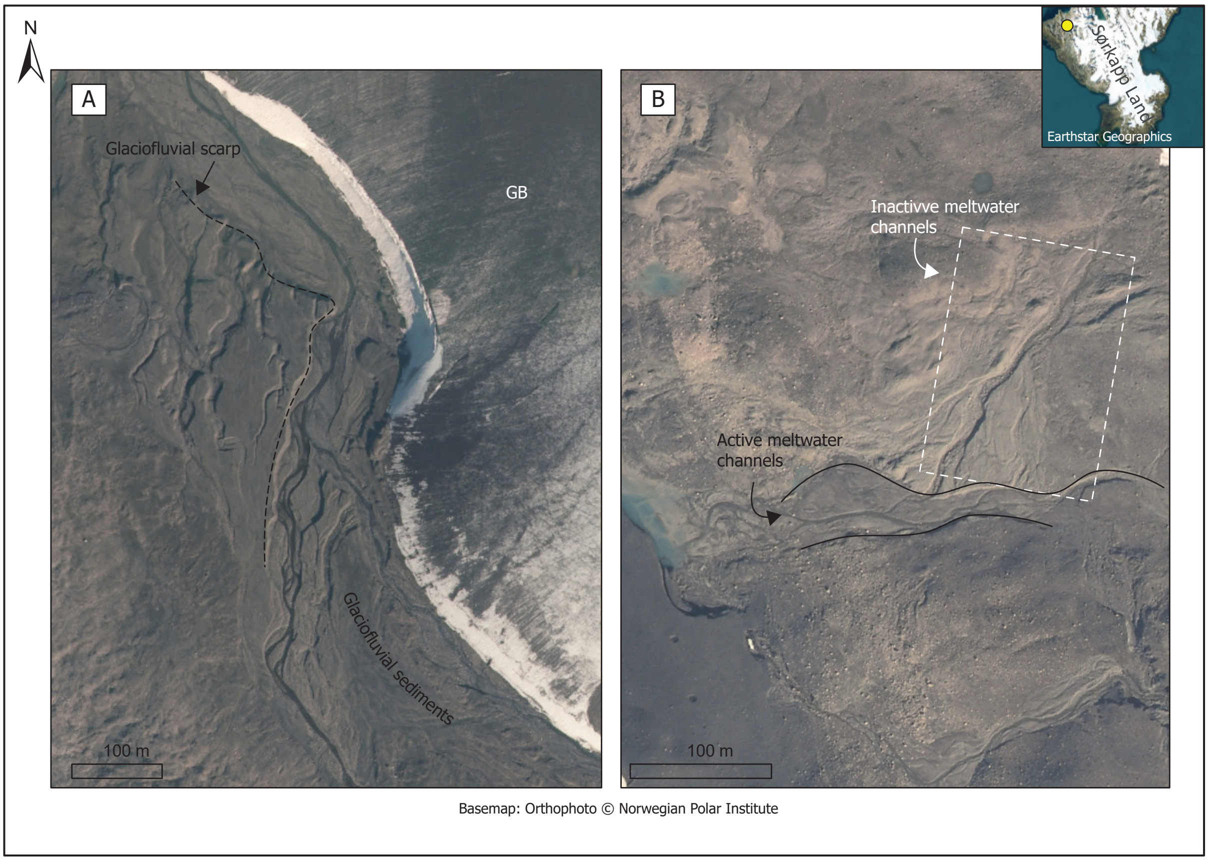
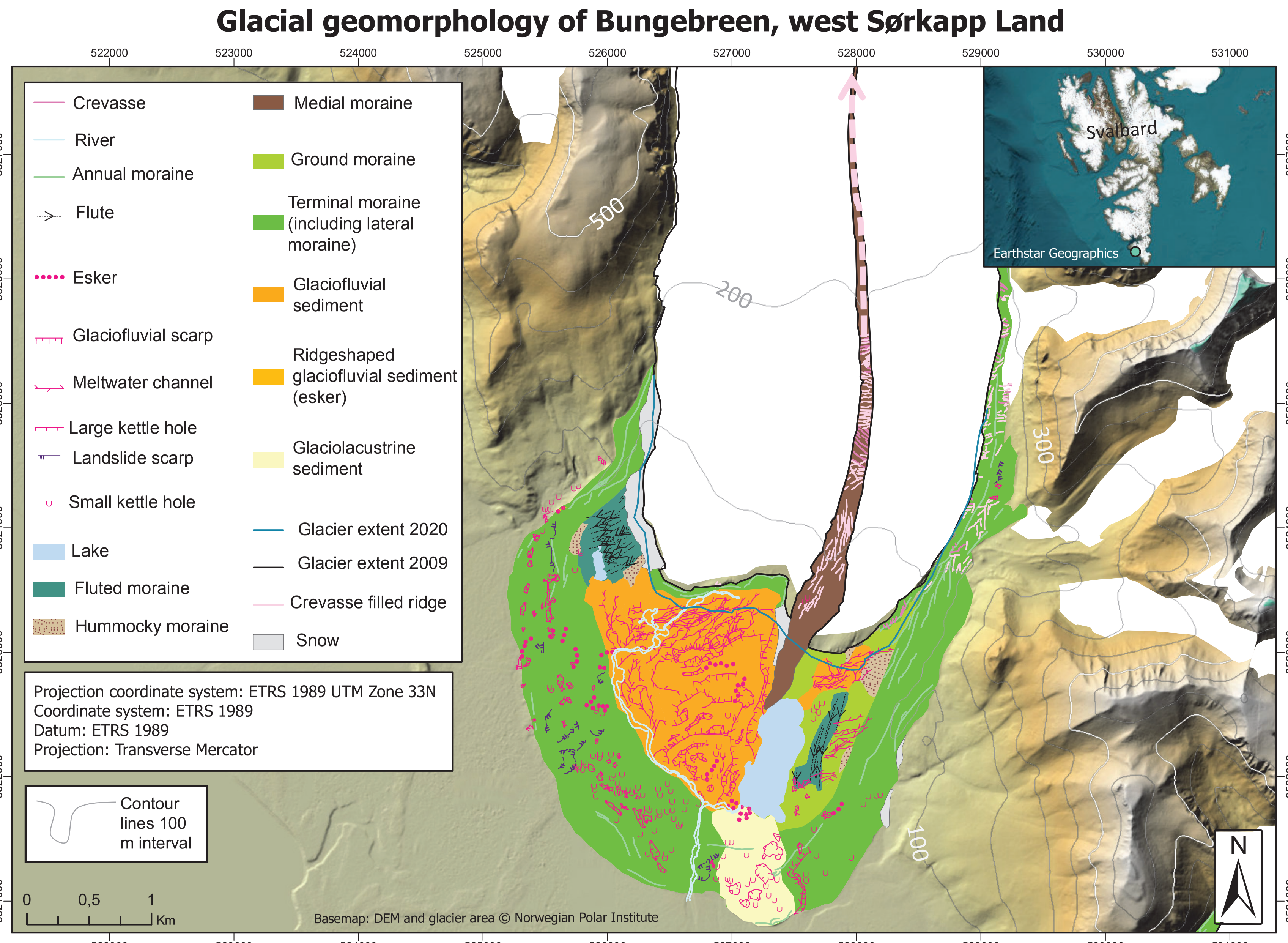


Figure 18: Glaciofluvial sediments near Gåsbreen (GB). A: Glaciofluvial sediments and scarps south of Gåsbreen. B: Inactive (relict) and active (newer) meltwater channels north of Gåsbreen. White box indicates relict meltwater channels. Below the box more active meltwater channels are seen (within the two black lines).

4.2 Bungebreen

The following descriptions resulted in a geomorphology map of the foreland of Bungebreen seen in **Feil! Fant ikke referansekilden.**.



Map 2: Glacial geomorphology map over the foreland of Bungebreen. Pink arrow indicates that crevasses and crevasse filled ridges continue upwards on the medial moraine as it extends further upwards

Bungebreen is a valley glacier of ca. 7.28 km length that is located on the westside of Sørkapp Land at 76.8°N, 16.1°E (Figure 11), between Stupryggen and Kvitgubben mountain massifs. It has a medial moraine that extends the length of the glacier to ca. 600 m below the glacier front. The medial moraine is surrounded by extensive sandur fans and has glacial lakes on both sides (Zwoliński et al., 2013). The glacier has advanced ca. 109 m between 2009 and 2020. There are some changes in the landscape between the 2009 orthophoto and the 2020 imagery. In the 2020 imagery, left of the medial moraine below the glacier front (76.789°N, 16.071°E), there appears to be several annual moraines (Figure 19B). These annual moraines are not present in the 2009 imagery (Figure 19A). Moreover, the medial moraine appears to be more degraded in the 2020 imagery compared to the 2009 orthophoto (Figure 19). In addition to this there is an ice-dammed lake by the top of the glacier, that appears to be larger in the 2020 imagery.

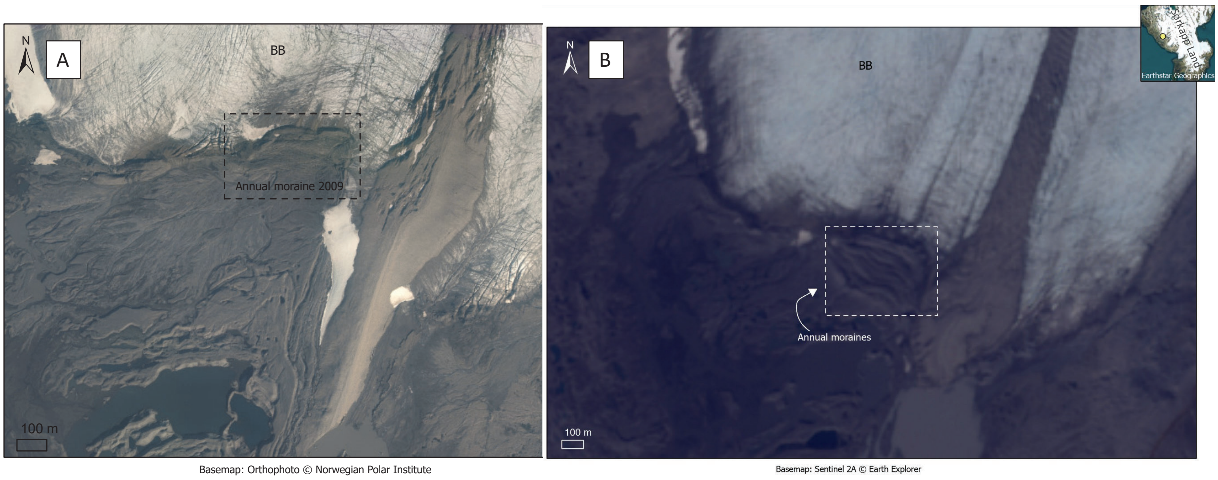


Figure 19: The emergence of annual moraines in front of Bungebreen (BB) after 2009. A: The black box indicates the area where the annual moraines in 2009. Note the form of the medial moraine to the left of the black box. Basemap: Norwegian Polar Institute (n.d.-b). B: The white box indicates the annual moraines in front of Bungebreen. Note the degradation of the medial moraine to the right of the white box. Basemap: Sentinel 2A downloaded from Earth Explorer.

From the aerial photos of Bungebreen taken in 1936 (Chapter 3.2) it is evident that the glacier had already then retreated from its terminal moraine extent (Figure 20). Furthermore, the area between the terminal moraine complex and the glacier has increased considerably compared to the area described in Klysz and Lindner (1982), due to the extensive retreat the glacier has experienced since the 1980s. The terminal moraine is believed to show the LIA extent (Figure 5) (Martín-Moreno et al., 2017). Directly below the terminal complex to the east there is a sandur. To the west there is a sandur that goes along an unknown feature, this is not mapped due to being outside of mapping limits (Chapter 3.4). The feature has the name Kvartsittrabben (kvartsitt meaning quartzite) leading one to believe it is made up of quartzite, meaning it is bedrock. In Figure 4 Kvartsittrabben is marked as quartzite (Atakan et al., 2015).

Figure 20: Aerial photo of Bungebreen from 1936 taken from a northeast direction. The glacier has retreated from the terminal moraine. Note the extent of and the absence of crevasses on the medial moraine. Image credit: Norwegian Polar Institute (from TopoSvalbard).

Terminal moraine complex

The terminal moraine complex consists of an end moraine and lateral moraines on each side of the glacier. Some parts of the terminal moraine (not the lateral moraines) appear hummocky but has not been mapped as hummocky moraine due to the whole complex being mapped as terminal moraine. The terminal moraine complex is degraded, especially the western part, but previously it has been defined as ice-cored (Zwoliński et al., 2013) (Figure 21). There are landslide scarps, typically in the western part of the complex (Figure 24C). These landslide scarps are due to landslides following degradation of the moraine. The complex includes many kettle holes, both large and small and most have irregular shapes. The kettle holes shows that there have been a lot of meltwater in this area. There are possible traces of a larger annual moraine within the current terminal moraine complex and was likely deposited around 1936

(Figure 22). Since both the aerial photos of Bungebreen (Figure 20) and the orthophoto made by the 1936 aerial photos (Geyman et al., 2022) shows the glacier at approximately the same location as the annual moraine.

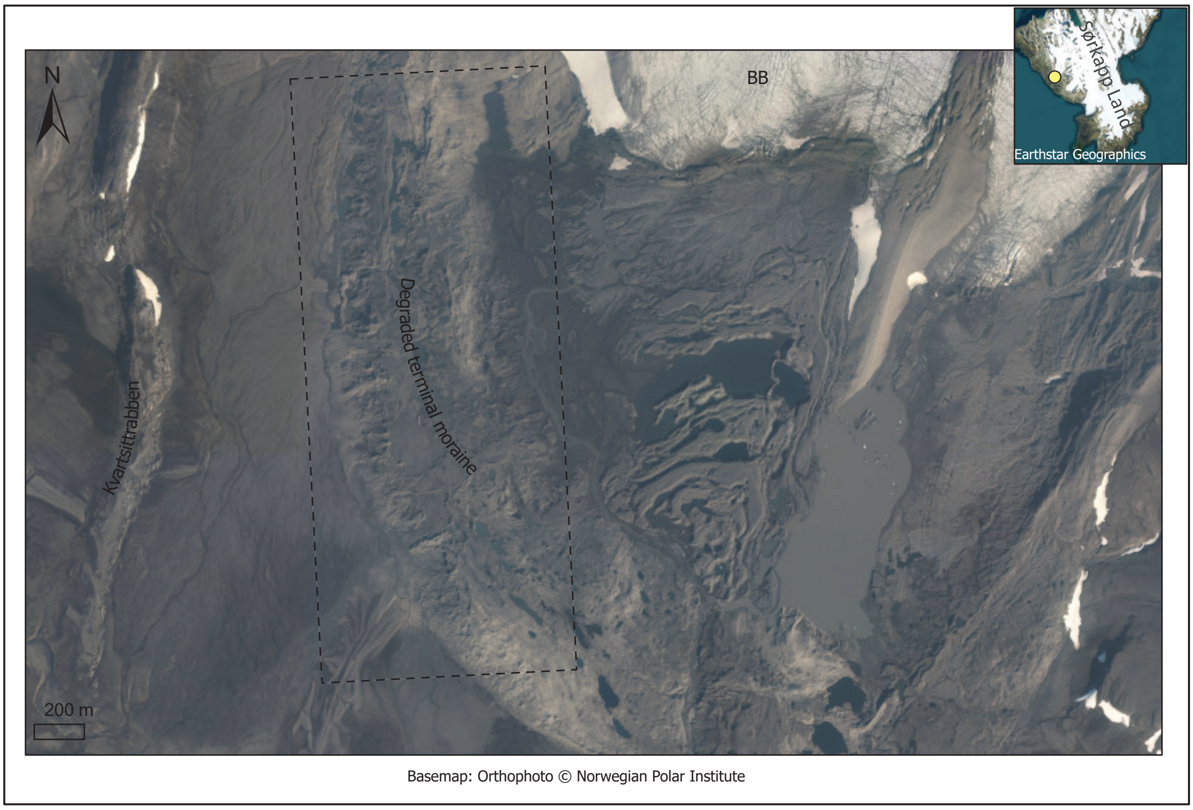


Figure 21: The foreland of Bungebreen (BB). The black box indicates the degraded western part of the terminal moraine.

The medial moraine has a rather different shape in the 2020 imagery compared to the 2009 orthophoto (Figure 19). The lower part of the medial moraine has been more exposed and appears more degraded in the 2020 imagery. On the glacier the medial moraine seems to have shifted somewhat in some places. In the 2009 orthophoto the medial moraine ends 600 m below the glacier front, this shows a previous extent of the glacier front (Figure 19). There are possibly glaciolacustrine sediments in the middle of the terminal moraine complex. Because the sediments there are much lighter than the surrounding sediments of the terminal moraine it is likely they are made up by finer sediments such as one finds in glaciolacustrine sediments. The area of glaciolacustrine sediments is where the medial moraine is in the aerial photos from 1936 (Figure 20). In this area there are also several large kettle holes (Figure 22). There are hummocky moraines in a minor area east of the glacier and by the smallest (most western) lake in the foreland. There are some sediments that do not fit in in any of the moraine type categories, these have been classified as ground moraine following explanation in Chapter 3.2.

Figure 22: Part of the terminal moraine of Bungebreen. The black line indicates the extent of glaciolacustrine sediments. The white line indicates what is likely a larger annual moraine from ca. 1936. Black arrow glaciolacustrine sediments.

<u>Flutes and fluted moraine</u>

Flutes and fluted moraine are made when the glacier advances (Allaart et al., 2018). When the ice retreats they can get diminished or completely destroyed, however sometimes they are preserved. They are common at lowland glaciers in Svalbard (Allaart et al., 2018), such as Bungebreen. When they are exposed from beneath the ice other processes will start to affect them (and therefore they have low preservation potential). In the foreland of Bungebreen the fluted moraine type is found east near to the biggest lake and near the smallest lake to the west (Figure 23). The most prominent flutes are mapped as lines.

<u>Crevasses and crevasse filled ridges</u>

There are traces of crevasses in some areas near the glacier. However, most of the crevasses and crevasse filled ridges are found on the medial moraine and on the eastern lateral moraine (Figure 24D). The direction of the crevasses and the crevasse filled ridges varies between horizontal and vertical. Below on the medial moraine the most common is vertical, while further on the medial moraine most of the old crevasses and the crevasse filled ridges have horizontal direction. Crevasse filled ridges often occur in the same places as the old crevasses such as on the medial moraine and the east lateral moraine. Some of the crevasse filled ridges are quite long and broad while others are quite short and small. The crevasse filled ridges on the lateral moraine follows the same pattern.

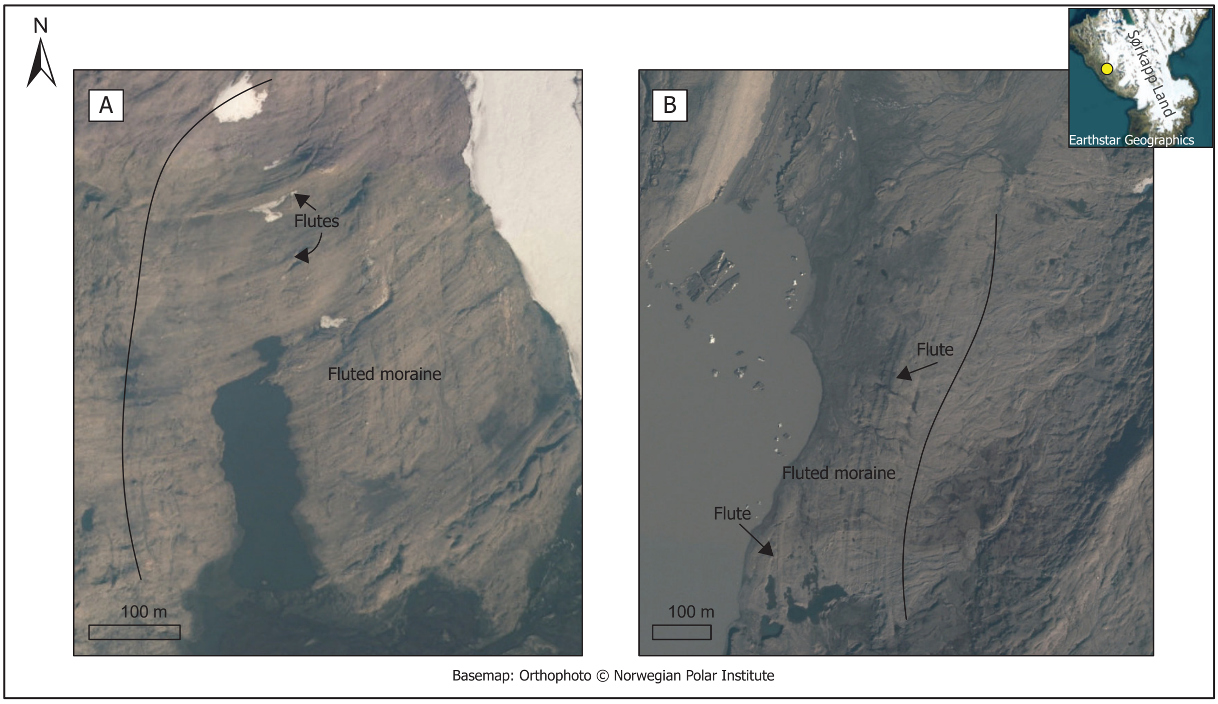


Figure 23: Fluted moraine in the foreland of Bungebreen. A: Flutes (black arrows) on fluted moraine on the western side of the glacier. B: Flutes on fluted moraine om the eastern side of the glacier. Note that these flutes appear more degraded than those on the western side.

<u>Eskers</u>

Eskers are found several places within the glaciofluvial sediments in the foreland of Bungebreen (Figure 24B). Some eskers in the area appears deformed. Some eskers are very short while others are quite long, and some are more undulating than others. Which made it hard to classify some of the eskers together with the deformation, may have led to mapping of too many eskers in this area. Some eskers are in the ice flow direction while others are not. Most of the mapped eskers are in the western area of the foreland by the glaciofluvial sediments.

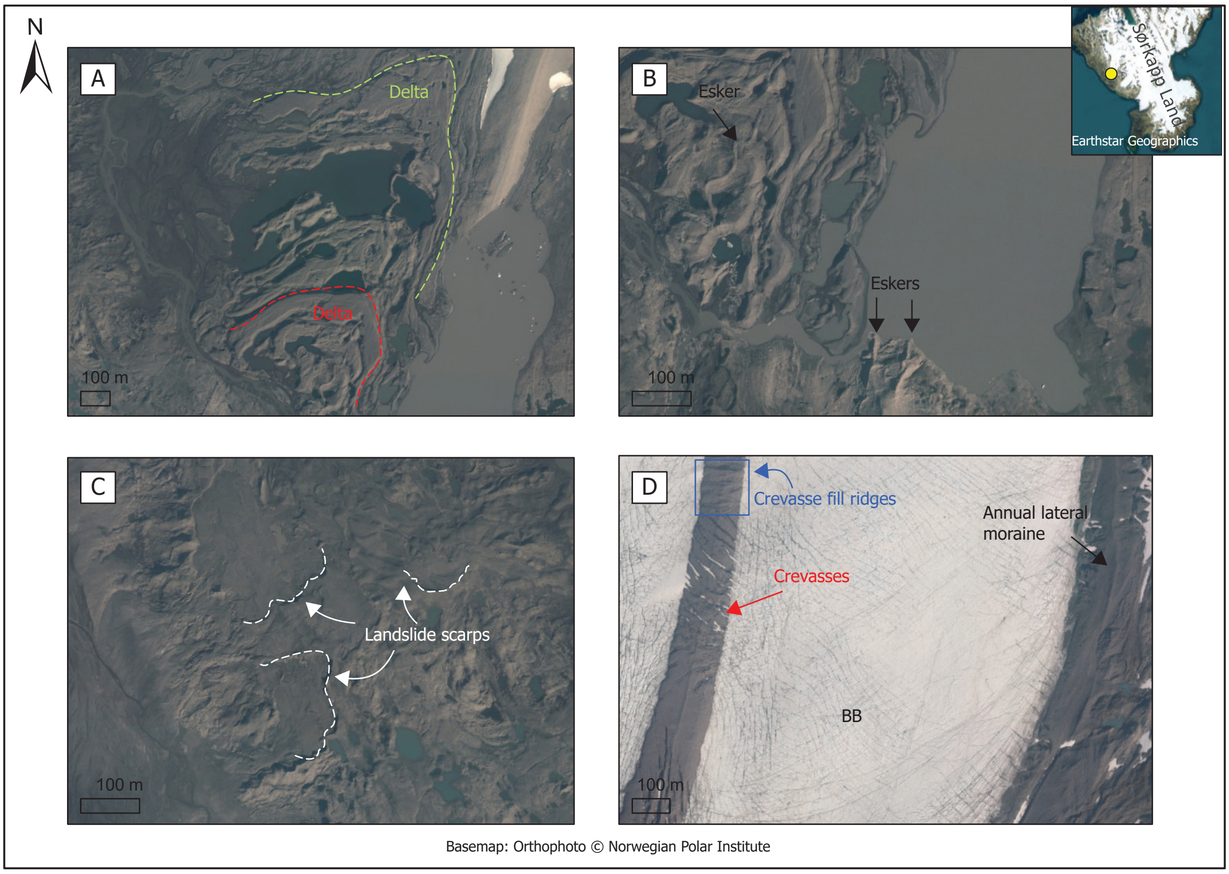


Figure 24: Landforms in the foreland of Bungebreen (BB). A: Possible locations of ice-contact deltas. B: Eskers indicated by black arrows. C: Landslide scarps indicated by white lines. D: Crevasses (red arrow), crevasse filled ridges (blue box) and annual moraines (lateral) indicated by black arrow.

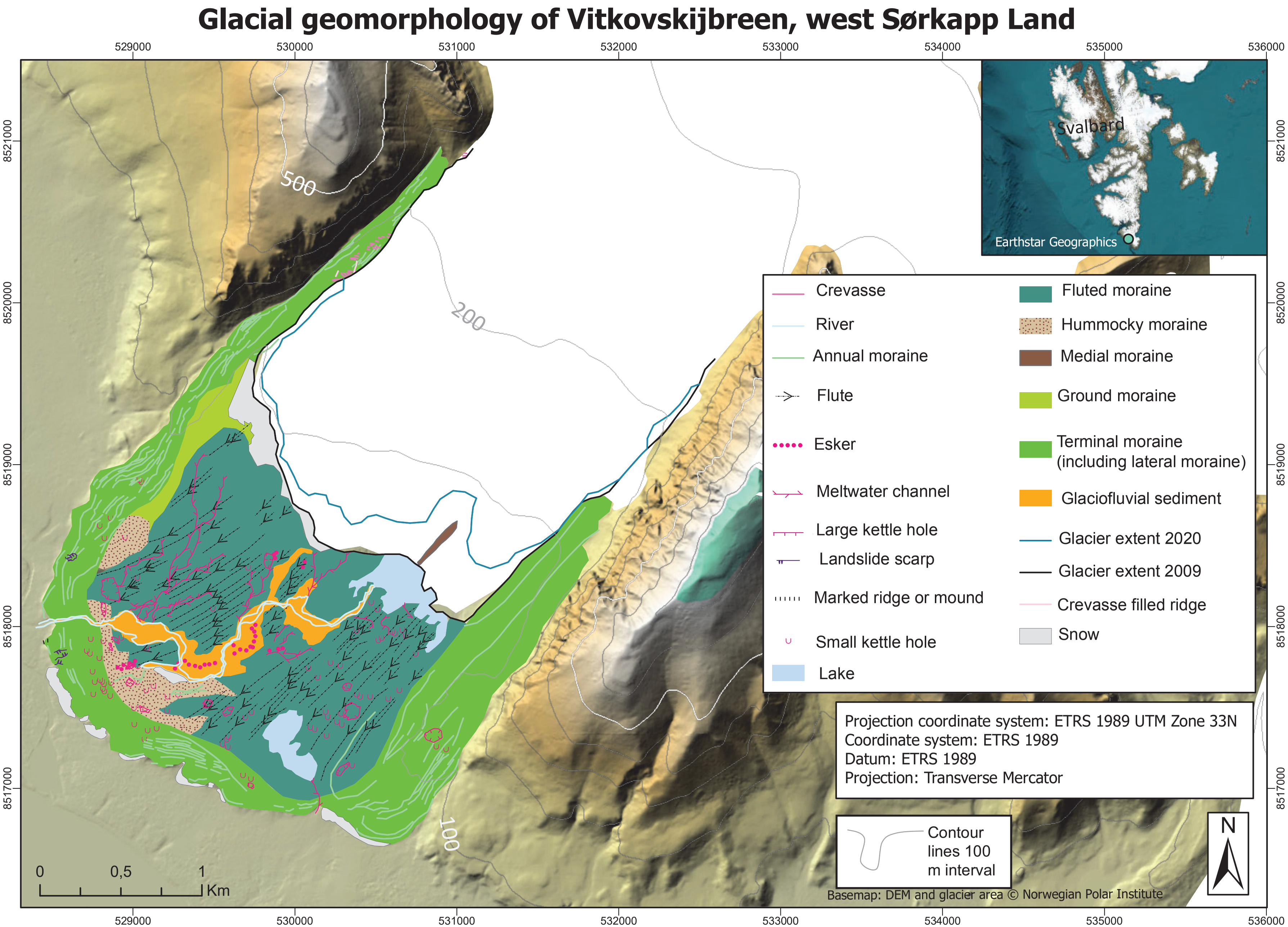
Glaciofluvial sediments

Meltwater from the glacier has left behind coarse grains (sand) in the form of an outwash plain in the foreland which is mapped as glaciofluvial sediments. The meltwater has gone in different directions at various times during the melting season and there are therefore many meltwater channels. Some appear to have dried up (lighter colour) while others appear to be active (darker colour). Since there are so many meltwater channels in different sizes and structures, every single channel has not been mapped (Chapter 3.4). There are some large kettle holes present within the glaciofluvial sediments.

There are possibly two previous ice-contact delta in the foreland (Figure 24A). Since the formation of the ice-contact delta, meltwater has cut into the it and made meltwater channels and lakes. The course of the meltwater channels has probably changed on a, if not seasonally basis, at least on a yearly basis. There are glaciofluvial scarps, cut by the glacial river, several places in the foreland, both nearby the glacial river and by old meltwater channels, and the presumed delta.

4.3 Vitkovskijbreen

The following descriptions resulted in a geomorphology map of the foreland of Vitkovskijbreen seen in Map 3.



Map 3: Glacial geomorphology map over the foreland of Vitkovskijbreen.

Vitkovskijbreen is a valley glacier located between the mountains Plogen and Hilmarfjellet at 76.7°N, 16.2°E (Figure 11). The foreland is dominated by an ice-cored terminal moraine complex with lateral moraines on both sides of the glacier (Zwoliński et al., 2013). The terminal moraine complex is made up by coarse-grained clastic sediments (Zwoliński et al., 2013). Vitkovskijbreen is ca. 5.64 km and retreaded ca. 169.8 m from 2009 to 2020. There are two lakes in the area between the glacier and the terminal moraine complex. The largest is near the glacier front, and the smallest is almost on the terminal moraine, near the eastern lateral moraine (Figure 26). In the 2020 imagery the lake in front of the snout is almost twice as big as in the 2009 orthophoto (Figure 25 and Figure 26). Furthermore, the western lateral moraine appears to have gotten degraded in the 2020 imagery, compared to the 2009 orthophoto (Figure 25 and Figure 26). Near the middle of the glacier front there is a small medial moraine where in the 2020 imagery the glacier has thinned and retreated around this area.

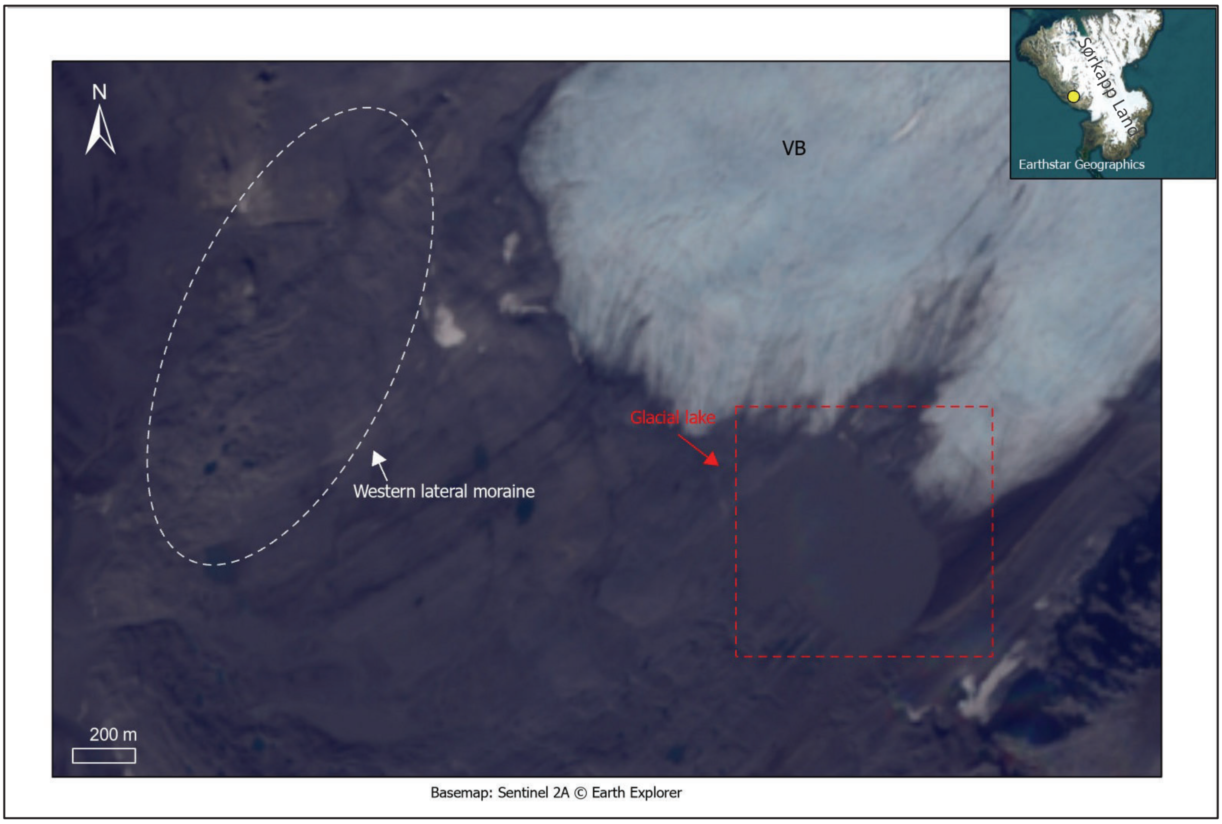


Figure 25: Part of the foreland of Vitkovskijbreen (VB) from a sentinel imagery from 2020. White circle indicates the western lateral moraine that has gotten degraded since the 2009 orthophoto from NPI. Red box indicates the glacial lake that has become larger since the 2009 orthophoto from NPI.

<u>Terminal moraine complex</u>

The terminal moraine complex includes a frontal moraine and lateral moraines on both sides of the glacier. The western lateral moraine is longer than the eastern lateral moraine. In contrast, the eastern lateral moraine is thicker and is quite broad and flat compared to the narrow west lateral moraine (Figure 26). Furthermore the eastern lateral moraine has a higher altitude than the frontal moraine. Evidence of previous crevasses can be found various places on the lateral moraines. However, much of the eastern lateral moraine is in shadow, and old crevasses could therefore not be mapped there.

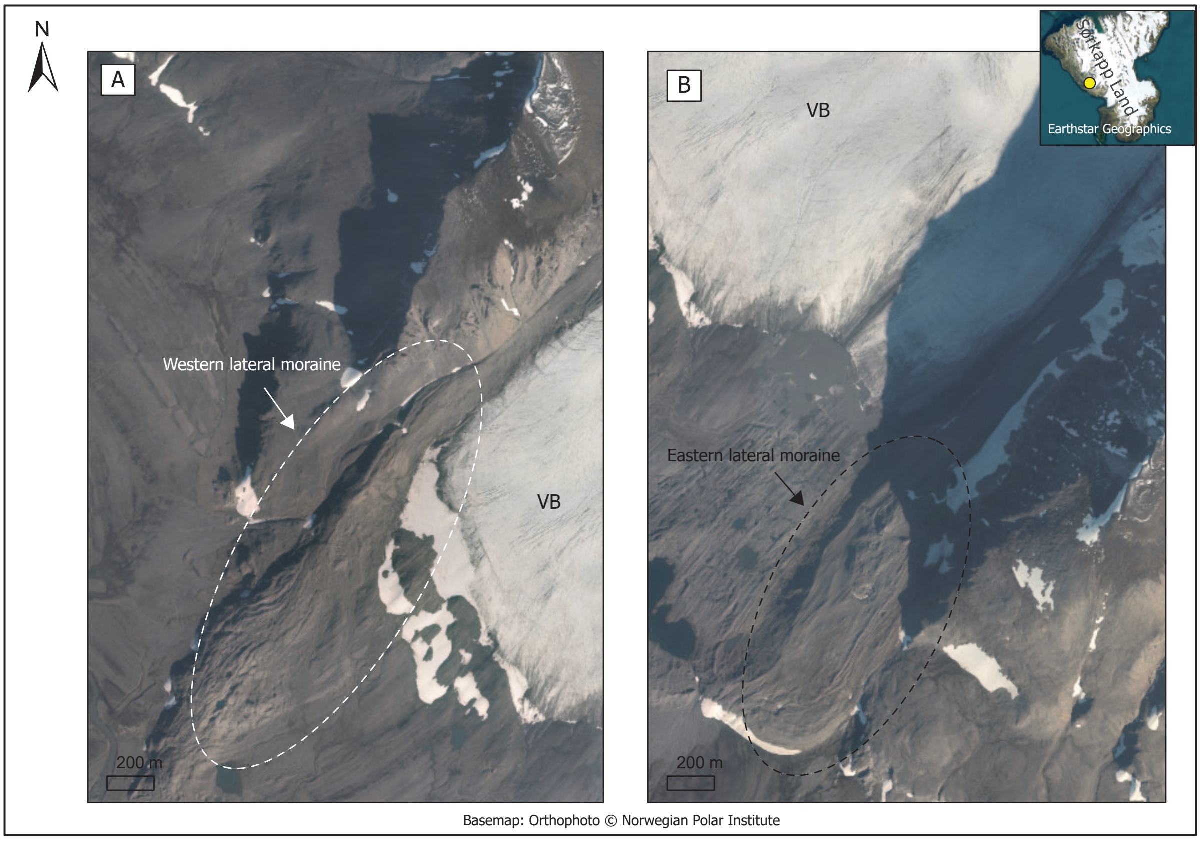


Figure 26: The lateral moraines of Vitkovskijbreen (VB). A: The western lateral moraine is indicated by white circle. Annual moraines appear as ridges. B: The eastern lateral moraine is indicated by black circle. Annual moraines are seen as ridges. Note the shadow on the eastern lateral moraine.

There is evidence of small and thin meltwater channels on the terminal moraine itself, where it is likely the ice margin was at a certain point in time (Figure 27). There are annual moraines present on both the terminal moraine and the lateral moraines (Figure 27 and Figure 29B). This terminal moraine complex is less degraded compared to that of Bungebreen.

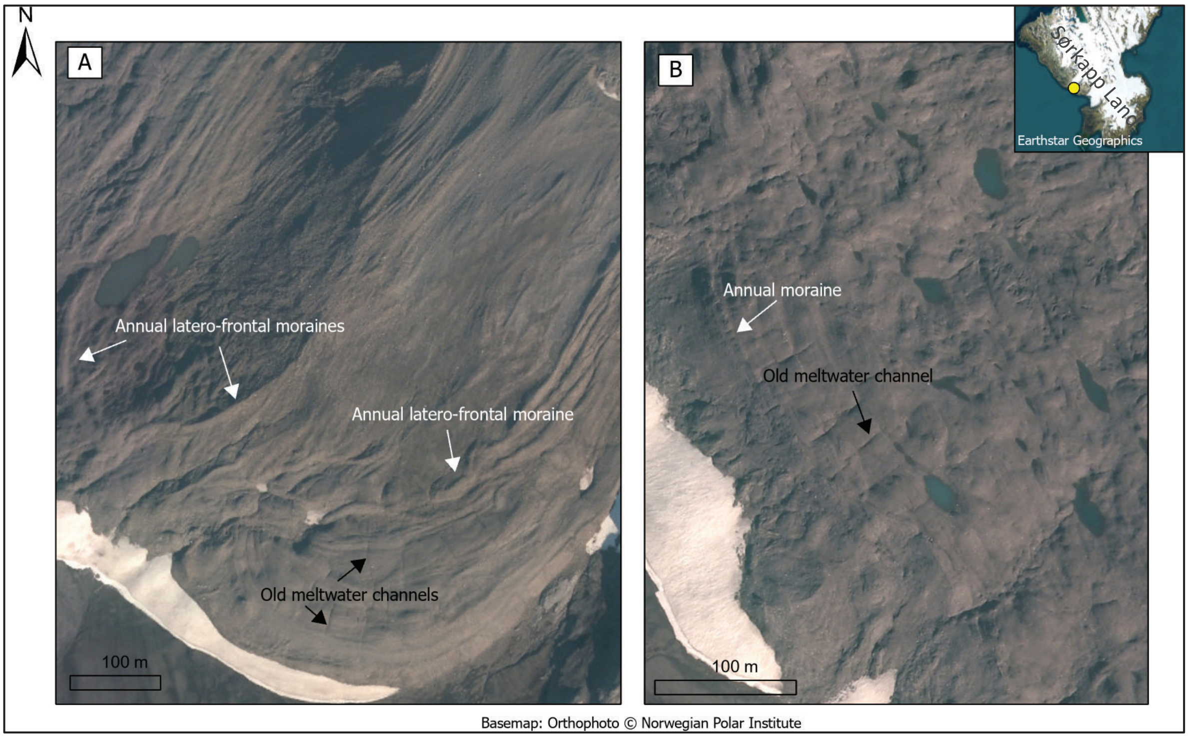


Figure 27: Landforms in the terminal moraine complex of Vitkovskijbreen. A: Examples of annual latero-frontal moraines (white arrows) and old meltwater channels (black arrows) on the eastern lateral moraine. B: Examples of annual moraines (white arrow) and old meltwater channels (black arrow) on the terminal moraine.

Flutes and fluted moraine

There is an abundance of flutes within the foreland of Vitkovskijbreen (Figure 28). Some flutes are skewed and disjointed. These have probably been reworked by either the retreating glacier or meltwater. According to Zwoliński et al. (2013) the foreland is made up by ground moraine. Since most of this area is mapped as fluted moraine, it indicates that the fluted moraine is made up by ground moraine (Zwoliński et al., 2013). There appears to be a distinct difference between the fluted moraine to the west and to the east of the foreland. The flutes on the west side appear to be more degraded (Figure 28).

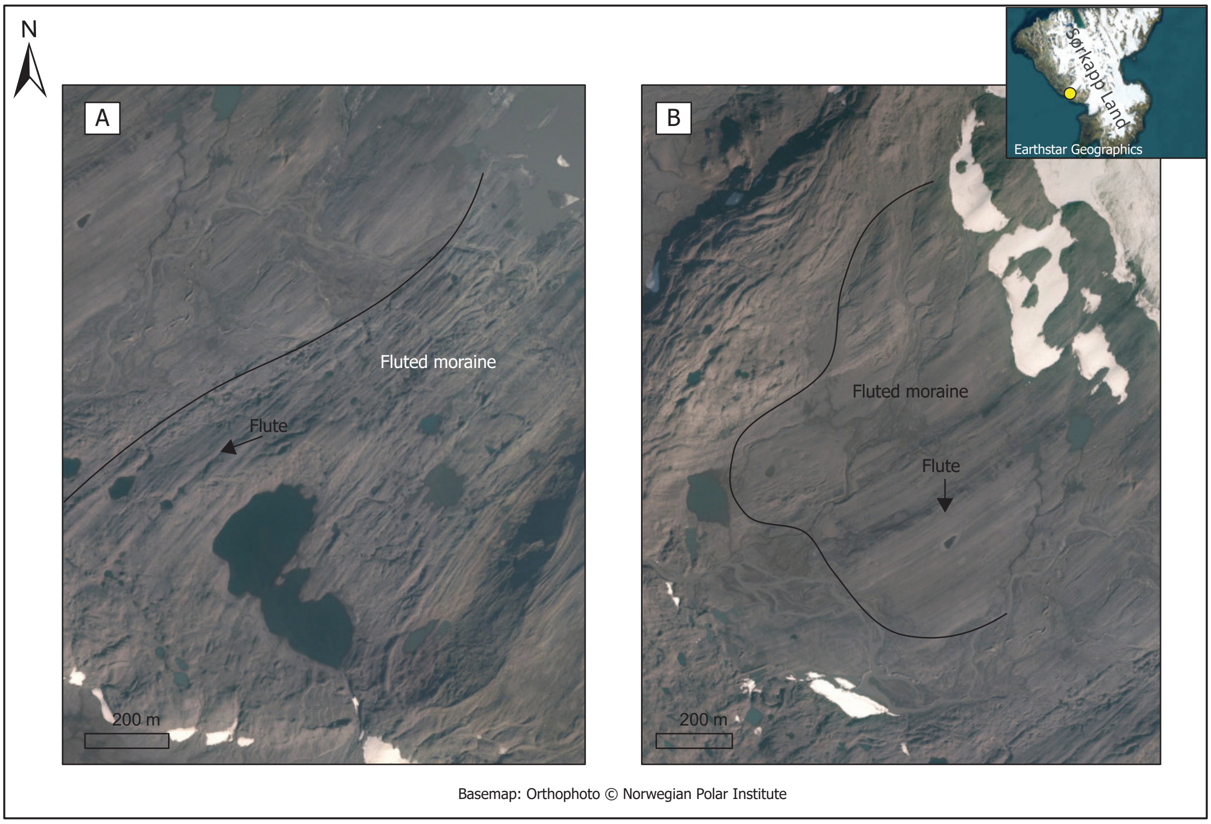


Figure 28: Fluted moraines in the foreland of Vitkovskijbreen. A: Fluted moraine west of the eastern lateral moraine (within the black line). An example of a flute is indicated with a black arrow. B: Fluted moraine east of the western moraine (within the black line). An example of a flute is indicated with a black arrow. Note the difference in height between the flutes in A and B. The flutes in B are degraded.

<u>Hummocky moraine</u>

There are two areas of hummocky moraine within the foreland. They are located directly within the terminal moraine complex. The area in the middle is the largest, while the area to the west is smaller. There are some small kettle holes found on the terminal moraine complex and in the areas with hummocky moraine. However, the largest kettle hole is one that has dried, on the eastern lateral moraine (Figure 29C).

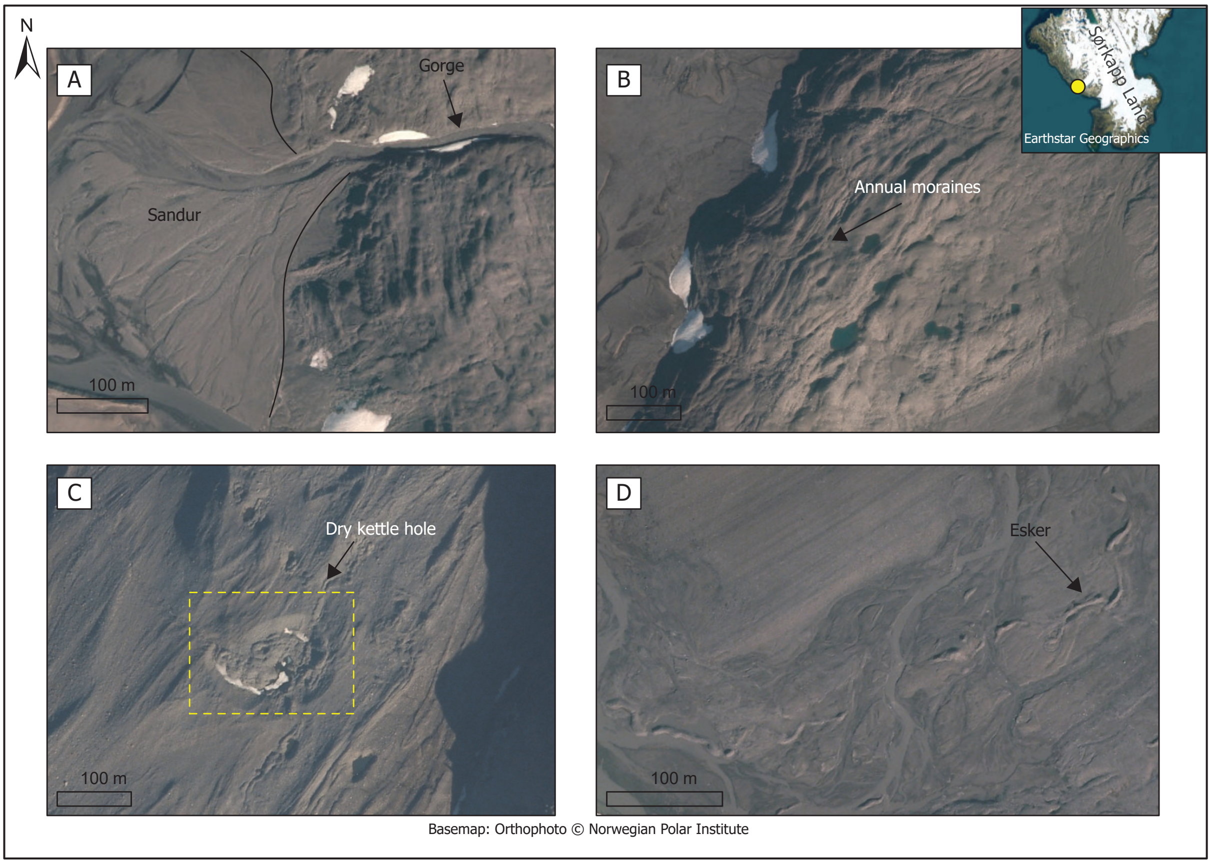


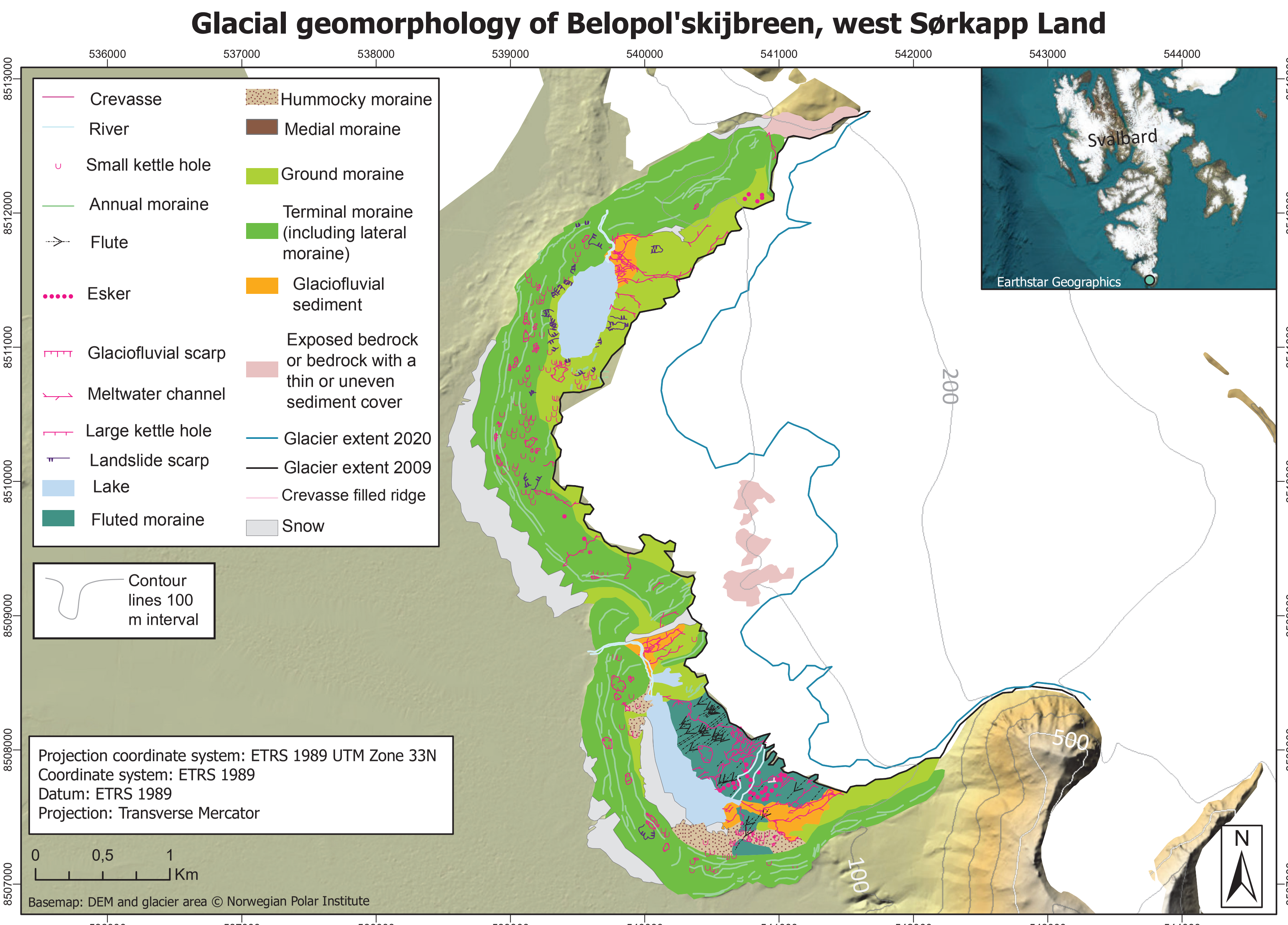
Figure 29: Landforms in and outside of the foreland of Vitkovskijbreen. A: Gorge (black arrow) in the terminal moraine where a sandur has developed outside of the terminal moraine (within black lines). B: Annual moraines (black arrow) on the terminal moraine. C: Dry kettle hole on the eastern lateral moraine. D: A long sinuous esker (black arrow) between the two areas of fluted moraine. Note the break in the esker cut by meltwater.

<u>Glaciofluvial sediments</u>

There is evidence of glaciofluvial sediments along the glacial river. There has not been found any evidence of an outwash plain inside the terminal moraine complex. However, there are two sandurs outside the terminal moraine complex. One where the western lateral moraine and the terminal moraine meet (Figure 29A), and the other is in front of the eastern lateral moraine. Compared to Bungebreen the extent of the glaciofluvial sediments in front of Vitkovskijbreen is quite restricted. The eskers in the foreland of Vitkovskijbreen are mostly in connection with the glaciofluvial sediments (Figure 29D). There are more meltwater channels on the western side of the river in the foreland, compared to the eastern side.

4.4 Belopol'skijbreen

The following descriptions resulted in a geomorphology map of the foreland of Belopol'skijbreen seen in .



Map 4: Glacial geomorphology map over the foreland of Belopol'skijbreen

Belopol'skijbreen is an outlet glacier of Sørkappfonna, located between Breskilknausen and St. Nikolausfjellet at 76.6°N, 16,6°E (Figure 11). The length of the glacier is ca. 4.79 km. Belopol'skijbreen retreated ca. 485.9 m between 2009 and 2020. This makes for the largest retreat of the glaciers in this study when considering the 2020 imagery. The terminal moraine complex consists of two nearly separated terminal moraines. The northern terminal moraine will hereafter be referred to as TM1 and the southern terminal moraine will be referred to as TM2. The foreland includes two major glacial lakes. The water in the lake behind TM1 is of a brown colour, while the lake behind TM2 is quite reddish. The differences in water colour could be due variances in bedrock and seasonal variations, among other things. There is a possibility that Belopol'skijbreen eventually will split into two different lobes as it continues to retreat.

In the 2020 imagery a new gorge has appeared (Figure 30) in the middle of the terminal moraine complex (on TM1) to the west of where TM1 and TM2 meet. Where the glacier has retreated the most (in the middle), additional bedrock appears to have been exposed (Figure 30) and new meltwater channels has been made since 2009. By TM1 red sediments (possibly red sandstone) has been exposed (Figure 30). Additionally, the middle part of the moraine complex appears more degraded in 2020 imagery.

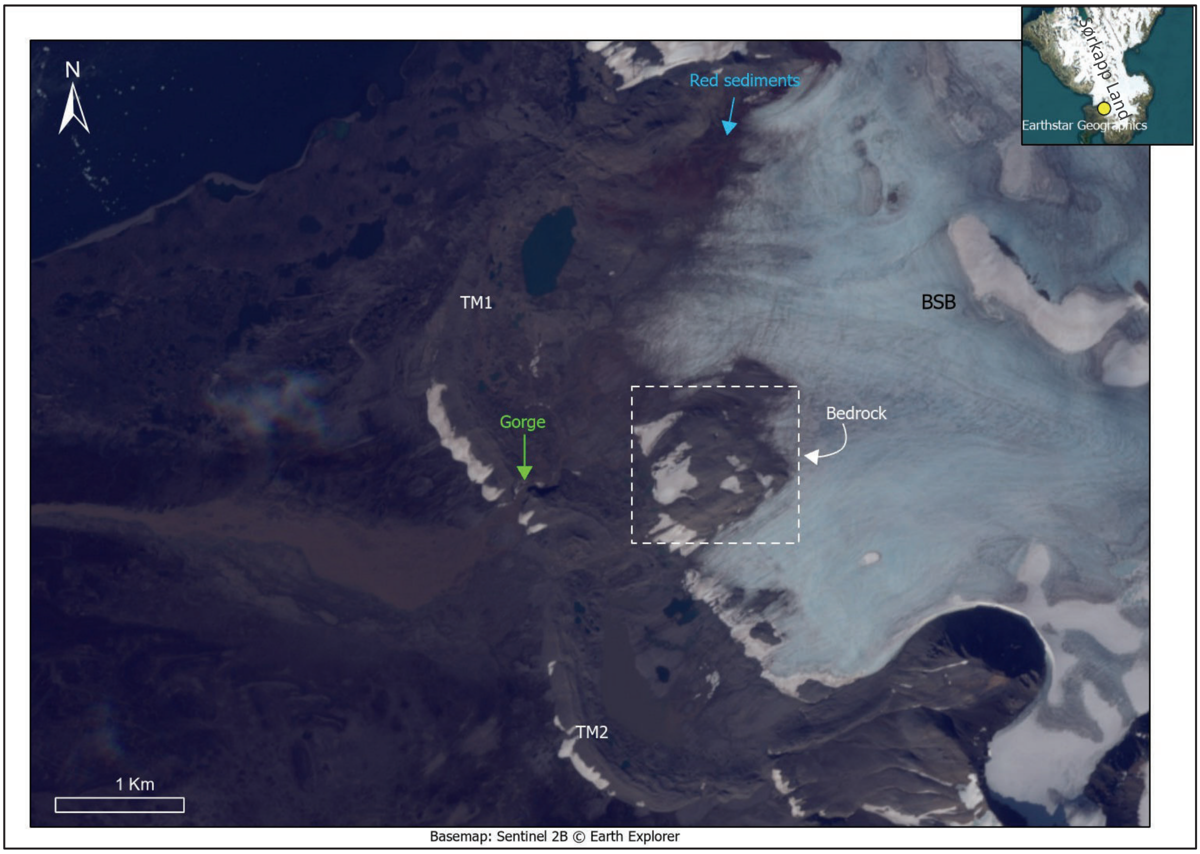


Figure 30: Overview of the foreland of Belopol'skijbreen (BSB) from sentinel imagery from 2020. Blue arrow indicates sediments that have been exposed since the 2009 orthophoto. They are of reddish

colour. Green arrow indicates a new gorge between the two terminal moraines (TM1 and TM2). White box indicates exposed bedrock that has been further exposed since the 2009 orthophoto.

There are some minor outwash plains below the terminal moraine complex and one major outwash in the middle of them. The meltwater comes together there to make Olsokelva (The Olsok River). This area below the terminal moraine complex is much larger (more land between the sea and the glacier) compared to the other glaciers mapped in this study. This area does not have the appearance of clear raised beaches as the beach sediments below Bungebreen and Vitkovskijbreen has. There is probably beach terraces there, but they have likely been degraded by waves, meltwater and other processes (or are difficult to observe on remote imagery). Newer beach sediments are seen by the shoreline.

Belopol'skijbreen has not any constraints to the west in the form of any mountains, but the tidewater glacier, Olsokbreen, flows in this area. It is evident that Olsokbreen has affected the lateral zone of Belopol'skijbreen, since the two marginal zones overlaps in some places (Figure 31A). There is a significant difference in the landforms left behind from tidewater glaciers and land-based glaciers. Sediments left behind from tidewater glaciers appear more "disordered" than those from land-based glaciers. The sediments left behind from Olsokbreen is similar to that of other tidewater glaciers such as Sefstrømbreen (Figure 31B) and Tunabreen.

Figure 31: Comparison of marginal zones affected by tidewater glaciers. A: The foreland of Olsokbreen and parts of the terminal moraine complex (TM1) of Belopol'skijbreen (BSB). The black line indicates the extent of Olsokbreen's marginal zone. B: The marginal zone of the tidewater glacier Sefstrømbreen (to the left in the image). Sefstrømmorenen indicates the extent of the tidewater glacier.

Terminal moraine complex

The terminal moraine complex consists of two terminal moraines (TM1 and TM2) and the area where they meet is somewhat complicated. TM1 has many landslide scarps and is steeper on the west side compared to the east side. TM1 appears to have been in contact with the lateral zone of the nearby tidewater glacier, Olsokbreen. On the orthophoto made of the old aerial photos from 1936 by Geyman et al. (2022) available at TopoSvalbard.no, Olsokbreen and TM1 of Belopol'skijbreen TM1 are seen to be connected (Figure 32). This strongly indicates that TM1 has been affected by Olsokbreen and it is likely that the tidewater glacier pushed into the moraine of Belopol'skijbreen at some point. There is a dent in the uppermost part of TM1 (Figure 34D). It is possible this dent was made by the ice mass at Breskilknausen (Figure 32). This is due to the fact that the moraine of Belopol'skijbreen appears to have been "cut into" by something with enough force to make a dent in the moraine. To make such a dent there must have been a lot of force involved, which could perhaps have come from such an ice mass.

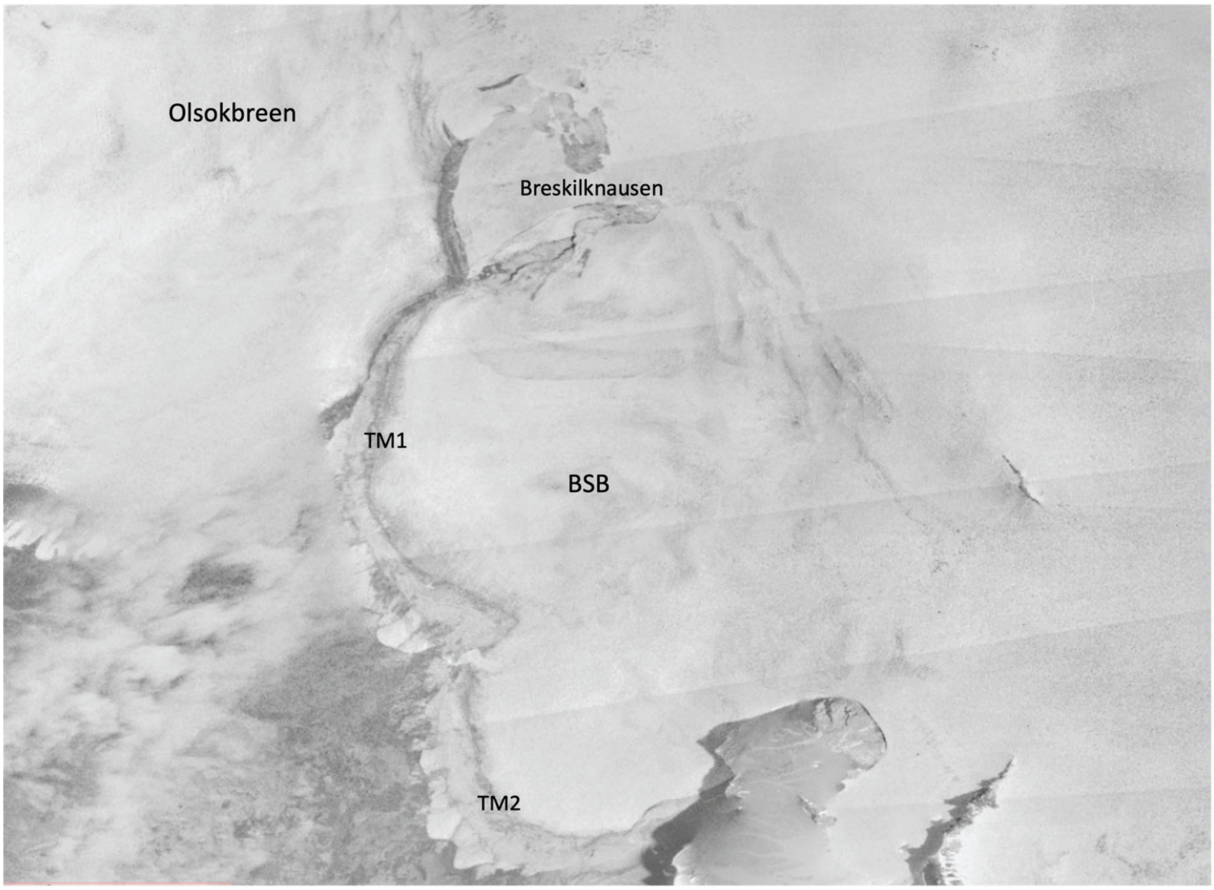


Figure 32: View over Belopol'skijbreen (BSB) and Olsokbreen from the 1936/1938 aerial photo orthophoto layer on TopoSvalbard.no (Geyman et al., 2022), Note the clouds to the bottom left of the image. The tidewater glacier Olsokbreen is seen to lay directly into parts of TM1.

On TM1 there are many kettle holes of various sizes. while there is only a few on TM2. The terminal moraine complex has some hummocky characteristics in certain places. By the eastern side of the Belopol'skijbreen there is a lateral moraine. On TM1 there is evidence of an ice margin position (Figure 34C). Here, meltwater would have gathered around the glacier front and meltwater channels would have formed and make the incisions in the moraine, that can still be seen later on.

In the middle of the glacier there is an exposed area, possibly bedrock (Figure 33A). However, since the colours of glacial sediments and bedrock can sometimes be very similar, at is here, it cannot be said with certainty that it is bedrock.

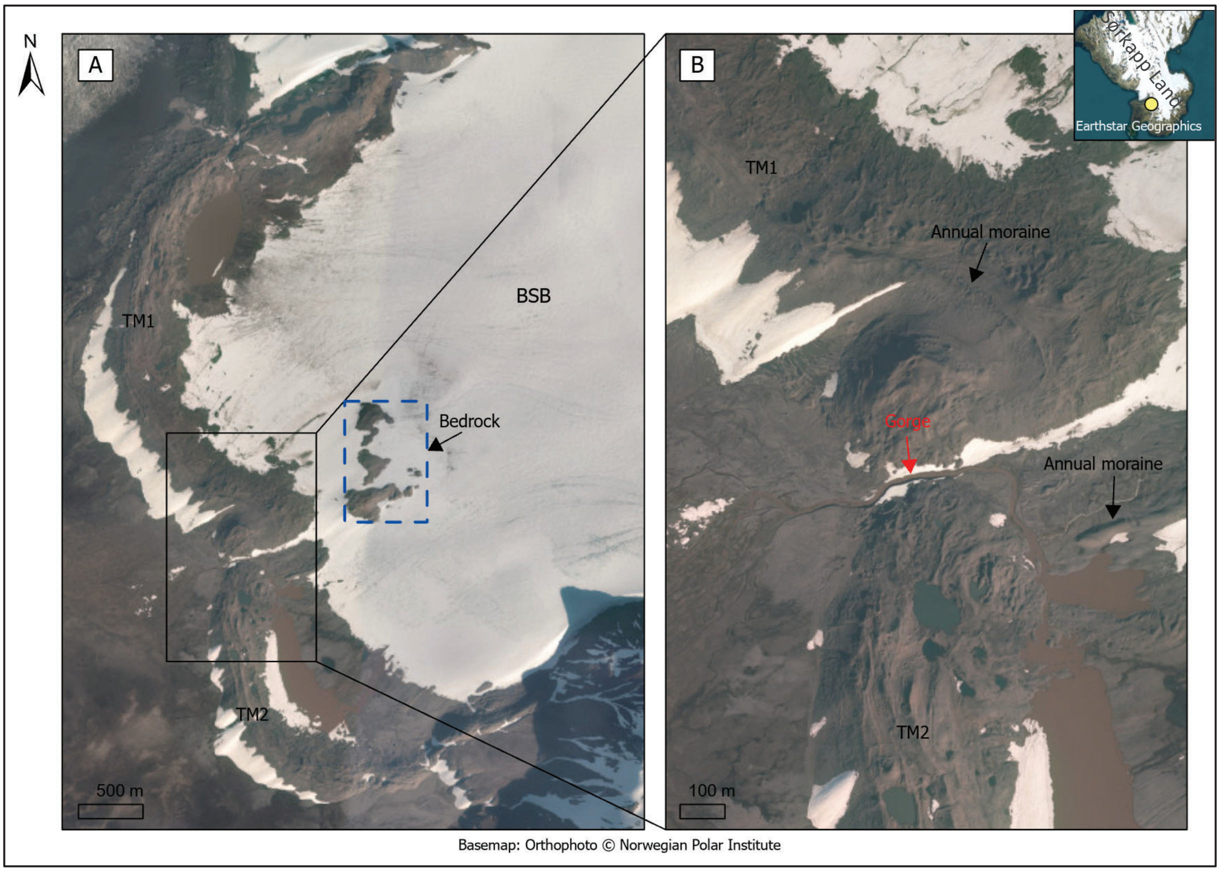


Figure 33: The terminal moraine complex of Belopol'skijbreen (BSB). A: Overview of the terminal moraine complex with TM1 and TM2 marked. Note the glacial lakes behind them. The blue box indicates exposed bedrock. Black box indicates the location of B in A. B: Overview of the area where TM1 and TM2 converge. Annual moraines are indicated with black arrows. The gorge through TM2 is indicated with red arrow. Note the difference in scale.

Glaciofluvial sediments and eskers

Glaciofluvial sediments are found in connection with large meltwater channels and outwash plains by the river behind TM1, in the middle of the two terminal moraines and on the east side of TM2. There are glaciofluvial scarps several places in the foreland, mostly by the lake of TM1 (Figure 34A), likely caused by solifluction. There is evidence of a previous small delta in the area behind TM1 (Figure 34A). There are some long interconnecting eskers behind TM2 (Figure 34B). They are quite narrow and very sinuous. In between the two terminal moraines and near TM1 there are some shorter eskers.

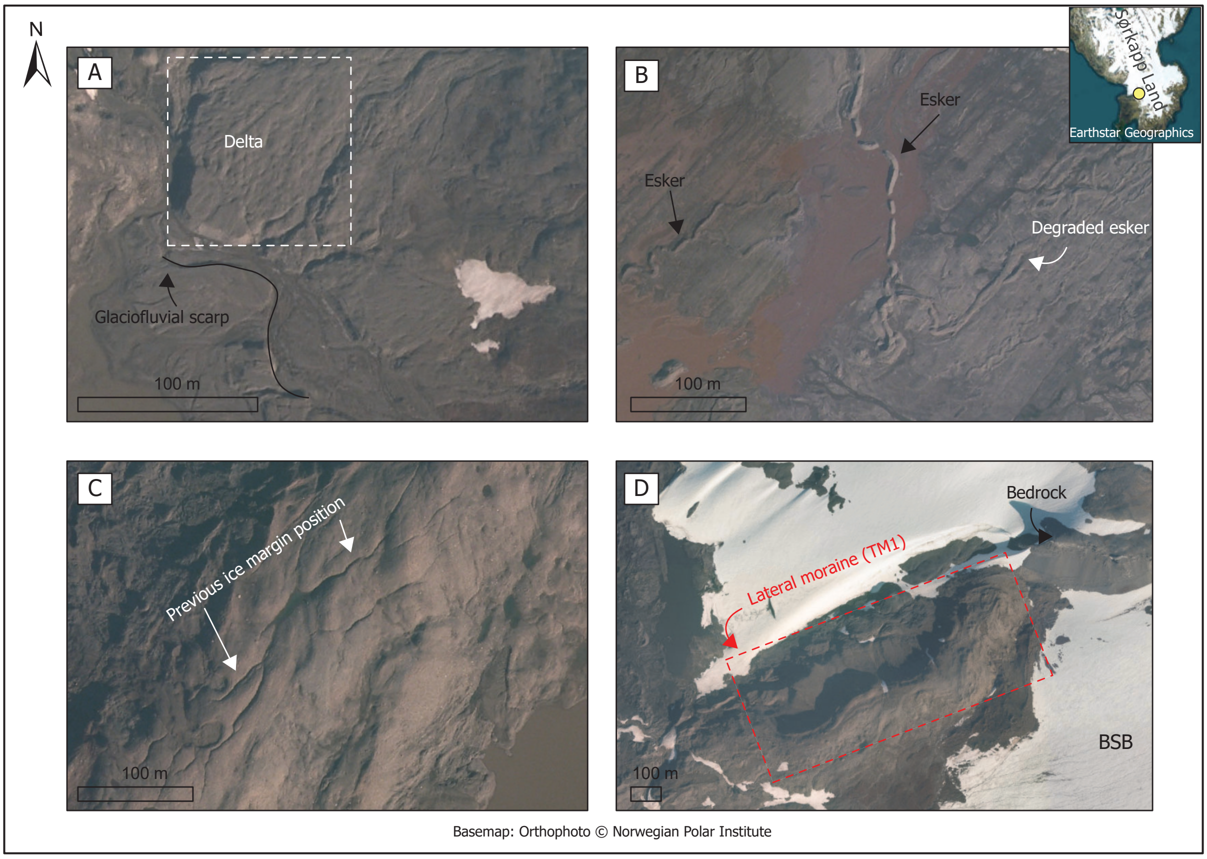


Figure 34: Landforms in the foreland of Belopol'skijbreen (BSB). A. Delta indicated by white box and glaciofluvial scarp inside black line. B: Eskers (black arrows) on fluted moraine and a degraded esker indicated by white arrow. C: Old meltwater channels that indicate a previous ice margin position on the terminal moraine (TM1). D: The most western part of TM1. The red box indicates the dent made into the terminal moraine. Black arrow indicates bedrock (Breskilknausen).

<u>Other moraine types</u>

There is a large area of flutes and fluted moraine behind TM2, contrary to behind TM1 were there are none. In the 2020 imagery it appears that even more fluted moraine has been exposed where the glacier front has retreated. There are hummocky moraines behind TM2, near the lake. The area is separated by a snow patch, so it is likely there is hummocky moraine in that entire area, but as areas covered by snow cannot be mapped (Chapter 3.2), that area is not classified as hummocky moraine (but is as snow). There are no hummocky moraines by TM1. Ground moraine is mostly found in front of the glacier behind TM1. However, there are also some between the two terminal moraines and in front of the glacier behind TM2.

5 Discussion

This study focused on South-West Svalbard and had the following aim and objectives. The aim of this research is to identify and map the glacial geomorphology of four land-based glaciers at Sørkapp Land in Svalbard. The investigation involved working with remote sensing by using satellite images, DEMs, maps and GIS. This aim was to be achieved through six objectives:

1. Examine previous studies concerning the geomorphology, glacial history, processes and dynamics, and glacial landsystems on Sørkapp Land and in nearby areas such as Hornsund to identify knowledge gaps.
2. Collect information about the Sørkapp Land landsystem and the thermal regime of the glaciers in this area.
3. Study the relation between landforms (e.g. crevasse squeeze ridges) and surge-type glaciers and establish if these are present at the forelands of the land-based glaciers in Sørkapp Land.
4. Develop a chronology for the landsystem at Sørkapp Land through published numerical datings together with the results from this study.
5. Create a revised model of the landsystem at Sørkapp Land.
6. Produce geomorphological maps in ArcGIS Pro.

First comes a comparison of the geomorphology maps from this study to the geomorphology map from 1984. Further, the application of different landsystem models for each glacier is discussed and whether the results are accordant with the reported majority of Svalbard glaciers, also included are some remarks on the use of landsystem models. Later, this study is placed in the context of other relevant studies, both in Svalbard and Greenland. Lastly, the study is placed in the wider context of climate change, including the implications of surging glaciers, to place the study within current issues.

5.1 Geomorphology map from 1984

Here, comparisons to each glacial foreland will be presented and significant differences between the produced maps from this study and the geomorphology map from 1984 (see description in Chapter 2.3) will be discussed. Since the glaciers have continued their recession beginning from the early 1900s, it is expected that a geomorphological map from 1984 and the mapping conducted in this study will be different. The differences will indicate potential geomorphological changes. As Belopol'skijbreen is not included in the map from 1984, no comparisons could be made to Map 4.

<u>Gåsbreen</u>

Since the expeditions in and prior to 1980, Gåsbreen has undergone a dramatic retreat easily denoted by more of the mountainside of Wurmbrandegga and its slopes being exposed. These changes are presented in this study as landslide material and debris flows (Chapter 4.1).

On the map from 1984 there are medial moraines near the glacier front, however not as extensive as the ones in this study. Some of the present medial moraines appear to occur where there previously were mapped debris cover. This is likely due to the retreat of the glacier, and exposure of sediments. However it could also be linked to an increase in debris production both internally in the glacier and that denudation processes have increased in the confining valley. The map from 1984 includes eskers and kames, these appear to be in the same area as some of the eskers mapped in Dudek et al. (Submitted) (at the edge of Wurmbrandegga and the terminal moraine). As mentioned in Chapter 4.1, there have not been observed eskers nor kames in this study in that area. Landforms mapped in this study that are not present in the geomorphology map from 1984 are listed in Table 2.

Table 2: Landforms mapped in this study at the foreland of Gåsbreen, that are not presented in the map from 1984.

Annual moraines	Glaciofluvial scarp
Meltwater channels	Kettle holes
Landslide scarps	Debris flows
Hummocky moraines	Ice patch
Fluvial sediments	Landslide material

At the time of the field expeditions there was a lake on the western part of the terminal moraine complex, close to Wurmbrandegga. No evidence for glaciolacustrine sediments around that location have been found in this study. In the 1984 map there is ground moraine outside of the terminal moraine complex, in the outwash plain. These have not been observed in this study. However, these could have been washed away or covered by sediments during the draining of Göes Lake, or by other large meltwater episodes. The lake is as previously mentioned (Chapter 4.1), no longer present. Furthermore, there are several patches of lateral moraines mapped at the side of Wurmbrandegga. This study has mapped mostly landslide sediments here, while Dudek et al. (Submitted) has mapped mostly hummocky moraine. It is possible that after the glacier retreated, the lateral moraines that were there has been taken over by slope processes such as debris flows, which has re-worked the deposits.

<u>Bungebreen</u>

The extent of the terminal moraine complex seems to match well with the extent of the terminal moraine complex in this study (Map 2), except for one inclusion at the eastern side of the eastern lateral moraine in the 1984 map. Here it was though that this lateral moraine was a terminal moraine of a different glacier. However, as Bungebreen has experienced such drastic retreat and the terminal moraine has degraded substantially, it is difficult to compare the two maps, and undoubtedly this indicates that major changes have occurred in the foreland since the initial investigations in the 1970s and 1980s. Furthermore, since the medial moraine gotten degraded as much as it has, its extent has changed drastically. Landforms mapped in this study that are not present in the geomorphology map from 1984 are listed in Table 3.

Table 3: Landforms mapped in this study at the foreland of Bungebreen, that are not presented in the map from 1984.

Eskers	Fluted moraines
Flutes	Kettle holes
Meltwater channels	Hummocky moraine
Annual moraines	Glaciolacustrine sediments
Glaciofluvial scarps	Crevasses and crevasse filled ridges

Roches mounteés were mapped by Klysz and Lindner (1982) at the mountain side of the Stupryggen mountain massif near Bungebreen (Chapter 2.2.1). These are not presented in the 1984 map. It cannot be said for certain whether that is because they were not observed in the field expeditions for the map or if they were discarded. It is possible the features were not prominent enough to be included on the scale of the map, however this is not the most likely explanation as roches mounteés are included other places on the map. The 1984 map includes the outline of a lake that were present in the aerial photos from 1936 that is next to where this study has mapped glaciolacustrine sediments (Chapter 4.2).

Vitkovskijbreen

In the geomorphology map from 1984 there is a lake on the western ice-proximal side of the terminal moraine complex, that is no longer present. Further, there are mapped a roches mounteé close to the (then) glacier front. These have not been identified in this study. Firstly, this could be due to such features being difficult to observe (i.e. similar colours) on remote imagery or it could have been misinterpreted as a flute or part of fluted moraine. Secondly, it is difficult to determine its exact location from the map. Hence, it is likely that the roches mounteés is present today, but it has not been mapped in this study. On the 1984 map there are plains of raised marine terraces outside the terminal moraine complex. Landforms mapped in this study that are not present in the geomorphology map from 1984 are listed in Table 4.

Table 4: Landforms mapped in this study at the foreland of Vitkovskijbreen, that are not presented in the map from 1984.

Individual flutes	Eskers
Hummocky moraine	Kettle holes
Meltwater channels	Small medial moraine
Landslide scarps	Annual moraines

In the map from 1984 debris covering the lower part of Vitkovskijbreen has been mapped. No such debris cover has been observed in this study, except for a small medial moraine (Map 3). However, it is possible the debris cover has down-wasted and therefore appears as moraine cover. Furthermore, the map has an extensive outwash plain compared to this study. The eastern latero-frontal moraine appears to have a different shape and thinner closer to the glacier front in the 1984 map, compared to the one in this study. The difference could be due to more of the latero-frontal moraine has become exposed as the glacier has retreated.

Overall differences in the map

Since the map from 1984 has a smaller scale, some mapped features had to be simplified. For example, the gorges seem to have been exaggerated, while the extends of flutes appear to have been condensed into patches of fluted moraine. However, it is possible that features such as flutes are easier observed on newer orthophotos, compared to field work and older aerial photos. Furthermore, the flutes could have become more pronounced since the field expeditions in the 1980s. The map from 1984 have not mapped eskers (or kames) in the forelands of Gåsbreen, Bungebreen nor Vitkovskijbreen. This could be due to the scale of the map (1:75 000). As such, the commentary of the map did not discuss the mapping of eskers. This study has mapped eskers in all the mentioned forelands (only one by Gåsbreen). While the eskers at Bungebreen and Vitkovskijbreen are connected to the glaciofluvial sediments it is possible (and likely) these landforms were exposed after the map was made and the glaciers retreated to their current positions.

To summarize, this study has contributed additional, detailed geomorphological landforms in new geomorphological maps and compared them to the geomorphology map from 1984. Moreover, as this study has been conducted at a later time when there has been extensive retreat of the glacier fronts, paraglacial processes have reworked the sediments in the forelands of the glaciers and thus has been included in the new geomorphology maps. The tables above summarize what is likely newly exposed landforms in the forelands and thus illustrate how the area is evolving due to glacial retreat and environmental changes. This chapter partly accomplishes objective 1, 2 and 5.

5.2 Landsystem

Evans (2005) recommends dividing different landscapes with different landforms into distinctive landsystems. Following, is therefore a description of each glacier and the most non-conclusive evidence in their forelands. Next is a synthesis of which landsystem category the landsystem of each glacier most likely is associated with. Then follows a discussion about whether the four studied glaciers are part of the same landsystem.

5.2.1 Gåsbreen

Debris cover

Gåsbreen has an extensive debris cover and several medial moraines (Map 1). The magnitude of the debris cover is most likely due to frost shattering of the mountain sides nearby (Silesiafjellet and Midifjellet). More frost weathering would lead to more debris to fall onto the glacier. Since Gåsbreen flows in a different direction than the other glaciers in the study area, the glacier likely receives a different amount of insulation which could influence frost weathering processes in the mountain slopes.

The absence of flutes and fluted moraine

Flutes are made when a glacier is advancing (Allaart et al., 2018). Gåsbreen has no evidence of fluted moraine, contrary to all the other glaciers in the study area. Forelands with flutes tend to be present in areas where glaciers has had the opportunity to advance in areas where they are not constrained by the topography (Allaart et al., 2018). A possible reason for the absence of flutes in the foreland of Gåsbreen is therefore the nearby topography, as the glacier has been restricted by the nearby mountain Wurmbrandegga (Figure 11) in the past (Figure 14). Until Gåsbreen retreated in the early 2000s the glacier was still adjoining the mountain ridge and it is possible flutes could not be formed under conditions of restricted flow. Furthermore, it is possible that flutes could have been formed even under such constraints but has been not preserved by being reworked. Moreover, the foreland was described in Jewtuchowicz (1965) to have large amount of meltwater destroying landforms. It is possible that this resulted in the disappearance of low-preservation landforms, such as flutes.

Sediments near Wurmbrandegga

The sediments along the edge of Wurmbrandegga (Figure 11) were some of the most challenging features to map in this study as it is heavily influenced by several processes, such as slope processes and thawing of dead ice (Chapter 2.2.2). The imagery being slightly distorted due the steepness of the edge further complicated the mapping. Dudek et al. (Submitted) investigated the landscape changes at the Gåsbreen foreland from 1938 to 2020 and mapped considerably more hummocky moraines near Wurmbrandegga compared to this study (Map 1). This study found more of the sediments to be landslide material and debris flows. As it may be difficult to perceive the difference between hummocky moraines and landslide material (as described in Chapter 3.4) this could explain the differences. Further, the study by Dudek et al. (Submitted) may have found evidence of hummocky moraines during fieldwork sessions which was not described in the resulting paper.

Furthermore, there are landslide scarps along Wurmbrandegga that is not easy to determine whether are actual landslide scarps or trimlines from when Gåsbreen was against the mountain side. Another landform that can be disputed is the sediments along Wurmbrandegga that are likely of fluvial origin (Figure 17). Fluvial fans are deposited below streams of snow patches (Wójcik & Ziaja, 1993). In the 2009 orthophoto there are snow patches over the sediments mapped as fluvial sediments, leading to strengthen their origin as fluvial not glaciofluvial. The presence of debris flows and fluvial sediments supports the theory that there are occurring geomorphological and hydrological changes in the foreland, likely due to the lengthening of the summer season (Ziaja, 2016) (Chapter 2.2.2).

<u>Eskers and kames</u>

Jewtuchowicz (1965) discovered eskers and kames on a field expedition in 1959 in Gåshamnøyra (Chapter 2.2.2), the outwash plain in front of Gåsbreen. These do not appear to be present in the examined imagery in this study. They have therefore not been mapped in this study, nor were they mapped in the study by Dudek et al. (Submitted). It is possible that the eskers and kames have been washed away since that field expedition or that the landforms were misinterpreted as Klysz and Lindner (1982) believed the eskers interpreted by Jewtuchowicz (1965) in front of Bungebreen were (Chapter 2.2.2). Since the glacier has retreated extensively since the field expeditions in 1959, and the presence of a glacier dammed lake has both appeared and disappeared it is likely that landforms such as eskers and kames has either been washed away or been reworked beyond recognition. Dudek et al. (Submitted) has not mapped the eskers in the assumed position described by Jewtuchowicz (1965), neither for their mapping for 1960 nor later. Furthermore, Baranowski (1982) meant the origin of the eskers and kames found by Jewtuchowicz (1965) likely was not glacial, but that of naled ice.

Eskers near the ice patch (Figure 17) mapped by Dudek et al. (Submitted) for 2010 has in this study been mapped as annual moraines as they are not as sinuous as most eskers. It is therefore more plausible that they are annual moraines. However, the sedimentology would be able to make the depositional history clearer. Indeed no eskers have been identified in this study where Dudek et al. (Submitted) have mapped such features. Further, no kames have been mapped in this study. As kames can be rather small in size as the kames noted in the foreland of Gåsbreen by Jewtuchowicz (1965) and described in Chapter 2.2.2, it could be they are too small to be observed on remote imagery. Another aspect regarding the annual moraines near the ice patch is that one leads in a different direction than the two other annual moraines in addition to being beneath them. This conveys a complicated retreat of the glacier front in this area, along with the ice patch.

Kettle holes

Dudek et al. (Submitted) have mapped many kettle holes in the marginal zone of Gåsbreen. This study has not observed the same. There are some large kettle holes and some small kettle holes, but kettle holes are noticeably more abundant at the other forelands in the study area. However, fieldwork conducted for Dudek et al. (Submitted) could have discovered many small kettle holes during fieldwork that cannot be noticed on the remote imagery. This demonstrates the limits of remote sensing, where you get an overview over large areas but can miss some of the details which further supports the concept that remote sensing should be used together with fieldwork.

Göes Lake

As explained in Chapter 4.1 there was a glacial dammed lake present in the foreland of Gåsbreen between 1985 and 2005. However no evidence of glaciolacustrine sediments have been identified in this study nor was any mentioned or mapped in Dudek et al. (Submitted). A question that arises is therefore: have glaciolacustrine sediments been reworked or washed away? Such catastrophic events as the sudden breach of an ice-dammed lake (called Jøkulhlaup) could possibly wash away deposits. Moreover, it is possible the catchment did not have favourable conditions for creating glaciolacustrine sediments, for example if the precipitation was low. If only small amounts of the meltwater lead into Göes Lake or if the lake was drained every summer that could explain the lack of glaciolacustrine sediments. Furthermore, it is possible that there are glaciolacustrine sediments present, but covered by other sediments making it impossible to observe them on remote imagery.

Gorges

Regarding the trend noted by Klysz and Lindner (1982) that the abandonment of the western gorge leads to the formation of a southern gorge (Chapter 2.2.2). There are inclinations of a gorge being abandoned on the western side of the terminal moraine complex, however as the terminal moraine complex do not have a southern side, a southern gorge has not been formed. Instead the active meltwater gorge appears to be in the middle of the terminal moraine complex. The placements of such gorges are important because they indicate where glacial meltwater flows and where it has flowed in the past and are therefore indicative of glacial retreat as well. Furthermore they may indicate where the foreland receives the most insulation. Also, the extent of the alluvial fans outside the gorges can indicate the velocity and sediment burden of the meltwater. However, sediment burden will not be assessed further here due the scope of this investigation. Since the

Classification of landsystem

Farnsworth et al. (2016) has marked Gåsbreen to potentially have surged in the past. However, since Gåsbreen is not mentioned in the text it is difficult to know what the reasoning behind that classification is, beyond the presence of CSRs. According to Evans (2005) a surging glacier landsystem includes the landforms seen on Figure 35. It is important to note that the presence of one or two of these landforms is not enough for classification of the entire landsystem (Evans, 2005). Some of the landforms that indicate surge activity, and are exposed in the inactive phase of a surge event, conveys information about surge activity that happened decades or over a century prior to the landforms becoming exposed (Farnsworth et al., 2016). Meaning that the landforms are often not indicative of an ongoing surge, but a past surge.

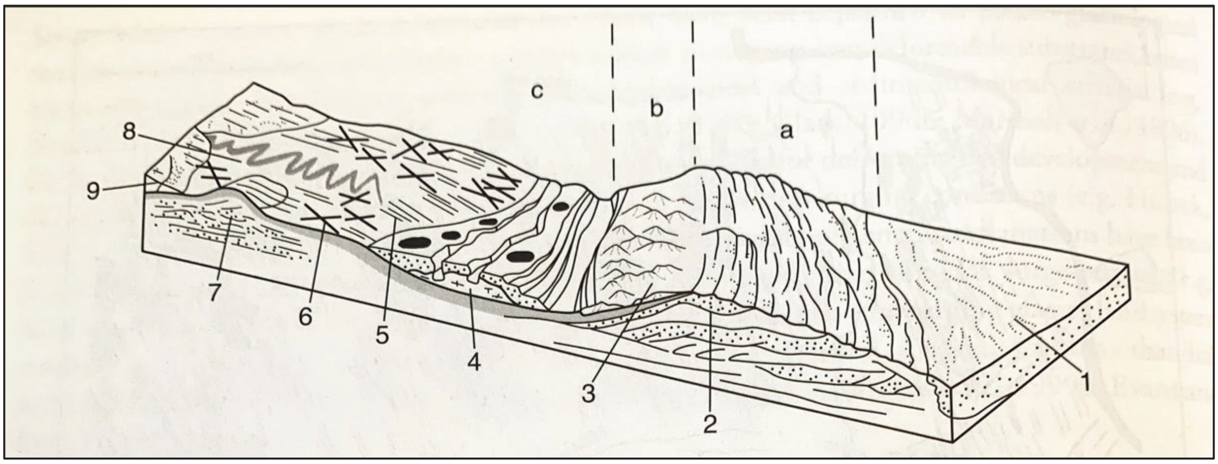


Figure 35: Landsystem model for the margin of a surging glacier from Chapter 11 in Evans (2005). a: outer zone with proglacially sediments that may develop into push moraines on areas with thin sediment cover, b: zone with hummocky moraines on the proximal-glacier side of topographic depressions, c: zone where flutes, CSRs and concertina eskers are present (Evans, 2005). 1: proglacial outwash plain, 2: thrust-block moraine, 3: hummocky moraine, 4: dead-ice covered by pitted and channeled outwash, 5: flutes, 6: CSRs, 7: overridden and fluted thrust-block moraine, 8: concertina esker, 9: glacier with CSRs emerging beneath the glacier (Evans, 2005).

A landform that is frequently associated with surging glaciers are so-called looped moraines (Farnsworth et al., 2016). None of the glaciers in the study area have such moraines. The landforms present at the foreland of Gåsbreen are annual moraines, one esker, glaciofluvial scarps, kettle holes, hummocky moraines, medial moraines, ground moraine, terminal moraine complex (including lateral moraines), glaciofluvial sediments, fluvial sediments and landslide material (such as debris flows). There has not been found evidence of CSRs in the foreland of Gåsbreen in this study. The only landform that indicates a surging landsystem are the hummocky moraines, which incidentally are not solely diagnostic of a surging glacier. The one esker is discarded as it is isolated and is therefore not enough to justify being used for classification. On the basis of only one of the landforms matching with those for a surge landsystem (Figure 35), the landsystem of Gåsbreen cannot be concluded to be of the surge landsystem described in Evans (2005). However, as surge glaciers are difficult to determine as explained in Chapter 2.3, the notion of Gåsbreen being a surging glacier cannot not be completely discarded, even though it appears to be unlikely based on this analysis.

Another possible landsystem for Gåsbreen is the landsystem for polythermal glaciers in Svalbard described in Chapter 4 in Evans (2005) (Figure 36). This landsystem is typical for the retreating glaciers in Svalbard (Evans, 2005). The landsystem can be divided into three zones: the outer moraine ridge, a moraine-mound complex and an inner zone consisting of various landforms with varying quantity, such as ridges, debris stripes, ridge networks, flutes and small moraine mounds (Evans, 2005). The glacier will have medial moraines and will be confined by rock walls on the sides of the valley (Evans, 2005). Since polythermal glaciers have both cold-and-warm based ice the landforms left behind depend on the proportion of this relationship (Glasser & Hambrey, 2001)

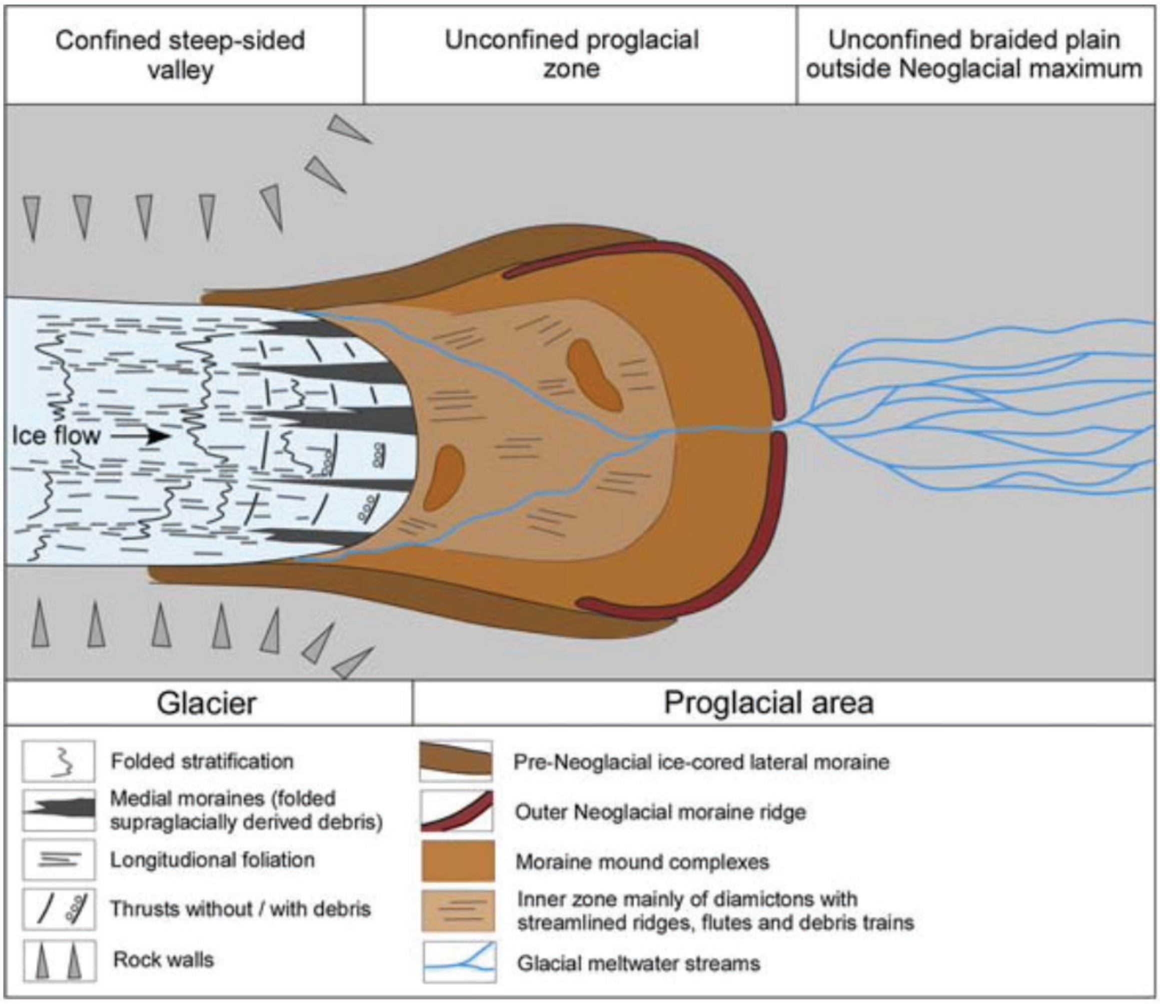


Figure 36: The landsystem for terrestrial polythermal glaciers in Svalbard described in Chapter 4 in Evans (2005) modified by Ingólfsson (2011).

Some of the landforms by Gåsbreen are included in the landsystem for polythermal glaciers in Svalbard. However, there is one key difference. There are no flutes present in the proglacial area of Gåsbreen. On the other hand there are several landforms belonging to the landsystem that are present in the foreland, such as the medial moraines and rock walls in the confining valley. Furthermore, the terminal moraine complex of Gåsbreen has an outer ridge, ice-cored lateral moraines (cannot be certain they are pre-Neoglacial). There are hummocky moraines inside the terminal moraine complex and there are glacial meltwater streams flowing through the terminal moraine complex and making an outwash plain on the outside of the terminal moraine complex.

Some of the differences between the modeled polythermal landsystem and the landsystem at Gåsbreen may be due to the fact that Gåsbreen largely flowed outside of its confining valley and onto a barrier, for an extensive period of time. From the above analysis it is difficult to discern which landsystem is the most likely for Gåsbreen. However, since much evidence of a surging glacier landsystem is lacking, the landsystem for polythermal glaciers is more likely, even though there are some discrepancies. As the foreland of is categorized as a polythermal landsystem, it indicates Gåsbreen is a polythermal glacier.

5.2.2 Bungebreen

Eskers

Jewtuchowicz (1965) discovered eskers in the foreland of Bungebreen on a field expedition in 1959 (Chapter 2.2.2). However, since then the foreland has changed drastically as the glacier has retreated and paraglacial processes has largely affected the foreland due to changes in the meltwater system. Even when a glacier is rather stable the seasonal meltwater can change flow directions from year to year. This could explain why the descriptions by Jewtuchowicz (1965) does not seem to correspond with the foreland observed in this study. Klysz and Lindner (1982) disagreed with Jewtuchowich's interpretation as explained in Chapter 2.2.2. Eskers are still present in the foreland of Bungebreen (Map 2), but one cannot be certain they are the same ones described by Jewtuchowicz (1965) since the foreland has changed so drastically and the eskers may have been reworked.

Furthermore, the surges that have occurred since the fieldwork conducted in the 1950s could also have reworked or distorted the eskers. When the ice-core of eskers melt out the eskers are destroyed or the sediment structure inside the esker is disturbed to such a degree that they later may be unrecognizable as eskers (Evans, 2005). This can therefore be the case for the eskers in the foreland of Bungebreen that was identified by Jewtuchowicz (1965), as they would not be possible to observe later on. Since eskers are an associated landform with surge glaciers (Evans, 2005), this is a likely explanation. It is difficult to say anything about whether Jewtuchowicz

(1965) or Klysz and Lindner (1982) were correct, as the eskers and kames does not appear to be present in the available imagery or at least it is very difficult to infer where the landforms they refer to actually were.

Terminal and medial moraine

Klysz and Lindner (1982) described the terminal moraine complex as ice-cored, but they noticed it had already then started to degrade. Since then, the terminal moraine has suffered severe degradation, this is clear by the many landslide scarps in the terminal moraine complex, especially on the western part of the complex and its loss of elevation (Figure 21). Therefore it appears a great part of the terminal moraine is no longer ice-cored. This (together with the large presence of kettle holes) confirms that the thawing of dead ice and slope processes have accelerated at the foreland as proposed by Ziaja (2016) (Chapter 2.2.2) However, the lateral moraines still appear to be ice-cored as they are still elevated and do not have landslide scarps.

At its highest, the medial moraine was up to 5 metres high in 1980 (Klysz & Lindner, 1982). However, it was already then observed that the medial moraine was degrading and was becoming more level with the glacier edge (Klysz & Lindner, 1982). Since the expedition in 1980, the medial moraine has been become fully degraded in most of the foreland and it is difficult to the see traces of it in some areas. On the present medial moraine there are depressions that are formed by crevasses and the sediments between them are in this study mapped as crevasse filled ridges (Map 2). When the glacier retreats, such ridges may lead to the formation of kettle holes (if they are ice-cored).

Kettle Holes

There is an abundance of kettle holes on the terminal moraine complex of Bungebreen compared to the terminal moraine complex of Gåsbreen. This is likely due to the terminal moraine of Bungebreen being considerably more degraded than the terminal moraine of Gåsbreen. When the terminal moraine is more degraded more of the ice-core has melted out which leads to the formation of kettle holes. The absence of snow patches below the terminal moraine is further evidence of the terminal moraine being degraded. The three other glaciers in the study area have much snow patches on the ridges of the terminal moraine, which indicate that their terminal moraine complexes are still ice-cored. However, the absence of snow patches has also been linked to longer summer seasons and changes in the hydrology of the region (Chapter 2.2.2).

Glaciolacustrine sediments

The mapped glaciolacustrine area overlaps with where the medial moraine was in a 1936 aerial photo (Figure 20). In the aerial photo the medial moraine appears to be ice-cored. As the ice melted out, it would lead to a lot of meltwater. A very large amount of meltwater could possibly have led to the formation of a small lake and production of glaciolacustrine sediments. Such a lake appears in the geomorphological map from 1984 over the Hornsund region (Karczewski et al., 1984). This theory is likely, considering that the melting of ice cores was here thought to lead to large depressions filled with silty-sand sediments by Klysz and Lindner (1982) (Chapter 2.2.2). The presence of several kettle holes indicates there has been much water present in this area (Figure 22). Or it could be that the medial moraine consisted of brighter sediments, and it only appears to be glaciolacustrine sediments in remote imagery. An additional theory is that the eastern glacial lake that is present in the 2009 orthophoto was at some point in time much larger and glaciolacustrine sediments were then deposited, however no evidence of this has been found, and it is unlikely such a large lake like that would have had to have been would not leave behind more evidence. The believed to be glaciolacustrine sediments must be studied in more detail before conclusions to their origin can be drawn.

There may be some glaciolacustrine sediments west of the mapped glaciolacustrine in the terminal moraine complex (Figure 22) as there are similar looking sediments there. But as there are no evidence of a previous proglacial lake in this area, it is unlikely glaciolacustrine sediments. Therefore they have not been mapped as such.

<u>Ice-contact delta</u>

There is evidence of two previous ice-contact delta in the glaciofluvial sediments (Figure 24A). An ice-contact delta has not been mentioned in previous studies. However, it is likely the ice-contact delta was formed after the expeditions to the area, due to the major glacial retreat. As may be the case since the area marked in red in Figure 24A matches well with the glacial frontal position in 1980 described by Klysz and Lindner (1982). The green line in Figure 24A indicates another ice-contact delta, though less extensive than the first. This ice-contact delta (green line) is likely formed at a later time, after the delta formed at the 1980 glacier front position. Meaning the glacier likely had a longer stand-still where the newest delta (green line) was formed. Also for this landform, the stratigraphy will need to be examined in the future to know the origin of the sediment. The glaciofluvial scarps found in several places in the glaciofluvial sediments and the ice-contact deltas, are the product of meltwater channels cutting into the sediments as described in Chapter 2.2.2.

<u>Disappearance of lake</u>

On the geomorphology map from 1984 (Figure 6) there is lake by the western lateral moraine on Bungebreen that is not present in the 2009 orthophoto, probably as a consequence of the glacier having retreated since the creation of this map. It is possible that the location coincides with where the small lake by the western lateral moraine is in the 2009 orthophoto. This may explain why there are possible traces of a larger lake by this small lake (Figure 23). It could be that the lake has either drained or dried up since the creation of the geomorphology map from 1984.

Gorges

Regarding the trend noted by Klysz and Lindner (1982) that the abandonment of the western gorge leads to the formation of a southern gorge. This trend was based on observation from the foreland of Bungebreen. As described in Chapter 2.2.2, Klysz and Lindner (1982) found that the western gorge had been abandoned in favour of a southern gorge. Since the degradation of the terminal moraine complex, especially the western part (Figure 21), traces of this western gorge are difficult to observe except for the outwash plain below it. The southern gorge is still active and provides meltwater to Bungeelva. This southern gorge appear to be wider than the gorges at the terminal moraines of the other glaciers, possibly indicating that considerably more meltwater has gone through this gorge.

Surges

Bungebreen is the only of the four investigated glaciers that has been clearly documented to have surged (Farnsworth et al., 2016; Sund et al., 2009) (Figure 9). A surge was first documented in 2004 and the evidence came from observing changes in the crevasses on the glacier (Sund et al., 2009). It is not described explicitly what the changes in crevasses showed at Bungebreen. However, the changes in crevasses Sund et al. (2009) refers to is the appearance of new crevasse fields. It can therefore be inferred that new crevasse fields appeared at Bungebreen in 2004. Then Bungebreen surged again between 2007 and 2008 and after this surge the lower part of Bungebreen increased its thickness by up to 20 m (Ziaja, 2016).

A question from this investigation is therefore whether a new surge occurred since the glacier front is further downstream in 2020 than in 2009? In 2009, Bungebreen was marked as being in stage 2 of an ongoing surge (Sund et al., 2009). In stage 2 the downstream part of the glacier starts to thicken (Sund et al., 2009). This is in accordance with the observations of Ziaja (2016) in 2008 (above). In Stage 3 the glacier accelerates downstream, which can be seen on satellite imagery as many crevasses forming at the glacier front (Sund et al., 2009). It is difficult to determine whether the thickness of Bungebreen has changed between the 2009 orthophoto and the 2020 sentinel imagery. Furthermore, it appears as though there were more crevasses at the glacier front in 2009 compared to 2020 where the glacier front appears more even. However, crevasse formation at the glacier front since 2009 has not been identified in this study. This could mean that the thickening of the glacier between 2007 and 2009 was a build up to a surge, but that stage 3 of the glacier was not initiated and that Bungebreen experienced a partial-surge as explained in Chapter 2.3.

It is important to note the timespan of surges. Observation of the active phase in Alaska indicated that the active phase lasts from 1-3 years (Lønne, 2016). Contrary, surges in Svalbard have been found to have lasted from a few years to over 10 years with the quiescent phase lasting between 100 to 150 years (Lønne, 2016; Sund et al., 2009). With such long timespans it was not possible within the scope of this study and the amount of data collected to conclude whether a surge happened after the last documented surge in 2007/2008.

Implications of new annual moraines

Chapter 4.2 described how what appears to be new annual moraines have emerged ahead of the glacier front of Bungebreen in the 2020 imagery. Furthermore, it was explained that the glacier has advanced compared with the 2009 orthophoto (Figure 19). The presence of the possibly new annual moraines may indicate (in addition to the 2020 glacier extent) that the glacier must have advanced or surged relatively recently (if the glacier had only retreaded there would be no such landform there). After comparing satellite imagery from Earth Explorer over several years it appears that the annual moraines appeared after 2014, however the imagery is occasionally quite dark and of poor quality which makes it difficult to determine exactly when the landform actually appeared. Which coincidently makes it difficult to determine whether Bungebreen has indeed surged since 2009.

Furthermore, there are other factors that could lead to a glacial advance except for a surge. An advance could be the result of internal dynamics in the glacier. If there have been changes in external factors such as precipitation, it is possible the glacier has slightly advanced resulting in changes internally in the glacier. Another possible explanation is that polythermal glaciers have been found to have a so-called forward momentum during overall recession which results in small winter readvances (Evans, 2005) and this could have led to formation of annual moraines. If Bungebreen is indeed a polythermal glacier this could be the explanation, especially since the advance appears to be rather limited. This means that the appearance of the annual moraines is an indication that Bungebreen has a polythermal regime. Furthermore, since the advance is rather small, it seems unlikely that it was a surge event leading to the newly exposed landform even though the glacier front has less crevasses in the glacier front like surging glaciers do after a surge event. However, no conclusion about how the possibly new annual moraines were formed can be drawn based on this analysis.

Classification of landsystem

The Bungebreen landsystem have landforms that appears in both the surge type landsystem (Figure 35) and the landsystem for polythermal glaciers typical for Svalbard glaciers (Figure 36). The landforms that indicate surge-type landsystems are hummocky moraines, flutes, eskers, proglacial outwash plain and pitted and channeled outwash. The landforms that indicate a polythermal landsystem are ice-cored lateral moraines, traces of an outer moraine ridge, moraine mound complexes, diamicton (ground moraine), flutes, medial moraine (one and of a different type than the ones presented in the landsystem as this extends the length of the glacier), glacial meltwater streams and rock walls in the confining valley. Since both landsystems are represented by several landforms, it makes it difficult to determine which landsystem applies the most for Bungebreen. Therefore, no definite conclusion can be drawn here as more data is needed to conclude. However, as the glacier has been observed to surge in the past it is likely the landsystem is indeed a surge landsystem, only with some individual characteristics that differ from the surge model (and applies to the polythermal landsystem).

5.2.3 Vitkovskijbreen

Difference in area of fluted moraine

In Chapter 4.3, a difference in the two areas of fluted moraine in the foreland of Vitkovskijbreen was presented (Figure 28). A possible theory is that the fluted moraine to the east (Map 3) is affected by bedrock. On Figure 37 the foreland of Vitkovskijbreen can be seen underlain by a geological theme map. A major fault (black lines) can be seen going in the opposite direction of the divide between the two different fluted moraines (blue line). Based on this map there is not enough evidence to conclude whether the difference in the fluted moraines is because of differences in the underlying bedrock. However, as there may be uncertainties to where the exact divisions of the different types of bedrock is, the possibility that the dissimilarity in fluted moraines is because of differences in the bedrock cannot be completely discarded based on this data.

On the other hand, it could be that the dissimilarity between the fluted moraine is the result of a difference in the amount of meltwater going through the different sections of the foreland. There could have been more meltwater on the western side, which has diminished the flutes there, while on the eastern side there might have been less meltwater and therefore the flutes on the east side are better preserved. A third possibility is that a large meltwater river eroded an edge that could have led to the distinct divide between the two areas of fluted moraine. However if that was the case, there would be a canyon-like feature through the two distinct areas and would likely not have been able to affect the whole of the western fluted moraine. Moreover, it is possible the difference in fluted moraines could be the result of various stages during the glacial retreat because ice in various stages of melting will lead to an uneven surface (Klysz & Lindner, 1982). Furthermore, both Bungebreen and Vitkovskijbreen has large snow patches directly in front of the glacier on the western side. This may indicate that this part receives less insulation than the eastern side and could perhaps explain the differences in fluted moraine areas in the foreland of Vitkovskijbreen.

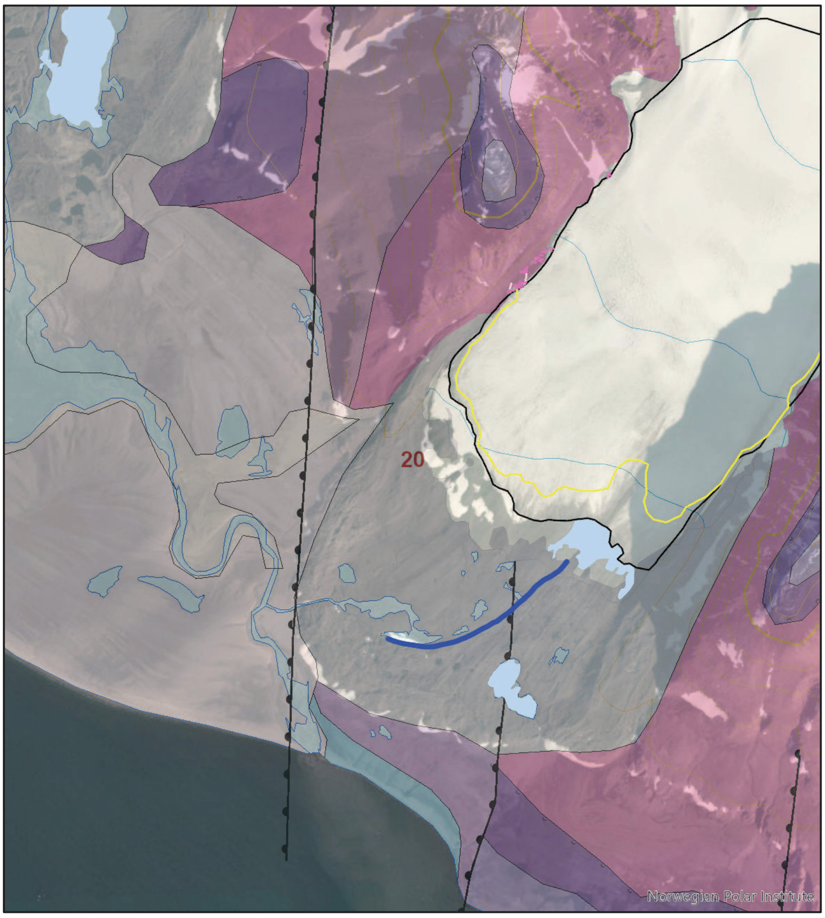


Figure 37: Overview of Vitkovskijbreen from the 2009 orthophoto from NPI overlain by a geological theme map from NPI. The black lines with dots are normal faults. The blue line shows where the split between the two different fluted moraines. Black line is 2009 glacier limit and yellow line is the 2020 glacier limit. The coloured patches represent different types of bedrock.

<u>Gorges</u>

Regarding the trend noted by Klysz and Lindner (1982) that the abandonment of the western gorge leads to the formation of a southern gorge. For Vitkovskijbreen this trend appears to be moderately applicable as there is a western gorge and a southern gorge in the terminal moraine complex. However the western gorge has not been abandoned. Further, the southern gorge is linked to a lake. This is interesting to note since the possible reason for the creation of the southern gorges has been thought to be from differences in different degree of retreat of the different parts of the glacier and differences in insolation (Klysz & Lindner, 1982). Based on the theory of Klysz and Lindner (1982) this means that the southern parts of Vitkovskijbreen does not receive more insolation than other parts of the foreland. Such could possibly explain the difference in fluted moraine in the foreland of Vitkovskijbreen. The presence of a southern gorge therefore supports the theory that the differences in fluted moraine is due to differences in meltwater fluxes. It is possible the western gorge becomes abandoned at a later time.

<u>Other landforms</u>

It is interesting to note that Vitkovskijbreen is the glacier in the study area with the most extensive area of fluted moraine as it covers almost the entire foreland. When looking at the whole area of fluted moraine it appears to have a convex shape, which could be due to major erosion from the glacier. Characteristics of the underlying bedrock could also impact the amount of erosion the glacier can exert. Further, this foreland appears to have the smallest area with glaciofluvial sediments and contrary to the other glaciers in the study area, the foreland of Vitkovskijbreen does not have an outwash plain inside the terminal complex. However, Karczewski et al. (1984) has mapped a considerable amount of glaciofluvial sediments in their map (Figure 6), so it could be it was difficult to observe the glaciofluvial sediments on remote imagery. Further, it only has three small sandurs outside of the terminal moraine complex, contrary to the large sandurs and outwash plains of Gåsbreen, Bungebreen and Belopol'skijbreen. Moreover, Vitkovskijbreen appears to still have an ice-cored terminal moraine, contrary to Bungebreen and Gåsbreen, which implies that thawing of dead ice goes slower here. When Vitkovskijbreen has considerable contrary evidence compared to the other glaciers, it indicates that there is something different either internal to the glacier or of the characteristics of the foreland. What that distinctive difference could be has not been uncovered in this study.

<u>Classification of landsystem</u>

Vitkovskijbreen is marked by Farnsworth et al. (2016) to potentially have surged following evidence of CSRs. However, since Vitkovskijbreen is not mentioned in the text one does not know where the evidence of the classification is from. This study has not observed CSRs in the foreland of Vitkovskijbreen. From this study the evidence for a surge-type landsystem (Figure 35) at the foreland of Vitkovskijbreen is a zone with hummocky moraines on the ice-proximal side of the terminal moraine, a zone with flutes and concertina eskers, however this zone should also have CSRs which are absent in this foreland. The evidence for a polythermal landsystem (Figure 36) is the ice-cored lateral moraines, an outer moraine ridge, an inner moraine mound complex, an inner zone with diamictons and flutes, glacier meltwater streams and rock walls in a confined steep-sided valley. Furthermore, the glacier has one small medial moraine. In view of this evidence it is most likely that Vitkovskijbreen has a landsystem like the one typical for Svalbard polythermal glaciers.

5.2.4 Belopol'skijbreen

<u>Differences between TM1 and TM2</u>

Firstly, it is noteworthy that the two different terminal moraine complexes (TM1 and TM2, Figure 33) of the two lobes of Belopol'skijbreen has noticeably different forelands. As described in Chapter 4.4, it is only behind TM2 that there are flutes, fluted moraine and hummocky moraine (Map 4). In the orthophoto from 2009 more of the foreland behind TM2 than behind TM1 has been exposed. However, after the dramatic retreat from 2009 until 2020, a large area behind TM1 has also been exposed. Based on sentinel imagery it does not seem that there are flutes and fluted moraine exposed behind TM1, however because of the low quality it remains unclear. One possible reason for flutes only being behind TM2 could be differences in constrains for the two lobes. The eastern lobe (TM2) is constrained by the mountain St. Nikolausfjellet, while the western lobe (TM1) has only a small rock outcrop on its western side. Previously, the western lobe was constrained by the tidewater glacier Olsokbreen, as seen in aerial photos from 1936 (Figure 32), yet since the retreat of both glaciers that is no longer the case. In other words, this difference in constrains may have led to different internal dynamics of the two different lobes which in turn could have led to the formation of different landforms, such as flutes, fluted moraine and hummocky moraine.

Another landform that has different coverage between the foreland of TM2 and not TM1 are eskers. There are some small eskers by TM1, while the eskers by TM2 are longer and more sinuous. Eskers are connected to the surging landsystem (Figure 35). Furthermore, there are many landslide scarps by the lake of TM1. This may indicate that slope processes are more active in this area of the foreland.

<u>Exposed bedrock</u>

In Chapter 4.4 it was explained uncertainties with the mapped bedrock in the central part of the glacier front. Wójcik and Ziaja (1993) observed rocky outcrops in the central part of the glacier in 1991. As the glacier front was much further downstream at the time of their expeditions, it is possible that the rocky outcrops they observed are the same bedrock mapped in the central part of Belopol'skijbreen in this study (Map 4). This may be possible since the glacier retreated behind this outcrop in 2020. During the same expedition it was observed that a small glacier (Toppbreen) had been separated from the larger Keilhaubreen (east of Belopol'skijbreen) and that this was likely due to influences of the relief of the glacier bedrock (Wójcik & Ziaja, 1993). Since Keilhaubreen is another outlet glacier of Sørkappfonna, comparisons between these two glaciers can be made. This means that the topography beneath Belopol'skijbreen may exert a strong influence on the separation of the two lobes and might continue to do so as the glacier retreats further. In Iceland topography have also been found to have exerted a strong control on the landsystem of an associated glacier and that this control can lead to landforms not normally associated with the actual landsystem (Chandler et al., 2020). Such topographic control could therefore also explain the different landforms in front of the two lobes of Belopol'skijbreen.

<u>Gorges</u>

Regarding the trend noted by Klysz and Lindner (1982) that the abandonment of the western gorge lead to the formation of a southern gorge. There is what appear to be a western gorge at TM1, but this does not appear to be quite abandoned, it could be water flows through during the height of melting season. There is no southern gorge at TM1 in the 2009 orthophoto, however large amounts of meltwater can be seen in the southern part of TM1 on sentinel imagery from 2020 and 2022 (Figure 30). This means that a southern gorge has been formed. For TM2 the opposite of the trend that has occurred. Here there is an abandoned southern gorge (there resides only a snow patch above it), while a western gorge appears to be quite active and is draining the large glacial lake within TM2. A possible reason for it being reversed for TM2 is that the glacier has a different orientation than Bungebreen and Vitkovskijbreen which likely has led to differences in insolation.

Classification of landsystem

Farnsworth et al. (2016) has marked Belopol'skijbreen as a potential surging glacier on the basis of CSRs. These have not been found during this investigation. However, there are other landforms that fits for the surge type landsystem. These are a zone with hummocky moraines on the ice-proximal side of the terminal (only applicable for TM2), a zone with flutes and concertina eskers (only TM2, regular eskers by TM1). The landforms that signify a polythermal landsystem are ice-cored lateral moraines, an outer moraine ridge, a moraine compound complex within the terminal moraine, an inner zone with diamicton, flutes and streamlined ridges, and glacial meltwater streams. Belopol'skijbreen is not confined by a valley, however there is a mountain constraining the eastern part of the glacier. It is difficult to conclude on such modest and diverging evidence. Especially considering there are no other studies to compare with. Nevertheless, it appears the foreland of Belopol'skijbreen is of a polythermal landsystem.

5.2.5 Remarks on the landsystem model

A question that arose during this study was: should eskers be included in the Svalbard polythermal Landsystem? Both Vitkovskijbreen and Belopol'skijbreen have large eskers, while Bungebreen has smaller eskers, but do not otherwise seem to fit the surge-type landsystem as CSRs are absent (even though Bungebreen has been documented to surge). Just like any other model, the landsystem models are simplifications of reality, and as such some landforms in the model may be absent from the actual landsystem. Similarly, landforms occurring in the actual landsystem, may be absent from the model since a model only represents the average and most common features. It has been proposed that since some landforms can be associated both with polythermal and surging glaciers, and some polythermal Svalbard glaciers exhibit a tendency to surge only sporadically, a new landsystem model for Svalbard glaciers accounting this should be conceptualized (Evans et al., 2012). The tendency for a foreland to display both surge landforms and polythermal landforms has been observed in some glaciers in Iceland (Evans et al., 2012) and in this study, most pronounced at Bungebreen which have had documented surges. Furthermore, the results from this study, where the landsystem analysis indicate all four glaciers to be polythermal glaciers, together with the results of Farnsworth et al. (2016) that marked the glaciers to either have surged (Bungebreen) or had potentially done so, indicates the need for a landsystem that incorporates landforms from both polythermal glaciers and surging glaciers as proposed by Evans et al. (2012). Further implications of surging glaciers are discussed in Chapter 5.5.1.

The differences in the forelands of the four glaciers in this study could potentially be due to differences in ice-flow regimes as proposed by Christoffersen et al. (2005) or the proportion between cold-or-warm based ice in the glaciers (Glasser & Hambrey, 2001). As all four glaciers in the study are likely polythermal it appears polythermal glaciers are common among the land-based glaciers in Sørkapp Land (Chapter 2.1.2). It must be noted that many of the other glaciers in the peninsula are tidewater glaciers (with most having surge activity) therefore the results of this study cannot be inferred for all the glaciers in the region (in addition to few data points). The fact that most of the land-based glaciers in this study are polythermal is in accordance with reports that show the majority of Svalbard glaciers are polythermal (Evans, 2005). This chapter accomplishes objective 1, 3 and 5 of this study.

5.3 Chronology

A goal for this study was to develop a chronology for the landsystem of Sørkapp Land. However, likely due to the issues with accessibility and the focus on tidewater glaciers in the region, as explained in Chapter 2.2 and Chapter 2.3, not many numerical dates have been uncovered. Only Butrym et al. (1987) and Salvigsen and Elgersma (1993) was found, which was not enough to develop a chronology for the study area. Even though Klysz and Lindner (1982) (Chapter 2.2.2) made a reconstruction of the glacial history of Bungebreen, it could not be verified during this study. Furthermore, some of the published dates are controversial (see Chapter 2.2.2). Therefore, only relative chronology has been possible for this study. The terminal moraine complexes were likely formed during the most recent glacial advance, the LIA, as described by Martín-Moreno et al. (2017) (and many others), however some of the lateral moraines (perhaps the eastern lateral moraine of Vitkovskijbreen) may be older following Ingólfsson (2011) and Figure 36. The new landform (possibly annual moraines) in front of Bungebreen is likely formed after 2013 following a small advance or a small surge. However, the results from this study did not yield enough data to achieve this objective and more data is needed to address this issue. Therefore objective 4 will need to be considered in future studies (see Chapter 6).

5.4 Comparisons with other studies

To further expand on the landsystems found in this study the results are compared to selected studies. Firstly other glaciers in Sørkapp Land, before both land-based and tidewater glaciers in Hornsund are presented. Next, glaciers at other parts of Svalbard (mostly north/central

Spitsbergen because most studies are done there) are compared with this study. Lastly, a relevance to Greenland is established.

5.4.1 Sørkapp Land

Belopol'skijbreen is the glacier that has retreated the most out of all the glaciers in the study area. This is interesting considering that Wójcik and Ziaja (1993) found the opposite to be true during their expeditions to southern Sørkapp Land in 1990 and 1991. In 1991 Belopol'skijbreen had retreated 0.3 km since 1961, and between 1936 and 1961 the glacier terminus had been essentially stable (Wójcik & Ziaja, 1993). However, the thickness of the glacier had been reduced with 50 m between 1936 and 1991 (Wójcik & Ziaja, 1993) which indicated the beginnings of recession. Also, during the expeditions in 1990 and 1991 the nearby glaciers Lyngebreen, Mathiasbreen and Keilhaubreen (among others) were investigated (Wójcik & Ziaja, 1993). The smaller glaciers such as Lyngbreen and Mathiasbreen were found to have had a retreat rate of ca. 1 km between 1936 and 1991 (Wójcik & Ziaja, 1993). The larger Keilhaubreen (which terminated at the shoreline in 1936) had retreated the most with 2 km between 1936 and 1991, and 0.6-0.9 km between 1961 and 1991 (Wójcik & Ziaja, 1993). Recently, the retreat rate of Gåsbreen was found to have increased since 1990 (Dudek et al., Submitted), the same is clearly the case for the other glaciers in the study area, with Belopol'skijbreen experiencing the largest retreat. Belopol'skijbreen is the only glacier in the study area that does not have mountain ridges on both sides of its marginal zone (Chapter 5.2.4). This would have affected both the glacier flow but also the amount of insolation the glacier receives and could potentially have influenced the severe retreat seen since 2009.

Could the dramatic retreat of Belopol'skijbreen be linked to climate fluctuations? Belopol'skijbreen is one of the most southern glaciers on Svalbard. However, it is likely that there are small differences between the most northern part of Sørkapp Land and the most southern part considering that the cold East Spitsbergen Current and the warm West Spitsbergen Current converges in the surrounding area (Chapter 2.1 and Figure 8). This is illustrated by the western part of the peninsula appearing less glaciated compared to the eastern side. Furthermore, Wójcik and Ziaja (1993) writes that sea ice occurs more often at the southern part of Sørkapp Land compared to the western part of Sørkapp Land, which strengthens the notion that the western and eastern part of the region is controlled by different climatic factors. It still remains unknown, what is the strongest influence on the southern part of the peninsula. However, it may be that the southern part is influenced by both the warm and cold ocean currents and that this leads to a difference in retreat in the various parts of Sørkapp Land.

5.4.2 Hornsund

Land-based glaciers

Werenskioldbreen is an east-west orientated land-based polythermal (Pälli et al., 2003) valley glacier located in the northern part of Hornsund. It has been named a textbook example of the Hornsund region land-based glaciers (Karczewski et al., 1984). It is logical to compare this glacier to the ones studied in this investigation as Hornsund is the nearest region and more work has been conducted there (Chapter 2.2 and 2.3). The foreland of Werenskioldbreen is characterized by glacial and fluvioglacial landforms undergoing changes due to melt-out (Zwoliński et al., 2013). The shoreline is dominated by raised marine terraces (Zwoliński et al., 2013), similar to those at Sørkapp Land. Similarly to Bungebreen it has a medial moraine extending the entire length of the glacier. The foreland consists of an ice-cored terminal moraine complex, outwash plain, ground moraine and fluted moraine (Zwoliński et al., 2013). It is therefore reasonable to compare the foreland of Werenskioldbreen with the forelands of the land-based glaciers of Sørkapp Land as they bear similar features and landforms. As Werenskioldbreen has similar landforms to Gåsbreen, Bungebreen, Vitkovskijbreen and Belopol'skijbreen it could be inferred that they indeed are most likely polythermal glaciers. A geomorphology map depicting the foreland of Werenskioldbreen in a scale of 1:25 000 is seen in Figure 38 (presented in the full geomorphology map from 1984 over the Hornsund region which can be seen in full in Appendix B). Werenskioldbreen has the same orientation as Gåsbreen. A presented reason for Gåsbreen not having fluted moraines was that it had a different orientation compared to the other glaciers in the study area (Chapter 5.2.1). However, since Werenskioldbreen has a similar aspect and yet has fluted moraines, this causes the reasons for Gåsbreen not having fluted moraines to be that of flowing direction to be unlikely. This adds more support to the theory that the absence of fluted moraines by Gåsbreen is due to the confining topography.

Tidewater glaciers

Since both the region of Hornsund and Sørkapp Land have numerous tidewater glaciers (Chapter 2.1.2), it is worth considering how the retreat and behaviour of the tidewater glaciers in southern Spitsbergen act in comparison to the land-based glaciers of Sørkapp Land. Tidewater glaciers in Hornsund have been found to have the fastest retreat rates in Svalbard (Błaszczyk et al., 2013). The main reasons for this are believed to be the maritime climate, contact with warm Atlantic water and the local topography (Błaszczyk et al., 2013). Because of this, the tidewater glaciers in the region are likely more sensitive to fluctuations in the climate-ocean system than other glaciers in Svalbard (Błaszczyk et al., 2013). Meaning the tidewater glaciers of southern Spitsbergen display a different pattern than the rest of the tidewater glaciers in the archipelago, probably due to their unique setting (influenced by both warm and cold ocean currents). A similar maritime climate (Chapter 1.2 and 2.1) also affects the glaciers in Sørkapp Land.

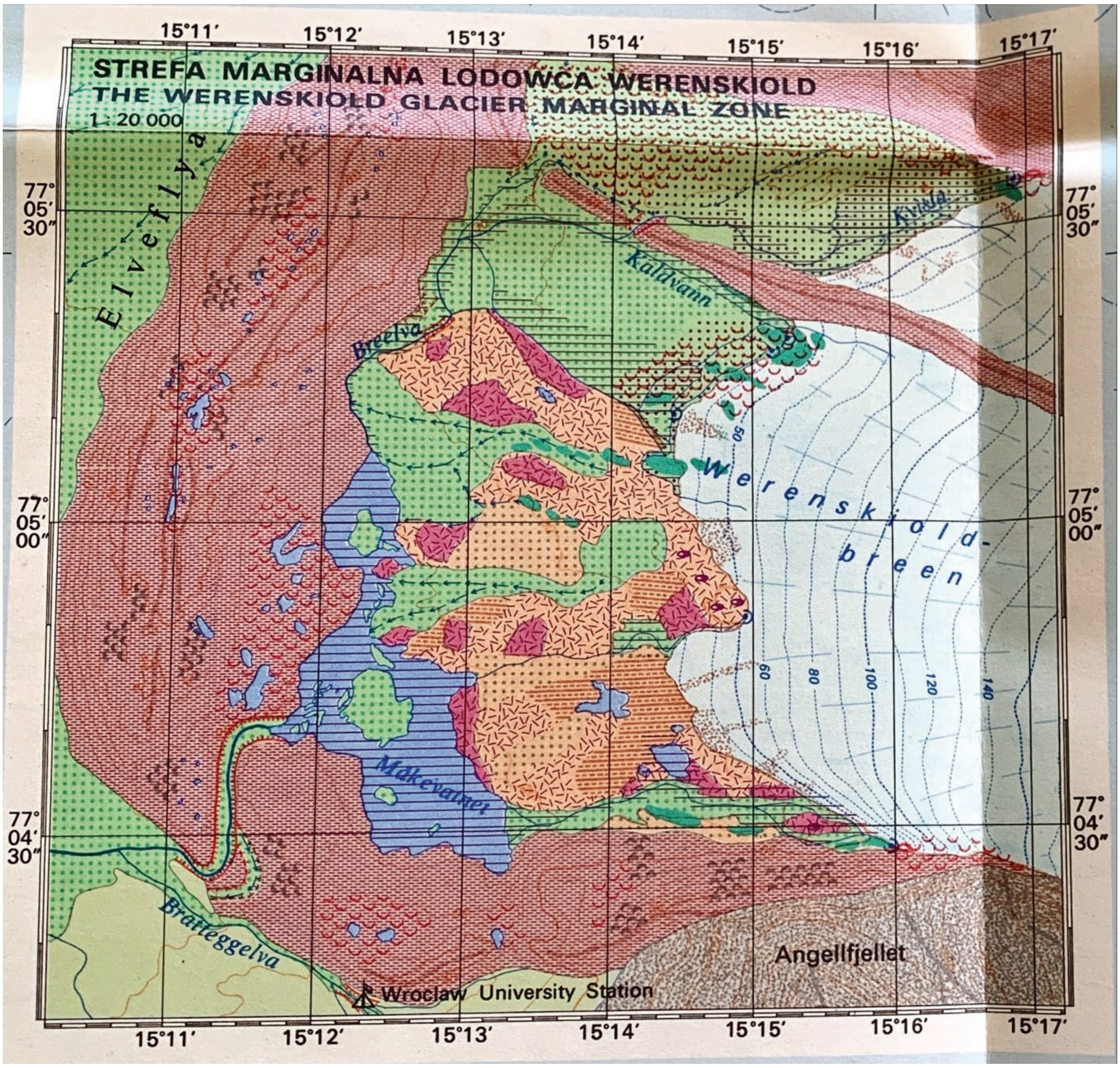


Figure 38: Scan of an inset map of Werenskioldbreen (North Hornsund) from the geomorphology map of the Hornsund region from 1984 (Karczewski et al., 1984). See Figure 7 for legend and Appendix A for the entire original map.

Belopol'skijbreen had the largest retreat in this study. Randbreen, which was a tidewater glacier at the eastern side of Sørkapp Land, terminated at the shoreline in 1936, just as Keilhaubreen (Chapter 5.2.4) did (Wójcik & Ziaja, 1993). However, Randbreen had retreated only about 0.5-1.3 km since 1936. This emphasizes that the cold ocean current on the eastern side of Sørkapp Land probably exert a strong influence on the glacial fluctuations on this part of the region, while the glaciers on the western coast are likely influenced by the warmer ocean current flowing along the western side of the peninsula instead. The sea water temperature has been found to important for the behaviour of tidewater glaciers in the Hornsund region as it affects air temperatures and melts the ice cliffs (Błaszczyk et al., 2013). This demonstrates the importance that ocean currents can have on glacier fluctuations and could be indicative that glaciers residing near warm ocean currents may face large retreat rates in the future.

Kavan et al. (2022) studied 11 tidewater glaciers in the south-eastern Spitsbergen. The glaciers had an average retreat rate of 48 m per year since 1970 (Kavan et al., 2022). Out of the 11 tidewater glacier, 4 had become land-based glaciers in the studied time period (last 50 years) (Kavan et al., 2022). During this transition the retreat rates had slowed down (Kavan et al., 2022). This could indicate that the tidewater glaciers at Sørkapp Land will display a similar retreat pattern. Since the tidewater glaciers are so strongly influenced by their setting, the same situation may be the case for the land-based glaciers in Sørkapp Land. The maritime setting may insert a deep impact on Sørkapp Land as it is likely heavily influenced by the convergence of the ocean currents. Such setting affects the rate of landscape changes as mentioned in Chapter 1.2.

Furthermore, the tidewater glaciers in Hornsund are important for the glaciers of Sørkapp Land because of the two tidewater glaciers Hambergbreen and Hornbreen that is connecting the peninsula of Sørkapp Land to Spitsbergen. Global warming will cause these two tidewater glacier to retreat, and form a strait between the Greenland Sea and the Barents Sea (Ziaja & Ostafin, 2015). A strait in that location has been found to do have formed previously between Early and Middle Holocene (Osika et al., 2022). Such a strait will probably largely affect the climate in Sørkapp Land and the glaciers residing there.

5.4.3 Svalbard

Two selected glaciers in central Svalbard, Hørbyebreen and Ragnarbreen, are presented as to determine whether there are major differences between land-based glacier in a maritime setting versus a continental setting. Both Hørbyebreen and Ragnarbreen have more of a continental setting (Ewertowski, 2014), while the glaciers in this study have a maritime setting.

<u>Hørbyebreen</u>

Hørbyebreen is a polythermal valley glacier in central Svalbard displaying landforms typical for polythermal glaciers, such as ice-cored latero-frontal moraines and fluted moraine (Evans et al., 2012). At Hørbyebreen the transition between glacial to paraglacial features for such as ice-cored moraines, glacifluvial sediments and other landforms were the greatest between 1990 to 2013 (Ewertowski et al., 2019). Before then, the glacier had experienced a decrease in glacial area from 62% to 34% (Ewertowski et al., 2019). Indicating that the largest changes happened before the substantial frontal retreat of Hørbyebreen. The landsystem of Hørbyebreen have been found to be of the polythermal landsystem common for Svalbard glaciers (Evans et al., 2012). However, the landsystem of Hørbyebreen also had landforms typical of surging activity (linear eskers and crevasse fill landforms) (Evans et al., 2012), drawing comparisons to Bungebreen which was found in this study to have landforms typical for both polythermal and surging landsystems. This further indicates that a polythermal landsystem also including landforms commonly associated with surging glaciers is needed. On the other hand, Evans et al. (2012) mentions that the landforms associated with surging activity found at the foreland of Hørbyebreen also can indicate a jøkulhlaup, which complicates matters further. Later, these were found to be surge-induced jøkulhlaups based on the evidence of low-amplitude landforms namely geometric ridge networks (Evans et al., 2022). However, as high-resolution data is not available for the study area this could not be investigated in this study. Nevertheless, it is worth mentioning as this is something that could explain some of the inconsistencies with the landsystem classification at Bungebreen.

<u>Ragnarbreen</u>

Ragnarbreen is a small valley glacier in central Svalbard, east of Hørbyebreen. According to Dudek et al. (Submitted) Ragnarbreen (and Midtre Lovénbreen) has had a lower elevation change of the terminal moraine compared to Gåsbreen. The main landform changes consisted of dead-ice melt out and debris flows (Ewertowski, 2014). However, the formation of a terminoglacial lake were one of the biggest landscape changes and is believed to have sped up the glacial recession (Ewertowski, 2014). The lateral moraine changed considerably, largely due to debris flows and backwasting in different degrees over time (Ewertowski, 2014). The terminal moraine was quite stable, however it still experienced ice melt out and minor debris flow activity (Ewertowski, 2014). At Ragnarbreen the lateral moraines were found to be the quite stable when comparing elevation in the periods 1961-1990 with 1990-2009, while the terminal complex was more stable in the same period (Ewertowski, 2014). The same appears to be true for Vitkovskijbreen and Belopol'skijbreen which have elevated, ice-cored lateral moraines while the terminal moraine appears to be at lower elevation and have started to degrade. Bungebreen appears to have the opposite landscape transformation as there the terminal moraine is very degraded while, the lateral moraine appears to have been more stable. At Gåsbreen the terminal moraine appears ice-cored still and some parts of the southern lateral moraine as well, however Gåsbreen has a very distinct landsystem due to the restricting topography by the mountain side of Wurmbrandegga. This could be due to differences in thickness of the debris cover, since the thickness of the debris cover hinders the ice to melt out (Ewertowski et al., 2011). This further indicates that there are major changes happening in the forelands of the land-based glaciers, mainly due to the increase of meltwater. Nevertheless, there are still local differences amongst the land-based glaciers in Sørkapp Land.

The studies from Hørbyebreen and Ragnarbreen highlights that the main changes in the glacial forelands in Svalbard appears to happen due to dead-ice melt out and slope processes because of an increase of meltwater. This appears to be the case for both maritime and continental glaciers. However, the rate of change may be faster for glaciers in a maritime setting since the glaciers there gets exposed to milder weather which exposes newly deglaciated land to be affected by weathering and other denudation processes (Chapter 1.2). Ice melt-out and slope processes was found in this study for Gåsbreen, Bungebreen and Belopol'skijbreen. Evidence of slope processes has not been as clear in the foreland of Vitkovskijbreen. Bungebreen appears to be the glacier where the foreland has undergone the most changes in terms of ice-melt out and slope processes.

5.4.4 Greenland

As mentioned in Chapter 1.1, melting ice from the GrIS and other glaciers in the Arctic contribute more to global sea level rise than the ice from Antarctica (AMAP, 2021). This makes it relevant to consider a similar landsystem in Greenland to the landsystems found in this study. A landsystem for polythermal surging glaciers has been established at the glacier Kuannersuit in West-Greenland. The polythermal glacier Kuannersuit was documented to have had surges between 1995 to 1998 (Yde et al., 2005). This polythermal surge landsystem is determined by thrust and stacked structure of naled, basal and meteoric ice in addition to the debris content and is divided into four zones (Roberts et al., 2009). The outer edge of the landsystem is characterized by linear moraines parallel to the ice margin (Roberts et al., 2009). Closer to the ice margin there will be hummocky and kettled topography (Roberts et al., 2009). Later, the landsystem will be occupied with CSRs and concertina eskers with crevasse infills (Roberts et al., 2009). The main landforms in this polythermal surge valley landsystem at Kuannersuit are naled (in different stages), supraglacial crevasse infill, concertina eskers, kettle holes, ice-cored ridges, ice-cored thrust moraines, outwash plains and subglacial material (Roberts et al., 2009). However, in the early post-surge period in this foreland, landforms such as CSRs and eskers were not found (Roberts et al., 2009). This landsystem from Greenland is quite different from the landsystems found at Sørkapp Land in this study. However, there are certain similarities such as hummocky moraines, kettle holes, eskers, ice-cored ridges and outwash plains.

As Bungebreen has been found to have a polythermal surging landsystem a comparison with Kuannersuit is interesting, although there are some large differences. For example, the landsystem of Kuannersuit does not seem to have an extensive terminal moraine complex such as Bungebreen. A similarity between the two forelands is the presence of hummocky moraines close to the ice margin. The forelands of Kuannersuit and Bungebreen does only have a few landforms in common. However, this difference could be explained if the glaciers were in different stages of surging. Moreover, it could be that there are fundamental differences between the surging glaciers in Greenland and Svalbard. Differences between the surging glaciers of Svalbard and Alaska have been found (Murray et al., 2003), the same may therefore be possible for the surging glaciers in Greenland and Svalbard, and this would have led to differences in their landsystems. However, comparing one single glacier to these four studied here, is not enough to make conclusions on. Regardless, it appears there is a need for a landsystem for the polythermal surging glaciers in Svalbard and findings of a dissimilar polythermal surging landsystem in Greenland supports that.

This chapter concludes the work on objective 5, as possible landsystems for the four land-based glaciers in Sørkapp Land has been described in detail in Chapter 5.1, 5.2 and this chapter.

5.5 Climate change

Since the retreat of glaciers causes the sea level to rise (Chapter 1.1) it is important to put this study in the context of climate change. First the implications of surging glaciers in the view of climate change are investigated before consequences of the future climate is examined.

5.5.1 Implications of surging glaciers

There has been a conception that ice mass loss, particularly elevation changes such as thinning of the glacier and the thickening of the glacier front may be indicative of a glacier's respond to climate change or a beginning stage of a surge (Sund et al., 2009). However, not all large mass loss (Chapter 2.3) is necessarily the result of climate change (Sund et al., 2009). On the other hand, a lowering of the elevation of a glacier does not certainly indicate the beginnings of a surge either (Sund et al., 2009). Further, there has been raised questions about how surge activity will be influenced by the changing climate (Schuler et al., 2020). This could mean that the glaciers in Svalbard cannot be solely seen as being influenced of climate change, there are other factors that must be considered as well, especially regarding the large amount of surging glaciers in Svalbard and the fact that it is unknown how they react to climate change.

Sund et al. (2009) believes the majority of the glaciers on Svalbard are surging glaciers, as much as 90% (Chapter 2.1.2). An explanation of the large differences in reported numbers of surging glaciers have been assigned to different methods and the fact that early studies excluded smaller glaciers as it was believed that only large glaciers were likely to experience surges (Sund et al., 2009). Furthermore, the fact that the surging glaciers on Svalbard have a very long quiescent phase also made it difficult to make comprehensive inventories (Sund et al., 2009). The low preservation potential of the landforms indicative of surges has also been allocated as a reason for under-reporting of surging glaciers (Sund et al., 2009). The inventory done by Sund et al. (2009) has the largest number of reported surging glaciers at 90% and it includes all large mass displacements, partial surges, surges in small glaciers, however because of the long quiescent phase and the different climatic conditions an exact number is not likely to ever be reported (Sund et al., 2009). Since an increase in surges has been linked to possible increasing contribution to sea level rise (Chapter 2.3), it is important to know how many surging glaciers there are on Svalbard.

It was predicted that surges in Svalbard would decline due to global warming (Schuler et al., 2020). However, since 2000, several large surges have been reported and it appears as though the amount of surges has increased, but it is unclear whether this is because of an actual increase in surges or because of better opportunities to observe surges (Schuler et al., 2020). Whereas, surging glaciers in Iceland has exhibited a reduced surging potential following the glacier recession since the start of the 1900s, (Christoffersen et al., 2005). The same could be the case for surging glaciers in Svalbard (Christoffersen et al., 2005). In fact the transition from surging glacier to non-surging glacier, has already been observed at Midtre Lovénbreen (Christoffersen et al., 2005; Hambrey et al., 2005; Hansen, 2003) and at Austre Brøggerbreen (Hambrey et al., 2005). Another glacier that may have had such transition is the potentially surging glacier Elisebreen (Christoffersen et al., 2005; Farnsworth et al., 2016). However, Elisebreen has likely lost its potential for surging due to thinning (first stage of a surge) and that the glacier is not rebuilding mass (Christoffersen et al., 2005). The reason for the loss of its surge potential has been linked to the Artic amplification (Chapter 1.2) following global warming (Christoffersen et al., 2005). If that is the case, there will probably be fewer surging glaciers in Svalbard in the future. However, with reports of both increase and decrease in surging glaciers in Svalbard, it is clear that there are unknowns surrounding this issue. Monitoring the glaciers closely is possibly part of the solution for this issue.

5.5.2 Future climate

A study that compared the spatial pattern of mass balance at 1595 glaciers in Svalbard over a 70 year time period made it possible to quantify how temperature and precipitation exerts control on ice mass loss as they were able to discard annual and decadal variables (Geyman et al., 2022). The results showed that melting rates are dependent on temperature (Geyman et al., 2022). Further, they made projections on how the glaciers of Svalbard will change during the 21st century (Geyman et al., 2022). The strongest control on glacier thinning were shown to be mean annual temperature and summer air temperature, rather than precipitation and solid precipitation or the warming trend for the 20th century (Geyman et al., 2022). Meaning that the Svalbard glaciers could survive the 20th century if they could get enough snow during winter, however if the glaciers are in a climate that has passed over a certain temperature “threshold”, they would not survive even with snow precipitation (Geyman et al., 2022). It is unclear whether the model was able to take into consideration that the precipitation over Svalbard will be increasingly rain during winter, not snow, due to climate change (Majchrowska et al., 2015).

Under a modeling of the highest emission scenario it was projected that ca. 1435 of the 1471 land-based glaciers in Svalbard would have disappeared completely by the end of the 21st century (Möller et al., 2016). The glaciers in the lowlands of Nordenskiöldland and the glaciers on the eastern island, Barentsøya and Edgeøya will disappear first while the large land-based glaciers in the highlands of north-east Spitsbergen will have remnants left until mid 22nd century (Möller et al., 2016). The beginnings of this disappearance of land-based glaciers could potentially follow a shift from tidewater glaciers to land-based glaciers (Kavan & Strzelecki, 2023) (Chapter 5.4.2), as was observed after the major glacial retreat of Svalbard, especially in south-east Svalbard (Kavan et al., 2022). This could have major consequences, both for the local environment by increasing the coastal areas (Kavan & Strzelecki, 2023). Also regionally, the effects may have a large significance, for example the split of Hornbreen and Hambergbreen (Hornsund) (Chapter 5.4.2). When these two glaciers split and eventually become land-based it will make Sørkapp Land become an island instead of a peninsula (Ziaja & Ostafin, 2015), this could potentially have major effects on the eastern side of the peninsula that so far is more glaciated than the western part. This could mean that land-based glaciers in low-land coastal areas are sensitive to climate change.

The highest increase of temperature in Svalbard has been projected to be in areas where the extent of sea-ice will be reduced (Førland et al., 2011). The amount of days with temperatures over 5°C will go from 50 days in the present climate to 75 days in 2021-2050 (Førland et al., 2011). As explained in Chapter 2.1 precipitation also exert a large control on the climate and that there are difficulties with measuring the precipitation in Svalbard. However, a trend at the measuring station near Longyearbyen (Svalbard airport) shows an increase of 2% precipitation per decade since the starts of measurements there (Førland et al., 2011). Furthermore, the loss of sea ice will likely influence Svalbard both locally and regionally as well as through large-scale atmospheric circulation (Førland et al., 2011) due to the Artic amplification (Chapter 1.2). Meaning that the future reduction in sea ice will strongly contribute to further changes in the Arctic climate (Førland et al., 2011), as well as the increase in temperature and precipitation (Chapter 1.1).

Svalbard is an ideal place to observe how glaciers interact with climatic factors, as infrastructure for research is well established in many places (Schuler et al., 2020). However, as this study shows, there are certain areas, such as Sørkapp Land, where there remains many unknowns. Nevertheless, the obtained knowledge from the research in Svalbard will help to contribute to an increased understanding of how the Antarctica and Greenland ice sheets (Chapter 1) may respond to future climate change, as Svalbard is already facing environmental changes due to recent global warming (Schuler et al., 2020). This chapter implies that the glaciers in this study is facing an uncertain future, together with the other glaciers in Svalbard and the Arctic.

6 Future research

The contribution of this study has led to several interesting ideas which would be excellent for future research in Sørkapp Land. These should ideally focus on geomorphology, glacial fluctuations, chronology and be more based on new fieldwork studies as stated by Chandler et al. (2018). Particularly Belopol'skijbreen should be studied further as descriptions of it are scarce. Furthermore, the sediments in the glacial forelands should be investigated to get additional and more detailed descriptions. Since previous research in Sørkapp Land has centered around the western part of the region, future research should include the southern (and eastern) parts as well. Therefore, similarities and differences can be further investigated and transformations of the landscape due to climate change can be detected. Furthermore, the following issues should be addressed:

- Retreat measurements by means of the common methods such as either centre-line, bow or box methods (Lea et al., 2014) should be done to more easily put the retreat of the studied glaciers in a larger context and be more comparable to other studies. For a method with proven less error, the extrapolated centre-line method of Lea et al. (2014) is recommended.
- It should be confirmed that the glaciers are polythermal and studies could find out how much of the glacier is cold and temperate, this can be done through GPR reading similar to that of Pälli et al. (2003) and Reinardy et al. (2019).
- Further studies regarding the landsystem of the glaciers mentioned in this text should follow the approach similar to Lee et al. (2018).
- Landscape changes should be traced by using comparisons of DEMs from different years.
- A chronology needs to be developed. Plausible methods are lichenometry to constrain the recent glacial fluctuations. To constrain older glacial fluctuations, the use of cosmogenic exposure should be undertaken. Radiocarbon dating is perhaps also an option but there may be challenges due to other processes which have dominated the study area recently.

7 Conclusions

This study has made detailed maps of the glacial geomorphology at the forelands of four land-based glaciers at Sørkapp Land in the Svalbard archipelago. Three glaciers were found to have retreated, while the last, Bungebreen, has advanced. Landforms were identified and later applied to a landsystem approach to be able to deduce their thermal regime. Landscape changes from 2009 to 2020 were identified. Where previous studies were available, landscape changes from the 1970s and 1980s were described. Comparisons to a geomorphology map from 1984 indicates geomorphological changes at the forelands of Gåsbreen, Bungebreen and Vitkovskijbreen. The comparisons highlight the major landscape changes of the area. Several differences between the four forelands were found and the reason for some are believed to be differences in insolation and topography. Topographic differences appear to exert strong control on glacier dynamics and have likely led to the formation of different landforms. The glaciers in Sørkapp Land are likely largely affected by their maritime setting. Ice melt-out and slope processes are important in the forelands of retreating glaciers in Svalbard, including Sørkapp Land. Furthermore, the following conclusions were made:

- The Bungebreen foreland appears to be more active due to a severely degraded terminal moraine complex and the appearance of a new landform in front of the glacier between 2009 and 2020. While some parts of the Gåsbreen foreland have been taken over by slope processes. Not much information on Vitkovskijbreen was found from other studies. However, there may be some differences between this glacier and the others due to the extensive fluted moraine in its foreland. At Belopol'skijbreen there are differences between the forelands of two different lobes of the glacier, which could perhaps be due to internal glacier dynamics or different topographic restraints.
- Each glacier was categorized after the landsystem approach based on information regarding the landsystem and the glacial thermal regime. Gåsbreen – polythermal landsystem, Bungebreen – surge-type and polythermal landsystem, Vitkovskijbreen – polythermal, Belopol'skijbreen – polythermal. Most glaciers in Svalbard are polythermal, this appears to be the same for Sørkapp Land. Through the investigation all four glaciers have been concluded to be polythermal glaciers. However, there is a need for a landsystem with both polythermal and surging landforms for Svalbard glaciers.
- A satisfactory chronology could not be obtained from the data collected in this study.
- Additional evidence has not been found regarding whether the glaciers are surge type to add to existing inventories. The findings rather reinstate that surge type glaciers are a complex subject. Monitoring the Sørkapp Land glaciers may lead to more information regarding surging glaciers, retreating glaciers and climate change.

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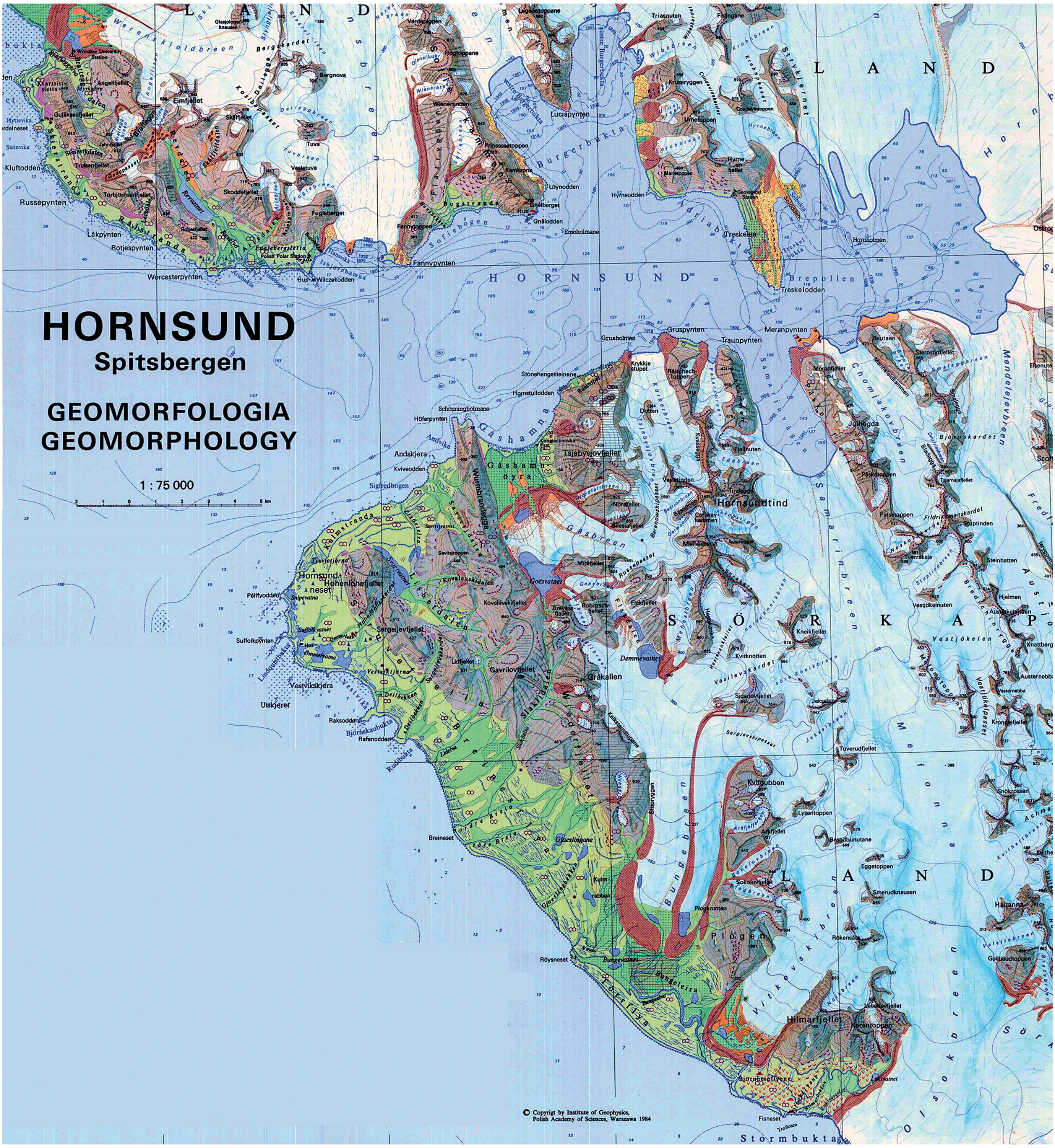
Appendix

Appendix A: scan of original map over Hornsund from 1984 (Karczewski et al., 1984)

Appendix B: fragment of Hornsund map from 1984



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