Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Social and Educational Sciences
Department of Geography

Vendela Gabrielle Solberg Hergot

Where the Arctic River Meets the Sea; Connections Between Fluvial and Shoreline Processes in Isfjorden, Svalbard

Master's thesis in Geography
Supervisor: Chantel Nixon
Co-supervisor: Lena Rubensdotter and Maria Jensen
June 2021

NTNU
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UNIS
The University Centre in Svalbard

NORGES GEOLOGISKE UNDERSØKELSE
· NGU ·

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Abstract

This thesis is a geomorphological and surface sedimentological study of five different locations in the large fjordsystem of Isfjorden, which is located on the western coast on Svalbard. This study aims to get a better understanding of the different coastal areas in this particular fjord system, analyse the changes over time to get a wider understanding of how the changing climate might have an impact on sensitive coastlines on Svalbard. Fieldwork have been conducted in the fall of 2020, and have resulted in detailed data about the coastal change in six different locations, combined with field observations in the surrounding area and the internal structure of some selected coastal landforms. Some sediment samples were taken at selected location, to serve as complimentary data for the analysis. The connecting watersheds to these areas have been analysed by satellite imagery, to be able to conduct a more correct analysis of the different types of change in the modern day coastal areas.

Historic aerial photos from 1990 have been delivered by NPI on five out of six different field sites, these have been analysed to gather more information about the past changes in these areas, because of this more in depth analysis have been made on how the coast have changed since 1990 to 2020.

Geomorphological and surface sedimentological research is something that lacks of information in Svalbard, and not much research have been done in this landscape before. Combined with the sensitive landscape in Svalbard, because of the geology, glacial history and the harsh weather conditions, combined with a changing climate causing increased temperature, especially during winter and spring season, increased precipitation, thawing permafrost and the increasing thickness of the active layer.

This analysis show that some of these selected coastal systems have experienced a large difference in the coastal areas between 1990 and 2020, and some of these areas show almost no difference in this time period. The cause of the change, and the cause of lacking change have been discussed, and some theories on what changes have been made, and forces making the change have been highlighted.

Sammendrag

Denne oppgaven er en geomorfologisk og overflatesedimentologisk studie av fem forskjellige steder i det store fjordsystemet Isfjorden, som ligger på det vestlige kysten av Svalbard. Denne studien tar sikte på å få en bedre forståelse av de forskjellige kystområdene i dette bestemte fjordsystemet, analysere endringene over tid for å få en bredere forståelse av hvordan klimaet i endring kan påvirke følsomme kystlinjer på Svalbard. Feltarbeid er utført høsten 2020, og har resultert i detaljerte data om kystendringen på seks forskjellige steder, kombinert med feltobservasjoner i området rundt og den interne strukturen til noen utvalgte kystlandformer. Noen sedimentprøver ble tatt på valgt sted for å tjene som gratis data for analysen. Forbindelsesvannområdene til disse områdene er analysert ved hjelp av satellittbilder for å kunne foreta en mer korrekt analyse av de forskjellige endringene i dagens kystområder.

Historiske flybilder fra 1990 har blitt levert av NPI på fem av seks forskjellige feltsteder, disse er analysert for å samle mer informasjon om tidligere endringer i disse områdene, på grunn av dette er det gjort en grundigere analyse av hvordan kysten har vært endret siden 1990 til 2020.

Geomorfologisk og overflatesedimentologisk forskning er noe som mangler informasjon på Svalbard, og det er ikke gjort mye forskning i dette landskapet før. Kombinert med det følsomme landskapet på Svalbard, på grunn av geologien, den glasiale historien og de ekstreme værforholdene, kombinert med et skiftende klima som forårsaker økt temperatur, spesielt om vinteren og våren, økt nedbør, tining av permafrost og den økende tykkelsen på det aktive laget.

Denne analysen viser at noen av disse utvalgte kystsystemene har opplevd en stor forskjell i kystområdene mellom 1990 og 2020, og noen av disse områdene viser nesten ingen forskjell i denne tidsperioden. Årsaken til endringen og årsaken til manglende endring har blitt diskutert, og noen teorier om hvilke endringer som er gjort, og krefter som gjør endringen har blitt fremhevet.

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To Maria

Thank you so much of giving me this amazing opportunity to work with a highly interesting topic and letting me travel to all of these amazing field areas in Isfjorden. This have been an experience that I will never forget, thank you.

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A special thanks needs to be given to the three polar bears that I have meet personally during fieldwork, our meeting did not help with the effectiveness of the fieldwork, but it was an incredible experience.

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Introduction

Motivation

Global warming in the arctic is occurring twice as fast as in the rest of the world (aka"Arctic Amplification (IPCC, 2007; 2014). Rapid warming can be observed on the Spitsbergen archipelago, located between 74N and 81°N and 10E 35°E (Figure1), in the form of melting glaciers, thawing permafrost, and increased slope activity, for example, debris flow slides (IPCC, 2007, 2014). Together with increased precipitation observed on Spitsbergen since 1912 (Eckerstorfer & Christiansen, 2011) when precipitation on Spitsbergen started to get measured regularly, and diminishing sea ice (IPCC, 2007), all of these processes are likely increasing the flux of sediment transport from inland to the coast as well as coastal erosion (De Haas, Kleinhans, Carbonneau, Rubensdotter, & Hauber, 2015).

At present, systematic mapping of the surficial geology and geomorphology of Spitsbergen is available for the following areas: Adventdalen (Tolgensbakk, Sørbel, & Høgvard, 2000); Braganzavågen (Rubensdotter, Larsen, & Lyså, 2016). Bjørndalen-Vestpynten (Rubensdotter, Romundset, Farnsworth, & Christiansen, 2015a); And Todalen, Gangdalen and Bødalen (Rubensdotter, Stalsberg, Christiansen, Eckerstorfer, & Tøyen, 2015b). See figure 2 and 4 for locations. Surficial geology maps have also been published for smaller area, for specific research projects in Dicksonfjorden, Fredheim, and Peuniabukta, for location look figure 2. Such maps represent a snapshot in time of local coastal geomorphology and surficial geology in specific coastal areas of Spitsbergen. Since the little ice age (19th to early 20th century) there have been observed large changes in the coastline around Svalbard, this is resulting in dramatic increase in sediment supply in certain areas retreating local ice, shortening of the winter season and sea ice season and the thawing permafrost (M. Strzelecki, Long, & Lloyd, 2013)

High Arctic Svalbard is especially sensitive to changes in the climate, and since 1980s Svalbard have experienced climate change at a double speed than the rest of the word (NPI, Unknown date). The changing climate in Svalbard does not only have an impact on the local environment in, but it will have an impact on the landscape is not located in the norther hemisphere, and could possibly have an influence on the entire atmospheric circulation in the Arctic (NPI, Unknown date)

This thesis is part of the DynaCoast and MovingCoast projects (Svalcoast). The aim long-term is to produce a map of dynamic coastal landforms and sediment transport along the entire coastline of Svalbard. This information in form of maps over the coastal landforms and processes along the coast on Svalbard will provide a tool for making environmental decisions for remote parts of Svalbard, including evaluating risk for cultural heritage located close to the shoreline in remote areas (Jensen & Rubensdotter, 2020).

The new data and maps that have resulted from this thesis will supply some missing pieces to the slowly growing body of knowledge about coastal processes and rates of change in Isfjorden Spitsbergen (Fig, 2). In combination with the new geomorphological maps produced for this thesis, comparisons were made to older maps and aerial imagery in order to quantify rated of change, and to answer three research questions that were developed to increase our understanding of the most important drivers of high Artic coastal morphodynamics over the past few decades. These research questions include; 1. What are the different morphological characteristics of large river- mouths in Isfjorden? 2. Is there a relationship between catchment characteristics and river mouth/ coastal development in different coastal areas of Isfjorden? 3. Are there observable changes over time in some of the river mouth systems of Isfjorden? If so, can these changes be linked to local or regional environmental factors?

Regional setting of Svalbard

Svalbard archipelago is located on the north-western corner of the Barents Sea Shelf, between 74°-81°N and 10°-35°W (Fig 2). In this area there is a large number of islands, covering an area of about 60,667km^2. The largest island of this archipelago include Spitsbergen, Nordaustlandet, Barentsøya, Edgeøya, Kong Karls land, Prins Karls Forland, and Bjørnøya (Dallmann, Blomeier, & Elvevold, 2015); Fig 2). In the late 2000s, Svalbard had a glacial coverage of ca 57% (Dallmann et al., 2015). Glacier distribution is more extensive on the west and the east coasts of Spitsbergen; the mass balance of these glaciers are mostly controlled by climate and topography (Dallmann et al., 2015). Bedrock geology weathering, and the effects of smaller glaciers and permafrost where the main drivers of landscape evolution during the Holocene (Dallmann et al., 2015). Climate warming now exerts a major control on landscape evolution, for example, increasing depths of the active layer can lead to increased erosion, and sediment transport during the summer melt season (Humlum, Instanes, & Sollid, 2003).

Climate and Oceanography

The climate on Svalbard is classified as polar tundra, which means that the average summer temperature is between 3 -12 °C (Nunez, 2020) The western side of the Svalbard archipelago experiences higher humidity due to warm ocean currents, but the humidity gets lower closer to the central northern part of the archipelago (Hanssen-Bauer et al., 1990). Svalbard is located in the middle of the main transport path for several large ocean currents including the Gulf Stream, which means that is has a relatively mild climate for its latitude (Hanssen-Bauer et al., 2019).

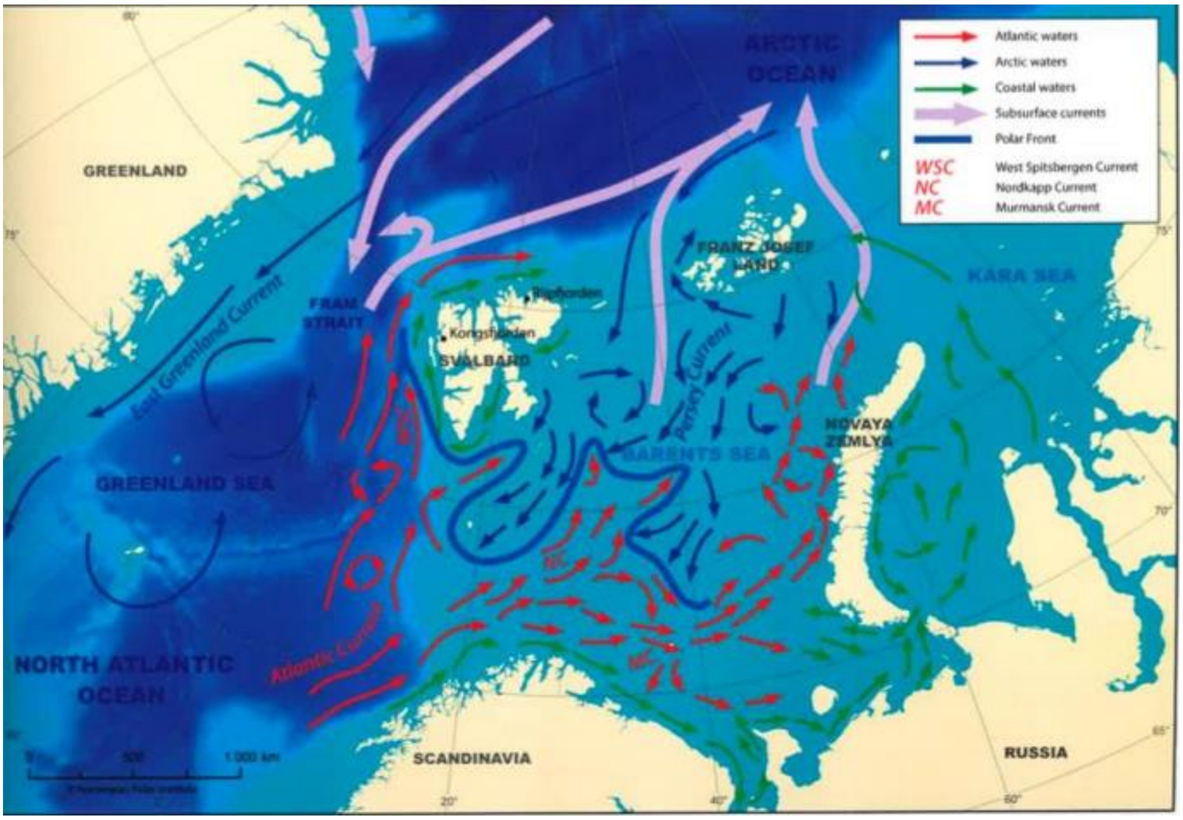

Figure 1: Illustration of the major cold and warm currents in the North Atlantic Ocean, Greenland sea and the Barents sea. Illustration after (Dallmann et al., 2015).

The West Spitsbergen current (WSC) transports warm water with high salinity from the Gulf Stream to the west side of Spitsbergen and continuous north (Fig 1). This differs from the east coast, which is dominated by cold polar water from the Arctic basin (Hanssen-Bauer et al., 2019).

Study areas

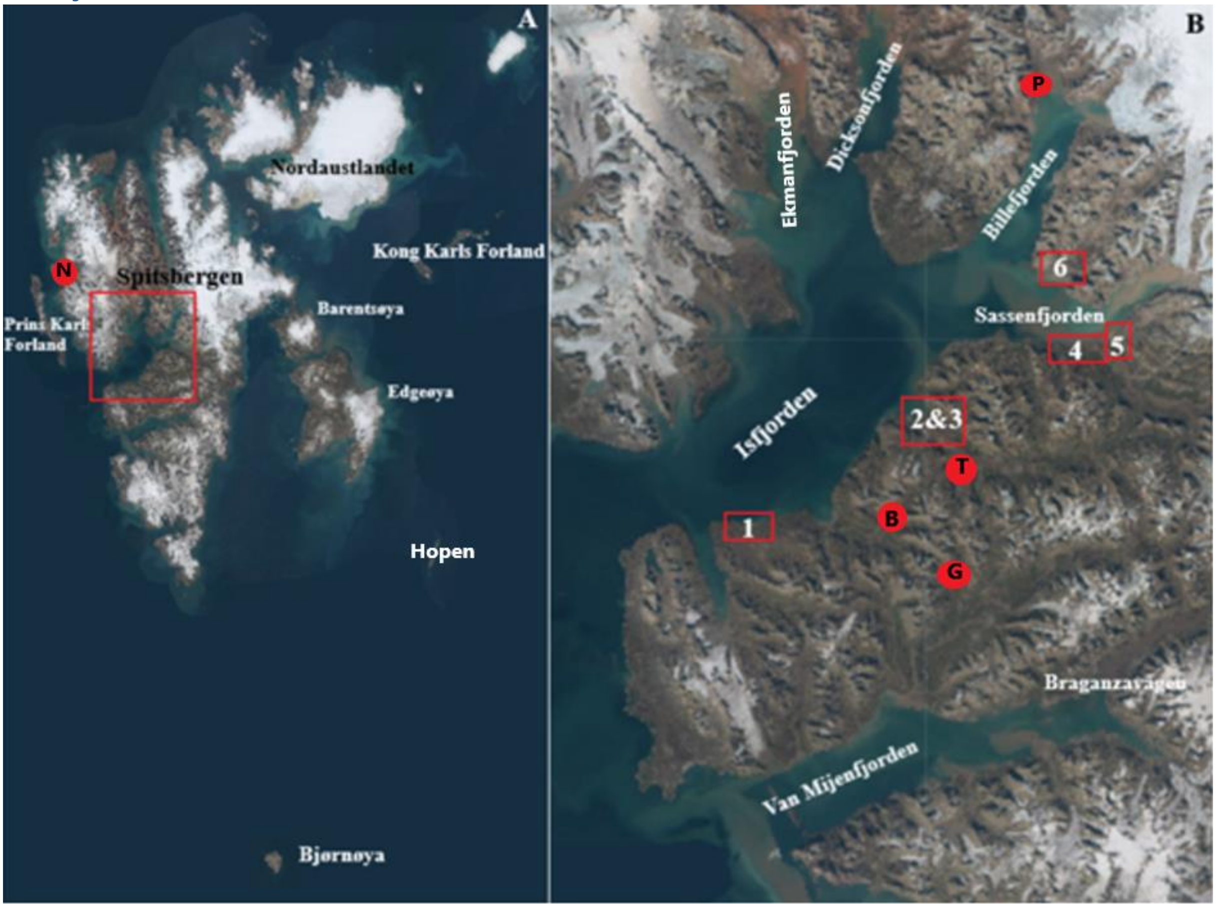

Figure 2: Locations of Svalbard (left) and the six study areas (right). All study sites are located in in the large fjord system, Isfjorden. Location 1: Hollendarbukta; Location 2: Longyearbyen; Location 3: Hiorthamn; Location 4: Sassen-west; Location 5: Sassen-east(fredheim); Location 6: Gipsvika. Red dot marked with "B" is Bødalen, Red dot marked with "G" is Gangdalen, Red dot marked with T is Todalen, Red dot marked P is Petuniabukt, Red dot marked N is Ny-Ålesund. Source: Map generated from Toposvalbard.no

Study sites in Isfjorden include Hollendarbukta, Longyearbyen, Hiorthamn, Sassen-west, Sassen-east, and Gipsvika (Fig 2). All of these sites are located in the larger fjord system of Isfjorden, that have its outlet into the west coast of the Svalbard archipelago. The first study area is Hollendarbukta and is the most southern study site in this analysis. The second study area is the coast around the permanent settlement of Longyearbyen, which is located in a smaller fjord arm of Isfjorden, Adventfjorden (Fig 2). Study area number three is located in the north side of Adventfjorden and does only serve as complimentary data to the thesis. Both the coastal areas around Longyearbyen and Hiorthamn is affected by human activity, which the other study areas are not to that degree. Analysis from these two areas will only be complimentary, since an analysis that discuss the natural processes is hard to differentiate from the human activity, but in-depth geomorphological mapping is also done in Longyearbyen. Study area number four is located in the southern inner part of Sassenfjorden, this is a large area, which contain a complex history of past and present processes. Study area number 5 is Sassen-east, and is located in the outlet of Tempelfjorden, and the inner part of Sassenfjorden. Sassenelva that runs in the Sassendalen valley and is splitting the study area of Sassen-west and east. Gipsvika is the northern most and the sixth study area in this analysis, that is a shallow bay area located in the north side of Sassenfjorden, with a bay facing in a south direction. All of these field sites, and the location can be found in figure 2.

Almost all study sites occur in rural areas, with some traffic by tourists on snow scooters during the winter and from local cabin owners during all seasons. The most trafficked areas are Longyearbyen, as it is a permanent settlement with a population of 2456 in 2021 combined with the small settlement in Ny-Ålesund (SSB, 2021)(Fig 2). Hiorthman is less trafficked than Longyearbyen, but there is still abundant human activity during all seasons, given its close proximity to Longyearbyen (Fig 4). Since Longyearbyen and Hiorthamn are more impacted by human activity than the other study sited, interpretation of natural coastal change and river mouth dynamics is difficult.

The relative sea level chance in these places can have a small differences, from studies done in Adventdalen valley there are evidence that the relative sea level has fallen by ca 70 m since the last glacial maximum (Lønne & Nemec, 2004).

Regional setting of Isfjorden

Isfjorden is an approximately 100 km long and 425 m deep fjord system and is the largest fjord system in Spitsbergen. The main fjord is called Isfjorden and contains thirteen tributary fjords and smaller bay areas (Forwick & Vorren, 2010). Bedrock sills occur in Dicksonfjorden, Billefjorden, Ekmanfjorden, and Sassenfjorden (Forwick & Vorren, 2010) (Fig 2). In this analysis Sassenfjorden is one of the smaller fjord systems where three out of six study areas are located.

Hollendarbukta

Hollendarbukta (site 1, Fig 1), is the southernmost study site in this analysis, and is located closest to the mouth of the Isfjorden fjord system. The main shoreline here is about 800 m long (Fig 3). Hollendar river (Hollendarelva in Norwegian) is located in the wide, U-shaped Hollendar valley (Hollendardalen in Norwegian), (Fig 3). The valley is a southeastern facing valley with a braided river (Hollendarelva). This valley system is fed by several smaller glaciated watersheds. The main valley system measures 18.5 km in length, from the outlet of Hollendarelva to the center of the Plassbreen glacier (Fig 3). The valley system near the coast is a relatively flat area, with no large mountains, in this area organic material can be observed in the sides of the valley, and close to the watershed. When entering the more glaciated areas there are several larger mountains ranging in the size up to 818 m above sea level. Hollendardalen valley is underlain by Paleogene and Neogene bedrock, including sandstone, siltstone and shale (Dallmann & Elvevold, 2015). No closer information about the bedrock geology can be found in this particular area.

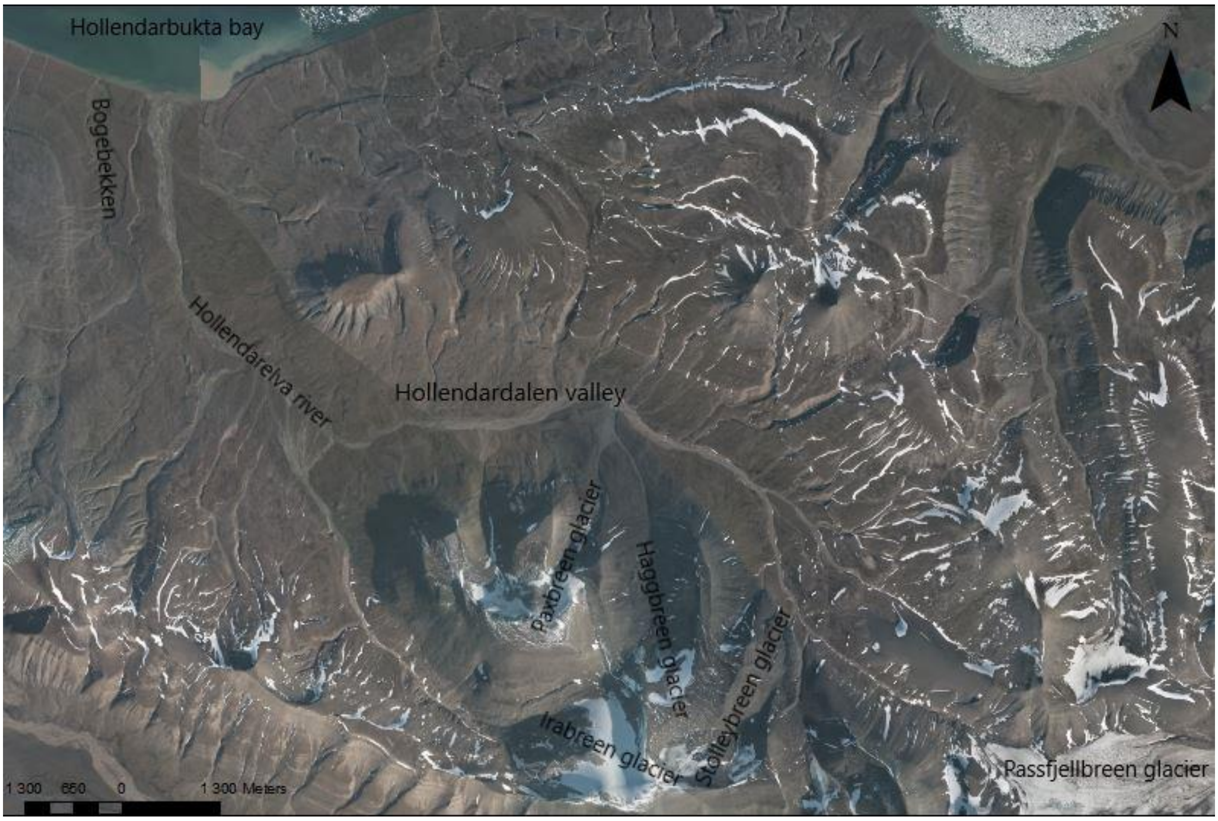

Figure 3: Overview over the Hollendardalen area, with names of glaceris and relevant rivers

Little information is available about this valley system, a geological map has been made over the area, but the most well-presented map is in the scale of 1: 250 000 (Dallmann & Elvevold, 2015), which makes it difficult to analyse the area closely.

Longyearbyen

Longyearbyen is located in the southeast corner of Adventfjorden, which is a smaller fjord arm of Isfjorden (Site 2, Fig 2). Longyearbyen is situated next to a large delta; the delta shoreline is oriented north-east – south -west. Sediment contribution to the delta, shoreline, and fjord comes from Advent river (Adventelva in Norwegian), which is a glacially-fed river (Fig 4), and from the surround slopes, in the form of avalanches and debris flow slides. There is a lot of human activity along Adventelva, Longyear river (Longyearelva in Norwegian), and Adventfjorden in general. Recently modifications have been made to the riverbanks to prevent Longyearelva from eroding in the wrong direction, which could threaten infrastructure and buildings in the town. During the summer of 2020, large numbers of boulders, sand, and gravel were removed from the riverbed and riverbanks to serve as building material for snow avalanche protection in town (NVE, 2020). This caused a large disturbance in the sediment flux during the 2020 melt season, and a greater volume of sediments were transported to the coast and fjord than normal, observation of this was made during fieldwork during the fall 2020.

Longyeardalen is situated in an area divided into different categories of bedrock formation. The uppermost outcrops were deposited during Paleocene and Eocene. In Lower lying areas there is a coal bearing stratigraphy that has developed during Paleocene and is a part of the Firkanten-formation (Dallmann & Elvevold, 2015). Below the coal seams are early Cretaceous sandstone, siltstone, and shale (Dallmann & Elvevold, 2015). Coal mining has been occurring around Longyearbyen since 1906 (Dallmann & Elvevold, 2015). Such mining activities have likely added to the sediment load of Longyearelva and Adventelva since this time.

Figure 4: Overview picture over the Longyearbyen area including Hiorthamn. Glaciers, valleys are named in this picture.

Hiorthamn

Hiorthman is located across Adventfjorden from Longyearbyen (Site 3, Fig 2), approximately 2.4 km from the Adventdalen delta. Hiorthman is the site of an old waiting station for transportation of coal in the local mines, which have not been active since 1921 (Sysselmannen, 2006). Today these buildings, such as Taubanestasjonen, only serve as cultural heritage. In this area the coastline is degrading rapidly, which threatens an important cultural heritage site (Nicu, Rubensdotter, Stalsberg, & Nau, 2021).

The geological setting of Hiorthamn is mostly the same as in Longyeardalen valley. The bedrock geology on the north side of Adventfjorden consists of a layered stratigraphy of Early Cretaceous and Palaocene siliciclastic material (Major & Nagy, 1972). The stratigraphy consists of layers with different thicknesses dark grey shales, silt stone, sandstone interbedded with minor coal seams (Lønne & Nemec, 2004). The area is also affected by small, ephemeral rivers cross some raised beaches here and exit into Adventfjorden.

Sassen-west

Sassen-west (Site 4, Fig 2) is located in the inner most part of Sassenfjorden, with Sassenriver (Sassenelva in Norwegian) dividing up study area 4 and 5. The shoreline considered in this thesis includes that from Sveltihel (Fig 5) to the western part of Sassenelva outlet, approximately 3.5 km long. In this area there are several generations of raised beaches here, which are visible from aerial photos, up to 14 km inland from the coast. Inland of the raised beaches vegetation and signs fluvial activity dominate the landscape.

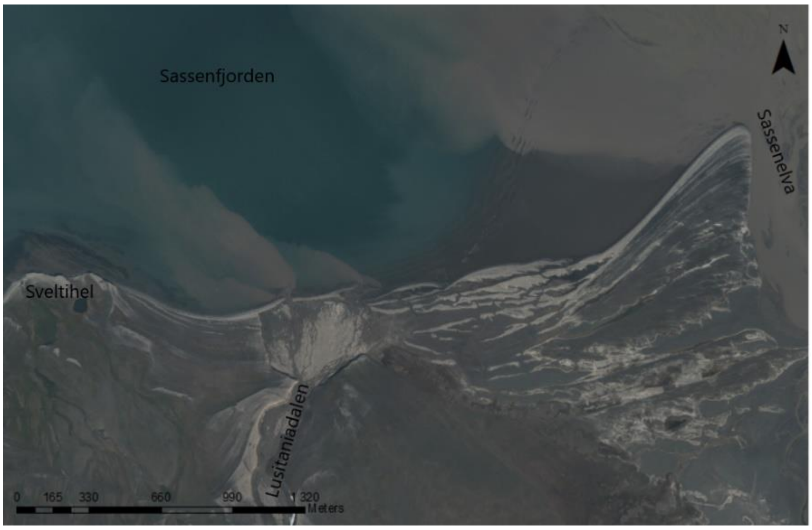

Figure 5: The coastline from the Sveltihel in the west and the Sassenelva outlet to the east. Sassenfjorden an Lusitaniadalen that contributes sediment to the Lusitaniadalen delta.

The main sediment contribution to the modern coastal system at Sassen-west is from Lusitaniadalen, glacio fluvial system fed by Lusitaniabreen glacier (Fig 6). A small, unnamed glacier at the top of Gattytoppen, also contributed meltwater to the Lusitaniadalen system. There is a possibility that the Sassen-west system also gets contribution from Sassendalen valley watershed, but there is an uncertainty on how much this system contributes. The Sassendalen watershed contains several larger and smaller glaciers, contributing a large amount of meltwater during melt season.

The bedrock geology in Sassen- west area contains bedrock consisting of silicified carbonate rocks, chert and Sandstone which originates from the Permian. In the more mountainous areas, the bedrock shifts to a Middle Jurassic bedrock, consisting of shale and siltstone. A small line of Lower Cretaceous is present between the Middle Jurassic and the mountains peaks, this layer contains shale, siltstone, and sandstone. The mountain peaks contains shale and sandstone from the Middle Jurassic (Dallmann & Elvevold, 2015).

Sassen-east

The Sassen-east study area is located in the north side of Sassenelva river (Site 5, Fig 2), which bordering site 4 (Sassen-west). The Sassen-east delta is located where Tempelfjorden meets Sassenfjorden (Fig 6). Most of this area is underlain by a delta that is fed by Nøyselva river in Nøysdalen (Fig 6). Nøysdalen is fed by meltwater from Fimbulisen (Fig 6). Nøysdalen is a U-shaped valley, with a small canyon feature just inland of the Sassen- east delta (Fig 6).

The bedrock geology in this area is not easily accessible because of the extensive Quaternary deposits over the area. But in recent years an outcrop of the Gipshuken formation have been exposed in the coastal areas due to coastal erosion (E. H. Sessford, Anne, 2013). This outcrop from Gipshuken is described as a platform of limestone, dolomite with shaley or sandy interbeds and thin layers of Gypsum (Major & Nagy, 1972).

Figure 6: Overviw picture over the Sassen- west and east area. including names of fjords, valleys, glaciers and rivers.

From other Geological maps over the area, show that the watershed area to Sassen-east contains two different bedrock layers. The Gipshuken formation, containing dolomite and limestone (Dallmann & Elvevold, 2015). The basic information about the bedrock geology is gathered from a map with the scale of 1:250 000, which does cause the information to be inaccurate doing closeup analysis.

Gipsvika

Gipsvika is located farthest to the north of all study sites and is situated in the north side of Sassenfjorden (Site 6, Fig 2 and 7). The Gipsvika Bay area has a southwest facing shoreline. Gipsdalen (Gips valley) is large, and contains major glacifluvial activity from Lomonosovfonna, and several smaller glaciers in the valley. Gipsdalen valley and Lomonosovfonna are located towards the northeast, and the whole valley heads out in Sassnfjorden in a southwesterly direction. There is a large amount of water that runs through this valley system, and the valley contains both active and inactive alluvial fans, which remove the coarsest sediments from the system before it reaches the coast.

Figure 7: Overview picture of the Sassen-west, Sassen- east and Gipsvika. With the names of fjords, rivers and glaciers.

The valley system at site 4 is surrounded by mountains ranging from 400 – 700 m above meters above sea level. These mountainous areas are well suited for snow accumulations during the winter season, and smaller watersheds contribute significant snowmelt to the main valley system in the spring and summer. Gipsdalen shows a long history of different generations of raised shorelines and inactive raised beaches up to 5 km into the valley from the shoreline. After this point the glacifluvial and fluvial systems, alluvial fans, and active debris flows dominate the landscape.

The bedrock geology in the Gipsvika area consist most of silicified carbonate rocks, chert, and sandstone, combined with dolomite and limestone, in the stratified layers of the mountains in Gipsvika gypsum is also present (Dallmann & Elvevold, 2015).

Previous research

Periglacial processes in Svalbard have already reduced glacial processes to a secondary role with respect to the dominant processes that influence landscape development since the last ice age (Mercier, 2000). The warming that has occurred since the Little ice age has had a significant effect on the slopes, valley floors, and glacial forelands across Svalbard in the past couple of hundred years. Glaciogenic landforms are denuded by fluvial, aeolian, or mass wasting processes, which have accelerated recently du to permafrost degradation (Etzelmüller et al., 2000; Lønne & Lyså, 2005). Only 1 % of the Arctic coastline has been investigated in sufficient detail that there is high quality quantitative data to analyse (Lantuit, Overduin, Solomon, & Mercier, 2010). Previous coastal geomorphological research in Svalbard has focused on the western coasts of the archipelago, such as Bellsund and Kongsfjorden (M. C. Strzelecki, Long, & Lloyd, 2017). Quaternary geological and geomorphological maps of Fredheim and Skansbukta were made in 2013 as a part of a master`s thesis (; both of which are situated in the inner parts of Isfjorden (E. Sessford, 2013). Other quaternary geological maps exist from around Isfjorden and describe the surficial geology land landforms, for example, Adventdalen (Tolgensbakk et al., 2000) and Bragnzavågen (Rubensdotter et al., 2016). Geomorphological mapping has also been done in Bjørndalen and Vestpynten (Rubensdotter et al., 2015a). Todalen, Gangdalen, and Bødalen (Rubensdotter et al., 2015b). Most recent research in the coastal geomorphology of Svalbard includes two projects led by UNIS Professors Maria Jensen and Lena Rubensdotter. These projects aim to "fill the gaps" in knowledge between what we know about coastal processes and geomorphology and what is to come in the future, these projects are still in progress, and will add to the ongoing problem that is the unmeasured changes along the coast of Svalbard (Jensen & Rubensdotter, 2020; Svalcoast). Knight & Strezelecki also emphasize that no previous studies on coastal conservation have considered periglaciation as an influence factor (Knight & Strzelecki, 2020). They also believe that coastal change in a non-paraglacial coast cannot be compared with a paraglacial coastline (Knight & Strzelecki, 2020).

Theory

Glaciation and deglaciation of Spitsbergen

During the last 2.6 million years of the Quaternary Period, the Svalbard-Barents Sea Ice Sheet (SBSIS) expanded and retreated several times (Hornes, 2015). Evidence of former glacial margins to inf in Svalbard; the best preserved are the ice-cored moraines that are clearly related to present-day glaciers (Lønne & Lyså, 2005). Nonetheless, we know that during the Last Glacial Maximum (LGM; 24 000 years ago) the SBSIS covered Svalbard all the way to continental slope (Hornes, 2015), of 2005 about 60 % of the archipelago was still glaciated (Lønne & Lyså, 2005). During the Bølling interglacial stage (15 100 – 14 200 years before present (Hornes, 2015). The SBSIS retreated from the western coast of Svalbard during the Bølling interglacial stage (15 100 – 14 200 years before present). During the Holocene Thermal Maximum (10 000 – 5000 years before present), many of Svalbard's glaciers had retreated onshore, but readvanced again by 4000 years before present (BP) as indicated by several moraines, although many of the moraines have not been dated; (Hornes, 2015). Since the Ice Age cold period that ended in the late part of the 19th century, the surface mass balance of Svalbard's glaciers and ice caps has generally been negative. It is believed that most of the glaciers had reached their full Little Ice Age extent around 1900, and then started retreating again in the 1920s, when summer temperatures started increasing (Nunt, Hagen, & Kohler, 2015). A study done by (Nunt et al., 2015) showed that Svalbard's glaciers normally retreat between 0 to 100 m/year, with an average of 30-40 m at average each year (Nunt et al., 2015).

Due to the ongoing overall deglaciation of Svalbard, postglacial rebound has lifted coastal landforms, like raised beaches, well above modern sea level (Dallmann, Blomeier, & Elvevold, 2015). During the LGM, large amounts of ice resulted in a depression of the earth's crust. When the ice melted, the weight that was holding the land down was gone, and caused the land to rise (Benn & Evans, 2014). Due to the growth and decay of glaciers and ice sheets on Svalbard since the LGM, relative sea-level curves that have been reconstructed for different localities around Svalbard show periods of both falling and rising relative sea-level, although most have been falling for the past x thousand years (Lambeck, 1995). Figure 8 visualize the glacial extent over the Fennoscandia area during LGM.

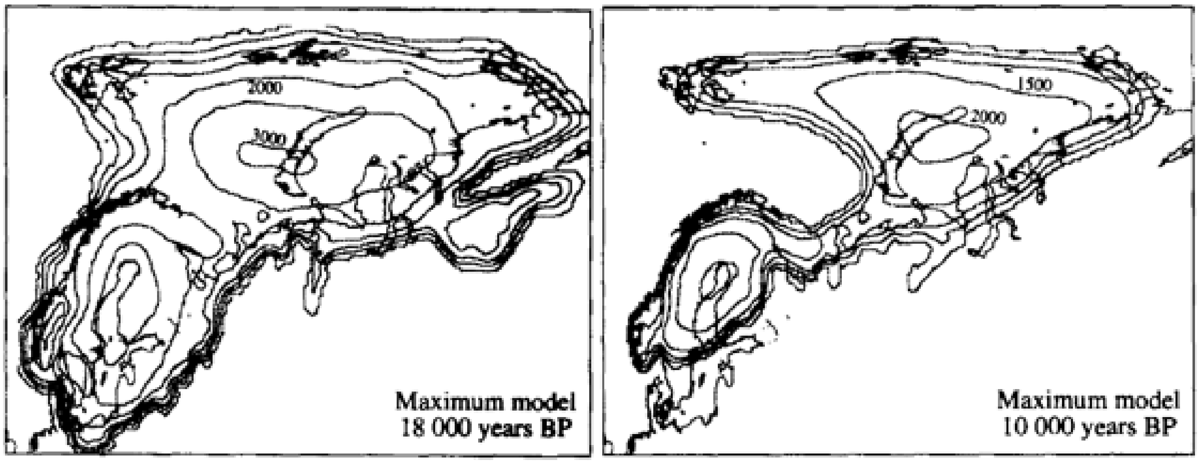

Figure 8: The maximum ice model. Left: 18 000 years before present. Right: 10 000 years before present. Figure after (Lambeck, 1995).

Changes in climate

Global warming has been amplified and especially in higher northern latitudes (IPCC, 2007). On average temperatures have increased at almost twice the global rate over the last 100 years (IPCC, 2007). It is also believed that the Arctic region will continue to warm more rapidly than the global mean in the future (IPCC, 2014).

The longest continuous series of temperatures, are collected at Svalbard Airport, and some of the oldest temperature observations is made in 1898. There have several warmer periods in the analysed period in Svalbard, 1930s and 1950s have been categorised as mild periods, and since 2000 there have been observed several exceptionally warmer years (MOSJ, 2021).

During the summer of 2020, a new heat record of 21,7°C was set on the 25th of July (Ekroll, 2020). In November 2020 a new record was set when the temperature suddenly rose, from 3,9°C to 9,4°C in under one hour. This incident was due to a storm centre outside Greenland (Pedersen, 2020).

At Svalbard Airport and Hopen Island (Fig 2), Svalbard experiences much harsh weather conditions, measuring precipitation during extreme weather conditions is especially difficult, and due to a small network of stations the datasets become smaller (Førland, Benesta, Hanssen-Bauer, Haugen, & Skaugen, 2011). The average temperatures during winter have increased in Svalbard Airport and Hopen (Fig 2) by 3.5° while the summer temperatures have increased by 0.5 – 1.0 °C (Førland et al., 2011). Data that have been collected at weather stations on Svalbard show increased temperatures at all stations, but the strongest increase is visible during winter and spring (Førland et al., 2011). There is no data on how much the annual mean temperature have been increased, but the stations show a trend in warmer temperatures. Due to long-term consecutive monitoring at Svalbard Airport in Longyearbyen, we know that there have been several periods where there have been warmer conditions (Førland, Janssesn-Bauer, & Nordli, 1997). The first recorded period was from 1920 – 1942, referred to as the 20th century warming period (Førland et al., 2011). The time after the warming period 40s the warming was a time where there was a drop in temperature, data from Longyearbyen airport and Ny Ålesund show a combined temperature drop between 1.5 – 1.8°C per decade. After 1966 all stations show a rising trend in the temperature, although mean data for the whole year from Longyearbyen airport show that there has generally been a rising trend in temperature since 1912 (Førland et al., 2011).

Studies of temperature and precipitation change on Spitsbergen, show that the change in temperature shows similar trends over the whole archipelago, but increased precipitation along the west coast is only representative for the west coast of Svalbard (Førland et al., 1997). Due to a lack of permanent weather stations around Svalbard, and the topography of the archipelago consist of 20% mountains, the precipitation is hard difficult to measure and get there are few long-term, consistent datasets (Førland et al., 2011).

The mean annual precipitation measured at Svalbard Airport between 1971- 2000 was 196 mm, but it is well known that precipitation gauges have difficulty measuring accurately during snowfalls and strong winds (Adakudlu et al., 2019). Estimated annual precipitation for all of Svalbard archipelago is approximately 120 mm. But this estimate cannot be used as a general fact for all field locations since the weather is controlled much by the topography and the local conditions.

Sea ice around Spitsbergen and Isfjorden

During the Eemian (125.000 years ago) the climate in the Arctic Ocean warmer than today, sea ice in the northern part of Spitsbergen was also reduced (Adakudlu et al., 2019). In the beginning of Holocene (12.000 – 10.000 years ago) seasonal sea ice could be observed at the west coast of Svalbard (Müller & Stein, 2014; Müller et al., 2012) During Holocene sea ice during the spring increased on the west coast of Svalbard, due to reduction of the insolation in the Northern Hemisphere (Müller et al., 2012).

Sea ice in the Arctic Ocean has shrunk by 2.7% since 1978 as recorded by satellite data. Sea ice is usually common in the areas around Svalbard, and in the fjords during winter and spring. But since Svalbard is located where it is, the influence of the warm, saline water from the Atlantic, and the less saline, cold water from the Arctic Ocean, mixes together, creating the West Spitsbergen Current, which have a negative impact on the formation of sea ice. The difference in these two currents influences the different coasts, where the west coast is usually ice free for a longer period of time, than the east coast, which is more influenced by the cold arctic water (Gerland & Pavlova, 2015). Sea ice can regularly from in coastal areas along the coast in selected fjords in Svalbard, which protects it from wave erosion. For the western coasts of Svalbard that are less protected, sea ice can develop over long periods of time, breaks loose often, and drifts away from the shoreline with the currents (Gerland & Pavlova, 2015). Glaciers that meet the ocean, contributes with fresh water, and then makes the water less saline (Gerland & Pavlova, 2015)

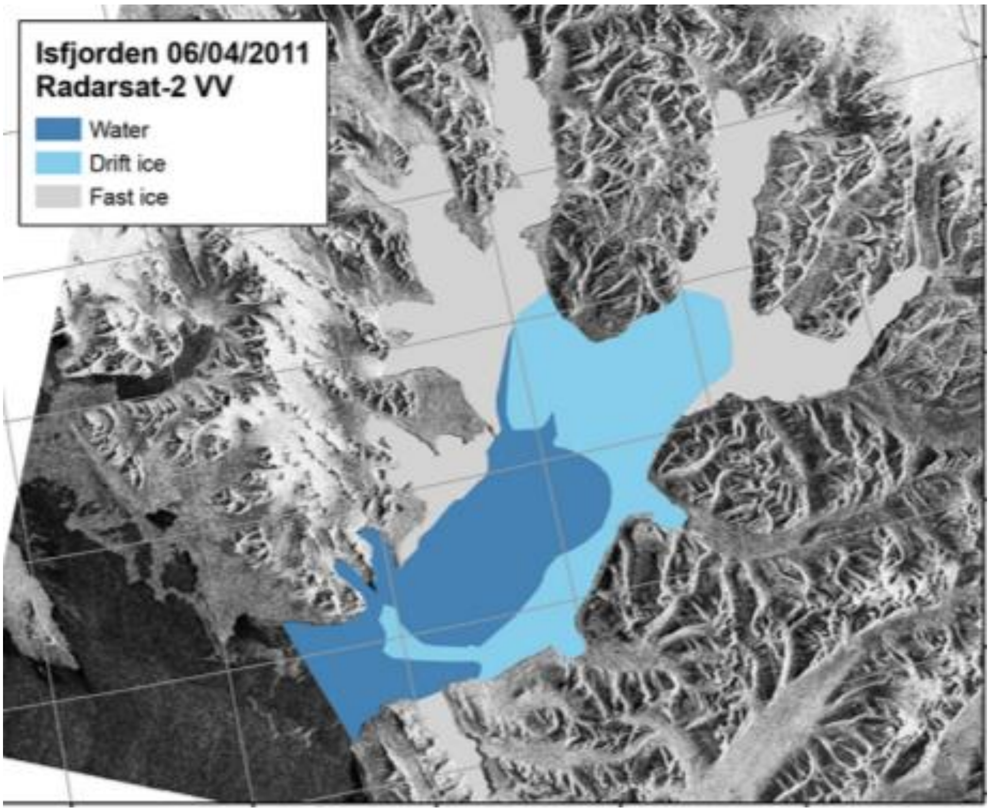

Figure 9: Visualization if the ice cover in Isfjorden, figure are made after satellite data in 2011. Figure after (Muckenhuber, Nilsen, Korosov, & Sandven, 2016).

Data collected between 2000 and 2014 show that there have been two different trends in the ice cover in the Isfjorden area. The study shows that there have been two periods where there has been more sea ice cover than normal, and two periods where it has been less sea ice cover than normal. The periods of more extensive sea ice cover were in the period from 2000- 2005, and from 2009 to 2011. The periods with less sea ice are measured to be in the period 2006 -2008, and the period from 2012 – 2014 (Muckenhuber et al., 2016). More research in this topic is needed to get more accurate data about the possible reasons for this change.

Permafrost and active layer in Svalbard

At a global level, the active layer temperature has increased up to 3°C in the Arctic, and have especially increased since 1980s (IPCC, 2007). The mean permafrost temperature in Svalbard at depths of 10 -20m vary from -2.5°C in coastal areas and -5°C in the central parts of Svalbard Permafrost has increased in temperature of between 0.06°C and 0.15°C per year at 10 m depth (Adakudlu et al., 2019). At two different locations in Adventdalen valley, near Longyearbyen (Fig 4), the active layer has deepened by 0.6 cm per year in loose sediments and 1.6 cm per year in bedrock. If the trends in the warming climate continue, the near surface permafrost in low lying areas and in coastal areas will thaw before the end of the century (Adakudlu et al., 2019). Monitoring of the active layer depth and temperatures in Adventdalen began in the year 2000, by UNIS (University centre in Svalbard). Active layer thicknesses have been ranged from a minimum of 74 cm in 2005 and 110 cm in 2008 (Christiansen, 2015).

Ocean currents

In the last few decades several fjords on Svalbard have experienced a reduction in sea ice during the winter season (Muckenhuber et al., 2016). The less extensive sea ice cover has been correlated to the increased transport of warm, Atlantic water into the fjords of Svalbard (Nilsen, Skogseth, Vaardal-Lunde, & Inall, 2016). Most fjords are the link between Arctic and Atlantic Ocean water masses and the terrestrial environment, where salt water and fresh water from rivers and melting glaciers mix (Skogseth et al., 2020). The artic fjords are special in the wat that they experience the normal mixing in the fjords, but also extreme variations in seasonal change cause of the formation of sea ice and glacial melt. The fjords on the west coast of Svalbard are in direct contact with the main Atlantic currents and can potentially be good analogues for future environmental change (Skogseth et al., 2020). The continental shelf around Svalbard of shallow banks between 50-100 in depth cross-cut by deep troughs ranging from 200-400 in depth (Skogseth et al., 2020). With models made out of the large Isfjorden system a large trough (Isfjordrenna) have become an important pathway for the Atlantic current to flow into Isfjorden (Nilsen et al., 2016). In the Isfjorden system there are several glaciers, and the water that comes from the warm Atlantic current can have potential to increase the melt rate of glacier (Skogseth et al., 2020).

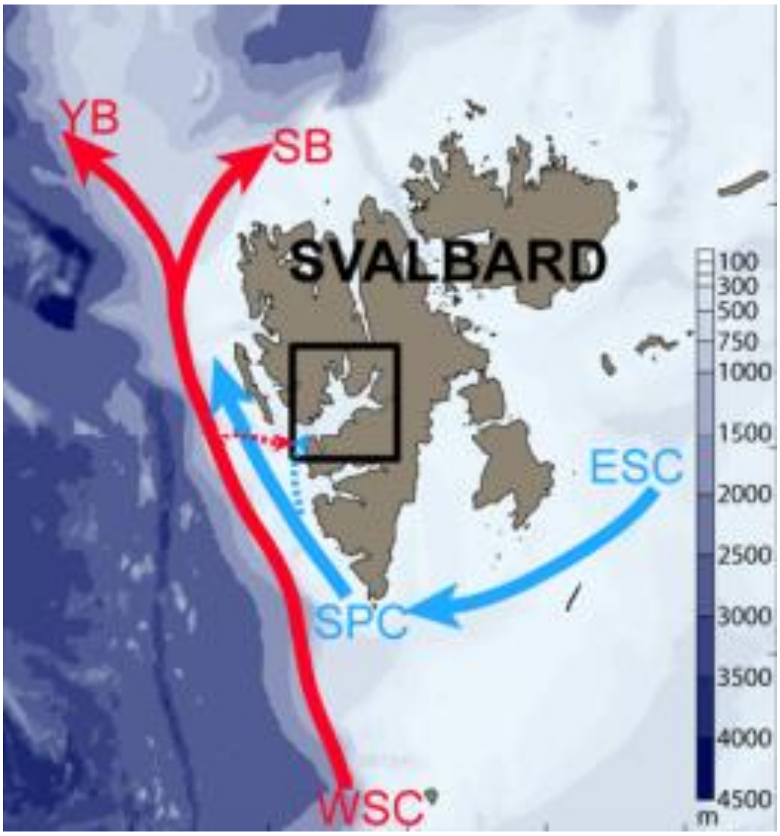

Figure 10: Bathymetry data around Svalbard Archipelago with the main currents West Spitsbergen Current (WSC) and the East Spitsbergen Current (ESC). When passing Svalbard the current splits into two different currents Svalbard Branch (SB) and the Yermank Branch (YB). The WSC and the SPC are splitting up and connecting in the Isfjorden system that is illustrated in the black box. Figure after (Skogseth et al., 2020).

Data from a long term, ongoing mooring program in Isfjorden that fjord systems in general, and especially Isfjorden, have become more dominated by the by the warm Atlantic water than the colder Artic water (Cottier et al., 2007). Furthermore, a significant reduction of the monthly averaged fast ice coverage was documented recently when the time period 2000–2005 was compared to that of 2006–2014 (After the winter in 2006 there has been a large change in the sea ice cover in the Isfjorden area which have resulted in less sea ice (Muckenhuber et al., 2016). This change has been observed and researched with taking samples in different areas in Isfjorden of temperature and salinity at different depths (Skogseth et al., 2020).

Currents measured by the mooring stations in Isfjorden, show that the mean depth-averaged current was strongest on the southern side of the mouth of Isfjorden (Fig 2). The speed of the mean depth current on the southern side was at 12 cm s^{-1} on 2010-2011, and at 18 cm s^{-1} in

2006-2007. Current speeds are measured faster on the south side of the fjord mouth than on the north side of Isfjorden. Slower speeds were measured close to Tunabreen in Tempelfjorden (Fig 7); likely caused by the surging tidewater glacier, Tunabreen, that started surging in 2016 which was an earlier than expected (Skogseth et al., 2020). In this case during surging, more fresh water enters the water column, and possibly enhanced the estuarine csirculation. (Skogseth et al., 2020). The time Prior to 2006, warm saline water from the Atlantic current was normally trapped below a layer of colder water with a warmer saline water on top. There was a shift in 2006 that made the warmer saline water thicker and higher up in the column and less of the colder water (Skogseth et al., 2020).

Sea level change

The coastal low lands area relatively flat areas along the coast of Svalbard, which were submerged following deglaciation in the late Pleistocene, and parts of the Holocene (Dallmann et al., 2015). Isostatic adjustment due to the melting of the ice, led to land emergence. Coastal and terrestrial processes then took over from marine/fjord processes in these coastal lowlands following emergence, reworking, marine and coastal sediments (Dallmann et al., 2015).

Global sea level has risen since 1961, with the average rate of 3.1 mm/yr since 1993 (IPCC, 2007). Due to This is with contributions from thermal expansion, melting glaciers including ice caps and polar ice sheets (IPCC, 2007), and other factors. The observed uplift rates of Spitsbergen are between 7 – 10 mm/year, where Bjørnøya (Fig 2) have experienced no significant changes (Adakudlu et al., 2019). Marine limits around Spitsbergen range from 80 – 110 m above sea level (Dallmann et al., 2015). Raised marine landforms and sediments on Spitsbergen tend to be sandy, gravelly beaches Organic debris, such as wood, peat, shells, and whalebones are often present and have been used to determine the age of the age of the raised marine sediments and landforms, and at which time this part of the landscape was underneath sea level (Dallmann et al., 2015).

Watershed characteristics around Isfjorden

The primary source of sediments in and along Isfjorden, Svalbard, are the steep-sided valleys and rivers that flow from glaciers through these valleys to the fjord. Climate change is impacting sediment supply through these systems due to increased melting of glaciers and permafrost and their trickle-down effects on river channel stability, erosion, and slope processes. The following subsections describe the most important processes and sediments in the watersheds surrounding Isfjorden with respect to sediment fluxes to the coast.

Slope failure, erosion and transport

Slope stability varies with time, and landscapes that are formed during glaciation are particularly unstable, especially immediately following deglaciation (McColl, 2012). Factors that contribute to this can be ice mass distribution, time since deglaciation, vegetation cover, hydrological conditions, seismicity, and erosion (McColl, 2012). Landslide activity is the most dominating factor in mountain areas (Korup & Clague, 2009). Especially when the glaciers retreat the landscape previously covered by ice is now exposed to the surroundings. Many factors may result in slope failure in both bedrock or sediments, factors like for example, debris flows, snow avalanches, wind erosion, frost processes, rivers digging through material like unconsolidated sediment or bedrock (Ballantyne, 2002). In many periglacial areas over the world the glaciers leave a thick, unvegetated glaciogenic deposit behind following deglaciation, these deposits are often found as lateral moraines (Ballantyne & Benn, 1994; Mattson & Gardner, 1991). These sediments are leaning against the slope, usually with a steep gradient, and are therefore very susceptible to erosion in the form of, debris flow slides, solifluction, and snow avalanches. When debris flows occur, an unsorted slurry of material gets transported down the slope (Ballantyne, 2002), and in many cases it enters a river system carrying the sediment further down in the valley. Along the valley sides, where the slopes are especially steep, unconsolidated sediments like till, are also prone to failure that results in the form of landslides, debris flows, or debris avalanches, in sone valleys there have been documented that debris sliding occurred 14 % more often during warm weather (Ballantyne & Benn, 1994).

Unvegetated valley floors are often an important factor for stabilising glacial forelands, because without the stabilising effects from vegetation, the forelands are more susceptible to larger mass -movements, deeper and more extensive freeze -thaw cycles, overland water flow, and wind processes (Ballantyne, 2002). Aeolian processes are also important to mention in relatively flat areas when discussing erosion, especially where there are fine grained sediments, which can easily be carried by the wind.

A warmer climate will affect the intensity of erosion and increase the water discharge from glaciers and therefore also the supply of sediments to river system. Landslides, slush flows, and debris flows are a common feature in steep slopes during high precipitation events and or combined with heavy snow melt (Høeg, Lied, Karlsrud, Gregory, & Norges geotekniske, 2014). Debris flows are most often triggered in the upper parts of a slope, usually the steep part of mountain sides (Dallmann et al., 2015). For the most part, debris flows tend to follow ravines or other already established depressions in the landscape (Dallmann et al., 2015). This combined with the thawing permafrost (IPCC, 2007) means that the active layer often contains.

Water is a decisive factor when it comes to debris flows, since a debris flow, is by definition, a slurry of sediment (at least 50% sand size or larger) and other debris (Høeg, Lied, Karlsrud, Gregory, & Norges geotekniske, 2014). In soils that contain abundant coarse sand and gravel, the possibility to build up a high water pressure is reduced because of the high permeability in the sediment, and hence, may be somewhat more stable than in finer-grained deposits (Høeg et al., 2014). Slopes containing this type of sediment are usually stable on slopes with gradients less than 37°, except during high precipitation events or snow melt (Høeg et al., 2014). Slopes containing finer sediments, such as silt and clay, have more cohesion between the particles, resulting in greater binding forces (Høeg et al., 2014). In clay rich formations on Svalbard, debris flows tend to be more common, with most of the debris flow slides happening during spring thaw, although they can occur any time as long the temperature is above 0° C (Dallmann et al., 2015). Usually roots from vegetation like trees and smaller vegetation act as a binding factor to the loose sediments on a slope (Høeg et al., 2014), but due to the lack of vegetation in the high arctic, this stabilizing factor cannot be taken to account.

Factors like frost heave also act as a binding force in the otherwise loose sediment, but obviously disappears during thawing of the active layer in summer. In areas where permafrost is present, the top layer can also behave as a liquid during summer seasons, depending on grain sizes of sediments and vegetation (Høeg et al., 2014). Erosion by rivers, and small melt water channels in loose sediment, can contribute to slope failure, this is an important factor in glacifluvial sediments. The erosion factor in rivers or slopes can have a higher rate of slope failure if the slopes of river terrace is exposed to human activity. A small disturbance in the slope can have massive a massive impact on the stability of the slope (Høeg et al., 2014).

Gelifluction, related to solifluction, is a relatively slow slope processes only located in areas with permafrost, and results in a lobe like features, often observed on the lower parts of a slope, and consisting of till or raised marine sediment (Dallmann et al., 2015).

Braided rivers

Glaciofluvial systems often take the form of braided rivers, which themselves, often occupy U-shaped valleys, where broad, flat valley floors do not force the water to run in one particular stream (Dallmann et al., 2015). Glacially-fed braided rivers are also characterised by high sediment loads and seasonally changing water levels, both of which further contribute to channel instability. Glaciofluvial sediments are often well- rounded cobbles, gravels and sand, with the size of the sediments usually decreasing further down in the river system. Mud flats deposited during floods can be observed at random in the riverbed, but more often the finer sediment is deposited closer to the river mouth (Dallmann et al., 2015).

Erosion

Coastal systems are one of the most dynamic areas on Earth. The natural processes that influence coastal dynamics include changing rates of sea level rise or fall, and short term and long term geological processes, such as accumulation or removing sediment and ice, causing a lift or lowering of the areas over longer periods of time. In recent years the influences of anthropogenic intervention like urbanisation and building of coastal infrastructure have also become an important driver of coastal change and possible change in habitat (Nicu et al., 2021). A comprehensive understanding of the dynamics of erosion in Arctic environments is still not well known. The erosion rate of Arctic coastlines is increasing, but most studies on coastal erosion have been done in temperate climates (Frederick, Thomas, Bull, Jones, & Roberts, 2016). It is believed that one third of the coastline in the world is affected by permafrost (Lantuit et al., 2012), and still there is much to be undiscovered in the artic coastal environment. Factors affecting coastal erosion include complex interactions between hydrodynamics, sediment dynamics in different cohesive and non- cohesive sediments (da Costa Araújo, 2004).

Spit bars and their evolution

Spit bars, also called a berm ridge by (Otvos, 2000), area landforms that are formed in the active part of a coastal system. These features are wave built with a gentle slope, consisting mostly of sand, gravel and sometimes boulders (Otvos, 2000). Beach ridges are a diverse type of landform, so the shape, dimensions and sedimentological composition are difficult to analyse and quantify (Otvos, 2000).

Spit bars can be found all over the world, and typically form from the longshore transport of material from an area of up-drift source (Randazzo, Jackson, & Cooper, 2015). In some areas down drift source of sediments can elongate the spit formation and also change the inlet/outlet of water sources (Aubrey & Gaines Jr, 1982). These inlets and outlets can be the outlet of a river system, and the inlet of tidal activity. When a spit formation is present in a coastal area these landforms are a good indication of change in the area. These landforms can respond quickly to external changes in the environment at a local level and more globally. This makes the spit bars not a uniform landform since they are so sensitive (Randazzo et al., 2015). Since spits can be found all over the world, these landforms can contain a large variety of material. These materials can vary a lot in grainsize, from large boulders to fine sand, but gravel spits are the most common in glacial and periglacial areas (Randazzo et al., 2015). Spits evolve in response to wave energy and changes in sediment supply. If the spits do not get enough sediment, they may begin to narrow, break, or disintegrate. Climate change is one of the long-term factors that can change the supply of sediment, water in river systems and wave activity. Periods of sea level rise can change the morphology of spit bars in a local area (Randazzo et al., 2015).

Beach ridges

Beach ridges are a relic, semi parallel, multiple, wave and wind-built features that form in intertidal or supratidal zones, ridges that are still under construction, located in the active part of the coastline, are called berm ridges (Otvos, 2000). A sequence of berm ridges usually forms with troughs in between, where. These swells have the characteristics as tiny valleys, there tidal deposits and water, sediments (including fine grained), and organic matter r can accumulate when the area is still in the active part of the shoreline. Salt water, layers of clay and later organic rick mud is introduced into the swells (Clemmensen & Nielsen, 2010). Beach ridges are common features on prograding coastlines all over the world (Goy, Zazo, & Dabrio, 2003).

Raised beaches, are sediments deposited by wave activity, and mostly contain sand, gravel and shell fragments (Masselink & Hughes, 2014). These usually form when there is abundant amount of sediment supply and in areas with a low offshore gradient (Masselink & Hughes, 2014). Raised beaches are common landform to see on Svalbard. The beach ridges have been the former beaches that has been deposited in the shoreline, and then raised above the present sea level. In Svalbard these can be seen many places due to the post glacial uplift, which is a result of a isostatic response to the removal of glacial ice. The glacial ice started melting between 10 000 -15 000 years ago (Winfried K. Dallmann et al., 2015). The last glacial maximum on Svalbard is dated to end between 10 000 – 15 000 years ago (Winfried K. Dallmann et al., 2015). Where the highest located beach ridge is located is defining the marine limit. On western coasts of Spitsbergen, the marine limit is believed 65m above modern sea level (Dallmann et al., 2015). Arctic beach ridges most often occur as a series of ridges parallel to the shoreline (Dallmann et al., 2015), but the orientation to the ridges tells us if the shoreline has changed its orientation in the past. The internal sediment in the ridges can contain driftwood, shells, whalebones or other fossil material, these can often be dated to determine a more precise rate of uplift (Dallmann et al., 2015).

The sizing diagram is mostly just to divide the sediment in different categories, and to determine of there is more of one type of sediment from another. The distribution of the most normal sediment sizes is modified after a different chart from (Høeg et al., 2014).

Method

The aim of this thesis is to use aerial images from Isfjorden collected in 2009 to produce quality geomorphological maps over the different areas, showing historic landforms and continuous processes working in the coastal areas today. These maps are then combined with information gathered from historic aerial images from 1990, and geomorphological mapping done in the field during summer/fall of 2020.

The data gathered from 1990, 2009 and in the field 2020 are combined to get information about past, and present change and development in the coastal areas at the different locations. Some of the areas analysed contains different types of geological features, sediment and mostly the same processes. But from place to place the processes and the results of the different factors differs a small amount to larger amount.

Fieldwork

Fieldwork took place during September and October 2020, over a total of 9.5 days. The half day was cut short due to a sudden encounter with two polar bears, which resulted in lot of time in a boat and not so much time in the field. The primary objective of the fieldwork was to collect field observations of coastal geomorphology made from aerial photographs and to map coastal landforms directly into ArcMap on a GPS-enabled Getac field tablet. A secondary objective of the fieldwork was to get close observations of sediments forming the younger and older spits at each study site as well as the inactive raised beaches above the modern coast. Previous maps and satellite photos were initially investigated on Toposvalbard.no in order to get a good overview of the study areas. Historical aerial photos can give good information about past processes, and landforms in the area (Fitzpatrick, 2014). Unfortunately, these were not made available before February 2021, and could not be looked at before the start of the fieldwork.

Mapping in the field

A field laptop (Getac) was brought to all the field sites, but it was not used in Gipsvika because of technical problems. A Small, handheld GPS was used to set points where the Getac was not used. GPS points were also used to mark the locations where sediment samples were taken. When mapping the active shoreline, the highest seaward erosion edge was used as a reference point. This method of mapping was used on all the field areas to see if there were any changes in the landform.

Figure 11:The erosion edge seen in figure 6 is an example of an erosional edge that was followed when mapping. When walking with the Gtac or handheld GPS the point was taken just above the erosion line. Photo: Vendela Hergot

Small trenches were dug into coastal landforms and descriptions of the internal structures and sediments were made. In addition to grain size and structure, observations were made on, texture, colour, amount and type of organic material, grading, sorting, density, contacts between layers, and water content.

Definitions of grain size in the field

There are several methods to recognize and determine different grain sizes in the field and in a laboratory. The have been used to different ways to measure the different grain sizes in this analysis, one during fieldwork and one during grain size analysis in the lab. This is done because of the finer sediments are much easier to spot and determine after processing in a sieving tower, during field work the smallest sizes of sediment. During fieldwork in different weather conditions the analysis of grain size can be difficult, a simple diagram was then used to put the different grain sizes into different categories.

Tabell 1 The different sizes of sediment and the belonging names. Source: (Høeg et al., 2014)

Type of sediment	Size
Type of sediment	Size
Blok	>600 mm
Rock	600mm>60 mm
Gravel	60 mm > 3 mm
Sand	2mm> 0.06 mm
Silt	0.006mm>0.002 mm
Clay	<0.002 mm

Sediment samples

Sediment samples were taken at three of the six field sites: Longyearbyen, Hiorthamn and Gipsvika. The decision to take sediment samples was added in the middle of the fieldwork, and for that reason not all locations are included. Since characterising the sediments in a great detail was not the main objective for this thesis, the process of taking the samples was not prioritised. Where samples were collected, a 10X10 cm square was outlined using a large ruler and samples were taken, layer by layer, resulting in that some areas having more samples than others. Samples were collected in plastic sip lock bags and stored in a fridge at UNIS before further analysis.

Mapping post fieldwork in ArcMap

Mapping started with delimiting the areas of interest and relevancy for mapping, and then starting to map the obvious features. These included the largest and most clearly visible beach ridges, the modern shoreline, riverbanks, and active rivers. These features were mapped out by drawing polygons, lines and points in ArcMap. Codes and visualisation tools that are used by the Geological Survey of Norway for defining areas and/features were applied in this thesis.

Landforms and sediments were mapped using the ESRI ArcMap10.6 software, (coordinate system *ETRS 1989 UTM Zone 33N*). Observations from the field were combined with historic aerial photos with and without infra-red resolution, and DTMs (Digital Terrain Models) of the local area. All of these services are delivered by The Norwegian Polar Institute.

The maps are presented in 1:6000 scale, and 1:10 000 scale to get a good overview over the area as well as finer details. Maps covering the entire watershed for each site are not included, but basic information about the watersheds (e.g. area, etc) are included in table 2. When mapping the points, lines, and polygons, the scale was set to 1:1000 in order to map the different landforms in detail at each location.

Creating maps with both a scale of 1:6000 and 1:10 000, ensures that the maps are easy to understand. Examples of previous surficial geological mapping in Svalbard can be found in Rubensdotter et al., 2015, Rubensdotter et al., 2016. These mappings have been used as inspiration for the thesis.

Tabell 2:Table over different data and datasets that is used for analysis in the different field sites. Source over data is NPI (Norsk Polarinstitut).

Area	Year	Date	Data type	Source	Resolution
Longyearbyen	1990	20 July	Vertical aerial image	NPI	1:7000
Longyearbyen	1990	20 July	Vertical aerial image	NPI	1:7000
Sassen west+ east	1990	22 July	Vertical/infrared aerial image	NPI	1:50 000
Hollendarbukta	1990	12 Aug	Vertical/infrared aerial image	NPI	1:15 000
Gipsvika	1991	18 Aug	Vertical/infrared aerial image	NPI	1:15 000
Spitsbergen	2014	12 Aug	Digital elevation model	NPI	5 meters
Spitsbergen	-	-	Basiskart Svalbard	NPI	-

Analysis of sediment samples

The procedure for analysing the sediment samples was a guide made for students in geology at UNIS. All of the samples were placed in separate metal bowls and marked with their sample code for later identification. Next they were dried at 105 degrees C for 14 hours. The samples were then taken out of the oven and cooled down to room temperature for 10 hours. All the samples were dry sieved in a sieving tower, which included mesh sizes of 20mm, 6,3mm, 2mm, 630 μm, 200μm and 63μm, and the pan at the base, representing grains sizes less than 63 microns. The total dried sample was weighed in a separate bowl before sieving. The sample was then placed in the top sieve (22 mm) in the sieving tower, and shaken for at least 3 minutes; the most fine grained samples were shaken for as long as 10 minutes. Once shaking was completed, the sediment retained in each sieve and in the bottom pan was removed and weighed separately.

Sources of error connected to fieldwork and post fieldwork analysis

Errors connected to fieldwork

Because of the ongoing pandemic caused by Covid-19, there was a lot of time lost due to complications in this situation. Closed borders in different countries prevented both professors and students from coming to Svalbard in the time period from march to July. When everyone connected to the project had arrived in Svalbard the time for fieldwork was limited, because of the approaching fall weather. Most of the days in the field happened in 2 weeks, that resulted in little time to process field data from one place, before the next field day in a different area. Because of the delays in fieldwork and the agreement on which areas that could be interesting to investigate, the knowledge about each area was not great before going into the field. The field areas should have been discussed long before the fieldwork started, so that the research history and practical information about the geological features were known before entering the field.

One field day was lost due to close encounter with two polar bears, fortunately this was one of the most visited areas during this fieldwork, so no study areas were lost due to polar bears. In retrospect it turns out that the valley system and the fjord system where most of the field sites are, is one of the main travel routes for polar bears. The polar bears that are just traveling through the land or if they were born in the area is expected to come back to the area, this would have been nice to know before selecting the field sites.

Errors connected to mapping

Making the maps in this analysis is exposed to lots of potential errors. Some of the areas mapped out were visited during fieldwork, observations during fieldwork contributed to the knowledge of the area mapped later. Not all the area that is mapped out was visited during fieldwork because of limited time in the field and large field areas to cover. The areas not visited during fieldwork is only interpreted by looking at orthographic maps, and the interpretation of the map does only come from these maps in these specific areas. Ideally these maps should have been taken into the field and then be confirmed that the mapping was done correctly. The method of mapping improves over time, and the act of geomorphological mapping in GIS is a learning by doing practice. After mapping the areas over an extended period of time it gets simpler and quicker, and the whole process becomes easier to understand. Geomorphological mapping done this way need some time to get used to, recognising the landforms, structures and other features needs experience.

Errors connected to sediment samples

Since the decision to take sediment samples were taken in the middle of the field work period, all of the field sites have not been sampled and is therefore inconsistent. The method for sampling was not agreed on or researched before going into the field, partly as a result of limited planning time with UNIS partners due to the covid delays (stated above). Method for sampling where consistent between field sites, however.

Results

Geomorphological mapping and observations

In this chapter geomorphological maps, observations from fieldwork, and results of particle-size analysis of sediment samples are presented for all of the study sites. Geomorphological mapping was conducted during field visits to all six field sites in the fall of 2020. All of the maps are made after the Norwegian SOSI standard, with some small modifications to accommodate the arctic coastal environment.

Hollendarbukta

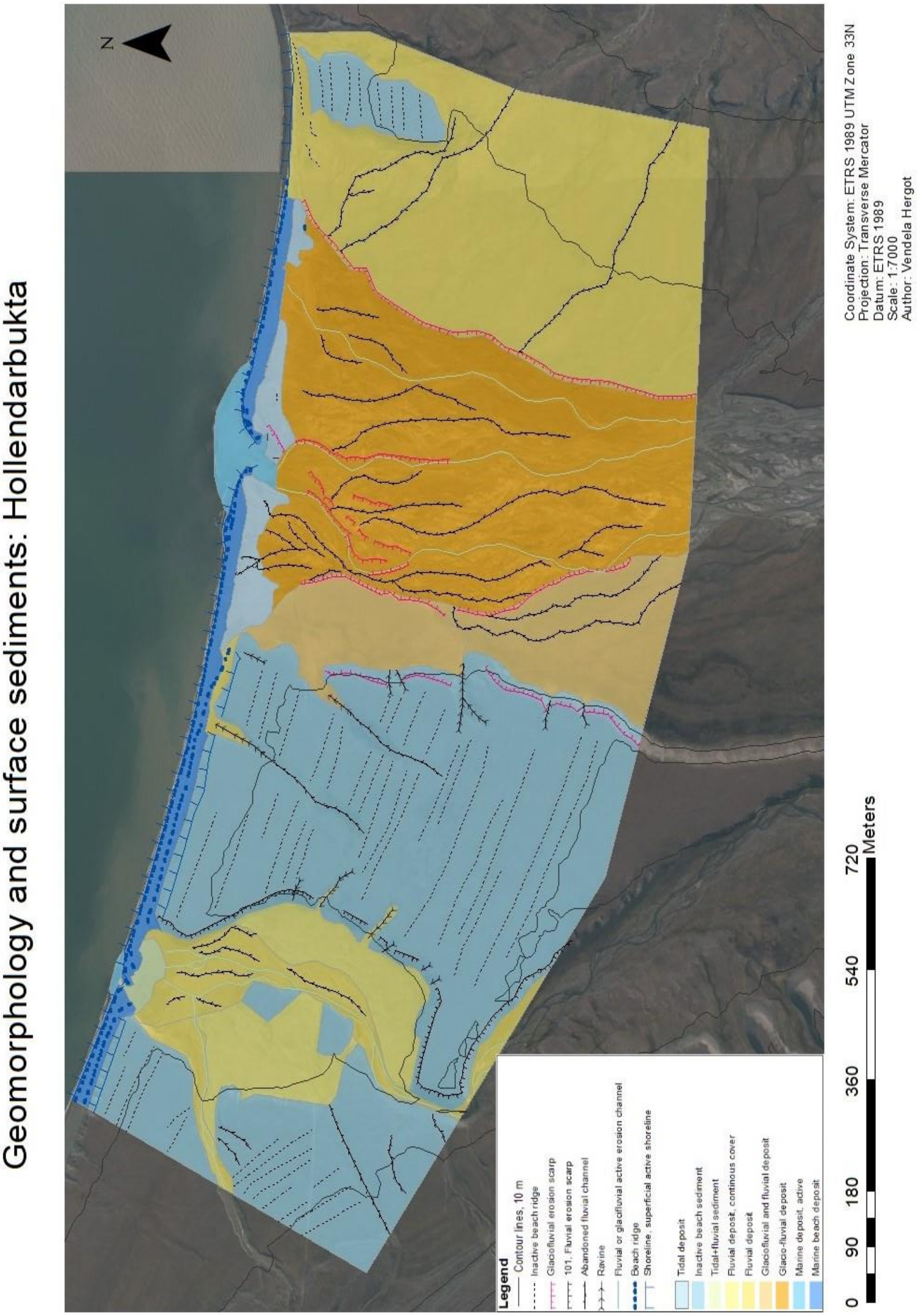

Figure 12: Geomorphology and surface sedimentological mapping done in the Hollendarbukta area. Map presented in a scale 1:7000, and is projected in the ETRS 1989 UTM Zone 33N coordinate system. Aerial orthophotos provided by the Norwegian polar institute (2009) is used as basemap.

Geomorphological mapping was conducted during field visits to all six field sites in the fall of 2020. All of the maps are made after the Norwegian SOSI standard, with some small modifications to accommodate the arctic coastal environment.

The geomorphology and the surface sediment have been mapped out over an area that measures 1.5 m^2, which is located in the bay area of Hollendarbukta. In this map the common features and processes that can be found in the coastal area of Hollendarbukta is mapped out, also including some of the surrounding area. This study area consists of two different riveroutlets, Hollendar elva and Bogebekken. The connecting watershed to Bogebekken is no longer glaciated, and is only affected by fluvial activity except for the river outlet, which include the marine processes. The main river of this analysis is Hollendarelva, which is still influenced by glacifluvial activity. This makes the surrounding area affected by both glacifluvial activity from the watershed, but also fluvial activity from the sides of the watershed, which can be seen in the eastern side of the mapped area in figure 12. This area contains areas with raised beaches that are raised between 4 and 20 above the modern day sea level. Small river channels and ravines have been forming on the raised area, this is the case on both riverbeds and sides of the river. The riverbed of Hollendarelva contains active and abandoned river channels, and some areas with harsh scars after erosion in the riverbed classified as glaciofluvial erosion. In the river outlet of Hollendarelva there is an area classified as a tidal deposit area, this area is located in a low laying area, there tidewater enters between the two present spits and covers the area with sea water during high tide. This area is also affected with glacifluvial activity from the watershed, but due to the size of the area, and the amount of sea water that covers the area, it is most likely that the area gets more affected by tide processes. The area in the outlet of Bogebekken in classified as a tidal+ fluvial sediment, this is due to the high beach ridges that are acting like a barrier, and the influence by fresh water that can accumulate towards the river outlet. The active part between the spits at both locations are marked as a marine deposit, due to the strong influence of the marine processes on the outside of the spits, and the tidewater that influences both areas. The beach ridges that are active in the present shoreline have been marked with a different colour of a darker blue colour, so the active and the inactive ridges can be easily distinguished.

On the active beach ridges in the modern shoreline overwash formations is seen on the inner side of the spit, this overwash formations is in a characteristic wavy pattern (Fig 13A). Close up of the overwash formations of rocks stacking on top of each other (Fig 13B). These features do not happen in a uniform pattern all over the beach ridges, but can be seen in some selected areas.

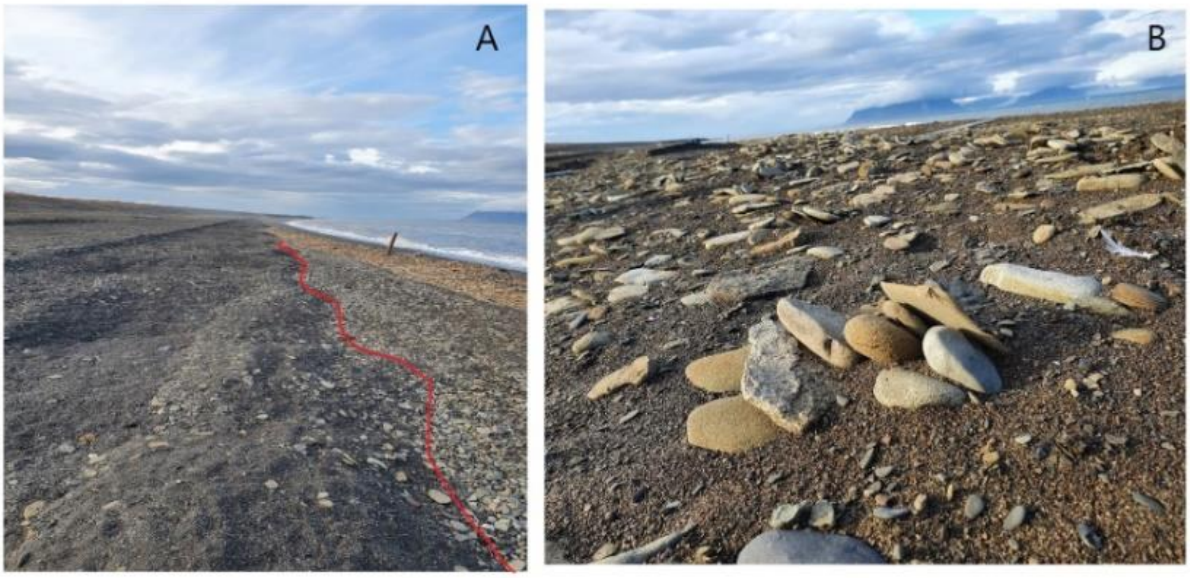

Figure 13: The western active beach ridge located in the outlet og Hollendarbukta. Picture A shows the overwash formations that is present on the outer beach ridge, further inland a sectond ridge is visible, and is the second active beach ridge mapped in the geomorphological and surface sediments of Hollendarbukta (fig?). On Picture B a closeup of the overwash is shown, showing the inland side of the active beach ridge, where there are rocks stacked on top of each other. Pictures: Vendela Hergot.

Inland of the modern beach, spits, and river outlet are flight of raised beaches approximately 1 – 18 m above present sea level. These raised beaches do not have distinct ridges, and difficult to spot in the field, because of the vegetation in the flat area. They are easier to spot on an aerial photo, where it is easier to spot the differences in vegetation colour, and the long lines created by the lighter colour on the subtle ridges, compared to the darker colour in the lower lying, wetter troughs.

Figure 14: Photo looking into Hollendardalen standing on top of the raised beach area between Bogebekken and Hollendarelva. This is an area where there are beach rides present, but are very difficult to spot in the field. Photo: Vendela Hergot.

Figure 15:Stratifyed fine grained sediment that have accumulated in the inland side of the western spit of the outlet of Hollendarelva. Some of the stratified layers have different colours, and different grading of the sediment, making the stratified layer clear. Picture: Vendela Hergot.

Both the inland and seaward sides of the beach ridge have deposits of fine-grained, muddy sediments where observed (Fig 15). Stratified fine grained sediment up to 7 cm thick (e.g. Fig 15) was frequently observed around the mouth of Hollendarelva on the inner sides of the spit (Fig 12).

Landscape changes between 1990 and 2009

Landscape changes between 1990 and 2009, as shown in figure 16, there has been a lateral change in the river outlet in an easter direction. In 1990 the barrier that separates the river outlet from the riverbed looks like it has a distinct shoreline with possible overwash formations on the barrier. There is a small accumulation of sediment on the right side of the picture, that possibly is an old outlet from the river that is a closed lagune in 1990. In the picture from 2009 the lagoon on the right side is still there, but it is not as long and has been filled up a bit with sediments.

The spit formation has changed between 1990 and 2009. the river outlet has moved towards the east by and in 2009 is located more in the centre of the river mouth. Braided rivers are not easy to keep track of since their multiple channels have a tendency to change multiple times during the melt season. Nonetheless, it looks like as though there are smaller but more channels in 2009, that are spaced out over a larger area.

Figure 16: Aerial photograph comparisons from 2009 and 1990. Picture to the left is an aerial photo from 2009. The right picture is an aerial photo from 1990. Pictures are not orthorectified and is not to scale. Source: NPI.

The comparisons pictures are not orthorectified, due to problems during the process, these pictures (Fig 16) are not to scale, but contribute to good visualisation in the analysis of the coastal changes from 1990 to 2009.

Comparisons to data collected in 2020

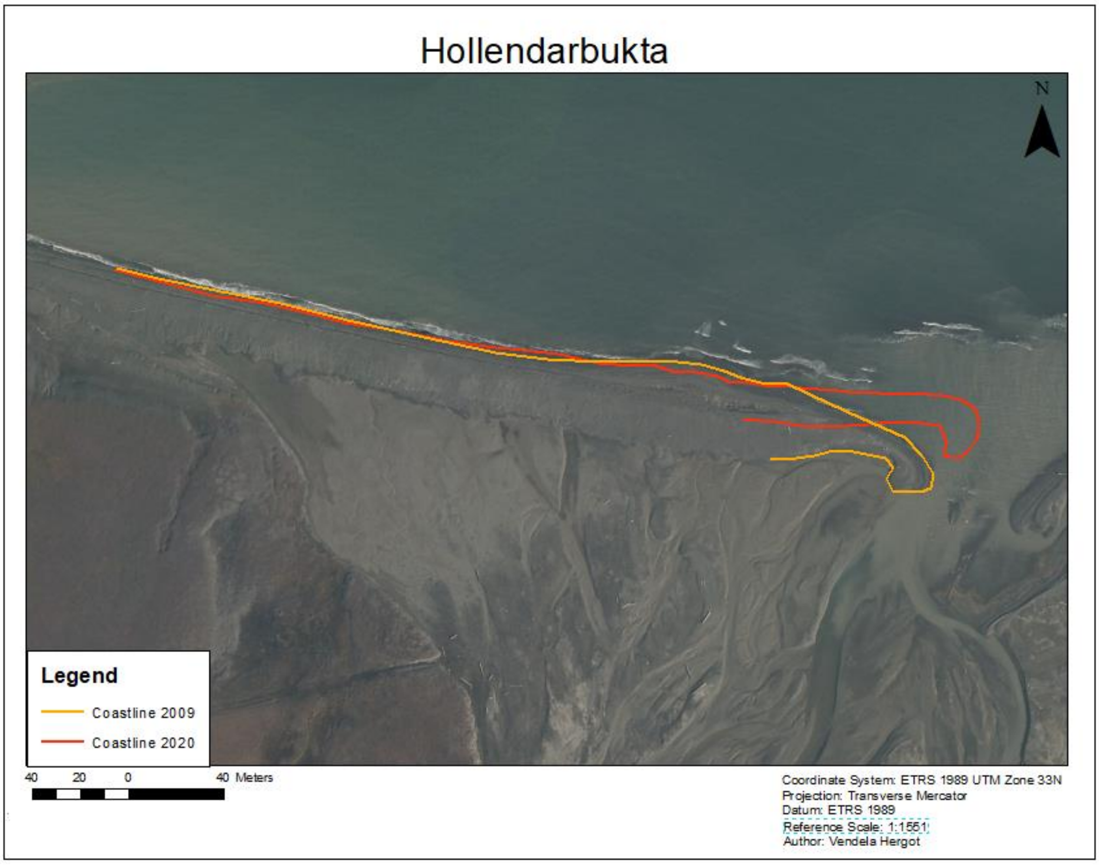

Figure 17: Changes along the western spit at Hollendarbukta between 2009 and 2020. The basemap in this figure was taken by NPI (2009). The red line represents GPS points that were taken along the active spit during fieldwork in the fall of 2020, the yellow line traces the spit present in 2009.

The GPS points made during fieldwork when following the present day spit at the high tide line on the western side of the river outlet of Hollendarelva. The measurements show that the spit have grown by 17 m in an eastern direction, and continued in a straight line, making the spit be located 28 m further out in the bay area than the spit from 2009. These changes have only been in the wester spit, and no change can be observed in the beach ridges west for the spit. The eastern side of the outlet have not been investigated, and therefore only the western spit contains data collected on fieldwork.

Cross sections in spits and surrounding area

Figure 18: Sediment descriptions were made at two different sites in Hollendarbukta. Picture 1 shows the general area where the sedimentological observations were made. The red circle with the number 10 in picture 2 shows the locations where 10 observations was made of the contents of the inactive beach ridge. In the red square in picture 17, sedimentological observations were made along a transect. The transect is located along the active spit on the west side of Hollendarelva. The red line in picture 3 outlines the transect made across the spit, towards its eastern limit. Along this transect, 9 observations were made, describing the sediments from the surface and down ca 10 cm. More information can be found in the appendix.

Sediments were observed at two different locations at Hollendarbukta, Point 10 (see Fig 18), is situated on an inactive raised shoreline. This area has been affected by both marine and terrestrial processes. During storms and high tide, it is possible for waves to reach this area. Since this point is located in a small slope at the foot, and water accumulated from precipitation can also seep through the slope. The internal sediment structure at this location shows interbedded layers of coarse sand, gravel. Up to ninety percent of the internal structure is matrix supported with some fine sediment in between (Fig 19). Some vegetation of the surface has resulted in some root growth in the uppermost layer. More information about the different layers can be found in the appendix.

Figure 19: Picture of the cross section nr 10 (for location see fig 18). Different layers of coarse sand and gravel is observed with some larger cobbled imbedded. More information about this cross section can be found in the appendix. Photo: Vendela Hergot.

Points 1-9 are from the active spit in the western side of Hollendarelva where it meets Isfjorden. These 9 observations are described more in detail in the table found in the appendix. The general observation in this area, is the larger cobbles that area accumulating in the surface layer, and close to the surface layer. The closer to the modern shoreline, the surface layer become more and more sandy. Most of the coarse cobbles have accumulated on top of the beach ridges, and closer to the ocean the grainsize decreases and is then replaced by finer material.

Longyearbyen

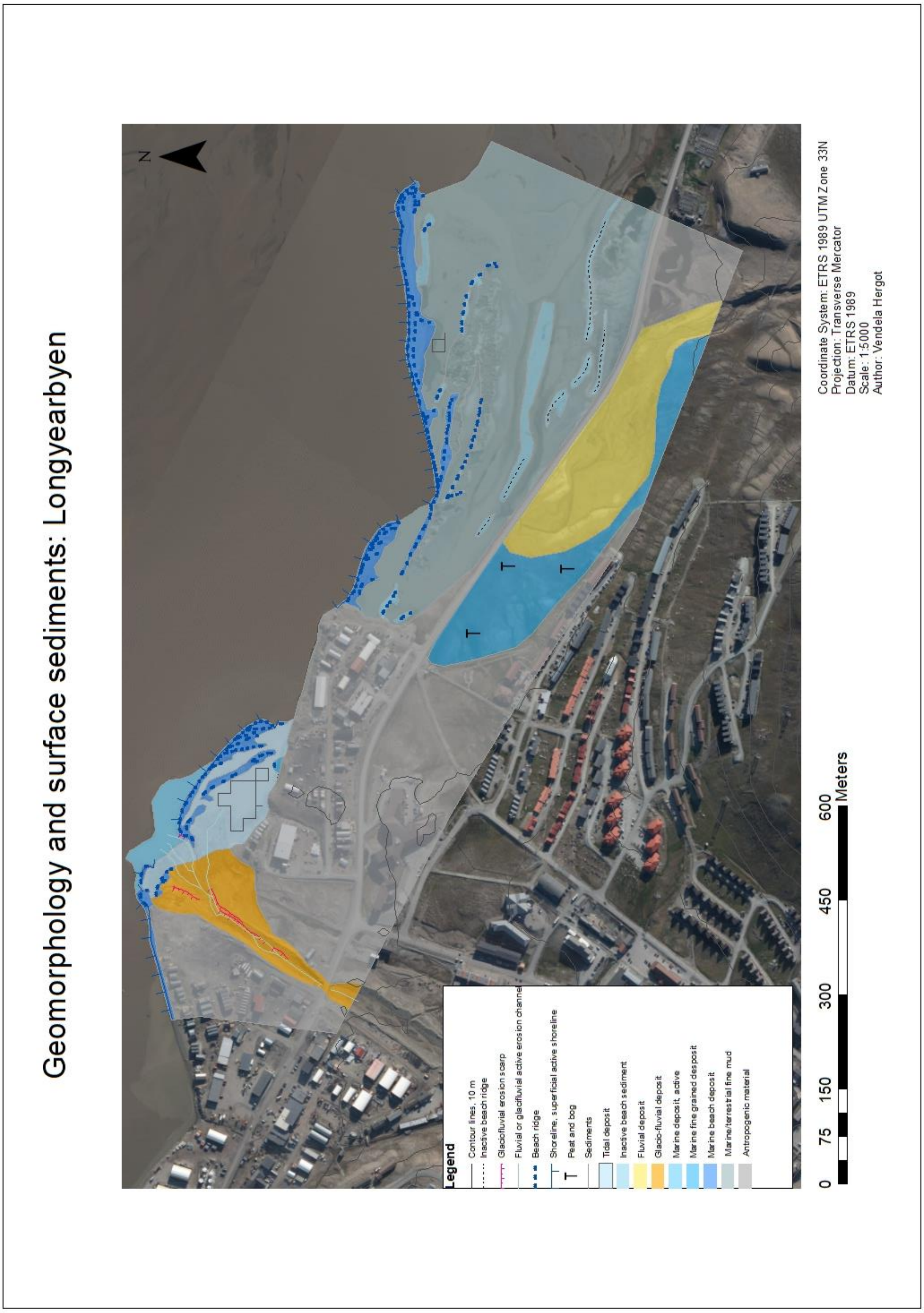

Figure 20: Geomorphology and surface sedimentological mapping done in the Longyearbyen area. Map presented in a scale 1:5000, and is projected in the ETRS 1989 UTM Zone 33N coordinate system. Aerial orthophotos provided by the Norwegian polar institute (2009) is used as basemap.

In the geomorphological map over the coastal environment in Longyearbyen the dominating features are spit bars, marine mud accumulations, tidal and fluvial sediment fluvial and glacifluvial contribution, and the anthropogenic structures and other traces of human activity. The most dominant feature of this coastal area is the degree of anthropogenic material in the area. Most of the area is affected by human activity directly or indirectly.

The riverbed in Longyearelva, for example, has had a lot of sediment removed or moved. This creates a lot of turbulence in the water, and lots of sediments gets carried down the river system into Adventfjorden. The spits along the coast of Longyearbyen (Fig 20), extend towards the east, and most of the sediment that Longyearelva carries down appears to be transported bur surface currents and longshore drift to the east when entering Adventfjorden (Fig 20). The shoreline is quite strait of the front of Longyearbyen, and the large delta at the mouth of Adeventelva. The spits are most prominent at two locations: in the outlet of Longyearelva and to the southern side of the outlet of Adventelva. The spit located to the east of Longyearelva outlet is larger and longer. These spits consist of a fine gravel material, with some larger cobbles accumulating on the beach ridge. The area on the on the inner side of the spits there are accumulations of marine mud, this is a fine grained sediment which also contains some organic material. The area where this mud accumulated is in the tide water dominated environment, this is especially the case for the areas in the outlet of Longyearelva river, and in the inner sides of the spits. This is an area with a low gradient, so tidewater will have an effect on the area. The marine mud is thick, and in some areas the mud has accumulated over 1.5 meters of sediment. This area has the most input from glacifluvial activity from both Longyeardalen valley that contains three glaciers, Larsbreen, Longyearbreen and a small contribution of meltwater and sediment from Platåbreen glacier (Fig 4). This site also gets contribution of both sediment and water from the Adventdalen watershed, this watershed contains several glaciers distributed over a large area and is located to the east of this particular field site look figure 4. The area with the largest amount of marine mud accumulated also gets contribution from a smaller watershed from Gruvedalen valley. This is a small valley leading up to a plateau where lots of snow and ice accumulates over the winter. This also contributes fresh water to the area, and some sediment.

Comparisons to historic aerial photos from 1990 and 2009

Figure 21: Aerial photograph comparisons from 2009 and 1990 in the Longyearbyen area. Pictures are not orthorectified and is not to scale. Source: NPI.

It can be difficult to see the changes in the pictures, since the photo from 1990 is in a light resolution, and in a lower quality than the other picture. In the Longyearelva river outlet the barriers towards the left have degraded and is not as prominent as before. The outlet of the river has changed from the right side of the delta, to be centred more in the middle of the delta. By the looks of it the spits in the right side of the picture have become smaller, and thinner. It looks like there are finer sediment around the spits, but this can also be caused that the pictures were taken on different tides. During fieldwork on the spit located to the right in the picture, an encounter with a local woman said that that area was used as a local landfill for glass waste. There is no literature about this, but it can be a factor of the size of the spits. But this is not taken into consideration since there is no literature about this action. In the picture from 2009 where Longyearelva river outlet gets deposited in the sea, the accumulation of sediment looks larger than in 2009, but this can also be because of the different tides the pictures were taken. From these two pictures, the difference in human activity is large. There is a lot of new buildings that has been built in the 19 years since 1990. This can have a large impact on how much sediments have been deposited by human activity when moving sediments for building masses and how much activity there has been in the riverbed to prevent further erosion in the river. Several buildings and infrastructure are located close to the river, so there has been extensive work done to prevent further erosion.

Comparisons to data collected in 2020

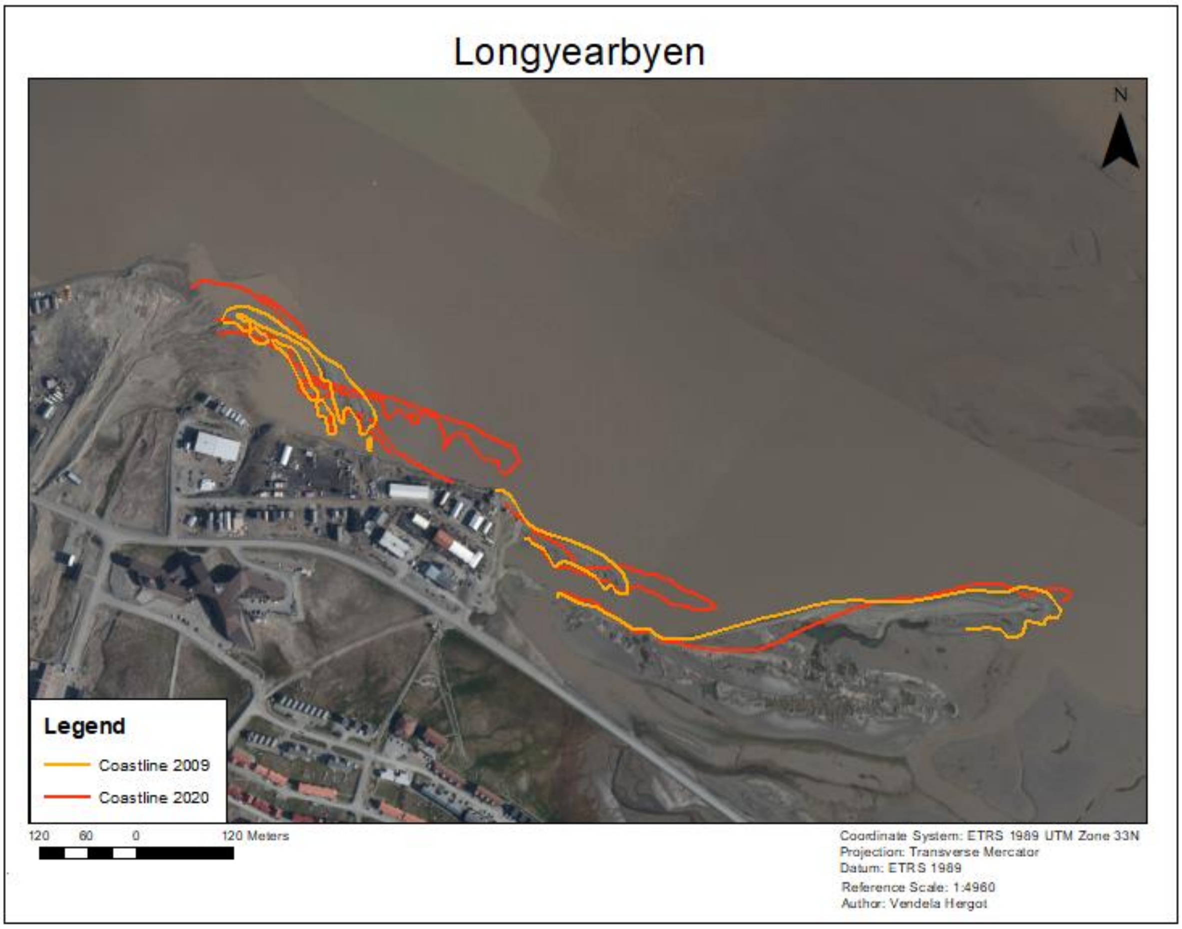

Figure 22: Changes in the coastal area of Lonyearbyen between 2009 and 2020. The basemap in this figure was taken by NPI (2009). The red line represents GPS points that were taken along the active spit during fieldwork in the fall of 2020, the yellow line traces the spit present in 2009.

Change have clearly happened in the years between 2009 and 2020. The yellow line in figure 22 is a trace after the spits that is visible in the basemap from 2009, and the red line is a line drawn through GPS points captured in 2020. The spits that were present in the outlet of Longyearelva in 2009, have become larger and longer since then. The sediment has experienced a lateral transport from the west to the east, and accumulated, creating a larger spit. The spit accumulation that can be observed in the easter part of the area, have become larger, but thinner.

Cross sections in spits and surrounding area

Figure 23: The location of this figure of the coastal area around Longyearbyen, with the red dot showing the location of the cross section that was analysed in the area, and the number of observation that can be found in table 1.

The internal structure of one of the spits in Longyearbyen was investigated, the spit chosen was the spit with the number 23 (look fig 23). This spit was chosen because the other spits in the right of the picture (fig 23) was impossible to get to by foot without help from others to get through the mud. The location where observations about the internal structure was made in the highest erosion edge in the spit. The internal structure was a very loose material, with stratified layers with sand and gravel in different sizes. The gravel is mostly sub angular to well-rounded and is horizontally oriented.

The Longyearbyen spit in figure 9 has a clear erosion edge. The erosion edge is about 30 cm high, and is matrix supported by mostly coarse sand with some larger rocks up to 5 cm in diameter. On the top layer there are no grading between or stratification between coarser or finer material. There is a uniform layer containing coarse sand, with smaller rocks ranging in different sizes under 1 cm. There are also some larger rocks up to 10 cm in diameter. No vegetation in the material. The top layer in Sassen- west area is more angular, but flat rocks and more vegetation in small patches. The flat rocks lay on top of a much finer coarse sandy material.

Sediment samples

The sediment samples from Longyearbyen were taken in two different layers, the top layer and a second layer. The grain size analysis data (see appendix, nr 23) shows that most of the sediment on the top layer was in a coarse material, and contained little fine material as medium sand, fine sand, and silt. In the second layer there was much less coarse material such as coarse and medium gravel, but more medium sand, fine sand, and gravel.

Hiorthamn

There have not been made a geomorphological map over the area of Hiorthamn, due to the lack of fieldwork and investigations in the area. This area does not contain many of the landforms and processes that can be visible at the other field sites. This area does not contain any sediment transfer to the investigated coastline, sediment storage is present further up in the watershed, but does not contribute to this particular coastal area.

Comparisons to data collected in 2020:

Figure 24: Changes along the coastline of Hiorthamn between 2009 and 2020. The basemap in this figure was taken by NPI (2009). The red line represents GPS points that where taken along the active spit during fieldwork in the fall of 2020, the yellow line traces the spit present in 2009.

The red line visible in figure 24 is the current coastline during fall of 2020, and the yellow line is the previous coastline in 2009. The coast has been eroded between 20 – 25 m since 2009, causing a threat to the cultural heritage at the location. In the area that is mapped out in figure 24, the coastline has eroded an equal amount along the coast.

Cross sections in spits and surrounding area

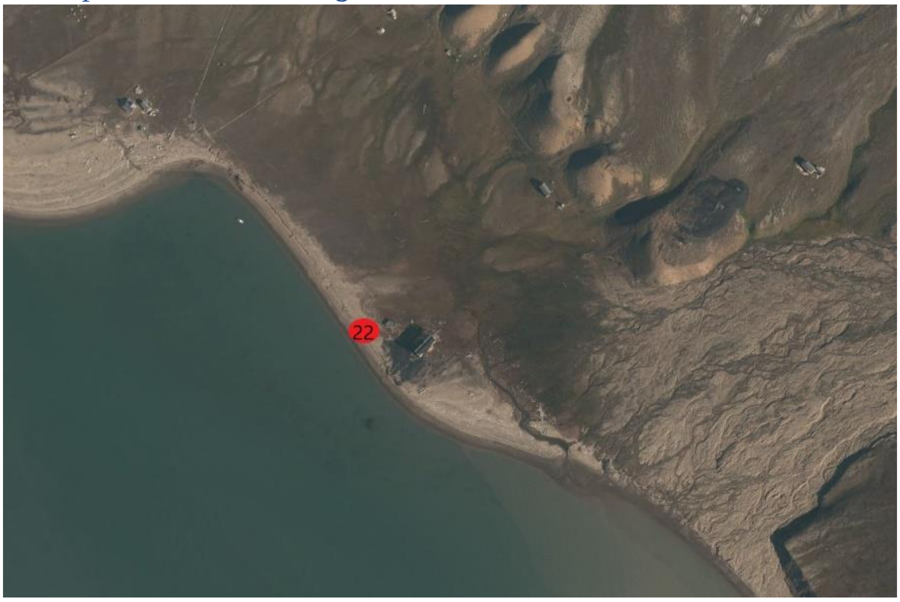

Figure 25: Location of cross section done in the Hiorthamn coastline. More information about this cross section can be found in the appendix, nr 22.

The shoreline around Taubanestasjonen which is an old coalmining station for transporting coal from the close mines has transgressed several meters especially since 2009. The internal structure of this shoreline is dominated with shaly flat rocks in different sizes, with all lying in a horizontal orientation. There is stratification of different types of sediment (Fig 26), with dense matrix supported gravel on the bottom and sandier towards the top layer. There are some stratified layers with coal, which is from previous coalmining activity. Towards the top layer the soil becomes darker as a sign of a higher content of organic material. The top layer is more sandy, with some frost shattered rocks. The erosion edge is unstable, and in several areas the slope has experienced toppling. Most of the coastline with a high erosion edge over 50 cm, have undermining features in the foot of the erosion edge.

Figure 26: Cross section and location for sediment sample Hiort1.1 and Hiort2.2

Sediment samples

The sediment samples were collected at two different locations in the Hiorthamn area (Fig 26). The first samples (Hiort1.1 and Hiort2.2) was taken in a small erosion edge to the east for Taubanestasjonen (Fig 26), this area does also experience extensive erosion (Fig 24). This section of samples was in a two layer stratigraphy, the surface layer and subsurface layer. The difference in the surface layer and the second layer was a difference in 25.1% between the amount of coarse gravel where the surface layer had the largest gravel content at 31.29%. There was a large difference in the content of medium gravel, where the surface layer only had 5.28% medium gravel and the second layer had 29.72%, making a difference of 24.44%. The amount of fine gravel, coarse and medium sand is mostly the same content in the two different layers. The content of fine sand differs from 2.43% in the surface layer and 6.65% in the second layer, which is a difference of 4.22%. Silt and clay content is both under 1%, 0.15 % in the surface layer and 0.67 % in the second layer. The accumulation of fine sand and silt/clay is larger in the second layer.

Figure 27: Locations of the two different location of the sediment samples in the Hiorthamn area. Nr 1 represents location 1, and Nr 2 represents location 2.

The second location (Fig 27) at Hiorthamn where sediment samples were sampled was in an erosion edge of about 63 cm. This erosion edge had contained 8 clearly stratified layers of sediment, the stratified layers was in a horizontal orientation, and each stratified layers contained different sizes of sediment, some layers also had a clear colour difference (Fig 28**)**. At this location 4 samples were taken; these samples were the 4 stratified layers from the surface layer. These layers where matrix supported, embedded with medium sized flat pieces of gravel, The loose texture made it hard no analyse the different layers, layer by layer. More detailed information about the sediment sediment samples can be found in table 3.

Figure 28: Cross section nr 1 at Hiorthamn, for location see fig 26. This cross section show different stratified layers of sediment, and sediment samples were taken from the four layers close to the surface.

Sassen -west

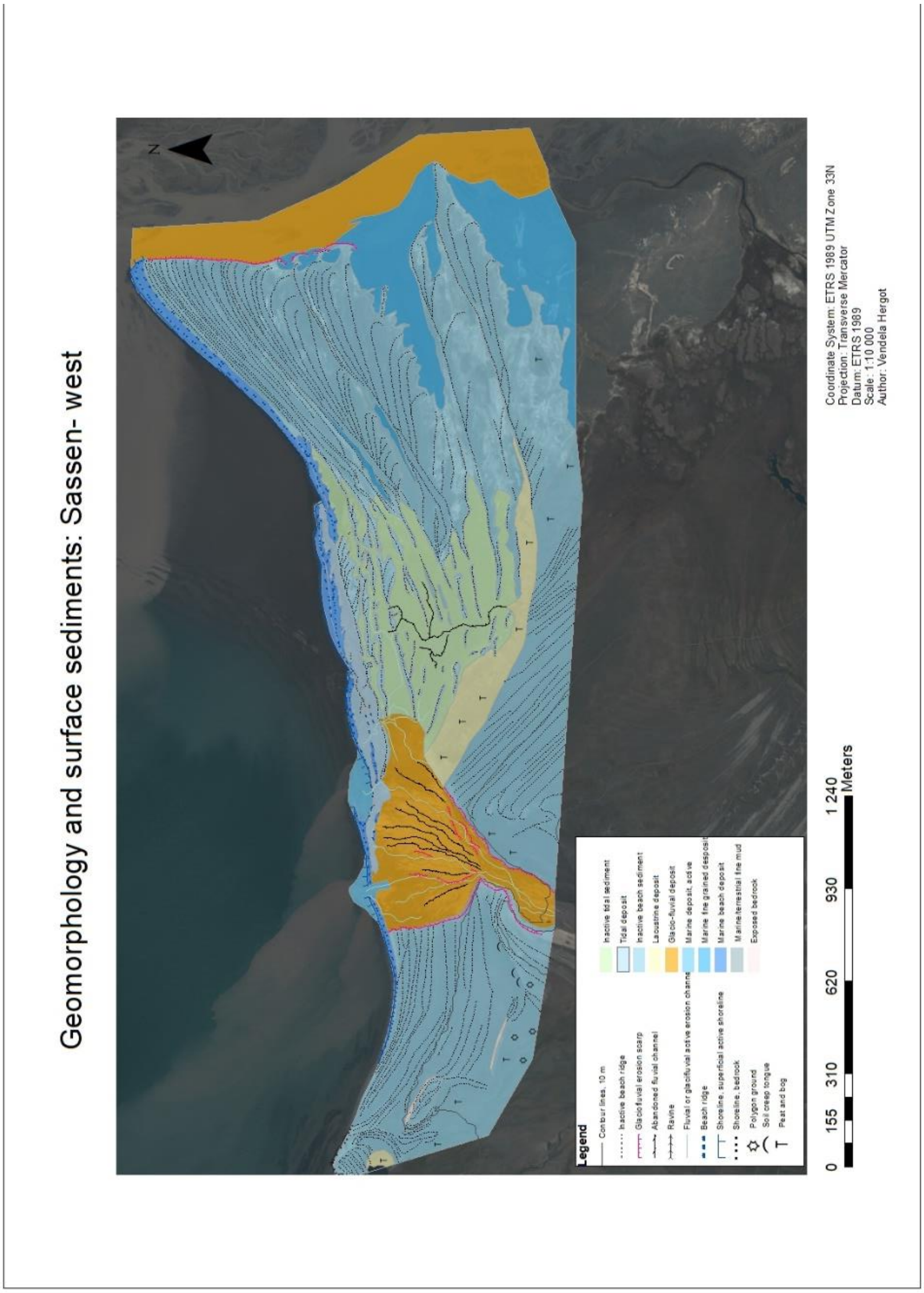

Figure 29: Geomorphology and surface sedimentological mapping done in the Sassen-west area. Map presented in a scale 1:5000, and is projected in the ETRS 1989 UTM Zone 33N coordinate system. Aerial orthophotos provided by the Norwegian polar institute (2009) is used as basemap.

The geomorphological map of Sassen-west is covering an area that is about 2.7 km^2 and covers the are from Sveltihel to the western side of the Sassenelva river outlet (Fig 6). This is an area that contains several generations of different landforms, and the previous history of the area can clearly be investigated in the area. This map contains the main features over the landforms and processes in the area. The main features are several generations of spit bars, overwash formations, marine mud accumulations, raised beaches, bedrock outcrops, and watersheds that contributes with glacifluvial activity.

The spits in the Sassen-west area are of several generations, and the active spits are the spits that are in the delta from Lusitaniadalen (see Fig 4) and the most outer spits that are following the coastline towards the Sassenelva river outlet. The surface layer on the spits varies a lot, but the most common sediment type on the outer spits are flat sub angular cobbles varying in size. The most common size is between 3-4 cm in diameter. The older spits that are situated further from the score have more sand on the surface layer, more frost shattered rocks and more vegetations growing.

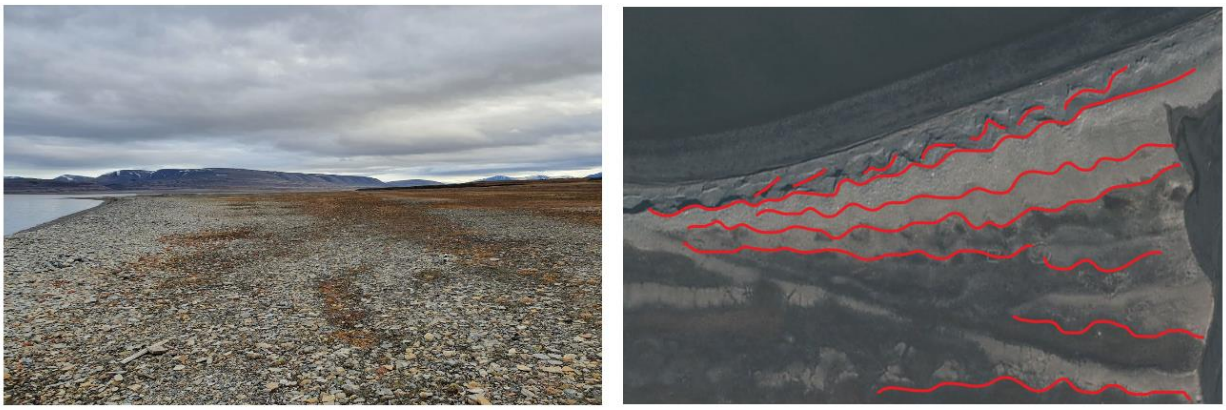

Figure 30: Picture to the left showing the overwash formations from the west to the east. The right picture is showing the overwash formations from an overview perspective, where red lines is drawn in to enhance the lines of the overwash formation. The lines are drawn over a basemaps from (NPI, 2009).

Overwash formations can be found in several places in the area, but the place presented here on the left side of the Lositaniadalen valley delta is the most prominent one. In figure 30 The clear overwash formations is drawn in with red lines, the lines furthest inland is the oldest and the overwash formations gets younger towards the sea. In the overwash formation that is the newest in the area, rocks could be found up to 6 m from the closest erosion edge and presents the incredible forces the coast experiences from season to season. The right picture in figure 30 is showing the overwash formation in the field, and in this figure it is clear that the formation is much clearer when the picture is taken from above.

The marine mud accumulations are large in this area, both in the delta from Lusitaniadalen valley and between the younger and the older spit bars. Between the older spits thick mud that responds to the amount of water that is present, especially during precipitation events. When visiting this area during the fall of 2020, it was right after a couple of days of precipitation. Water from these events gets accumulated in the low laying mud areas, and because of a low to zero gradient the water will be accumulated until it evaporates. Between the larger older spits channels of water would keep the mud with a high water content and make it impossible to cross on foot.

The raised beaches in the area can be found in both the older spits near Lusitaniadalen valley delta, the larger spit area towards Sassenelva river outlet and further up the slopes away from the coast. Some of the oldest raised beaches can been seen over 1.4 km inland from the coast in this area. The younger raised beaches are covered in frost shattered rocks, with some growth of vegetation in small areas. The most prominent raised beaches have a lighter colour to the top of the ridge seen from far away, and then more vegetation is gathered between the ridges.

Figure 31: Picture taken above the bedrock coastline in fig?. The accumulated lighter areas are a coarse gavel material, that indicated the past beach ridge in the area. The more vegetated area contains a finer material than the old beach ridges, accumulating more moisture and finer sediments. Picture: Vendela Hergot

In this particular area there is also bedrock outcrops, these outcrops can be found in the modern coastline and at 179 m and 400 m inland from the modern coastline. The bedrock outcrop located by the shoreline is larger than those who can be found further inland. The pictures in figure 32 show the two different types of bedrock outcrop that is in this area. The smallest one is located about 400 m inland, and has much vegetation growing on top and shows signs of weathering.

Figure 32:Picture of two different bedrock outcrops in the Sassen- west area. The left picture is located about 400 m inland from the modern coast, surrounded with old raised beaches and vegetation. The picture to the right is the bedrock coastline in the modern coast at Sveltihel (fig?). In the right picture there is also smaller ridges due to wave erosion and sea ice during winter and spring. Pictures: Vendela Hergot.

shoreline, which makes the clear erosion edge shown in figure 32. in between the large erosion edge and the sea there is evidence of ice push in the sediments. These features are areas where sediment have been moved by the sea ice and/or large pieces of ice being pushed onshore during storms. This is something that can happen in all seasons, since large ice blocks can be seen and were present during fieldwork. These blocks of ice are most likely to originate from Tunabreen, which is a surge type glacier (Location of Tunabreen see Fig 7).

Comparisons to historic aerial photos from 1990 and 2009

Sassen – west with its long shoreline has experienced little change in almost 20 years from 1990 to 2009. The large spit formation on the right side in fig 33 is almost unchanged.

The delta formation that comes from Lusitaniadalen seem unchanged, except for the spits and barriers in the coastal sone. Figure 33 show evidence of a thinning and shortening of the spit formation from 1990. The unnamed river from Lusitaniadalen has changed its outlet from being more into the land and the spit area to the right, to migrating outwards towards the sea. In the closeup picture in figure 6 the barrier that had the delta closed in 1990, has been thinned and have more outlets in 2009.

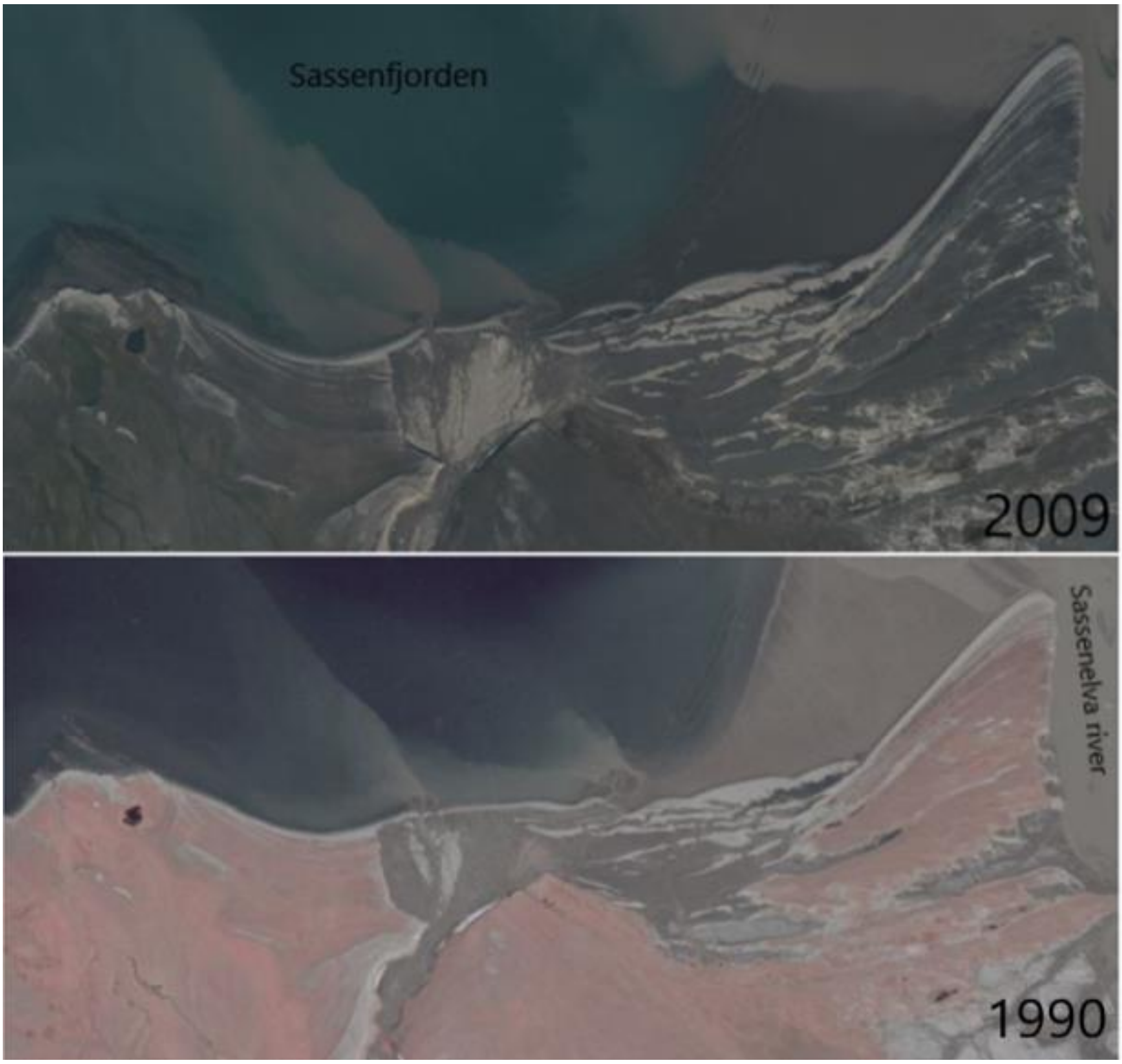

Figure 33: Aerial photograph comparisons of the Sassen-west area from 2009 and 1990 in the Longyearbyen area. Pictures are not orthorectified and is not to scale. Source: NPI

In this area by the looks of it there has been minor changes over the last 19 years. From the pictures it looks like the unnamed river is carrying less water in 2009 than in 1990. It also looks like the water from Lusitaniadalen carries less water and sediments into the right eastern part of the delta, that leaves the area much dryer and experiences less change. But the water content in the river can also look like it has been less extensive since the pictures could have been taken at different times. The photo from 1990 could have been taken in the melt season, and the 2009 picture can be taken after the melt season has ended.

Comparisons to data collected in 2020

The data collected during fieldwork of 2020, show a change in the erosion and the accumulation of the spits and the barriers that are in direct contact with the modern coastline. This coastline has experienced a lateral change in an eastern direction, where some of the spits present in 2009 have become thinner and was more split up in 2009. In 2020 the most prominent spit in the outlet of the delta has become tinner, but longer. The spit located to the east, has experienced a lateral drift in the eastern direction, causing build out and a lengthening of the spit. In 2020 the spit was formed into one continuous spit. The spit in 2020 was 20 m shorter than the spit in 2009, but have an extra build out into the ocean that measures about 50 m. The green lines in figure 33, shows that the coastal landforms have not changed structure and looks since 2009.

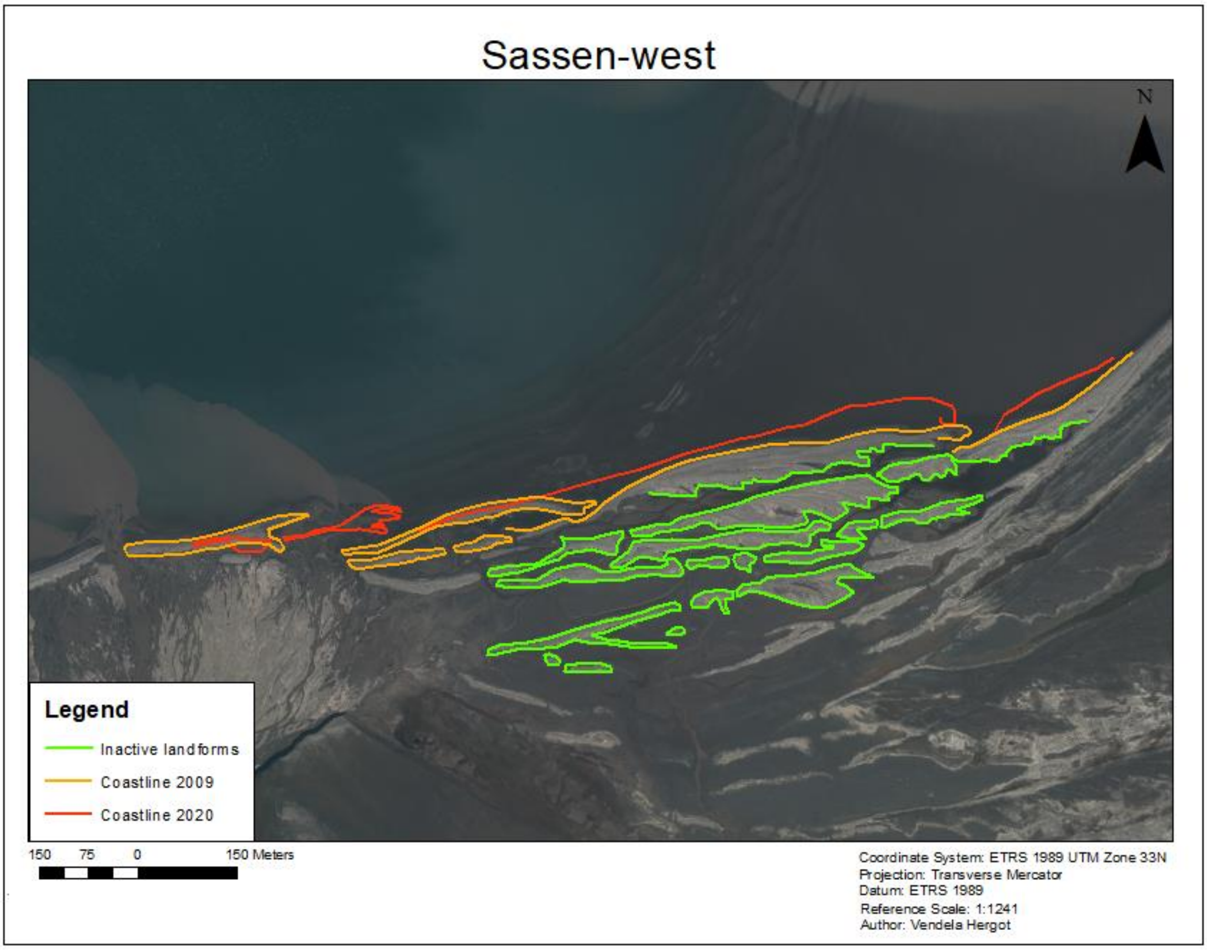

Figure 34: Changes along the active coastline of Sassen-west between 2009 and 2020. The basemap in this figure was taken by NPI (2009). The red line represents GPS points that were taken along the active spit during fieldwork in the fall of 2020, the yellow line traces the spit present in 2009, the green lines represent the inactive landforms that have not changed since 2009.

Cross sections in spits and surrounding area

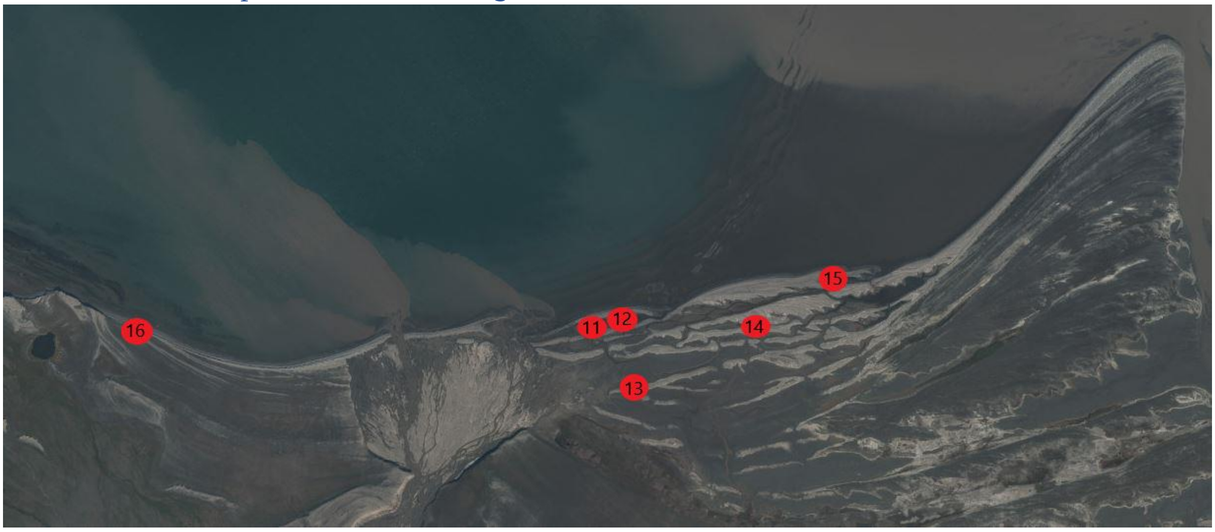

Figure 35: In the Sassen-west aera six landforms at different locations were investigated, at these locations both the surface layer and the internal structure were observed, closer description of the different locations marked in the map with a number, correspond to the numbers in table 1. More information about these cross sections can be found in the appendix, with the belonging numbers in this figure.

The areas that were investigated in the Sassen-west area are areas with landforms of different age and past and present processes working on them. Nr 16 (look figure 35) is placed in an area close to bedrock meeting the sea, and is located in a steep erosion edge. This cross section is a clast supported material, consisting of smaller and larger rocks ranging from 0.3 – 10 cm in diameter. Mostly subangular material, with a thin layer of silt covering the larger rocks. Nr 13 and 14 are located in older inactive spits, and is mostly affected by terrestrial processes but can also be affected by marine processes during extreme tide and during storms. The area around nr 13 and 14 are characterised by raised spits, with thick marine mud in between. The marine mud accumulations are described closer in (fine mud accumulations). The form of these inactive spits has not changed in the period from 2009 to the fall of 2020. Nr 13 contains much more sand than nr 14, and the gravel content is much higher in nr 14 than 13. The gravel at both places is angular to sub angular, at location nr 13 the gravel on the top layer has been affected more by frost shattering than on nr 14. Small amounts of vegetation were found round nr 13 and not 14, which establish the fact that the spit formation at nr 13 has been inactive for longer than 14.

Nr 11 and 12 are located in marine mud accumulations in the inner part of an active spit bar. Both nr 11 and 12 are almost identical to each other, but there are some small differences. At nr 11 there is no stratification, and no grains can be felt when rubbing the material between the fingers. At nr 12 grains can be felt when rubbing the material from the top layer between the fingers and after 20 cm down in the mud there is a clear stratification which separates the material. At 20 cm depth there is a clear stratification between the silty material on the top and a layer of blended coarse sand and gravel. Both of these areas are close enough to the sea that the water content is controlled in large part from the difference in tidal activity.

Nr 15 is located on the inner side of an active spit and is directly affected by marine processes. The whole formation is dense packed material, most of the spit is matrix supported with a more clast supported top layer which is dominated by flat angular rocks. The inner side of the spit where this observation has been made has not changed since 2009, but the outer part of the spit has changed a lot since 2009 (see Fig 35).

Sassen-east

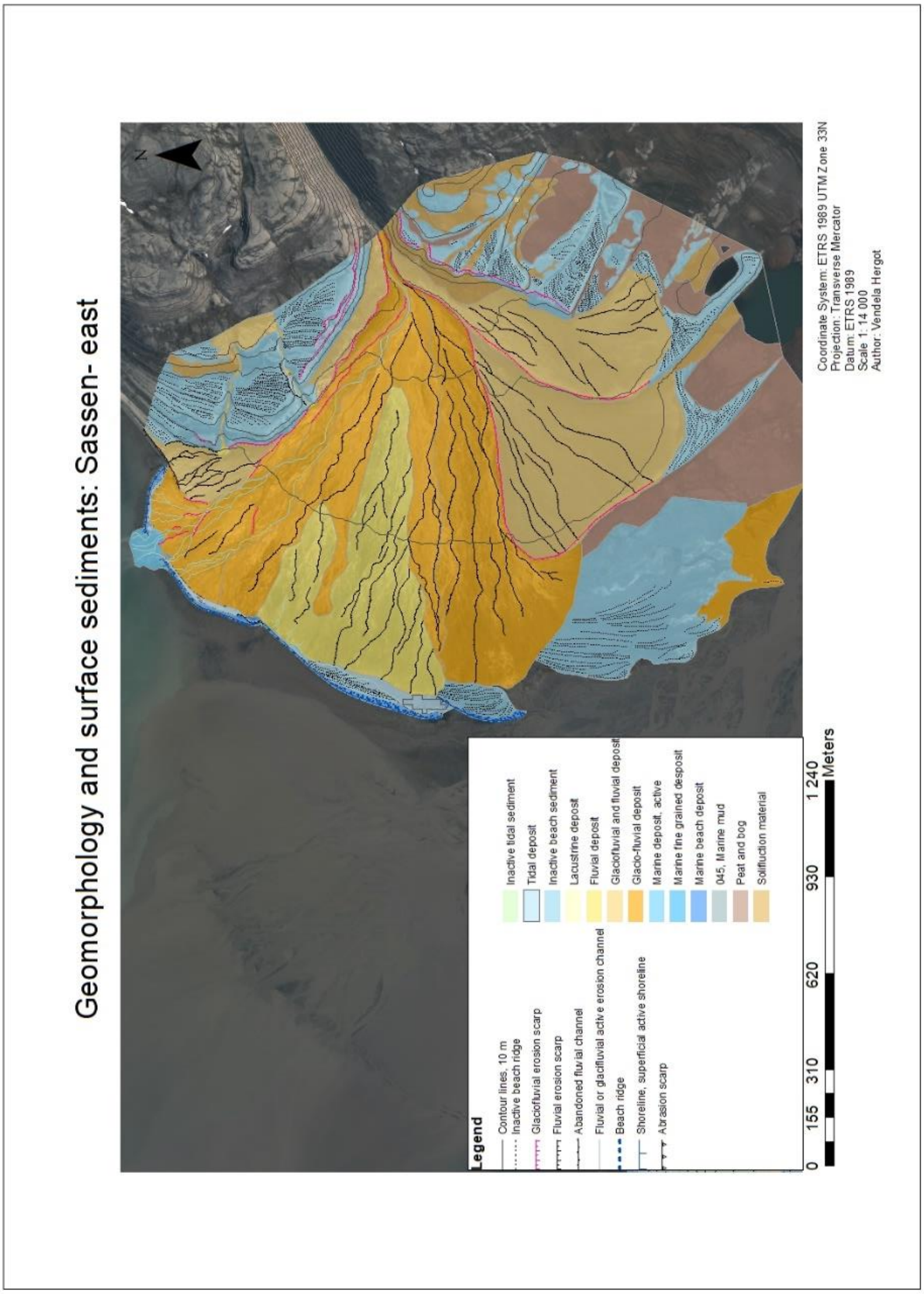

Figure 36: Geomorphology and surface sedimentological mapping done in the Longyearbyen area. Map presented in a scale 1:5000, and is projected in the ETRS 1989 UTM Zone 33N coordinate system. Aerial orthophotos provided by the Norwegian polar institute (2009) is used as basemap

The geomorphological map over Sassen-east covers an area that is about 4.78 km^2, and covers an area that clearly shows several generations of landforms and shows the processes that work on the area in modern times and the historic processes that have shaped the area to what it is today. The most prominent landforms and features in this area is the large delta that has been accumulating sediment in several generations from Nøysdalen. Spit bars that are accumulating in the river outlet from Nøyselva river and inward into Sassenelva river outlet, marine mud accumulations in combination with the marine tidal environment, overwash formations and raised beaches.

The delta in this area is a large that gets contribution from one glacifluvial river. The river that contributes glacifluvial sediment to the delta is Nøyselva that runs through Nøysdalen valley and ends up in an outlet glacier from Fimbulisen glacier (Fig 6). The fluvial activity from Nøysdalen has contributed accumulations in different areas at different times is this area. Where Nøyselva river meets the delta, the river has eroded a V-shaped valley, that also tells us that fluvial activity has been going on for a long time. The different areas in the geomorphological map show that there are parts of delta formations on different areas, these are now raised over the present sea level. On these raised areas old inactive beach ridges can be found. Some areas are clearer than others, some of the ridges that originally did not have a high topography is more affected by vegetation than other ridges. The ridges are in the typical beach ridge form that have been visible in the other field sites. Where coarse material is cantered on top of the ridge, and the finer sediment is accumulating in between the ridges. In the finer sediment there is more vegetation growing, which consists of a more dense and thick mossy vegetation with some grass growing.

The delta is partially divided up in sections where the delta has been inactive for a long time, and where the Nøyselva river is still active today. The southern part of the delta is the part that have been inactive the longest and have a lot of vegetation growing in the old river channels and on the sides. Vegetation seems to grow larger and faster in the areas that contain finer material. Where the delta meets the sea, there are some distinct spits that have been forming. Except the spits that are forming in the outlet of Nøyselva river all of the spits area stretching into the outlet of Sassenelva river outlet. Most of the spits are inactive, but some small changes can be seen under “Comparisons to data collected in 2020”. Since these spits have shown little change in the last 11 years the surface layer on the spits is affected with frost shattering, and some vegetation can be found in the area. The same as the older spits the coarse sediment is accumulating on top of the ridge with some finer material in between the rocks.

Figure 37: Surface layer in an active spit in the Sassen- west area. The picture shows that the spit is covered in gravel, with the most of the structure being angular due to frost shattering, and sub- angular due to fluvial activity.

As seen in figure 37 the surface layer on the active spits is containing a large variety of gravel which are for the most part sub- angular. Some of the rocks have sharp edges due to frost shattering. Finer material is accumulating in between the rocks, together with some small amount of vegetation.

Fine grained mud and tidal sediment are collected in the inner side of the spits that are closest to the sea, in some areas the spits have tidal inlets where the water and sediment area being transported inland during tides and storms. This accumulating on the inner sides, with little runoff. This area also gets some contribution from fluvial activity during precipitation events. There are more marine mud accumulations in the outlet of the Nøyselva river outlet, but the mass of marine mud is not comparable to other field sites. The amount of mud is much less than and have also more coarser grains and thicker consistency. Several areas close to the new spits have a layer of fine mud which has accumulated over a layer of dark vegetation with hairy like texture.

Figure 38: Picture showing the outer spits, with overwash formations. On the inner side of the spit fine grained mud and a combination of tidal and fresch water gets accumulated.

Overwash formations can be seen on the larger spits that is connected to the sea and makes a wavy formation on the inner side of the spits. This can be seen in figure 38. These wave formations are in in a gravel sediment that lays in a uniform layer in the wavy pattern. Some rocks are located on the outside of this pattern but lays maximum 1 m away from the main pattern. The underlying beach ridge consists of a finer material, with less gravel and more sand.

Comparisons to historic aerial photos from 1990 and 2009

Figure 39: Aerial photograph comparisons of the Sassen-east area from 2009 and 1990 in the Longyearbyen area. Pictures are not orthorectified and is not to scale. Source: NPI

There has been a small change in almost 20 years in this area, and most of the change has happened in the right side of the delta where the Nøysdalen river outlet is (Fig 39). The picture from 1990 in figure 7 show that the river had a much larger outlet though different channel than in 2009. In 2009 it looks like the mass of water has degraded and it not carrying as much sediment than in 1990. The barriers surrounding the Nøydalen valley delta have only two outlets in the barrier in 2009, but in 1990 there are several outlets. This can also be something that changes several times during a melt season and is dependent on the mass of water that is carried down. The picture form 1990 is taken the 22nd of July, that is in the meltwater season. There is no information on when the photo from 2009 was taken, and the time the picture was taken. Since the tidal difference can be a large influence in the information, it is difficult to be sure about it. The spits that are surrounding the inactive parts of the delta looks the same, but the amount of vegetation has changed. The vegetation in the picture from 1990 has a red/brown colour and is dark in the picture from 2009. From the 2009 picture, it looks like the vegetation cover is much more extensive and covering than the photo from 1990.

Comparisons to data collected in 2020

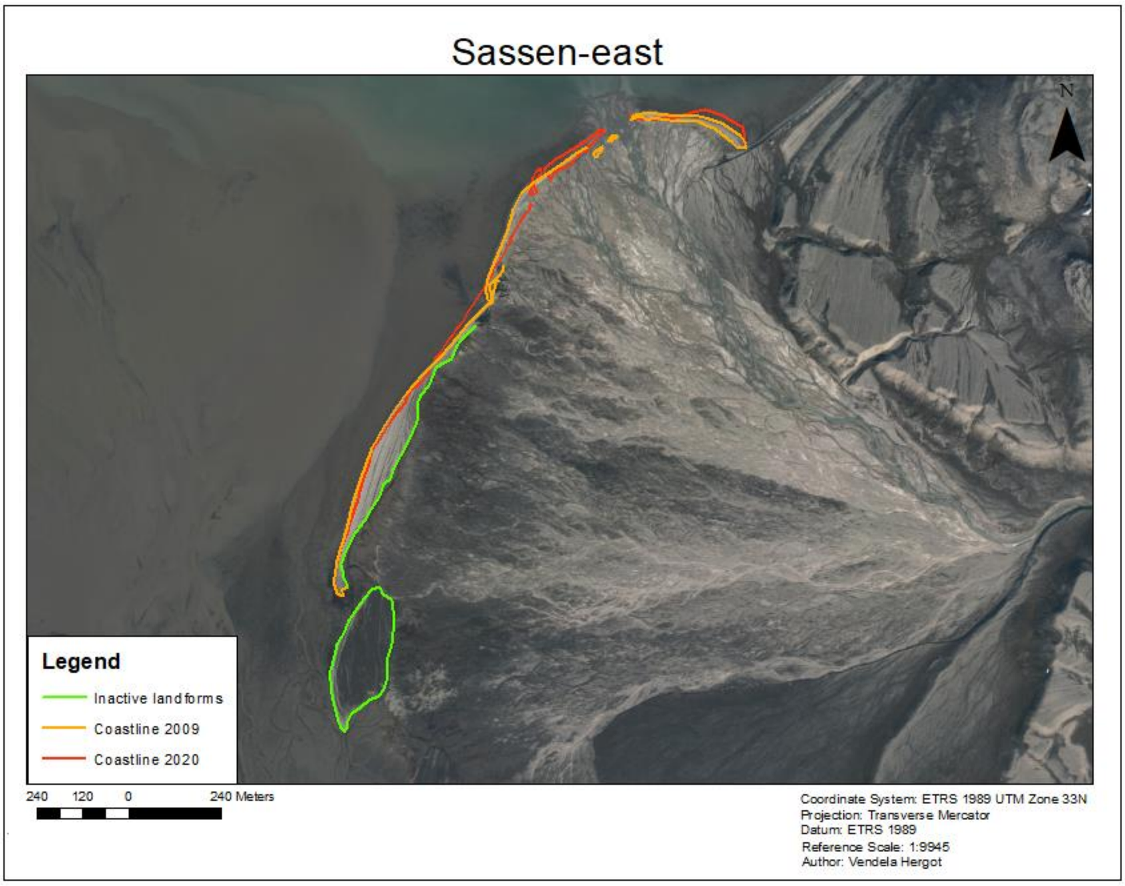

Figure 40: Changes along the fluvial delta of Sassen- east between 2009 and 2020. The basemap in this figure was taken by NPI (2009). The red line represents GPS points that were taken along the active spit during fieldwork in the fall of 2020, the

yellow line traces the spit present in 2009, and the green line represents the landforms that are unchanged since 2009, and can therefore be classified as unactive.

The data collected during fieldwork of 2020, resulted in an overview over the changes done in the area since 2009 (Fig 40). In figure 40 the green line represents the inactive landforms in the area, and edges that have been unchanged since 2009. The yellow line represents the tracing done of the coast that was present in 2009, these tracings following the outlet most edge of the landform, or close to a high tide erosion edge. The red line is a line created after tracing GPS points set during fieldwork, to map the landforms in the area. As seen in figure 40, the southern part of the delta remains almost unchanged. In the largest spit, before the active delta the spit has a sediment loss of about 10 m.

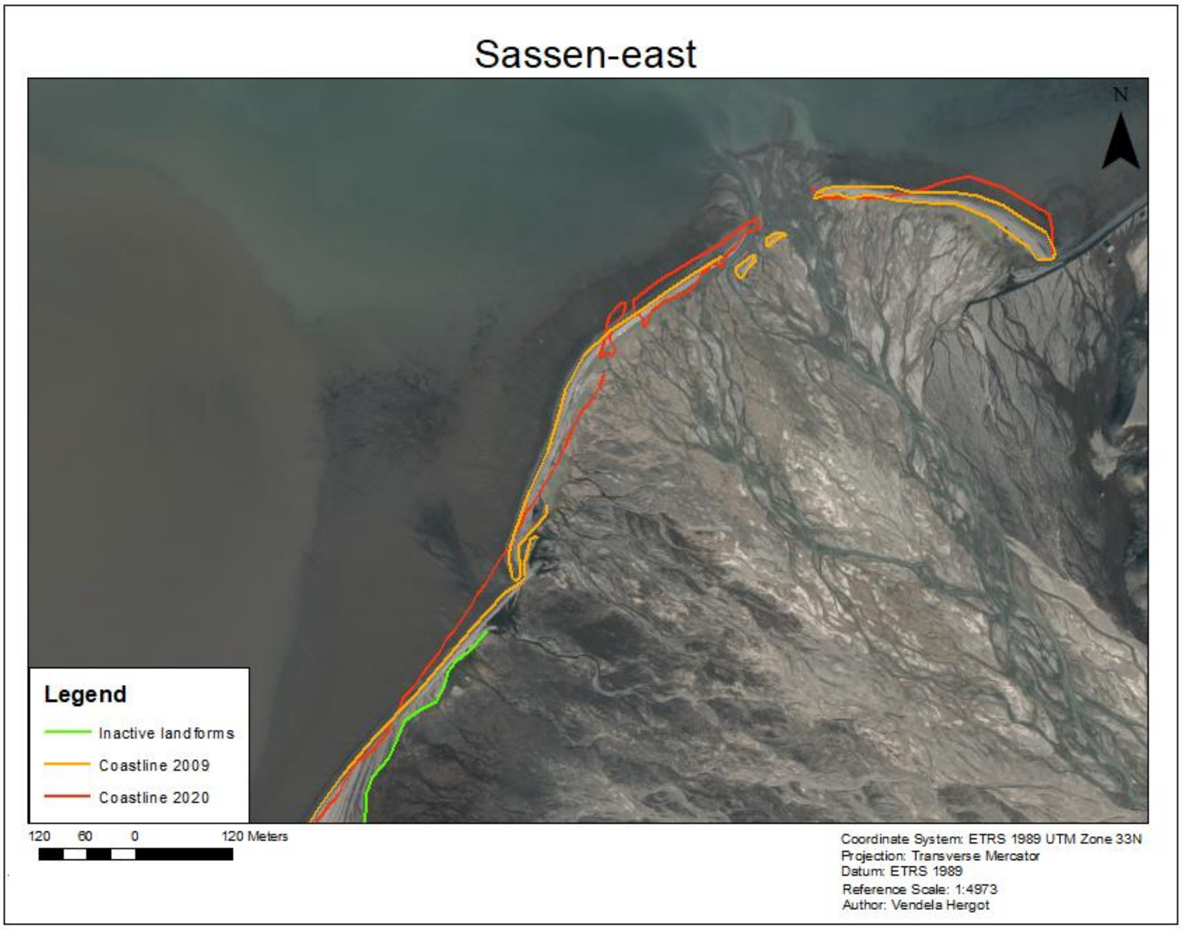

Figure 41: Closeup picture over the same areas as fig 40, this figure is more centred around the outlet of Nøyselva, and the changes in the outlet. Where the green line is showing the inactive landforms that have not changed since 2009, the yellow line showing the coastline in 2009, and the redline is traced after GPS points used to track the modern coastline in 2020.

Figure 41 shows a close-up picture of the outlet of Nøyselva, with the changes observed in 2020 compared to the present spits and barriers in 2009. From this figure we see that the spits and barriers have broken more up into different sections, during the time from 2009 to 2020. Lines from 2009 show that the barriers around the outlet of Nøyselva were made of two larger spits with some smaller accumulations in the river outlet. The lines created by the data in 2020, show that the spit have split up into three different spits, and are separated from each other. Smaller river channers have their outlet between the smaller spits, resulting in a much more active river delta than in 2009.

Cross sections in spits and surrounding area

Figure 42: Three landforms internal structure was investigated in the Sassen-east area. Nr 17 and 18 is located in two different spit bars. And nr 19 is located in an erosion edge in the active Nøyselva river from. More information about these cross sections can be found in the appendix with the belonging numbers.

These observations were made at three different locations in the Sassen-east area. Nr 17 and 18 are made in two different spit bars in the delta area (Fig 42). These spits are in direct contact with marine processes, with tides and storms during summer and winter. These two spits show no change in the period from 2009 to 2020. That puts them in the category of inactive spits, but since they are in direct contact with a moving body of water both from Sassenelva river and from the waves from Sassenfjorden. There is a high possibility that these areas will change with changing processes. Both of these areas are dominated by clast supported sub angular gravel, with a high organic content. The shoreline at nr 17 and 18 are both affected with a shoreline with a high content of an unknown organic material.

Figure 43: Pictures at point 18 (fig 42). Photo nr 1 is looking towards the Sassen-west and into Sassendalen valley, in a south direction. Picture 2 is a closeup of the organic material that is in between the erosion edge in the active spits in Sassen- east delta.

The organic material located in the coastal sone in Sassen-east have accumulated between the spits and the water, the organic material is a thick brown material that is dry and soft, but what this organic material consists of is unclear. This material is surrounding a large amount of the area and can act as a protective layer towards the top layer of the spits, and the erosion edge.

Figure 44: Cross section Nr 19 shown in fig 42. This is an glacifluvial eroded river edge, eroded by the Nøyselva river. More information about this cross section can be found in the appendix with the belonging nr.

Point nr 19 is located in an active erosion edge at the Nøyselva river (Fig 44), Nøyselva river gets water from Nøysdalen watershed. The Nøysdalen river system is a 26.4 km long river system, that ends in a glacial arm from Finnbulisen glacer. This river was visited at the end of the melt season in fall of 2020, and the river was containing a small amount of water.

The erosion edge in the Nøydelva riverbed has a high organic material content, compared to other sites. Material is matrix supported with a mixed material ranging from sand to large rocks up to 10 cm in diameter. All of the internal material is sub angular to well rounded, on the top layer there are more angular rocks due to frost shattering. All of the rocks have a thin layer of fine silt dust, which can act as a binding material in the erosion edge which is stable and firm.

Gipsvika

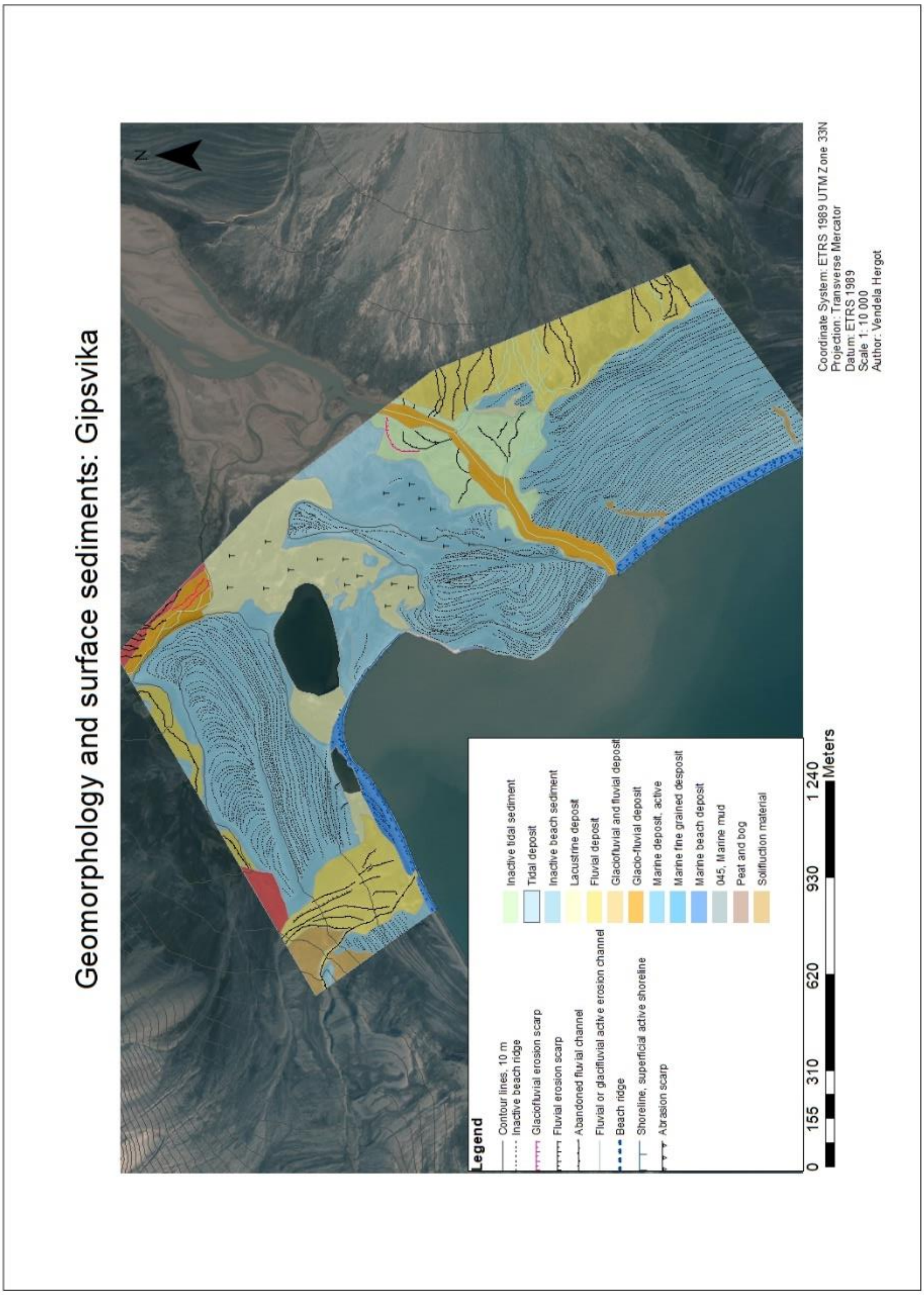

Figure 45: Geomorphology and surface sedimentological mapping done in the Gipsvika area. Map presented in a scale 1:5000, and is projected in the ETRS 1989 UTM Zone 33N coordinate system. Aerial orthophotos provided by the Norwegian polar institute (2009) is used as basemap.

The geomorphology and surface sediments have been mapped out in the Gipsvika area. This area is located in a shallow bay area, containing a large riversystem of Gipselva. The mapped-out area of Gipsvika is a mapped area that measures 2.22 km^2. The map highlights the most prominent features in the area, to clearly visualise the surface sediments, and the result of the active processes in the area. The most prominent feature of this area is the raised beaches, that are surrounding the area, close to the modern shoreline, and further up the valley. Many of the raised beaches are today overlapped by other sediments and vegetation, The sediments covering the old raised beaches get covered most often by slope processes like debris flows, and fluvial sediment in areas due to alluvial fans. There fluvial fans show a long history of activity, this is visible by the inactive fluvial channels, that are either dry or filled with vegetation. In areas that are in a slope with a prominent gradient, the solifluction lobes can be seen, this can only be seen in the study area in the south facing slope on the north western side of the study area. In this area there is glacifluvial rivers that enters the study area, there the main river is Gipselva river, which have been categorised in the map as glacio fluvial deposits. Some larger areas in the map have been classified as Lacusterine sediments, this is due to the depression in this area observed during fieldwork, these areas are also filled with a recognisable amount of vegetation. The sediment that is the most prominent in this area is the inactive beach deposit, this sediment is usually featured together with the inactive beach ridges, but is also occurring on larger areas where there are large amounts of vegetation and like peat and bog. In the sides of the river, further up from the outlet, there is evidence of an inactive tidal deposit, that also is surrounded with fluvial activity from the alluvial fan and meets the boarder of the inactive marine deposits. In the coastal area where the modern beach is located, the sediment is classified as marine beach deposits, to express that this is an area that is in contact with the active marine processes, in this area beach ridges are visible. In the areas where the active marine sediment and the beach rides are not shown in the map, is where the bedrock meets the sea. The bedrock seen from above is not a large feature but is larger seen from the ground since the bedrock edge is steep, this can be seen in figure 46.

Figure 46: Bedrock feature in the north facing shoreline in Gipsvika. Picture taken along Gipselva facing outwards to the bay with Tempelet mountain in the left of the picture. Photo: Vendela Hergot

Eolian deposits is represented with point symbols in the maps, due to the uncertainties of how large area the sediments are covering. This sediment was spotted during fieldwork, points are then set at the locations where the sediment was observed.

This area shows evidence of the pervious marine processes that have been working in the area in the past, but now it shows evidence of the terrestrial processes taking over. The terrestrial processes show evidence in glaciofluvial erosion, fluvial erosion, inactive abandoned fluvial channels, and ravines.

Figure 47: Overwash formation in the Gipsvidka area. The formation is made more clear by the red lines present in the picture. This shows a layered formation there the overwash is overlaying some organic material, and then the overwash covers the organic material. The lighter shade of sediment in the formation is then covered in organic material from the seaward side. Picture: Vendela Hergot.

Overwash formation is something that is one of the prominent features of this area, in addition to the raised beaches. The overwash feature is in a wave pattern which in this case in close to the modern beach. The wavy pattern, which is shown in figure 47, has the red lines to make the pattern clear. The lighter gravel in the picture has accumulated over an underlying layer of organic material. On the seaward side the overwash gets overwashed by more organic material. It is unclear if this organic material is of a terrestrial or marine origin. This formation contains more coarse material, sand can be found under the surface layer but is not present in the surface layer.

Comparisons to historic aerial photos from 1990 and 2009

Figure 48: Aerial photograph comparisons of the Gipsvika area from 2009 and 1990 in the Longyearbyen area. Pictures are not orthorectified and is not to scale. Source: NPI

The study area in Gipsvika has experiences little change the last 20 years. There is a small change in the amount of vegetation on selected areas, but the amount of vegetation is mostly the same. In figure 48 there are two arrows pointing to a change in the river outlet. It looks like there has been more erosion in the sides of the outlet from 1990 to 2009. In the left side of the river, it is difficult to see since there is a shadow of the cliff in the 2009 picture. But it looks like there has been a small change in the amount of vegetation deposited in 2009. On the right side of the river the arrow is pointing towards a small area there the river has eroded inward in the raised beaches. But this can also be caused that the different pictures are taken on low or high tide, which is impossible to know. The small lake in picture has no name, but this looks like it has either contained more water in 2009 or the vegetation around has grown a lot. The large river delta that is located in the right side of picture 48 looks like it has more vegetation in 2009 than in 1990, but this can also be because the looks in the resolution in the different pictures.

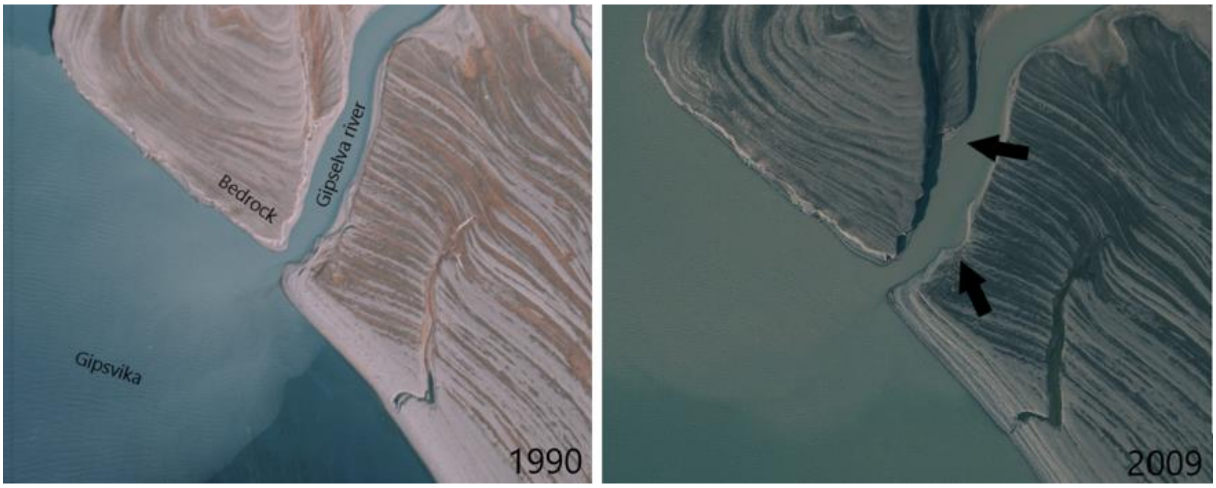

Figure 49:Zoomed in picture from figure 48, zoomed into the river outlet. The bedrock named in the 1990 picture looks unchanged, but the accumulation on the right side of the bedrock structure has changed. Where the arrows are pointing there has been a change in a change in accumulation of sediments. There was a higher amount of vegetation in 1990 than in 2009

In figure 49 the picture shows that it has not been large or several changes in the 19 years. The sediment accumulation the arrows in figure 49 is pointing to has decreased since 1990, and the outer part of the river outlet looks larger in 2009 picture. These different things can be highly influenced by the difference in tide. There is a possibility that the changes are less than it looks because of the difference in tide at different times.

Surface layer in the surrounding area

Figure 50: Presentation of the different surface layers that are precent in Gipsdalen. All of these pictures show surface material from inactive raised beaches in the area. Picture 1 is taken from the north side of the river, looking towards Tempelet and the southern side of the bay area. Picture 2 is taken at the same location as picture 1, but facing north into the closest slope to the north side of the area. Picture 2a is also taken at the same location as picture 1 and 2, but shows the surface layer in the raised beaches. Picture 3 is taken where eolian material was discovered in the field, and mapped in fig 45. All Pictures: Vendela Hergot.

In picture 1 in figure 50 is an overview picture over the area of raised beaches in the south western part of Gipsvika that was unable to get to during fieldwork. The picture shows generations of raised beaches on the other side of the river, and the top layer of the bedrock cliff with inactive raised beaches. The sediment was highly affected with chemical weathering and frost shattering. Most of the rock where angular with some sub angular rocks. Picture 2 is taken in the same area, but picture 2 is an overview picture over the area, and 2a is a closeup on the top layer of the inactive raised beaches. The sediments shown in picture 2a is angular rocks that has been affected with chemical and frost weathering. There are some areas with vegetation containing different types of moss, and small areas with grass. There are smaller and larger rocks in the sediment, in between the sediments there are aeolian sediment accumulation which contain only fine material. Some of the larger flat angular rocks has been affected by frost processes over a long time and have changed their orientation to vertical position. Picture 3 is looking into Gipsdalen valley and shows several V-shaped valleys and a large area where fine rained mud is accumulated. This large area is the possibly the source for the aeolian sediment accumulation on the raised beaches. At the location where picture 3 is taken the amount of aeolian accumulated sediment is large compared to other investigated areas in Gipsdalen valley. The ground is soft when walked on and can easily be manipulated by a shovel.

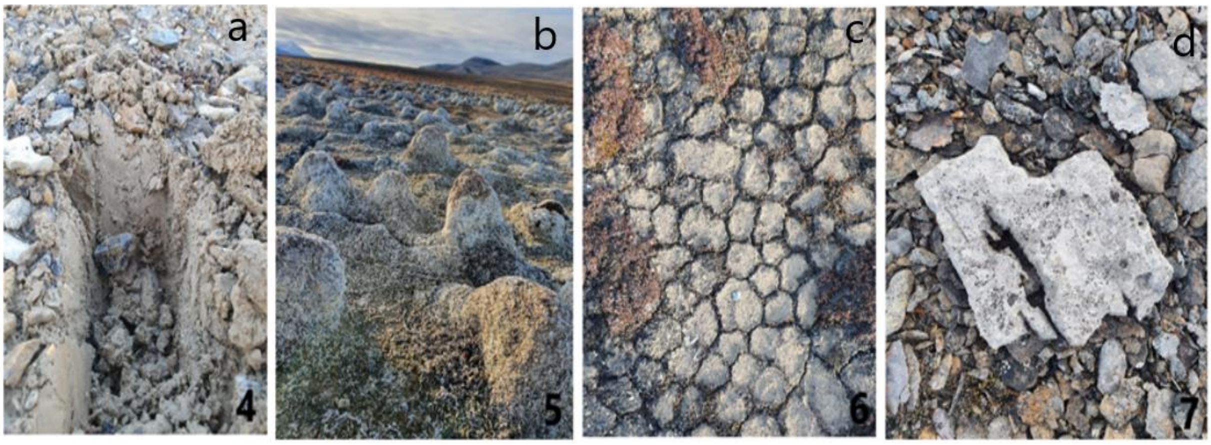

Figure 51: These pictures show the different surface layers that can be found in the Gipsvika area. Picture a, is a small cross section into some Eolian material. Picture b, is the surface layer containing lots of organic material that have grown into small mound shapes in the valley. Picture c, is a area between some of the larger raised beaches in the area. Picture d, is a piece of gypsum that have been weathered.

The different surface layers that can be found in the Gipsvika area, contains a large diversity of layers. Figure 51 shows that there have been many processes working om this area over a longer period of time. Due to the amount of eolien sediment on selected areas, the amount of vegetation in different aeras, and the physical evidence of weathering.

Sediment Samples

The sediment samples taken I Gipsvika how a small amount of coarse material than other field areas in this analysis. No organic material was found in the samples, most likely due to the closeness to the modern shoreline. There is a larger amount of fine gravel and coarse sand, more information about the sediment samples can be found in table 3.

Sediment samples

Tabell 3: The codes of all of the different sediment samples and the coordinates the samples where sampled. Information about the amounts if the different sizes are included in the table.

		Gravel			Sand			silt + clay
		Coarse	Medium	Fine	Coarse	Medium	Fine	
	Coordinates	Coarse	Medium	Fine	Coarse	Medium	Fine	silt and clay
LYB 1	78.22306°N 15.67153°E	47.12%	13.40%	11.76%	14.18%	12.73%	0.65%	0.11%
LYB 2	78.22306°N 15.67153°E	9.80%	11.18%	17.83%	18.16%	22.62%	1.36%	0.75%
Hiort 1.1	78.24810°N 15.70098°E	31.49%	5.28%	5.41%	18.70%	36.18%	2.43%	0.15%
Hiort 2.2	78.24810°N 15.70098°E	6.48%	29.72%	7.62%	11.49%	37.01%	6.65%	0.67%
Hiort 1	78.24849°N 15.69886°E	0.00%	7.26%	8.17%	19.02%	59.20%	4.88%	0.47%
Hiort 2	78.24849°N 15.69886°E	0.00%	8.01%	18.86%	22.31%	46.31%	3.98%	0.48%
Hiort 3	78.24849°N 15.69886°E	0.00%	7.88%	8.89%	16.11%	56.83%	9.19%	1.26%
Hiort 4	78.24849°N 15.69886°E	0.00%	21.61%	20.90%	21.53%	29.21%	5.15%	0.82%
Gips 1.1	78.43997°N 16.57272°E	0.00%	5.55%	48.89%	20.70%	15.92%	7.50%	0.67%
Gips 1.2	78.43997°N 16.57272°E	0.00%	9.71%	77.59%	11.41%	0.77%	0.31%	0.05%
Gips 1.3	78.43997°N 16.57272°E	0.00%	2.20%	29.35%	53.02%	13.57%	1.00%	0.00%
Gips 1.4	78.43997°N 16.57272°E	0.00%	3.86%	61.51%	30.84%	2.70%	0.29%	0.12%
Gips 2.1	78.44026°N 16.56916°E	44.28%	47.72%	6.96%	0.64%	0.19%	0.08%	0.05%
Gips 2.2	78.44026°N 16.56916°E	3.31%	78.87%	12.88%	2.80%	1.74%	0.29%	0.00%
Gips 2.3	78.44026°N 16.56916°E	0.00%	3.75%	2.64%	3.32%	65.20%	24.16%	0.00%

The table above show all of the results after the grain size analysis, with the sorting of the material and the percentage.

Discussion

The geomorphological maps presented in this thesis are based on data collected from six different locations along the south coasts of Isfjorden, each documenting landforms created by ongoing coastal, fluvial, and glacial processes and their interaction with ancient landforms created by similar processes under different climatic and environmental regimes. At almost all locations, the mapping documents evidence from past glaciation and sea-level change. Aerial photos going back ca. 20 years elucidate some of the most dramatic coastal change that has occurred during this time period and allows speculations to be made about the most important drivers of this change. The mapping of the main field sites are discussed below in terms of their present coastal geomorphology, changes to the coast since 1990, and how this change may or may not relate to the physical characteristics of their adjacent catchments.

Hollendarbukta

Modern coastal environment

The coastal area of Hollendarbukta is complex and impacted by two different rivers: Hollendarelva and Bogebekken. Each river delivers sediment to the coast from different catchments with different characteristics. The different sediment types mapped along the coastal area at Hollendarbukta reflect these differences (Fig 12). The bay area of Hollendarbukta shows two spits: one that grows from the west, and one from the east. Between the spits is the river outlet/tidal inlet between Hollendarelva and Isfjorden that is affected by both fluvial activity from the catchment and wave and tidal activity from the fjord. During high tide, fjord water floods the mouth of Hollendarelva, contributing to the deposition of small mudflats. During storms, waves produce washover fans (e.g. Fig. 13) and may cause some erosion of the spits and fluvial deposits. The mudflats inside of the spits are comprised of thin (7 cm) laminated fine material, most likely consisting of silt and clay material, interbedded with fine gravel (Fig. 15). Some of the layers are grey/green in colour, while others are lighter and darker shades of brown, which likely reflect different sediment sources up valley or from the fjord, and the amount of organic material present. In some areas a layer of coarse sand and fine gravel forms a thin veneer over the mudflats. Changes in grain sizes in the mudflat are likely related to intermittent periods of high energy conditions in the river. The coarser gravel in these stratified layers is well rounded and sub-angular, suggesting that it has been fluvially transported some ways downstream.

The seaward side of the spits and beach ridges are formed in coarse sand, with larger cobbles accumulating on the ridge (Fig 13a,b). The beach ridge that ends in the western spit at Hollendarbukta is mapped westwards to the outlet of Bogebekken (Fig 12). The mapped area extends ca. 870 m, and the same beach structure continues the entire way to Bogebekken, where there is coarse sand on the seaward side, cobbles on the ridge, and overwash fans on the inland side of the beach ridge. The overwash fans are formed by beach sediment that is thrown up on the by wave activity during high energy events, like storms. A loose and irregular feature of the beach ridge here (Fig 13a) is likely formed by blocks of sea ice that are covered by sediment during winter. When the ice melts it leaves behind these loose piles of sediment.

A Holocene relative sea-level curve has not been reconstructed for the area around Hollendarbukta, but there are flights of raised beaches in the area up to at least 15 m above mean sea level (amsl). Two of the closest relative sea-level curves to Hollendarbukta presented in (Forman et al., 2004) from inner Isfjorden and an area ca. 40 km south of Hollendarbukta show relative sea-level falling after deglaciation from 90 to 65 m amsl down to msl. For the curve that is ca. 40 km south of Hollendarbukta, there is a small transgression around 4000 years before present, followed by regression to msl. Another study done close to Longyearbyen indicates that relative sea-level has fallen by ca. 70 m since the deglaciation (Lønne & Nemec, 2004). These two areas cannot be measured the same way, as their local glacial histories may have been different, but a marine limit of somewhere between 70 and 65 m asl is a fair estimate for Hollendarbukta.

Historical coastal change

Aerial photos from 1990 compared to aerial photos from 2009 (Fig 15) document an eastward shift of the Hollendarelva river outlet/tidal inlet in an eastern direction. Between 2009 and 2020, the same river outlet migrated a further 17 m eastwards (Fig 16). The curved part of the spit has also moved 15 m outwards into the ocean during this period. In contrast, the outlet of Bogebekken experienced minimal changes between 1990 and 2009 (Fig 15). A possible explanation for the drastic change at Hollendarelva compared to almost no change at Bogebekken is a change in the rate of erosion and transport of sediment from the much larger, glaciated Hollendardalen drainage basin. With an increased flux of sediment and water to the coast combined with active wave processes producing overwash fans, and longshore currents growing spits across the mouth of the river, it would be easy for channels to fill with sediment, forcing the main channel to enter the fjord in a more eastward position. Increased temperatures and precipitation on the Svalbard archipelago (Ekroll, 2020) during the same period could easily have led to greater slope instability and erosion, especially with deepening active layers, seasonally higher water levels (especially in Hollendarelva, which is glacially fed, but also higher overland flow during precipitation events), leading to a greater overall flux of sediment to the coast. Blockage of the sediment-laden braided river at the coast due to ongoing spit development and possibly higher wave energy on this shallow coast would reduce energy levels in the western channels and drop out of suspension their coarsest material (sands, gravels), enabling overbank flooding and redirection of the main river channel towards the east.

Bogebekken is a much smaller river compared to Hollendarelva and drains a non-glaciated catchment (Fig 3). Given its proximity to Hollendarelva, Bogebekken is subject to the same climate, and wave and longshore drift processes, however, the river itself plays a much smaller role in driving coastal change. There is no evidence of excessive erosion or deposition the since 1990; it is only the main riverbed that has experienced some change, due to small scale erosion, and deposition. Since this river system is only affected by fluvial activity, some new erosion scarps have been observed, and the accumulation of sediment in mud flats. In the coastal zone the river outlet have experienced a accumulating factor from the inland, causing a small build out in the river outlet.

Catchment characteristics and coastal change

The coastal area of Hollendarbukta contains a braided river outlet, partially closed by two spits (Fig 3 and 12). The riverbed inland of the outlet is underlain by muddy sediments, with some ridges of coarse gravel and sand, and well-rounded cobbles. The mouth of the valley that contains the bay area of Hollendarbukta is generally flat, with no large mountains nearby, and no large mountains over 500 m amsl this low in the valley system. Slope failure is more likely to happen in mountainous areas (Korup & Clague, 2009), but is also controlled by factors like hydrological conditions, wind erosion, river erosion, frost processes, and general erosion in unconsolidated sediment (Ballantyne, 2002). A small amount of vegetation can be seen in the low-lying areas of the drainage basin, except for the areas that have been recently eroded. The braided river is broadest at the river mouth, where it measures 450 m across; towards the upper reaches of the watershed, the river gets narrower, due to downcutting in till close to the glacier Passfjellbreen (Fig 3)The coarsest sediments in Hollendarelva accumulate in riverbanks further up into the watershed, while the finer sediments are transported to the river outlet (Dallmann et al., 2015).

Debris flow scars along valley sides of Hollendardalen, some of which overlap, indicate a long, active history of slope failure in this drainage basin. Due to the low-relief topography along the coast, slope failure tends to happen further up into the watershed. Some of the larger sediment in the river outlet is well-rounded material, indicating that it has been worked on by fluvial processes over a long period of time and that some of the coarsest material is eventually making its way to the coast. The outlet of Hollendarelva has shifted towards the east, most likely by sediment accumulating in the riverbed, forcing course changes in the river channels. Combined with a lateral transport of marine sediment (spits) from west to east, the river outlet has move eastwards. The coastal landforms on either side of Bogebekken have not been so dynamic because Bogebekken is less impacted by the effects of climate change (increased precipitation and warmer temperatures) than Hollendarelva. Bogebekken does not drain a steep, mountainous, glaciated catchment, and because of this, it has not experienced the same increased meltwater, slope activity, and overall sediment flux compared to Hollendarelva during the past couple of decades. The lesser (although still important) role of longshore drift and wave processes are thus clear at this field site. Therefore, the spits, river mouths, and beach ridges at Hollendarbukta indicate that glaciofluvial processes, together with climate change, have been the main drivers of coastal change since 1990. Longshore currents and wave energy (possibly increasing) have also played important roles but are not dominant.

Longyearbyen

Modern coastal environment

Longyearelva flows through Longyearbyen and is therefore affected by human activity, as is the coastal zone adjacent to Longyearbyen. Sediment from Longyearelva has been removed and moved such that the river is not allowed to erode freely in the landscape and threaten local infrastructure. These interventions have caused excessive amounts of sediment to be carried by the river redeposited on the coast and in Adventfjorden (Fig. 20). At the outlet there is a clear delta feature, with some spit develop directly in the front, although most of the spits have accumulated to the west of the outlet (Figs 20 -21). On the inside of the spits is a tidal marine environment that gets submerged during high tides and is subaerially exposed during low tides. The sediments here consist of fine silt and clay deposited by Longyearelva during melt season. There is abundant organic matter in the sediments that gives off a strong smell when stepping on it. The origin of the organic matter is unclear.

Spit development next to the outlet of Longyearelva is towards the east (Fig. 20), with no spit development to the west. Lateral transport of material from west to the east is likely here as wave activity is the strongest coming into Adventfjorden. The outlet of Longyearelva is located approximately 1 km from the delta in front of Adventelva (Fig 4), which gives the waves not enough time to build up energy to change direction in the lateral transport of sediment. From the spits that have accumulated in the river mouth area, there is 500 m to the next spit development towards the east. The eastern spits are larger and stretch farther into Adventelva delta (Figs 4 and 20). The Adventdalen delta is a large delta that measures almost 2 km across and carries a lot of water and sediment. The Adventelva delta consists of a very fine muddy type of sediment, which is different from the spits, which consist of coarse gravel and cobbles. Therefore, the sediment that is building the spits is likely sourced from Longyearelva and the Longyeardalen watershed, that gets transported eastwards by longshore currents. On the inner side of these spits there are thick layers of mud, that are submerged during high tide. This mud is very fine grained and contains little organic material except for the areas that still submerged during low tide. The sediment in Adventelva is a very fine-grained and there is a good chance that this sediment is mixing with the finer sediment from Longyearelva, accumulating a lot of sediment in this muddy area.

It is important to remember that this area is affected by human activity to a large degree, and all the processes acting in this area cannot be seen as 100% natural compared to the other field sites in this analysis. Human activity has affected this area to a large degree since the coal mining started in 1906, so it is difficult to estimate the relative importance of the different drivers of coastal processes.

Historical coastal change

The western side of the Longyearelva river outlet has changed little since 1990 based on a comparison of aerial photos to recent mapping (Fig 20), although the barrier in front of Longyearelva broke up between 1990 and 2009 (Fig 21). The outlet of the river was located more towards the east in 1990, and in 2009 it was more located in the middle of the small delta (Fig 21). Where the river had its outlet in 1990, has since evolved into a spit by 2009. These spits are accumulating sediment towards Adventelva, and curling inwards into the coastal area, almost closing off the area creating a lagoon. Further east there is a structure that does not look natural in the landscape (Fig 21), and is most likely man made, but no information can be found about the origin of this feature. This feature is gone between 1990 and 2009, it is unknown if this structure has been eroded away by natural processes, or if it has been removed manually.

The spits located by Adventdalen delta (Fig 21), have basically the same structure today as they did in 1990, with some small changes. The photos from 1990 and 2009 were possibly taken at different time of day, season, and during different tides, and as a result it is difficult to conclude whether or not there have been significant changes to the area. Since there is a large amount of fine sediment accumulating in the shallow waters around these spit forms, it can be difficult to analyse the exact changes in the coastal area.

With data from 2020 (Fig 22) it is clear that the spits around the outlet of Longyearelva have become larger and longer since 2009, although again, it is not known if the aerial photograph was taken at low or high tide. The largest spit close to the Longyearelva outlet appears to have moved in an easterly direction ca. 186 m, and the area is much more affected by spits in 2020 than in 2009 and 1990. There has also been a change in the coastal area of Longyearbyen since the 1990 to present. In 1990 there was a barrier across the western part of the Longyearelva dela (Fig 21), and during the time from 1990 to 2020, spits have formed and grown larger. This development may be related to the change in the sea ice after 2006 (Muckenhuber et al., 2016), or increased temperatures that have been rising on average since 1912 (Eirik J Førland et al., 2011).

Catchment characteristics and coastal change

Due to the human interactions in and around the Longyearbyen area, it is difficult to determine what factors and processes have affected the coastal processes. Three different glaciers are contributing meltwater to the Longyeardalen watershed (Larsbreen, Longyearbreen, and a smaller contribution from Platåbreen). The mountain slopes of Longyeardalen show much scaring by debris flow landslides, in both the low-lying areas as well as at higher elevations. If these debris flows do make reach the river, they form a major source of bedload and suspended load in Longyearelva. But since the town has infrastructure on both sides of the valley, gullies have been dug to protect the roads, thus limiting sediment transport to the fjord. During melt season the glaciers in the Longyearelva drainage basin contribute large quantities of both water and sediment to the river system.

The drainage basin around Adventelva is much larger than that of Longyearelva, and includes several larger glaciers connected to smaller watersheds that contribute sediment, meltwater, and other slope and glaciofluvial processes combined with human activity. Large amounts of Adventdalen are affected with human activity, like an active coalmine, buildings, roads, and human interference, resulting in increased erosion and sedimentation. Adventelva is a braided river, where most of the finer material gets transported furthest down in the watershed, and the coarse material accumulates further up into the watershed. Large alluvial fans contribute sediment to the river system, but most of the coarse material stays on the alluvial fans. Fine-grained sediments accumulate in the low-lying areas of the Adventelva river system, the easternmost spits in this field area, east of the Adventelva delta, are formed in these fine sediments transported by Adventelva.

The changes in the coastal system around Longyearbyen have been mapped out, with contributing data from geomorphological mapping that sets a focus to the ongoing processes in the area. Because of the complexity between the human interactions and the natural processes, it is not clear if the changes that have happened in the area are because of the changing climate, other natural processes, the human impacts, or all three.

Hiorthamn

This area contributes only to the study to help visualize the large changes that have happened to the coastline hear, near Longyearbyen since 2009 (Fig 23). A limited field investigation was conducted due to limited time in the field available and harsh weather. Hiorthamn is an area where historic aerial photos were not available for this project, and for that reason it is difficult to know what changes occurred here before 2009.

Catchment characteristics and coastal change

From 2009 to 2020 the coastline at Hiorthamn has eroded by an average of 20 to 25 m (Fig 24) Hiorthamn is located on the north side of Adventfjorden, and is more directly impacted by wave activity in Isfjorden. Waves that enter Adventfjorden from a northwest direction hit the coast at Hiorthamn with much greater force than at Longyearbyen. There are a few locations at Hiorthamn where sediment is accumulating as well. A potential source of sediment for these areas of accumulation growing coastline is sediment from Telegrafdalen connected to the watershed of Hiortfjellet (Fig 51). This outlet does not create a distinct deltaic landform at the coast, and thus may not be delivering much sediment. The wave force in Adventfjorden is the strongest when coming into the fjord from Isfjorden and thus it is more likely that lateral transport of sediment from the northwest to the south east is the source of sediment to Hiorthamn. The smaller river system that meets the water further out in the fjord before the Hiorthamn area, contributes to the sediment supply, but the sediments get deposited before coastline that is mapped out in this analysis. Since this part of Hiorthamn does not get any contributing sediment, the erosion rate will continue. With thawing permafrost areas, the rate of erosion goes up, and increased the rate of erosion could possibly transfer more sediment into the area, where the coast is eroding the most sediment. But this is not easy to predict, and an important piece of the cultural heritage could be gone by then.

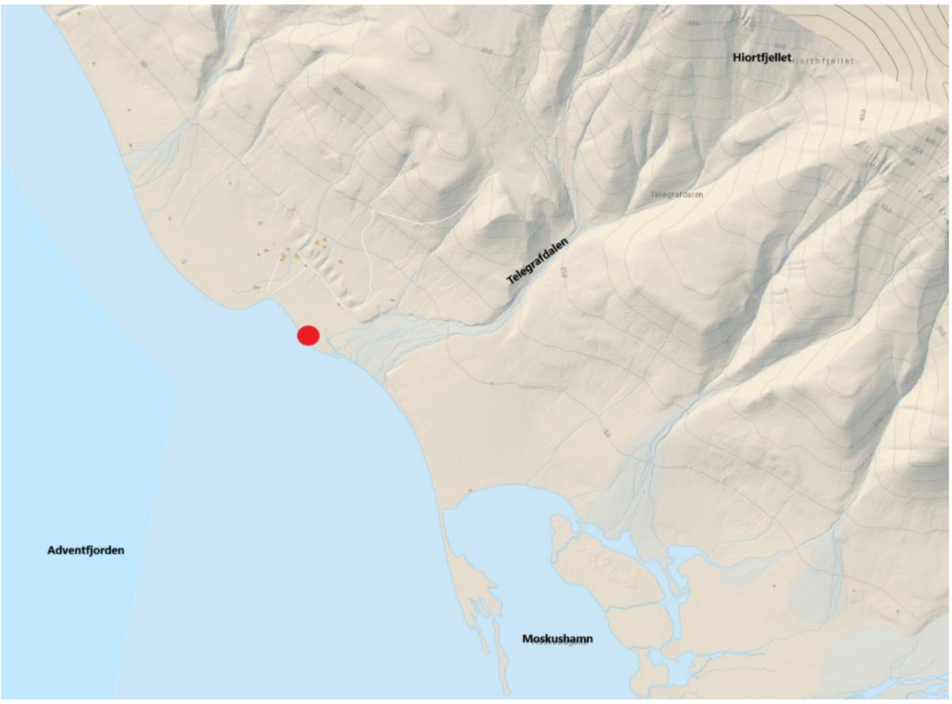

Figure 52: Red dot is the location of taubanestasjonen and Hiorthamn, the catchement area from Telegrafdalen and Hiortfjellet is shown and the location of Adventfjorden and Moskushamn..

Sassen- west

Modern coastal environment

The Sassen-west area contains the river outlet of Lusitaniadalen river and Sassenelva that divides this field area into Sassen-west and east. The coastline from Sveltihel to the outlet of Sassenelva contains a bedrock exposed shoreline, as well as 3.3 km of sedimentary landforms, including a delta, modern spit accumulations, and older spits (Fig 28). In the river mouth area from Lusitaniadalen (Fig 28) there is a delta that cuts across inactive raised beaches, and is contributing to sediment accumulation at the modern shoreline. In this delta there has been little progradation into the fjord, as most of the shoreline appears as a straight line from from Sveltihel to Sassenelva outlet (Fig 5), although some of the active spits break up the coastline. The sediment that is building this delta is likely sourced from the glaciated Lusitaniadalen watershed. Large, rounded cobbles observed along the outer, seaward edge of the delta suggest significant fluvial transport.

On the west side of the bedrock part of the coast there are several generations of overwash fans, the oldest of which, show more frost shattering of cobbles and heavier vegetation growth compared to the younger, fresher-looking, less vegetated overwash fans. Overwash fans form during periods of strong wave activity, which can occur in all seasons in this area. The multiple generations of overwash fans suggest that wave energy is high here, and therefore there is potential for coastal erosion. This is something that was not observed along the coastline so close to Sveltihel (Fig 5), but there must be lateral transport of the sediments in order for them to reach the most eastern part of the study area.

To the east of the Lusitaniadalen delta there is a large area that shows evidence of spit growth over a long period of time. Due to the conditions in the delta at Lusitaniadalen it is possible that the source of sediment for the spits is the Lusitaniadalen watershed. The spits that have been building out from Sassenelva clearly show that the sediments have come from the west, and were deposited by wave activity from the west towards the east (Fig 22). Due to the form and structure of the spits and the large bedrock coastal feature at Sveltihel, there is a strong likelihood that all of the sediment has originated from Lusitaniadalen and not from the larger valley system of Sassendalen (Fig 5).

Sassendalen drains a much larger drainage basin, with a complex river system, several smaller drainage basins, and multiple glaciers contributing both sediment and water to Sassendalen and its coastline.

Historical coastal change

In the area between the Lusitaniadalen river delta and Sveltihel, there has been minimal change since the 1990 although the small coastal processes documented during fieldwork could not be spotted on aerial photos. During fieldwork of 2020, the coastal area on the western coast on Sveltihel did show signs of erosion (Fig 32), and also ice push features. Since there is little previous data collected from here, it is difficult to say if these are normal seasonal features of the coast or if they reflect long-term change. Since the small erosion edges seen in the field cannot be spotted on aerial photos from 1990 or 2009, it can possibly be determined as a seasonal change. In the Lusitaniadalen delta where the river outlet was located in 1990, the outlet is still in the same area in 2009. Between 2009 and 2020 the outer spit moved 100 m towards the east and has decreased significantly in both length and thickness. Since the western part of the study area is almost unchanged from 1990 to 2020, all of the sediment has been moved towards the east from the outlet of Lusitaniaelva Only the spits that are in direct contact with the modern coast have experienced lateral movement to the east, making the spits longer and broader. Since the barrier around the delta from 1990 has decreased in size since 1990, and the spits have migrated east, it is possible that the currents and wave activity in the fjord have increased in energy, causing greater erosion and transportation rates. Since the eastern part of the study area shows evidence of high sedimentation rates in the past, and showing features like all of the several generations of beach ridges. This sediment is most likely coming from the Lusitaniadalen watershed, and it could be possible that the sedimentation rates have decreased for this watershed during the time from 2009 to 2020. As there is evidence of higher sedimentation rates in the past, it is possible that the coast has gone one with a high sediment budget to a negative sediment budget. This in turn has allowed the sediment-starved coast to be impacted more heavily by marine processes, which are causing erosion and transportation elsewhere.

Due to the lack of weather station and information about the permafrost situation in the area, it is hard to say if there has been a drastic change in the temperature, precipitation, or the temperature of the permafrost. This area is a very complicated area, with many complex, interacting terrestrial and marine processes and evidence of a dynamic past. Sassenfjorden is a large fjord, and also contains the outlet of Tempelfjorden where Tunabreen (tidewater glacier) is located. More data about the most prominent processes like temperature during all seasons, if and when the sea ice gets a grip on the fjord, precipitation in the coastline and further up in the watershed, and the monitoring of the melting glaciers and thawing permafrost is needed.

Tempenfjorden and parts of Sassenfjorden are some of the few areas in the western coast of Svalbard where sea ice is still present during winter and spring (Muckenhuber et al., 2016) (Fig 9). The sea ice protects the coastal area during the winter and spring, attenuating wave energy and preventing erosion. How much the sea ice has had an effect on the coastline in this area is unclear.

Catchment characteristics and coastal change

The main watershed that contributes sediment to the Sassen-west area is the drainage basin connected to Lusitaniadalen. This drainage basin contains the Sassen-west coastal zone, that is also building out a spit structure into Sassendalen watershed (see section about Sassendalen watershed). The watershed´s highest point is Lusitaniafjellet which is located 926 m above sea level, that also serves as the backwall of the cirque glacier, Lusitaniabreen (Fig 6). The slopes surrounding Lusitaniadalen are steep and scarring from debris flows can be observed high up in the watershed, which is the more typical palace for debris flows to happen, and then possibly follow the depressions of ravines or earlier slope failures (Winfried K. Dallmann et al., 2015). At the end of the glacier, there is evidence for smaller debris flows in till that led down to the small beginning of Lusitaniaelva. On the sides of Lusitaniadalen there are several areas where larger and smaller ravines can be found, contributing sediment to the river system during slope failure. High up in the river system there is little vegetation in the sides of the valley, causing less resistance to erosion and keeping the sediment together (Høeg et al., 2014). Further down in the watershed the vegetation cover is more visible, causing stabilisation in the slopes, but the slopes are also at a lower gradient towards the coast.

The riverbed of Lusitaniadalen when entering the old coastal zone (glacioisostatically uplifted; (Winfried K. Dallmann et al., 2015) starts to spread out and has incised into the older coastal sediments. Here also the river is braided, and although braided rivers tend to deposit their coarsest material further up in the river system, due to the short river, the coarser sediments are easily transported farther down the system as well as the finer sediment. Some of this sediment goes right out in the fjord and some accumulates in the coastal zone. The inactive older spit area contains large amounts of mud, where the areas located furthest to the coastline are submerged during high tide.

Sassendalen

The Sassendalen watershed is a massive watershed that contains a large river system, several sub- watersheds, other river systems that are connected to the Sassenelva system, including several large and small glaciers. The river system in Sassendalen is the largest river system in this analysis, with parts of the Sassenelva being broad as 1.4 km. In Sassendalen there is evidence of glacial retreat and higher former sea levels. Raised beaches can be seen on aerial photos up to 7 km into the valley from the modern shoreline, although these features are being overwritten by terrestrial fluvial processes like alluvial fans and river erosion. Farther into the valley there is a larger amount of organic material that conceals these older coastal landforms. Approximately 20 km up valley, there are landforms that looks like old raised beaches, but it is unclear if these are in fact beaches. Along the valley sides are large alluvial fans, debris flows, solifluction lobes, and river terraces. Most of the river terraces have evidence of frost segregation, that indicates that the areas have been undisturbed for a long periods of time.

At the outlet of Sassenelva there is no build out of coarse sediment that can be directly linked to the sediment in the watershed. Sassenelva is the river that is splitting the study areas of Sassen- west and east apart. The spit features in Sassen-west (Fig 28) can be directly linked to the sediment supply from Lusitaniadalen. The delta in Sassen- east can be directly linked to the sediment supply from Nøysdalen, which is the valley system that serve the Sassen -east delta with sediment (Fig 6), and the delta formation in Sassen-east is directly linked to the sediment supply from Nøysdalen. The spit formation in Sassen- east also indicates that the spits are growing into Sassendalen, and not from Sassendalen and outwards. In the outlet of Sassenelva there large areas where fine sediment is accumulating. By this observation it seems like the large river system of Sassenelva does not have enough energy to move coarse grained sediment down to its outlet; only the fine-grained sediment gets carried down and accumulates in mudflats close to the outlet. With bathymetric data near the outlet of Sassenelva in Sassanfjorden, it would be easy to see how shallow the area is, and how much sediment from Sassendalen has accumulated in the fjord.

Sassen- east

Modern coastal environment

The river mouth of Nøyselva is located in Sassen-east (Fig 36), where it ends in a glacifluvial delta, with spit growth along the coast, towards the south. At the river mouth of Nøyselva there are spits surrounding the area, that are connected to a barrier. On the inner side of the spits, fine mud have accumulated where fine sediments like silt and clay are deposited. This fine-grained material contains a lot of water. Nøyselva is a glacifluvial river, that originates from the large glacier Fimbullisen, where a lot of this fine material likely originates from . Freshwater from the watershed accumulates in the troughs behind and between the the spits and barriers, and during storm events or extreme tides, saltwater over tops the spits and barriers. This also leads to the development of some overwash fans (Fig 38). Due to the harsh coastal environment in this particular fjord, there is a lot of wind and wave power on this coastline.

Further south in the delta are several older inactive spits, all of which show no change since 1990. Data collected during fieldwork in 2020 confirms that the delta closest to the river outlet of Nøyselva have experienced a change. The spits that have accumulated in the past in the Sassenelva riverbed, are of a darker colour than the rest of the area, indicating that the landforms are vegetated and have been stable for a long period of time. It is possible that these spits formed when the most eastern spit of Sassen-west was younger and not so large. These inactive spits in Sassen- east area seem protected by the Sassen-west area and do not get eroded by the coastal activity. These spits accumulated in the Sassenelva riverbed and can get some sediment contribution from this river. Due to the low energy water in the outlet of Sassnelva, no coarse sediment is then being deposited in the coastal sone. Some of the finer material carried down from the Sassendalen watershed, can contribute to the fine sediment accumulation around these inactive spits, and might be possible to be seen during low tide or in combination with less water in Sassenelva after the melt season is finished.

Historical coastal change

The Sassen-east area have experienced some changes at the river outlet of Nøyselva. In 1990 there were no barriers surrounding the outlet, but in 2009 the outlet has been somewhat closed off by barriers. The most southern spits in this area that are located towards the outlet of Sassenelva (Fig 39), have remained unchanged since 2009, and by visual analysis of the historic aerial photos from 1990, it does not seem that there have been any large changes to the area except for at Nøyselva. In 2009 the coastline was much more closed, causing the river to have two smaller outlets (Fig 40). The closing up can be caused from the decreasing number of sediments that are being carried down to the outlet. Due to the increased precipitation rates and the air temperature in general on Spitsbergen (Adakudlu et al., 2019), there could have been an increase in erosion rates and the transfer of sediments to the coast. But the river system seems sediment starved of sediments (Fig 39), allowing wave activity to make a barrier around the delta, with one outlet from Nøyselva. During field work in 2020, the barrier around the active part of the delta, had begun to split up, making several smaller river outlets. It then seems that the sediment transport from the Nøysdalen watershed has increased its activity, and more sediment is being transported to the coast. The increase in sediment transport, can be explained by the increasing rates of precipitation and the increasing temperatures (Adakudlu et al., 2019).

The spits that are located further inside the Sassenelva outlet are unchanged, and may have been protected by the massive amounts of fine material that have accumulated in the outlet of Sassenelva. In the northeast part of the delta, there is some evidence of coastal erosion, where the delta has built out into the now modern sea level. The erosion edge is located above the present day sea level, due to the isostatic adjustment after the last glacial maximum. As there appear to be only changes in the outlet of the delta area, it can be more easy to come to the conclusion that there has been a change in sediment flux, vs changing currents and wave energy in the fjord.

In Sassen-east, there is evidence of past coastal change in the form of raised beaches on all sides of the Nøysdalen delta. These formations seem to have happened in different stages, due to the district platform features it has. These raised beaches have also been heavily affected by Nøyselva, and the river’s capability to erode sediment. These raised beaches show that there has been a large change in both the terrestrial and the marine environment. Relative sea level has fallen, beach ridges have been stranded, and become inactive. The terrestrial processes have continued to work the landscape, by fluvial/glacifluvial erosion, wind erosion, deposition of sediment and frost processes.

Catchment characteristics and coastal change

The catchment area in Sassen- east is one of the smallest in this thesis, this catchment contains a valley system called Nøysdalen, that contains the river Nøyselva. This catchment contains no larger sub-watersheds, but has some V-shaped ravines, indicating fluvial activity, that also can be combined with slope failure as debris flows that usually follows depressions like ravines (Winfried K. Dallmann et al., 2015). Before Nøyselva spreads out into its delta feature it flows through a small canyon, suggesting that this particular area has not been glaciated for a long time, and that fluvial processes have been important. Further up, Nøysdalen widens into a U-shaped valley, which appears to be underlain by glaciofluvial sediments as the river has incised down into them. These sediments can contribute to a high sediment flux during glacial melt or precipitation events as they are soft and easily erodible. This valley has not been investigated during fieldwork, so all of this information has been acquired from analysing aerial photos. There are no alluvial fans present in the valley, but there is evidence of debris flows, that may contribute to the sediment flux in the river system. The valley system ends up in a glacial arm from Finbullisen (Fig 5) and is the only glacier in the area. By investigating the watershed, the valley looks like there is a lot of till accumulation on the slopes and in the valley floor that is not affected by the river. Which must mean that the river is digging down in the sediment and not in the slopes, making the sediment supply smaller than it potentially could be. Due to the conditions in the watershed, and the structure and appearance of Nøyselva delta, it possible that the sediment supply has been large before, and when the sediment flux has decreased, the buildout of the delta also decreased.

Gipsvika

Modern coastal environment

The river mouth of Gipselva, which has its outlet in Gipsvika, is bordered by a bedrock feature on the northwest side of the outlet, and inactive raised beaches on the southeastern side. This river outlet is connected to a large watershed of Gipsdalen, which contains abundant alluvial fans, and large and smaller glaciers that contribute fine sand, silt, and clay particles. There is an active watershed below Tempelet mountain, which contains a good-sized snow/ice accumulation, although it is unclear if this is an active glacier or just a large permanent snow patch.

On both sides of the river outlet and along the main channel of Gipselva, thick deposits of fine-grained mud were observed. The areas where the mud was observed are submerged during high tide. These mudflats are a common feature of Gipselva, although it is uncertain how far up the valley the tidewater reaches. The bay area at Gipsvika is very shallow. The sediment that accumulates in the bay area appears to be very fine grained. Within 40 m from the modern shoreline out in the bay area, the fine sediment ranged from being a few centimetres deep, to over 20 cm before hitting a harder underlayer. Collectively, these observations confirm that Gipselva transports a lot of fine-grained sediments into the fjord. Due to the width of the river outlet of Gipselva, and the fact that it is a large, braided river, the coarsest sediments are not carried all the way down to the outlet.

On the southern side of the Gipselva outlet there is a large, flat area where beach ridges have formed. It is not clear whether these have been uplifted by glacioisostatic adjustment since it is such a low-lying area, or if they reflect active, recent progradation of the shoreline. The coastal area of this watershed has fresh erosion scarps, and no vegetation showing that this area still contributes to the sediment transfer in the area.

On the north side of the bedrock formation at the coastline, the bedrock feature slowly disappears and is replaced with beach sediment. Overwash fans were observed here on the north side of Gipsvika, potentially indicating that this side of the bay area experiences a more intense wave climate than the south side. Since these formations are so large and visible in the north side of the outlet (Fig 47).

Historical coastal change

At the Gipsvika field site GPS points were not set along the active coastline because of technical problems with the Getac laptop and a curious polar bear that shortened time spent in the field. The inspected coastal area was only the north side of the river, where bedrock is present at the modern coastline. Because of the shallow bay area where Gipsvika is placed, it was not possible to get to shore with a boat on the southern side of the river outlet. These problems meant that no GPS point was set on either side of the river outlet, so it is difficult to say clearly if there have been some small changes in the area since 1990. The analysis from the river outlet from 1990 compared to aerial photos from 2009 (48 and 49), shows almost no visible changes during this period. The only small changes in the area are mud accumulations on the sides of the river, that gets covered during high tide. The Gipselva river seems to deliver mostly finer particles to the fjord where they deposited in the shallow water of Gipsvika bay. Gipselva is a large braided river system, and with the size of the system, it is more likely that the coarse sediment is accumulating further up in the valley (Winfried K. Dallmann et al., 2015). Since the river is so broad, the energy of the river is decreased, and not able to carry a heavy load.

Another potential reason for little observable change since 1990 at Gipsvika is that the sediment transport from the watershed connected to Tempelet (Fig 7) has been low from 1990 to 2020. But a decreased sedimentation rate creates an imbalance in the sediment budget, which could result in increased rates of erosion at other locations. Increased rates of erosion have not been observed and it is unknown where the sediment that comes from the Tempelet watershed gets deposited. Another possible explanation could be possibly be that the rate of erosion is equal to the rate of sedimentation. There is no information to be found about surface currents in the Gipsvika bay area, so it is hard to say if the near coastal currents could have an impact on the stable coastline.

Due to the location of Gipsvika on the north side of Sassenfjorden, and close to the open waters of the larger Isfjorden, this area is in the right location to experience extreme weather conditions during open water season during the period when the sea ice starts to form. Gipsvika, together with Sassen-west and Sassen-east, are protected by sea ice during the winter and spring (Muckenhuber et al., 2016). But since there are no obvious changes in the coastal area, it is difficult to see any implications of reduced sea ice on the coastline at Gipsvika.

Catchment characteristics and coastal change

The Gipsdalen watershed is a large valley system containing several sub-watersheds, some of which have no glaciers, and others with (11 glaciers in total). The watershed contributes a lot of glacifluvial activity and sediment transfer of coarse and fine material. Gipsdalen is a wide valley, that measures about 3 km across. In this valley there are several alluvial fans, with active glacifluvial and fluvial activity, contributing sediment to the main river system. Due to the large valley and the connective sub-watersheds the watershed has the capability of collecting a large amount of precipitation, as it accumulates abundant snow and ice during the winter and glaciers provide meltwater in the summer. This valley system is also oriented in a north -east direction, and is such a wide valley that all of the slopes are exposed to sunlight during the summer months.

The alluvial fans present in Gipsdalen valley are the evidence that there is a lot of sediment carried down from the slopes and the smaller watersheds. The alluvial fans in the valley show that the sediment supply in the valley is large, but it does not get carried further down in the river system, as the larger material accumulates on the fans, while the finer material like silt and clay particles are carried further down the system.

In the mountain stratigraphy in Gipsdalen there is stratified layers of gypsum, which is an easily erodible rock, that can be seen at several locations on the raised beaches in the area. On the raised beaches on the north side of the river outlet pieces of gypsum can be observed, all of which showed scars from chemical weathering and frost shattering. It is possible that the erosion rates in this watershed are different compared to other valley systems, due to the gypsum itself. The erosion rate of the gypsum in this valley is different, and it can possibly have some effect on how the coast is building out, eroding, or how the sediment is distributed in the watershed and in the bay area.

Gipsdalen is also a south facing valley system and is the only valley system in this analysis with this feature. How the watershed is placed, how the precipitation and snow accumulate in this area due to the fact that it is south facing system, can maybe have an impact on how the valley responds to the changes in climate. This is something that need more research to determine if this is something that can be used as a potential factor.

Limitations

Most of the different field sites were only visited once (except Sassen-West). All of the field areas are large, and it takes time to do geomorphological research in the field. More days in the field, and longer time spent in the field could result in more correct and detailed data.

When doing research in the Arctic there are several unforeseen and uncontrollable factors, then can possibly ruin the field day, or make it more complicated. During this field season the largest problems were harsh weather conditions, polar bears and technical difficulties with the GPS. Encounters with polar bears was the most exciting and with the most annoying implications, as one whole field day was spent looking for two bears, and the last field day one very curious bear was close enough that everyone needed to be on high alert, causing more stress towards the bear and not the fieldwork.

Geomorphological mapping is a learning by doing process, the mapping has been an ongoing process during several months. By gaining more knowledge and experience, the understanding gets more correct, resulting in that the geomorphological mapping is an ongoing process that never gets completely finished.

As Lantuit et al (2012) emphasize, there is little research done in geomorphology in the Arctic and as such, limited background studies and data to build on. Since there are such few weather stations located in Svalbard (Eirik J Førland et al., 2011), detailed data on temperature and precipitation are non-existent outside of Longyearbyen airport.

Future research

As we can see from this analysis, there are many processes and factors that is unknown about the geomorphological research in the Arctic. There are not many studies done in this field in the Svalbard area, and there is a lot of missing information that is crucial to have in this type of analysis. High quality, continuous datasets on the precipitation are crucial for analysing the possibly increased rate of erosion, sediment flux, deposition and how much of an influence different river can contribute to change in the coastal system. For this analysis most of the weather data is collected from Longyearbyen Airport, and due to mountains, fjords and temperature, the difference in precipitation will be too large to be comparable between the different areas. Precipitation is difficult to measure, especially in an area like Svalbard. Precipitation will not be measured 100 % correctly if it rains during windy conditions and during precipitation as snow during winter. These types of stations do also need to be visited regularly, and this is difficult to manage in the Svalbard area. Temperature is more easily measured than precipitation, but instruments need maintenance to work. Measuring the depth of the permafrost and the active layer is equally important, due to the increased rate of slope activity that can occur. Data about the temperature, precipitation and permafrost is vital information when analysing coastal change, and for better and more accurate measurements this data should be available.

More data about the currents in the different fjords and bay areas, would have helped understanding the coastal processes that not necessarily leaves a mark on the areas that is being investigated. How these coastal currents have changed over time would have been interesting to see, and to further analyse these rural areas in the future.

Making continuous updates on how the coast changes year by year, or at least every 5 years would been a nice contribution to the understanding of the coastal system in the different areas. Coastal geomorphology in areas not containing bedrock in the coastline are more sensitive to erosion, and therefore more susceptible to coastal change. With data that shows that Svalbard area experiences more precipitation, higher temperatures during all seasons, especially during winter and summer.

Detailed geomorphological and sedimentological mapping of the surficial sediments in the entire watershed enclosing the rivers of the six field sites would help to get a more correct overview of the whole valley system and enable the development of sediment budgets for each field area.

Since there has been so little research on this topic in rural areas in Svalbard, small contributions of knowledge will help the analysis a lot. This is an ongoing learning practice, and especially since the Svalbard archipelago is sensitive to climate change, there is reason to believe that the changes happening especially in coastal areas will quickly accelerate.

Conclusion

In this thesis geomorphological and surface sedimentological maps have been made for five different locations in the large fjord system of Isfjorden, which is located on the western cast on Svalbard. Fieldwork has resulted in detailed data about the coastal change in six different locations, combined with field observations in the surrounding area and the internal structure of some selected coastal landforms. Some sediment samples were taken at selected location, to serve as complimentary data for the analysis. The connecting watersheds to these areas have been analysed by satellite imagery, which will allow for a more correct analysis of the different types of change in the modern day coastal areas.

Historic aerial photos from 1990 have been delivered by NPI on five out of six different field sites, these have been analysed to gather more information about the past changes in these areas, because of this more in depth analysis have been made on how the coast have changed since 1990 to 2020.

Geomorphological analysis in the Arctic is not an easy task, but it can show much information on how the landscape have been affected and then reworked by past and present factors. Combined with the sensitive landscape in Svalbard, because of the geology, glacial history and the harsh weather conditions, combined with a changing climate causing increased temperature, especially during winter and spring season, increased precipitation, thawing permafrost and the increasing thickness of the active layer.

This analysis shows that some of these selected coastal systems have experienced a large difference in the coastal areas between 1990 and 2020, and some of these areas show almost no difference in this time period. The cause of the change, and the cause of lacking change have been discussed, and some theories on what changes have been made, and forces making the change have been highlighted.

Given the small amount of data at each location when it comes to the changing climate, not knowing the rate of precipitation, temperature, permafrost conditions combined with information about the active layer, the unknown factors of the different currents in each fjord system, it is difficult to draw a defined conclusion on what have happened in the past, precent, and what is might to come in the future.

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Appendix

Sediment descriptions over cross sections in active spits and surrounding area on each location. The numbers of each description under "Location nr" correspond to figures over the areas where cross sections was investigates, (Fig 18, 23, 25, 35, 42). The table explains the type of landform that was investigated, and the depth of the cross section made and their descriptions.

Area	**Location nr**	**Type of landform**	**Depth**	**Description**
Hollendarbukta	1	Active spit	20 cm	Loose texture, no soil or organic material, matrix supported with large amounts of coarse sand as matrix material, contains approximately 40% small flat well-rounded rocks ranging from 0.3mm - 3cm in diameter.
Hollendarbukta	2	Active spit	20 cm	Loose to firm texture, no soil or organic material, matrix supported containing coarse sand, larger rocks ranging from 0.3 cm - 2 cm in diameter increases with depth. Rocks present furthest down is well rounded flat and thin, some larger round rocks present.
Hollendarbukta	3	Active spit	20 cm	Loose texture, matrix supported where small rocks ranging from 0.3 cm - 2 cm in diameter is supported by a coarse sand matrix. No soil content but some organic accumulation on the top layer. Uniform layer with no stratification.
Hollendarbukta	4	Active spit	20 cm	Loose to firm texture, small amount of organic material in first 5cm measured

				from the top layer, more organic material on the top layer, larger rocks ranging from 0.3 cm - 4 cm in diameter in the top layer, rocks decrease in size with depth. Matrix supported with equal amount of small flat thin well-rounded rocks in the size range 0.5 cm in diameter and coarse sand. No stratification.
Hollendarbukta	5	Active spit	20 cm	Firm texture, small amount of organic material at all depths, stratification separated in to two layers, top layer clast supported ranging of well to semi rounded rocks with the size from 0.3 cm - 4 cm in diameter with coarse sand as matrix. grainsize is decreasing with depth, with some larger well-rounded rocks about 2 cm in diameter.
Hollendarbukta	6	Active spit	20 cm	Loose texture, some clasts of organic material in the top layer, top layer consists of small to larger rocks ranging from 0.3 cm- 10 cm in diameter, all rocks are flat well rounded. Matrix supported with high amount of coarse sand in the matrix material, content of mall flat well-rounded rocks increase with depth, size of rocks about 2 cm in diameter. No stratification.
Hollendarbukta	7	Active spit	20 cm	Loose texture, no organic material. Matrix supported, coarse and fine sand

				in the top layer, top layer with coarse and fine sand layer is about 2 cm. From 2 cm and down matrix supported coarse to verry coarse sand, content of small rocks increases with depth. The rocks present are flat well-rounded ranging from 0.2 cm - 1 cm in diameter.
Hollendarbukta	8	Active spit	20 cm	Loose texture, matrix supported, finer material in the top layer, coarser material increases with depth. No clear stratification, material contains more water.
Hollendarbukta	9	Active spit	20 cm	Firm texture, clear stratification with 2 cm of course and fine sand in the top layer, under the first stratification a matrix supported material with small rocks that are sub rounded ranging from 0.3 cm - 3 cm in diameter. wate accumulated furthest down in the section.
Hollendarbukta	10	Active spit	50 cm	Firm texture, top layer is fine gravel sediment with some organic material as root growth. First 10 cm contains a matrix supported verry coarse and material with some larger rocks ranging from 1 cm - 4 cm in diameter. New stratification that is about 5- 20 cm thick, with clast supported material, a uniform size of the largest sediment that is about 3 cm in diameter.

				Next layer and the thickest layer that dominated the section contains a uniform layer of verry coarse sand with no larger rocks present.
Sassen-west	11	Tidewater mudflat	30 cm	No stratification, even layer with fine silty material, no feeling of grains when rubbed between fingers. Can be rolled into a sausage but will not hold its form cause of high water content.
Sassen-west	12	Tidewater mudflat	30 cm	Clear stratification with 20 cm og thick fine silty mud on top, no grains can be felt when rubbed between fingers. High water content so the hole does not hold its shape when investigated. Underneath the 20 cm of mud there is a coarse layer of sand, gravel and a prominent number of angular rocks ranging in the size of 1 cm - 4 cm in diameter.
Sassen-west	13	Inactive spit	10 cm	Matrix supported with coarse sand, larger number of rocks in the top layer than internally in the spit. Flat thin well rounded to angular rocks lays flat on the top layer. Internally there are some rocks presents ranging in the size from 0.5 cm - 3 cm in diameter. Small amount of organic vegetation on the top layer
Sassen-west	14	Inactive spit	5 cm	Angular gravel on the top layer with some sub angular rocks, size of the rocks ranging from 0.3 cm - 3 cm in

				diameter. Internal structure is dense with coarse sand in a brown shade. No stratification. Significant number of thin layers green moss in different spots.
Sassen-west	15	Inner inactive side of active spit	30 cm	Dense texture, no organic material, clear stratification. Top layer consists of small and large flat angular rocks, ranging in the size from 0.3 cm - 5 cm in diameter. A matrix supported layer of coarse sand with some larger rocks scattered around in the layer. Clear layer of a thin clast supported layer with fine sand and silt between the bigger clasts, firm texture. Further down the sediment gets more wet and water accumulates in the bottom of the pit. The bottom layer consists of some very coarse sand and small rocks that are sub angular.
Sassen-west	16	Current erosion edge in shoreline	Ca 50 cm	Very loose material. Clast supported consisting of smaller and larger rocks, rocks in the size from 0.3 cm - 10 cm in diameter. Diverse number of rocks, rocks that are very angular and sharp, sub- rounded and well rounded. Rocks have a thin layer of silt on the top and can be used for friction to hold the formation together.
Sassen-east	17	Inactive inner part of active spit	25 cm	Clast supported with rocks in the range from 0,5 cm - 4 cm in diameter. High organic content between the clasts, with

				depth the coarse sand content gets higher. Rocks on the top layer and internally are mostly flat and sub-rounded. Some rocks are more angular, and some are more rounded than others.
Sassen-east	18	Erosion edge in current coastline	Ca 23 cm	Clast supported with very high organic material; organic material is unknown. No difference in structure of the top layer to the internal layer. Gravel ranging in the size from 0,5 cm - 2 cm in diameter. Mostly sub angular, small amount is angular. No stratification.
Sassen-east	19	Erosion edge in current active river	Ca 30 cm	Matrix supported with some organic content, fine sediment and small roots from vegetation in the matrix. Some larger rocks in combination with small rocks. Size of the rocks ranging from very coarse sand to rocks that can be up to 15 cm in diameter.
Gipsvika	20	Inactive spit	10 cm	Very soft loose material when lifted carefully, gets dense when manipulated. Aeolian mass, accumulated in the northeast side of inactive spit formation. Larger rocks internally in the size range from 0,5 cm - 3 cm in diameter. Top layer contains a combination of angular to sub angular rock that can be up to 3 cm in diameter. Small areas with growing vegetation.

Gipsvika	21	Erosion edge in the outlet of Gipselva river	Ca 29 cm	Clear stratification loose. top layer first 6 cm, clast supported, no sand present, cobbles in the size 0,5 cm - 4 cm in diameter. Second layer from 6 - 9 cm, clast supported, smaller grain size ca 0.2 - 0.4 cm in diameter. Third layer from 9 to 11 cm, clast supported, loose texture, no orientation on sediment, sub angular sediment ranging in the size 0,4 - 1 cm in dimeter. Fourth layer, 11 - 20 cm, denser texture, small flat thin rocks ca 1 cm horizontally oriented, matrix supported, large diversity of different size of sediment from coarse sand to small rocks up to 1 cm in diameter. Higher watercontent than the other layers.
Hiorthamn	22	Erosion edge in the present coastline	72 cm	Loose material with clear stratification, layers of coal and organic material. Flat thin rocks size up to 10 cm in diameter horizontally oriented. Layers of sand, whole section mostly materix supported.
Longyearbyen	23	Erosion edge in active spit	34 cm	Loose matrix supported, very coarse sand. Thick layer 7 cm of a material that contains gravel ranging in the size 1 - 5 cm in diameter. No organic material

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