Distribution of ribbed moraines and their connection to subglacial water

in the Oppland region of Norway

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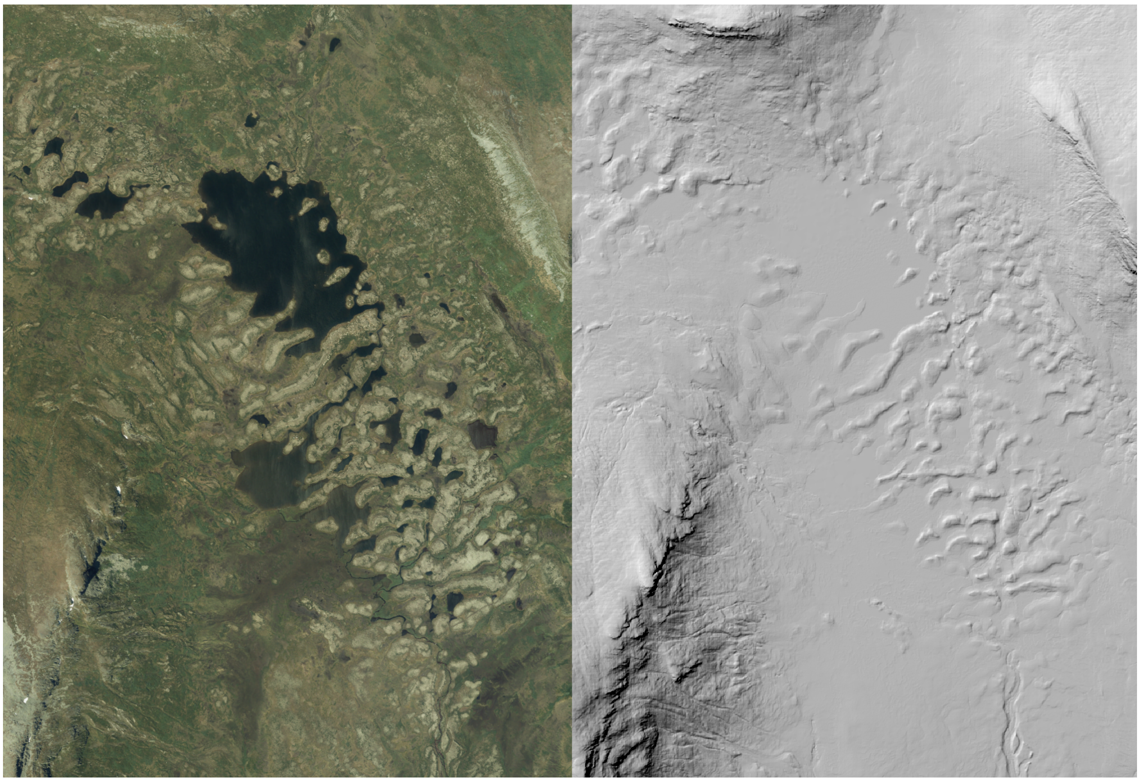

Joscha Sommerkorn, 15th of June 2020

"Distribution of ribbed moraines and their connection to subglacial water"

Supervisor: Karianne Staalesen Lilleøren (UiO), Co-supervisor: Thomas Vikhamar Schuler (UiO)

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Front page image: Aerial photo (left) and LiDAR DEM hillshade (right) of a ribbed moraine field around the Stortjernet Lake, Øystre Slidre Kommune, Innland Fylke, Norway. The images are part of the datasets "Norge i Bilder" and "Høyde DTM1" from the Norwegian Mapping Authority, used under licence CC BY 4.0. ©Kartverket

Abstract

The origin of ribbed moraines (Rogen moraine) is a long-discussed topic in the field of geomorphology. As per today, no consensus on their formation has been reached apart from a subglacial origin. This study will test the hypothesis that water presence in the form of water-saturated till or possibly a film of stagnant water under the ice sheets of the last glaciations may have caused the formation of ribbed moraines. This hypothesis, suggested in a similar form by Sollid and Sørbel (1994), has not been investigated or tested so far.

The hypothesis is investigated in two steps. Firstly, ribbed moraine fields and other subglacial landform fields were mapped across the Oppland Region of Norway using new LiDAR elevation data. In a smaller area around the Langsua National Park, a detailed map and a field trip were completed to further investigate the morphology of ribbed moraines and their spatial relations to other landforms. Secondly, a model of the subglacial hydrology was constructed for the region. The model computes areas of low hydraulic gradient, possible subglacial lake positions and theoretical flow paths of subglacial streams at high resolution. High-resolution output is achieved using present-day topography data in conjunction with down-scaled ice sheet thickness data from an ice sheet reconstruction model.

Mapping of subglacial landforms shows a clear continuum between ribbed moraines and hummocky bedforms across the study area, with indications for an extended continuum including glacial lineations in some locations. Glaciofluvial channels were found entering and exiting ribbed moraine fields. A widely quoted map of the ribbed moraines distribution in Southern Norway was deemed incomplete. The constructed model of subglacial hydrology was found to deliver a resolution highly suitable for interpretation with only limited and easily identifiable limitations. Modelled flow paths correspond well with flow directions interpreted from glaciofluvial traces.

The modelled hydraulic gradient shows that ribbed moraine fields are consistently found in areas of low hydraulic gradient throughout the study area. This indicates that these results indicate that ribbed moraine formation is triggered by water presence at the glacial bed in the form of water-saturated till. This study suggests that water presence may facilitate instabilities at the till-ice interface, forming ribbed moraines and hummocky bedforms. Larger amounts of water are expected to have flowed at low velocity in a spread-out flow pattern between the formed ribbed moraines and hummocky bedforms during the deglaciation.

Acknowledgements

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Thanks to Thomas Vikhamar Schüler for support and supervision on the modelling parts of this study, helping me to understand and successfully write about the underlying formulas and physics of the model I was constructing.

Thanks also to Henry Patton from the University of Tromsø for providing data from the ice sheet reconstruction model for the use in this thesis.

A huge thanks to the my fellow study friends of the Geoscience Master program whom I have almost lived together with for the last 2 years. Gaute, Kristian, Robin, Hilde, Elin, Kosovar, Viktor, Karoline and Lise; without the comradeship and community spirit we had together in rooms U07 and 217 I would not have come as far as I have today. Especially not without all the laughs, fun and heartwarming moments we have had together. Our travels to Svalbard, Iceland, Finse and the Alpes will be remembered! An especially large thanks to Kristian for joining me on my field trip and being an excellent chauffeur, mobile photo scale and soil sample digger!

One big point remains; I want to thank my family for always being there for me, your support and fun and caring ways are always a real boost! Thanks to dad for looking over and correcting my sentence structure, this definitely boosted my thesis. The 5-star hotel feeling during the Coronavirus situation of the last few months also greatly helped me and my thesis!

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1 Introduction

Ribbed moraines are wave-like ridges of unconsolidated sediment mainly observed in relatively flat terrain of Arctic Canada and central Scandinavia, areas that were previously glaciated during the last ice ages (Figure 1; Hättestrand and Kleman, 1999). Ribbed moraines are normally found grouped in distinct fields in the landscape, and they are often easily recognisable in aerial or satellite photos due to their characteristic patterns as well as the fact that small lakes are often present between the ridges (see Figure 1; Dunlop and Clark, 2006). The formation principles of ribbed moraines have been puzzling scientists since they were discovered. Having been attributed to being either terminal moraines or dead-ice terrain shortly after their discovery, the consensus soon became that these landforms were the result of subglacial processes, but per today no further consensus on their formation could be reached. Some studies indicate that the landform is formed due to shear processes in ice and till Bouchard (1989); Aylsworth and Shilts (1989), whilst other hypotheses attribute their formation to stacking of till at the transition between cold and temperate ice (Hättestrand and Kleman, 1999; Sarala, 2006). One recent hypothesis suggests that ribbed moraines are formed due to dynamic instabilities at the till-ice interface (Dunlop et al., 2008).

A study by Sollid and Sørbel (1984) put forward the idea that ribbed moraine formation may be the result of the presence of subglacial water pockets under the ice sheet. It is now well known that water is present at the glacial bed under temperate conditions due to the discovery of many large subglacial lakes beneath the Antarctic Ice Sheet, totalling more than 350 to date (Wright and Siegert, 2012). These findings have shed new light on the subglacial fluvial dynamics and the spatial and temporal distribution of water beneath ice sheets, sparking a scientific focus on the effects this may have on ice sheet dynamics (Siegert, 2000). For example, newer studies have found that frequent water exchanges between subglacial lakes are likely, even indicating that these water exchanges may happen rapidly in several cases (Wingham et al., 2006). In addition, King et al. (2004) identified an area of thin ponded water in the onset area of the Rutford Ice Stream in Antarctica using seismic surveys, and radar studies through the Antarctic Ice Sheet by Carter et al. (2007) have found areas of fuzzy or indistinct lakes which are also thought to be ponded water or water-saturated sediment. Despite these findings, a possible connection to the formation processes behind ribbed moraines has not been investigated since it was originally suggested by (Sollid and Sørbel, 1984).

Very little mapping of ribbed moraines has been carried out in Norway since a overview map of ribbed moraine distribution in Southern Norway was compiled by Sollid and Sørbel (1994). This overview has a low resolution and a high scale (Figure 3), resulting in ambiguities on where ribbed moraines are present and limiting the use for more detailed studies. The recent availability of extensive high-resolution landscape elevation data based on LiDAR scanning technology (Norwegian Mapping Authority, 2019d) provides an opportunity for renewed mapping of ribbed moraines at higher levels of detail, likely facilitating new insights. Digital elevation models (DEMs) derived from this high-resolution remote sensing technology can be used to check and expand earlier mappings of ribbed moraine areas, and to analyse the morphology of the local ribbed moraines with increased precision and expanded sample sizes. Additionally, high-resolution DEMs of the landscape give excellent opportunities to analyse the spatial relationships between ribbed moraines and other landforms, as well as to analyse the position of ribbed moraines fields in the general landscape setting.

With this background, the main goals of this study will be to:

- Investigate the feasibility of the idea that subglacial water presence may have been an important factor in ribbed moraine formation by modelling hydraulic drainage patterns under the last glaciation.
- Re-evaluate the existing map of ribbed moraine distribution over a regional study area in Southern Norway in light of new map data.
- Investigate the relations of ribbed moraines with both other associated landforms as well as glaciofluvial traces through detailed mapping and fieldwork.

Therefore, ribbed moraine fields will first be mapped in a regional setting using new high-resolution LiDAR elevation data as a basis for comparison with the existing ribbed moraine distribution map. A more detailed mapping campaign will investigate the relationship between ribbed moraines and glaciofluvial landforms, ribbed moraines and associated landforms, as well as ribbed moraine fields and the surrounding landscape. A field campaign will be used for ground truthing of the detailed mapping to confirm mapped landforms and to gather additional observations in the area. Observations from mapping and from the field will be used to attempt to identify the the relations of ribbed moraines to glaciofluvial traces and other associated landforms.

Furthermore, this study will construct an ice sheet hydrology model of the last Fennoscandian glaciation based on known physical relationships and a paleo ice sheet reconstruction. The model will be used to calculate areas of low hydraulic gradient, areas of potential subglacial lakes and the paths of subgalcial drainage beneath the ice sheet for several time steps. This modelling will be done with high spatial resolution so that the resulting drainage patterns can be compared to patterns identified during the mapping process. This will be done to examine if areas of ribbed moraines coincide with areas where water could collect beneath the ice sheet, as this would be an indication that the ribbed moraine formation process may be either directly or indirectly linked to water presence beneath the ice sheets.

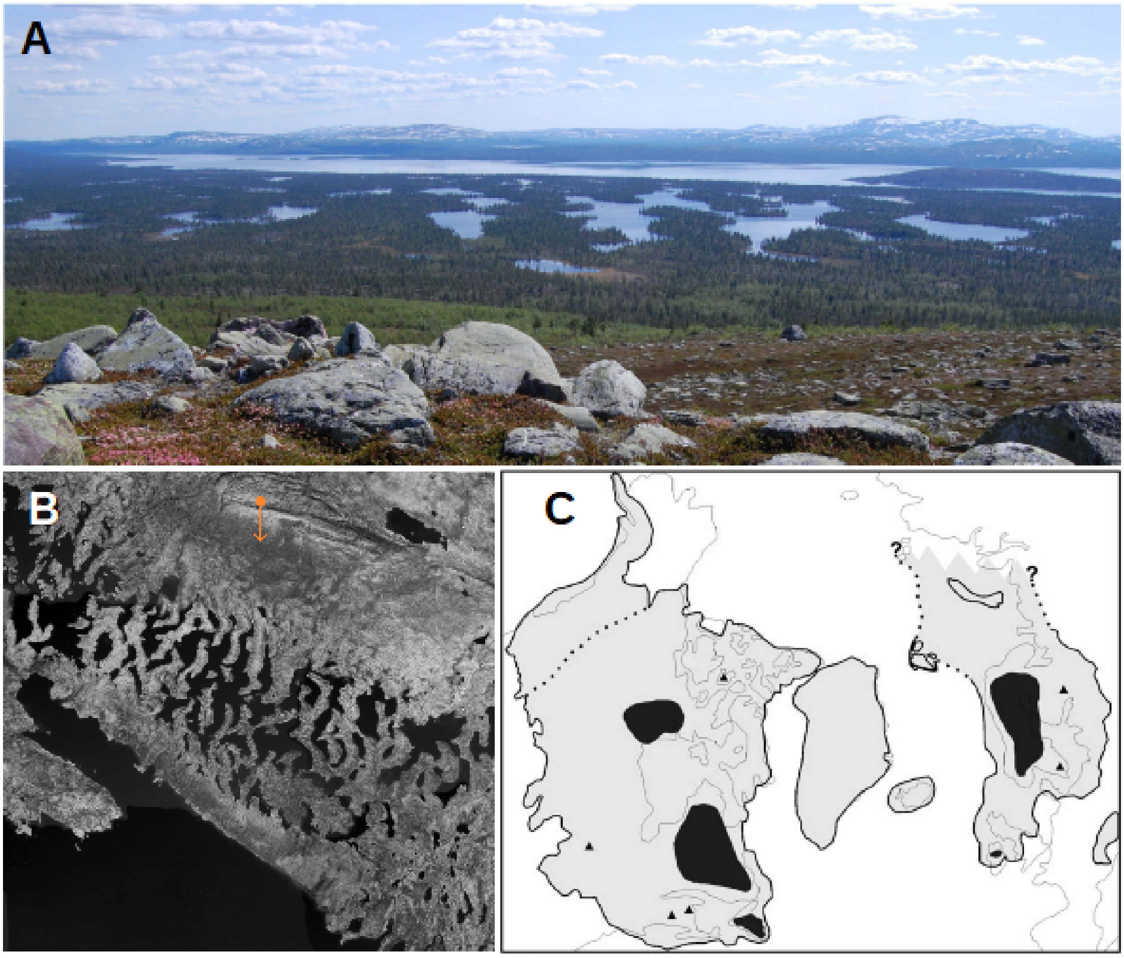


Figure 1: ***A*** - *Picture of the lake Rogen area in Härjedalen, central Sweden. Rogen moraines (or ribbed moraines) were first described in this area. The ridges with small lakes in between them in the foreground are ribbed moraines. Picture published by Wikimedia Commons user Wenkbrauwalbatros, available under licence CC BY-SA 3.0.* ***B*** - *Greyscale aerial photo of ribbed moraines by Lake Rogen, with the picture position and direction of picture A shown in orange. Aerial photo from the Swedish National Land Survey, available under licence CC0.* ***C*** - *Approximate global ribbed moraine distribution, with areas of common ribbed moraine cover in black, other known ribbed moraine populations marked as triangles, and the approximate maximum extent of northern Hemisphere ice sheets during the last ice age marked in grey. Modified after Hättestrand and Kleman (1999), with additional positions from Ely et al. (2016) and Möller and Dowling (2015).*

2 Background and study areas

2.1 Description of the study areas

This study investigated two study areas, one regional and one detailed. The regional study area will be used to map areas of different landform fields. The detailed study area will be used for mapping of individual landforms and fieldwork.

The regional study area is situated in the southern and middle part of the former Oppland Fylke in Norway, now the west and south-west parts of Innlandet Fylke (Figure 2). This area has good availability and coverage of LiDAR elevation data key to the mapping process, as well as the abundance of ribbed moraines identified in a previous study by Sollid and Sørbel (1994). According to an automatic landscape classification by Etzelmüller et al. (2007), the area consists of several landscape types ranging from hills with low and moderate slopes in the southeast via glacially scoured low and intermediate mountains and valleys in the centre of the study area to low and high mountain plateaus in the northwest of the study area. The study area therefore covers a diverse glacial landscape and an elevation interval of around 120 masl (meters above sea level) to a maximum of around 1700 masl. The geology of the region consists mainly of pre-Phanerozoic metamorph bedrock, which also covers large parts of the rest of southern Norway (Sigmond, 1992). However, the area also includes some Cambro-Silurian sandstone and shale from the Caledonian orogenesis in the mountainous areas in the north-west of the region, and in the south-east of the region (Sigmond, 1992).

For more detailed mapping, an area in the middle of former Oppland Fylke, now west in Innlandet Fylke, was chosen (Figure 2). The chosen area is a flat area of relatively high elevation known as Huldreheimen or Gausdal-Vestfjell which includes the Langsua National Park. The local study area consists of a plateau at around 800-1100 meters above sea level (masl). Some higher mountaintops rise above this plateau, such as the mountaintops "Skaget" with 1686 masl or "Gråhøe" with 1779 masl, which are the highest mountains in the area (Figure 2). According Etzelmüller et al. (2007), the landscape in this area is mainly comprised of a combination of high and low mountain plateaus. The north-west of the area includes some higher paleic mountains with glacial incisions, and the area is surrounded to the south-west and north-east by glacially scoured valleys and low mountains. As the treeline in this area is at around 1000 masl and birch forests normally dominate near the treeline (Bryn and Potthoff, 2018), the vegetation of the area is dominated by low birch trees and bushes as well as large areas with near-ground alpine vegetation. In addition, large parts of the landscape are marsh areas, and there are a large number of lakes present (Figure 2).

2.2 Regional glacial history

The large-scale topography of southern Norway and Sweden today is presumed to have been caused by uplift of the landscape during the Cenozoic, drastically lifting the west of Fennoscandia and less so the east (Martinsen et al., 2008). Remnants of high mountain plateaus in Norway (also present in the study area) indicate that the landscape was eroded to a flat surface before this uplift occurred (Martinsen et al., 2008). Since this uplift process, the region has undergone frequent glaciations

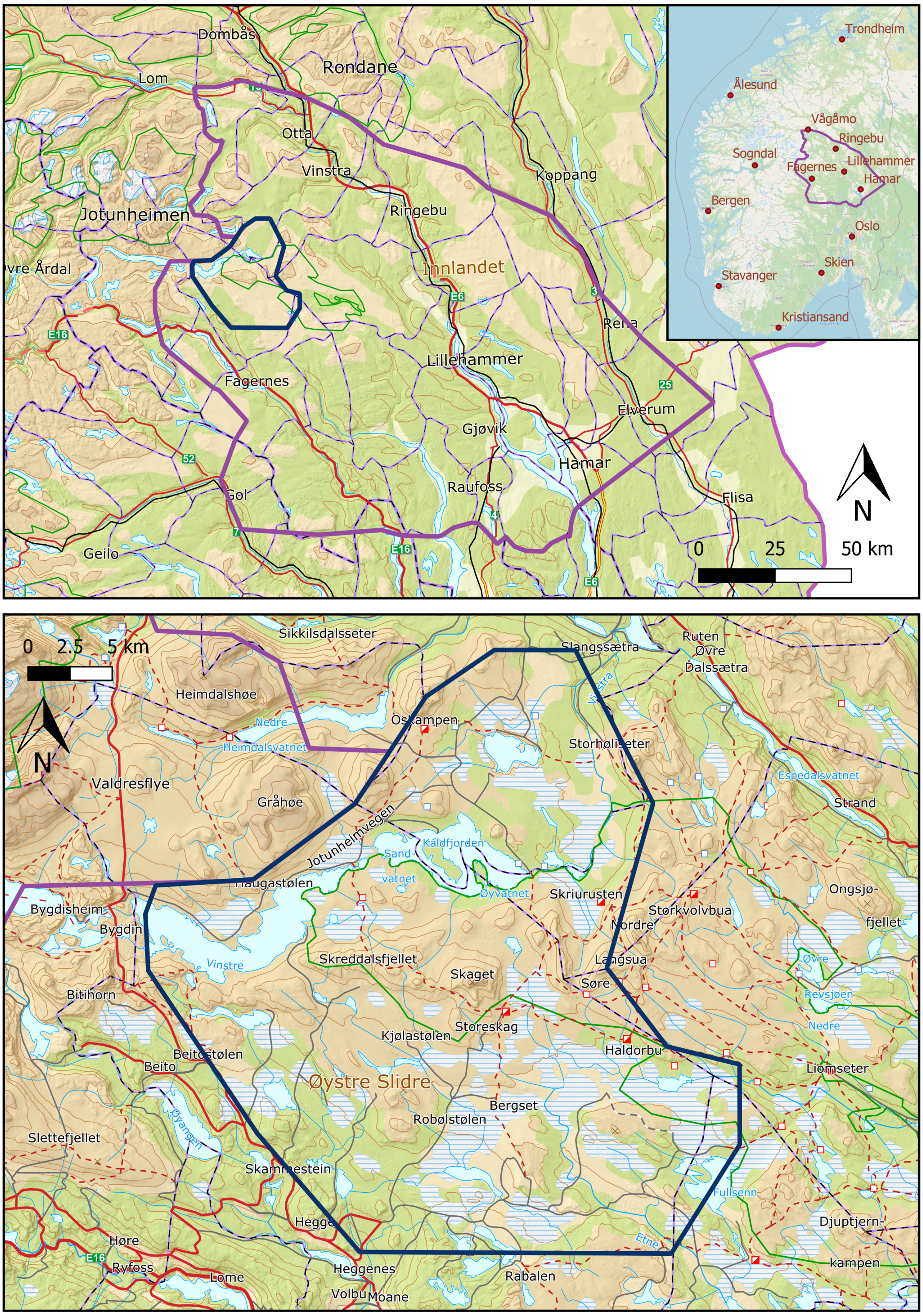


Figure 2: *Overview map of the detailed and regional study areas. The purple outline shows the larger regional study area, whilst the dark blue outline shows the detailed study area. Map data from the Norwegian Mapping Authority under licence CC BY 4.0.* ©Kartverket

and interglacial periods, which re-shaped much of the large-scale topography of the area (Vorren and Mangerud, 2008). Glacial valleys cut into the plateaus, often forming deep lakes and fjords due to over-deepening (Fredin et al., 2013). Most of the landscape is scoured to the bedrock, making old rock geology visible, and as a consequence almost all of the loose sediment that is still present in the landscape today (Figure 3) was deposited in the last glaciation and deglaciation (Vorren and Mangerud, 2008).

The last glaciation to cover Norway was the Weichselian glaciation of Fennoscandia, Barents Sea and the British Isles (Vorren and Mangerud, 2008). This Fennoscandian part of the ice sheet formed mainly in the Scandinavian mountains and is thought to have advanced slowly onto the flatter terrain in all directions dependant on the climatic situation (Olsen et al., 2013). After fluctuating in size for several thousand years, the ice sheet reached its largest extent at around 23 thousand years ago (from now on abbreviated to "kya"), covering large parts of northern Europe (Hughes et al., 2016). The thickness of the ice sheet is thought to have been around 2 km thick at this time (Patton et al., 2016).

After reaching its maximum size, the ice sheet retreated relatively fast, but with several standstills along the way, so-called stadials. The edge of the ice sheet reached the regional study area at around 11000 years ago, and had largely split up into mountain local glaciers by 9000 years ago. This retreat of the ice sheet, and especially the stadial periods in its retreat, have left behind visible traces in the landscape. Each break in the retreat leaves a terminal moraine from the sediment that has been deposited from the melting ice front. Using these prominent moraines, the recession of the ice sheet throughout the deglaciation can be followed and dated. (Hughes et al., 2016)

During this deglaciation process, vast amounts of meltwater were released from the melting ice sheet, carrying large amounts of sediment with it. This sediment was formed into different prominent landforms, such as glaciofluvial channels, which can be identified at many locations in the landscape today. It is possible to identify several different type of channels in the landscape, stemming from different formation conditions. Proglacial channels, which transported water form the glacier front, are plentiful and often easily identifiable. As large amounts of water exited the glacier front at many locations where water does not flow today, these channels are often large and dry, and therefore very visible in the landscape. Another prominent landform occurs when such proglacial channels enter glacially-dammed lakes, which are also not present in the landscape today. Fast-flowing proglacial water entering the stagnant water of a lake causes deposition of much of the water-transported sediment, subsequently forming a delta. When the lake recedes due to the damming glacier ice melting, the deltas are left behind i the valley, often together with shorelines of the lake in the valley sides. In addition to proglacial processes occurring during the deglaciation, glaciofluvial traces of water flow between valleys and valley glaciers during the late stages of the deglaciation can also be identified in the landscape. These channels can often be found in valley sides, sloping gradually in one direction. (Fredin et al., 2013)

Glaciofluvial processes also impact the landscape underneath glaciers, leaving behind esker ridges and subglacial channels. Eskers are ridges of coarse sediment that has been deposited by subglacial river systems underneath stagnant or very slow-moving ice. They are visible in many different shapes and sizes, and normally have a meandering river pattern to them. Eskers are normally interpreted to have formed during the deglaciation when the ice sheet was characterised by melting and little ice movement, rather than older stages of the ice age. They are therefore useful for approximate relative dating of landforms using cross-cutting relationships. Subglacial channels form when the subglacial water flow beneath the ice has eroding properties instead of the deposition properties forming esker ridges. These channels can be hard to distinguish from proglacial and lateral channels as there are no noteworthy morphological differences to the other channel types. They can however be identified by their setting in the landscape, as they can achieve flow directions which are not possible for channels following the landscape gradient under atmospheric pressure, such as proglacial and lateral channels. (Fredin et al., 2013)

The other main category of large glacially induced landforms that are easily identifiable in the landscape are so-called subglacial bedforms. This category includes so-called streamlined landforms such as drumlins and flutes, which are ridges of sediment and sometimes partly rock that form in the direction of the glacier movement. Ridges transverse to the ice flow, called ribbed moraines or Rogen moraines, can also be found in previously glaciated landscapes. These landforms are thought to have formed as a result of the dynamics between the moving ice and the subglacial sediment, hence the name bedforms. As the subglacial conditions under ice sheets are not yet fully understood, most of the formation processes of these bedforms are still being investigated and discussed, as will be done with ribbed moraines in this study. (Benn and Evans, 2010)

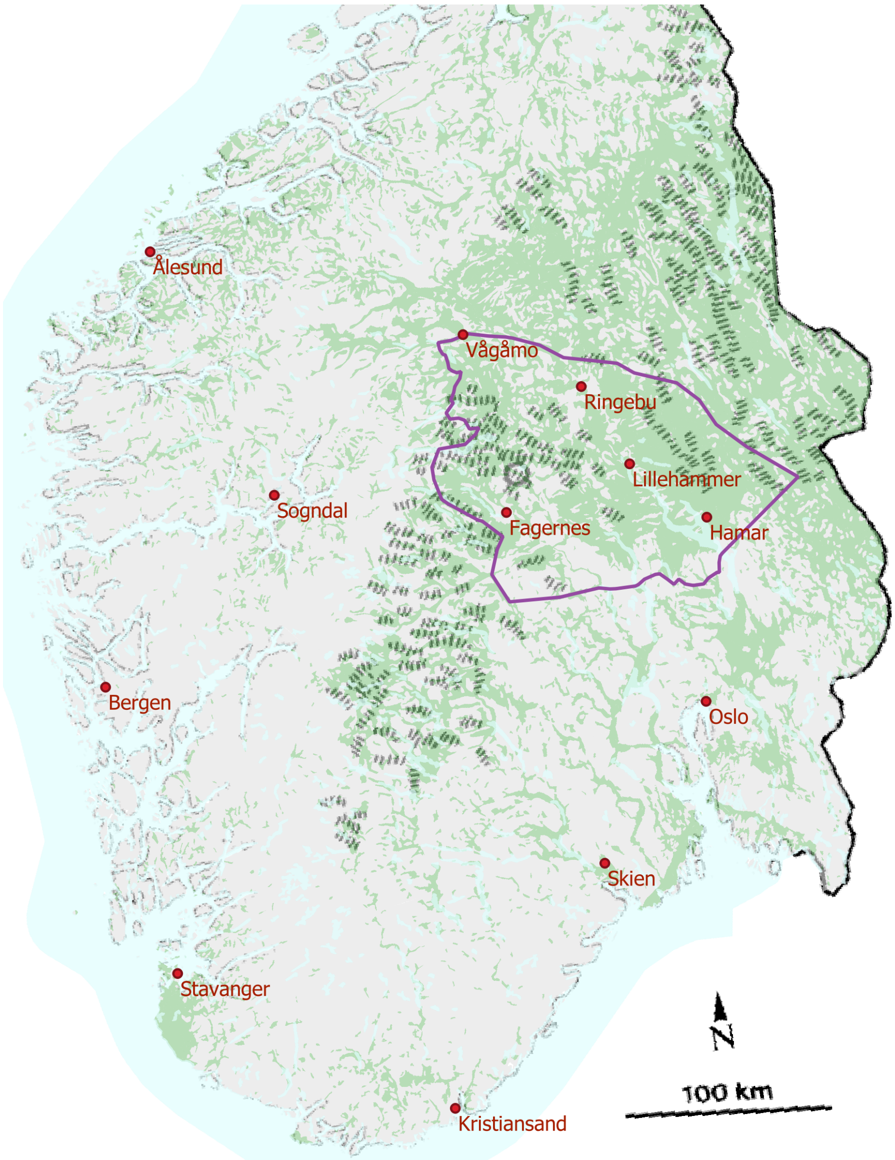


Figure 3: *Map of the distribution of ribbed moraines in southern Norway (marked with black transverse ridges; modified after Sollid and Sørbel, 1994) as well as the distribution of unconsolidated sediment in southern Norway (marked in green). In addition, the outline of the regional and detailed study areas investigated in this study area marked in purple and dark blue respectively. Unconsolidated sediment cover data is provided by the Norwegian Geological Survey (under license NLOD 2.0, see Table 2 for more information), originally based on the Quaternary sediment map of Norway by Thoresen (1990).*

2.3 Ribbed moraine morphology and classifications

Ribbed moraines are one of the more noticeable landforms left in the landscape by the last glaciation (see section 2.2). As there is no consensus on their formation per today, the term is used to describe a morphology. The most important morphological traits associated with ribbed moraines are described below.

- Ribbed moraines are wave-like, undulating ridges in the landscape (Figure 1), that are oriented transverse to the presumed ice flow direction.
- The ridges are comprised of unconsolidated sediment in the form of glacial till, and can contain different internal sediment structures depending on their location (Möller and Dowling, 2018; Benn and Evans, 2010).
- Ribbed moraines have varying forms and shapes (Figure 27; Dunlop, 2004)
- Ribbed moraines have varying dimensions, as shown by Dunlop and Clark (2006) who mapped and analysed a large sample size of ribbed moraine ridges. The calculated minimum, maximum and average dimensions found by Dunlop and Clark (2006) are listed in Table 1.
- They are found in fields in the landscape, covering anything from a few square kilometres and up to fields of several thousand square kilometres. (Dunlop and Clark, 2006)
- They are found in Canada, Norway, Sweden and Finland (Figure 1), and the majority of ribbed moraine areas situated near or under the presumed ice divides of the last glaciation (Hättestrand and Kleman, 1999). Some outliers are known, such as in southern Sweden (Peterson et al., 2017; Möller and Dowling, 2015), or Newfoundland (Fisher and Shaw, 1992).
- Ribbed moraine fields are often observed in relatively flat areas of the landscape, such as wider valley floors or plain-like landscapes (Lundqvist, 1989; Sollid and Sørbel, 1994; Dunlop and Clark, 2006, and others).

Throughout the years of research on ribbed moraines, countless observations regarding their morphology have been made in different locations and regions of Scandinavia and Canada. Studies have for example observed a jig-saw puzzle structures that fit together (Kleman and Hättestrand, 1999; Hättestrand and Kleman, 1999) or that ridges have "horns" at each ridge end that point down-stream (Lundqvist, 1989). Also, observations surrounding the situation of ribbed moraine fields in the landscape around these has differed from study location to study locations. Several observations of ribbed moraine fields predominantly in the Scandinavian landscape observe ribbed moraine fields in convex parts of the landscape such as valleys, whilst associated streamlined terrain in the form of drumlins and flutes is found in the concave parts of the landscape such as hills around them.

Extensive mapping and the use of spatial analysis allowed Dunlop and Clark (2006) to map and analyse 33 000 ribbed moraine ridges in central Sweden, central Ireland and central Quebec, Canada. Using this dataset, they investigated commonly cited but actively debated observations mentioned above using statistical and numerical methods. The study was not able to confirm several common perceptions of ribbed moraine morphology, while confirming several other established

Table 1: *Table showing the calculated average dimensions of a sample of ribbed moraine ridges mapped in Ireland, Central Sweden and Quebec, Canada (Dunlop and Clark, 2006).*

Dimension	**Minimum**	**Average**	**Maximum**
Length	45 m	688 m	16.2 km
Height	1 m	17 m	64 m
Width	17 m	278 m	1116 m
Wavelength	12 m	505 m	5800 m

observations. One observation which the study was not able to replicate was the jig-saw puzzle observation of the planar ridge forms fitting together. Dunlop and Clark (2006) also found no statistically significant indication of ribbed moraine populations being localised in depressions or on upstream or downstream-facing slopes, contrary to previous literature. In addition, the study found that there are strong spatial associations between ribbed moraines and drumlins and fluting lineations. Many variations of the "classic" morphology of ribbed moraine ridges were also found, suggesting there is a larger spread of morphologies than previously noted in literature.

Several earlier studies have proposed different classifications of ribbed moraines types:

- Aylsworth and Shilts (1989) divided ribbed moraines mapped in the Keewatin region of northern Canada into "classic" Rogen moraines, blocky ribbed moraines, fish-scale ribbed moraines and dune-shaped moraines.
- Hättestrand (1997) examined four main categories of ribbed moraines: Rogen moraines as defined and described by Lundqvist in 1969, hummocky ribbed moraines, Blattnik moraines and minor ribbed moraines.
- Dunlop (2004) set up a comprehensive classification, dividing ribbed moraine ridges into 13 categories based on their morphological distinctions (see parts of the classification in Figure 27). This classification in turn was used actively in Dunlop and Clark (2006).

Even more study-specific classifications exist (Trommelen et al., 2014; Putniņš and Henriksen, 2017, and others), and per today none of these classification has had a breakthrough and has become widely. This study will predominately attempt to use the classification by Dunlop (2004) in further descriptions of different types of ribbed moraines. This classification is comprehensive, diverse and has been successfully used in a study with a large sample size (Dunlop and Clark, 2006).

In addition to different classifications, there has also been some confusion and ambiguity surrounding the terms "ribbed moraine" and "Rogen moraine", which are often used synonymously. The term "Rogen moraine" was first defined by Lundqvist in 1969 (Lundqvist, 1989) and used to describe landforms at the Lake Rogen location in central Sweden. Lundqvist (1989) pointed out that his original paper from 1969 gave a specific definition of the term, defining Rogen moraines as "a landscape of moraine ridges transverse to the corresponding ice flow direction and showing transitions to drumlins at least in some places within the area under consideration." (Lundqvist, 1969, as cited in Lundqvist, 1989). To avoid further confusion, this study will consistently use the general term "ribbed moraine", which does not necessarily include a transition to drumlins, but neither excludes this possibility.

2.4 Ribbed moraine research history

In Scandinavia, successive ridges transverse to ice flow resembling ribbed moraines were first described in the early 20th century and were often interpreted as a type of front moraine or a melt-out moraine in a dead-ice terrain setting. Later, studies found several instances of eskers and other landforms super-imposed on these perpendicular moraine fields, indicating that these were formed subglacially in contrast to other moraines. This effectively caused ribbed moraines to be described as a separate landform, with formation theories shifting towards different subglacial formation principles, which has since become the general consensus regarding the formation of most ribbed moraine populations. The following sections will try to provide an overview of the most important observations, ideas and hypotheses that have been suggested for ribbed moraine formation since this consensus on a subglacial origin.

Shear and stack explanations

Several studies surrounding ribbed moraines suggest a formation principle where shear of debris-rich ice caused by compressive stress stacks debris locally. When this is followed by melt-out of the ice, this is assumed to produces ribbed moraine ridges (Minell, 1980; Bouchard, 1989; Aylsworth and Shilts, 1989). Many of the studies have different views and hypothesis regarding the exact processes, principles and initiating conditions that were present during and after formation.

Connection to cold ice extent

New findings suggesting that pre-glacial landscapes may have been preserved under the ice sheets lead to ideas that the ice sheet may have been frozen to the glacial bed (cold-bases) in the mountainous areas of Norway and Sweden. This causes several studies to suggest that ribbed moraines may have been formed at the boundary between zones of cold and warm-based ice under the ice sheets. This hypothesis was suggested in Sollid and Sørbel (1984) and Sollid and Sørbel (1994) as well as an evolved hypothesis by Hättestrand (1997) and Hättestrand and Kleman (1999); Kleman and Hättestrand (1999), and a slightly different approach by Sarala (2006).

Sollid and Sørbel (1984)investigated different moraine types in central Norway, finding that many parts of the landscape at higher elevation showed signs of glacial drainage under cold-based conditions indicating a mainly cold-based deglaciation in these areas. The article suggested that ribbed moraines formed in the transitional phase between warm and cold-based conditions under the ice sheet and were then preserved under cold-based ice throughout the rest of the glaciation, including the deglaciation. This reasoning was backed up by observations of ice flow lines inferred from ribbed moraine fields not matching up with flow lines during the last glacial maximum (LGM), but rather the flow lines of a smaller Fennoscandian ice sheet, presumed to be of pre-LGM configuration. The specific formation process is assumed to be a shear-based movement carrying material up and in the glacier flow direction before deposition. Sollid and Sørbel (1994) additionally suggested that since ribbed moraines were mostly identified in depressions in the Norwegian landscape, water may have accumulated at these positions during transition between warm and cold-based conditions. It is assumed that the transition between warm- and cold based conditions happened from the top downwards, with higher-lying areas turning cold-based first and preserving the streamlined features found here, whilst water collected in the lower-lying depressions which were still warm-based. Sollid and Sørbel then suggest that the Rogen landform was a result of processes during the gradual freezing of these water pockets in conjunction with the ice movement above, though a specific formation process was not mentioned in the article.

Hättestrand (1997) used the same basis with a different configuration to suggest a formation principle for ribbed moraines. (Hättestrand, 1997) also pointed out that the inferred flow lines of ribbed moraines in both Norway and Sweden did not fit with LGM flow directions, but instead attributed the flow lines to an ice sheet in deglaciation configuration rather than pre-LGM conditions. A shear and stack process was suggested in the study, with till breaking up during thawing and parts of the still frozen till being dragged up onto other till blocks in a boudinage-type process. Hättestrand and Kleman (1999) used this so-called "fracturing theory" from Hättestrand (1997) together with other indications of cold-based ice sheets such as blockfields and tors, to infer the extent of cold-based conditions under maximum extent of the last the Fennoscandian ice sheet. This created some attention, as it was one of the first attempts at clearly defining the extent of cold-bed conditions under the last glaciation, but the feasibility and accuracy of the proposed ribbed moraine formation principle suggested was questioned in subsequent studies (Möller, 2006; Dunlop and Clark, 2006).

Later, Sarala (2006) added to the hypothesis of Hättestrand and Kleman, suggesting a more specific formation process for ribbed moraine formation at the cold-temperate ice-bed interface. The suggestion by Sarala (2006) is backed by sedimentological investigations in northern Finland, and argues for a two-step formation process. Firstly, subglacial till cover is thought to break up under cold-based, compressive ice-flow conditions, just as in the hypothesis by Hättestrand. Rather than a boudinage-type process however, a freeze-thaw erosion-deposition process is proposed to transport till and bedrock blocks from between precursor ridges to the top of the ribbed moraine ridges.

Two-step explanations

Several studies have put forward hypotheses where a two-step formation process is favoured, often arguing that other landforms could have been remoulded into a ribbed moraine. Boulton (1987) argued that ribbed moraines could have developed from streamlined landforms such as drumlins and flutes after an approximately 90°change in ice flow direction. Boulton (1987) also indicated that ribbed moraines may be a precursor for drumlin formation.

Lundqvist (1989, 1997) also indicates that a two-step model is likely, as this would potentially explain the wide variety of sedimentary compositions and internal structures that had been observed inside several ribbed moraines in central Sweden. The studies did however not specify an original or pre-cursor landform or structure. Lundqvist also recognised, but did not explain, a spatial connection between ribbed moraines and streamlined terrain in the form of flutes and drumlins, even defining the term "Rogen moraine" as describing specifically fields of transverse ridges surrounded by streamlined landforms (see Section 1.3).

Later on, also Möller (2006) argued strongly for a two-step formation process due to a number of new sediment analyses from ribbed moraines in Sweden. Möller (2006) refrained from proposing a specific mode of formation, but suggested pre-cursor ridges to play a part in the process.

Continuum ideas

Close spatial proximities and transitional landforms between ribbed moraines, hummocky terrain, Drumlins and flutes have been noted for some time, e.g. by Lundqvist (1989, 1997) and Boulton (1987). Several hypotheses have tried to explain these landforms in a single framework, observing and describing the close spatial connections between these landforms and launching conceptual explanations.

Aario (1977a,b) identified transitional forms between ribbed moraines and streamlined bedforms during investigations in Finland. Aario (1977a,b) subsequently suggested a continuum in size and form between these landforms, suggesting they are formed by the same or similar processes. The suggested continuum spans from ribbed moraine fields and subglacial hummocks, named the hummocky active ice assemblage, via a drumlin assemblage spanning drumlins and other glacial lineations, to a fluting assemblage. Aario (1977b) imagined the forming process of these subglacial landforms to be the consequence of either an up-down ice flow forming transverse features or a spiral ice flow forming streamlined features, with a transitional flow between these.

A slightly different approach attributes the change from transverse ridges to lineations to the pressure environment in the glacial ice flow. Based on geomorphological mapping and sedimentological investigations using ground penetrating radar surveys in northern Canada, Stokes et al. (2008) suggested that streamlined terrain are formed under extensional flow conditions of the ice. Ribbed moraines are on the other hand formed by compressive flow caused by the ice “sticking” to the subglacial bed due to localised cold-based conditions.

Recently, Ely et al. (2016) tested for a size and shape continuum between ribbed moraines, glacial lineations and flutes using spatial and numerical analysis. A clear continuum between different sizes of ribbed moraine ridges was found and a clear continuum between different glacial lineations was found. There was no continuum in shape and size between these two classes however, and in addition, flutes were found to form a distinctly separate continuum to the other two classes, in contrast to what Aario (1977a,b) envisioned. Unfortunately, Ely et al. (2016) did not include hummocky forms into their analysis, but acknowledged their presence, speculating that they may be the missing link in a complete continuum from ribbed moraines to glacial lineations.

Instability models

In addition to suggesting that ribbed moraines originate form a two-step process, (Boulton, 1987) set up a conceptual model for till deformation, originally intended to explain drumlin formation. This model explained a process of till instability, in which areas of structurally weaker till are highly impacted by deformation of the overlying ice, whilst structurally stronger areas have more friction with the ice, slowing the ice flow at these locations. The interactions between faster-flowing ice and slower flowing ice, so-called ”sticky spots”, is suggested to have formed drumlins. Later on, this conceptual model was used to develop a function for the deformation of till beneath glacier ice, which was later developed to also fit ribbed moraine formation (Hindmarsh, 1998a,b,c, 1999, as cited in Dunlop et al., 2008). However, these conceptual models were left untested due to few quantitative measurements being available (Dunlop et al., 2008).

Extensive mapping and statistical analysis of approximately 33 000 ribbed moraine ridges was able to test several widely-quoted observations surrounding ribbed moraine morphology and ribbed moraine fields (Dunlop and Clark, 2006). In addition to confirming and falsifying several observations quantitatively, the study also found strong spatial associations between ribbed moraines and drumlins and fluting lineations. Dunlop et al. (2008) then attempted to model ribbed moraine formation using the instability theory, comparing the modelling results to the statistical results from the previous dataset acquired in Dunlop and Clark (2006). Their findings showed that it was possible to use the numerical instability model altered from Hindmarsh (1999) to recreate ribbed moraines in a model of the subglacial environment. This numerical model of the coupling between ice and sediment flow beneath ice sheets was the first of its kind, and was named the "Bed ribbing instability explanation".

Megaflood explanation

Fisher and Shaw (1992) attribute the ribbed moraines of the Avalon peninsula in Newfoundland to water sheet-flow of subglacial megafloods. The article suggests that sudden water flow forms ribbed moraine ridges in a ripple-creation process, which is based on glaciofluvial sediment forms in several ribbed moraine ridges. Fisher and Shaw also indicate that this explanation can be applied to drumlin formation. This hypothesis is disputed by Benn and Evans (2010), who argue that it is not compatible with accepted glaciological theory.

Equifinality

Möller and Dowling (2018) argue that it is likely that different subglacial ice-sediment processes create the same morphological shapes of subglacial landforms. The article attributes the formation of the ribbed moraine morphology to at least three different process combinations, based on sedimentological observations from several ribbed moraine fields in different areas. Möller and Dowling (2018) therefore conclude that there is an equifinality in the shape of subglacial landforms resulting from different subglacial ice-sediment processes.

3 Methods

3.1 Mapping

3.1.1 Map data

Three main data formats were used as a basis for mapping in this study. “Web Map Service” (WMS) or “Web Map Tile Service” (WMTS) datasets were used for many datasets. WMS and WMTS datasets utilise constant import of the newest footage via internet connection, and therefore avoid time-consuming and data intensive download processes. This type of data is however restricted in the fact that no calculations or other numerical analysis operations can be performed on these datasets, meaning they are usable only for purposes of visualisation and observational mapping of features. Therefore, georeferenced raster data was also downloaded in the form of GeoTIFF files. Georeferenced raster data visualised numerical data in grid coordinates, and this data format can therefore be analysed numerically, changed, and visualised in a number of ways. Using the above formats, features were mapped using shapefiles, a data format which can represent geographical information in either points, lines and polygons. All datasets were handled and processes in the geographic information system program QGIS.

The main data type used in mapping in this study is Light Detection and Ranging Digital Elevation Models (LiDAR DEMs). LiDAR technology has seen a widespread use for surveying and mapping purposes in the last decades, as it is a very accurate and effective way to collect three-dimensional data of both landscape and vegetation (Hodgson and Bresnahan, 2004). A large use for LiDAR technology is for aerial surveying of landscapes in order to create large-scale DEM data at high spatial resolution. The Norwegian Mapping Authority, which is responsible for administering map data and supplying positioning services in Norway, started a LiDAR scanning campaign in 2016 with the goal of collecting high resolution elevation data for large parts of the Norwegian Landscape (Norwegian Mapping Authority, 2019a). This project, called national detailed elevation model (Nasjonal Deltaljert Høydemodell - NDH), will establish a DEM with 1x1 meter spatial resolution for the whole of Norway instead of the 10x10 meter resolution available nationwide before (Norwegian Mapping Authority, 2019d). The landscape is scanned using LiDAR instruments mounted on airplanes, sometimes helicopters, measuring a minimum of 2 measurement points per square meter of landscape (Norwegian Mapping Authority, 2019a). After the scans are completed, a raster dataset is created from the point data collected, and vegetation as well as anthropogenic features such as buildings and bridges are removed from the dataset. The Norwegian Mapping Authority aims for the project to be completed in 2022 (Norwegian Mapping Authority, 2019d), but datasets are published and updated continuously, and are available free of charge in the web portal Høydedata (`www.hoydedata.no`). The resulting DEM dataset, called “Høyde DTM1”, is therefore already available covering most of Norway, including the study area. In this study, the complete Høyde DTM1 dataset was utilised as a WMS layer in QGIS (Table 2). Several LiDAR DEM projects were also downloaded individually as raster data for the detailed mapping and spatial analysis parts of this study (Table 2).

Aerial photographs were also used widely during mapping as a supplement to the DEMs, to double check and further investigate features recognised in the DEM hillshades. Aerial photos of the study areas are available through the Norwegian Mapping Authority, who through their ongoing project "Nasjonalt program for omløpsfotografering" (National program for repeat photography) collect repeat photography for the whole country every 5 to 10 years (Norwegian Mapping Authority, 2019c). The data from this program as well as the comprehensive digital archive of previous aerial photos are freely available in Norway through the web portal Norge i Bilder (`www.norgeibilder.no`) or the central archive for aerial and satellite photos (Norwegian Mapping Authority, 2019b). The newest photography available at a spatial resolution of minimum 50 cm. In addition, the newest photos from the campaign are also available through a WMTS layer (Table 2), and have minimum spatial resolutions of 50 cm. This aerial photo layer was used extensively double check features identified in the LiDAR DEMs.

Bedrock geology maps as well as Quaternary sediment maps from the Norwegian Geological Survey were used to aid geoscientific interpretation of the study areas. Bedrock geology map data is utilised to check if landform-like features do not in fact represent faults or other bedrock geological lineations and features. The printed paper Quaternary sediment map of Norway at a scale of 1:1 000 000 (Thoresen, 1990), the Glacial geology map of Norway at a scale of 1:1 000 000(Sollid and Torp, 1984), and a Quaternary geology and geomorphology map of the Oppland Region at a scale of 1:250 000 were used (Sollid and Trollvik, 1991). These were used to identify areas of interest for mapping and fieldwork as well as understanding the regional Quaternary geology and previous landform interpretation.

In addition, map data from the national map of Norway was used to aid orientation and map visualisation. This dataset, also provided by the Norwegian Mapping Authority and available through the web map portal Norgeskart (`www.norgeskart.no`), shows lakes, rivers, glaciers and rough vegetation type in addition to roads, towns and other anthropogenic features on the landscape. Using the WMS dataset of this map, individual topological elements of the map such as those mentioned above can be added to QGIS projects.

3.1.2 Regional mapping

Ribbed moraine fields and associated landform fields will be mapped in the regional study area (Figure 2). This is done to be able to compare the mapped ribbed moraine fields with an existing ribbed moraine distribution map (Figure 3) compiled by Sollid and Sørbel (1994).

Mapping the extents of ribbed moraine fields and other landform fields was completed using polygon shapefiles in QGIS. As a basis for mapping, the WMS-datasets "DTM1" and "Norge i Bilder" from the Norwegian Mapping Authority were used (Table 2). A hillshade of the DEM dataset "DTM1" was used at a scale of 1:40 000 meters to identify areas of interest which seemed to show undulating till resembling ribbed moraines or features of similar morphology. When areas of interest were found, the scale was decreased to 1:20 000 meters to draw the outlines of the fields of similar morphology. The WMTS data layer "Norge i Bilder" containing aerial photos was used as a control mechanism to double check features of conflicting morphology. The regional study area (Figure 2) was scanned manually and systematically to identify landform features and assign them to the following three field categories:

Table 2: *Table showing the digital map datasets used in this study during mapping and modelling. Explanations regarding the data format can be found in Section 3.1.1. All datasets can be found on the map data web portal Geonorge (www. geonorge. no), the national database for map data. The provider name Kartverket represents the Norwegian Mapping Authority, and the described datasets are available under licence CC BY 4.0 (www. creativecommons. org/ licenses/ by/ 4. 0). NGU represents the Norwegian Geological Survey, and the described datasets are available under licence NLOD 2.0 (www. data. norge. no/ nlod/ en/ 2. 0).*

Dataset name	**Data format**	**Provider and licensor**	**Description**	**Date(s) accessed**
Topografisk Norgeskart	WMS	Kartverket	National topographical map of Norway, showing land cover, contour lines, roads and transport links.	08.2019 to 06.2020
Norge i Bilder WMTS	WMTS	Kartverket	Aerial photo layer of Norway.	08.2019 to 06.2020
Høyde DTM1 WMS	WMS	Kartverket	1m spatial resolution LiDAR DEM covering most of Norway. Some sparsely populated areas such as high mountain areas are not yet covered by this dataset.	01.2020 to 06.2020
Valdres 2007	GeoTIFF	Kartverket	1m spatial resolution LiDAR DEM of the Valdres Valley from 2007.	16.05.2019
Lillehammer Gausdal 02pkt_2010	GeoTIFF	Kartverket	1m spatial resolution LiDAR DEM of the upper part of the Gausdal municipality from 2010. Part of the NDH project, and included in the DTM1 dataset.	13.09.2019
Midt-Gudbrandsdalen 01pkt 2009	GeoTIFF	Kartverket	1m spatial resolution LiDAR DEM of the mountainous parts of Midt-Gudbrandsdalen from 2009. Part of the NDH project, and included in the DTM1 dataset.	23.10.2019
Midt-Gudbrandsdalen 07pkt 2009	GeoTIFF	Kartverket	1m spatial resolution LiDAR DEM of the inhabited parts of Midt-Gudbrandsdalen from 2009. Part of the NDH project, and included in the DTM1 dataset.	23.10.2019
DTM 50	GeoTIFF	Kartverket	DEM dataset covering the whole of Norway at 50m spatial resolution.	13.11.2019
DTM10	GeoTIFF	Kartverket	DEM dataset covering the whole of Norway at 10m spatial resolution.	13.11.2019
Løsmasser WMS	WMS	NGU	Map of unconsolidated Quaternary sediment as well as glacial traces and landforms in the Norwegian landscape. Southern Norway is covered at 1:250000, with many areas also covered at a scale of 1:50000.	08.2019 to 06.2020
Berggrunn N50 WMS	WMS	NGU	Bedrock geology map of Norway showing rock layers and major faults. The whole of Norway is covered at 1:250000, with many areas also covered at a scale of 1:50000.	01.2020 to 06.2020

- **Ribbed moraine fields:** Fields of clearly identifiable ribbed moraines were assigned this category. Transverse ridges are deemed to be distinct enough for this category if the ridge crests can confidently be marked by lines, with a minimum of 5 clear transverse ridges in close vicinity to each other needed to constitute a field.
- **Hummocky/ribbed fields:** This field type includes the ribbed moraine fields defined above, as well as other less distinct landforms that may be associated to ribbed moraines. In addition to the ribbed moraine ridges of the ribbed moraine fields, this field type therefore includes individual transverse ridges not near other transverse ridges, hummock landforms, as well as features that resemble ribbed moraines and hummocks but do not show characteristic features.
- **Streamlined fields:** Areas of predominant glacial lineations, flutes, drumlins and other streamlined till features are assigned this category. As a control mechanism, the dataset "Berggrunn N50" (see Table 2) was sometimes used to check if mapped features could have their origin in rock geology instead of glacial processes. Areas were only marked as streamlined when there was high confidence that the morphological features were not attributed to underlying geological formations.

After mapping was completed, the spatial distribution of the different fields in the landscape was analysed manually. In addition, a statistical analysis of the elevation distribution of the mapped fields was also undertaken. This is accomplished using the "zonal statistics" tool in the QGIS program. This tool can extract statistics from a raster file for each of the entities of a shapefile. As input for the zonal statistics tool, one of the map layers is chosen as well as the DEM dataset "DTM10" which supplies elevation data. The tool then calculates median, maximum and minimum elevation of each field. These statistical parameters for each field were then plotted in respect to distance along a northwest-southeast axis through the regional study area.

3.1.3 Detailed mapping

For more detailed investigations into the regional ribbed moraine morphology as well as their spatial relationships to other landforms in the area, a smaller area for more detailed mapping was chosen from inside the regional mapping area. As mentioned in the introduction, an area around the Langsua national park in the Gausdal-Vestfjell area was chosen for detailed mapping, as can be observed in Figure 2.

In preparation for mapping, individual LiDAR DEM projects of this area were downloaded as raster files from the Norwegian Mapping Authorities elevation data portal "hoydedata.no". In addition, WMS data in the form of the nationwide LiDAR DEM, aerial photo layer, national map layer, rock geology map layer and Quaternary geology map layer were added to the QGIS program. See Table 2 for a full overview of all map data used. Mapping was done at a scale 1:5000, with overview scales at 1:10000 and 1:20000 if needed.

The following landforms were identified and their position marked using either a point or a line:

- **Ribbed moraine ridges:** ridge crests of ridges which are situated approximately transverse to the ice flow direction are marked with a line. Ridge length must be twice the width to qualify for this category. If this is not the case, they are marked as hummock mounds. Transverse ridges that show significant signs of esker or a glaciofluvial channel morphology are excluded from this category.

- **Hummock mounds:** irregular-shaped or rounded mounds with no obvious process origin. They are marked with points at approximately their highest point.
- **Streamlined marks:** flutes and glacial lineations (such as drumlins and similar forms). Straight, or more rounded parallel ridges in otherwise relatively untouched sediment are categorised as streamlined features. They are marked with lines on their ridge crest.
- **Streamlined hummock mounds:** hummock mounds with visible streamlining marks are categorised as streamlined hummock mounds. They are marked with points at approximately their highest point.
- **Eskers:** thin, meandering ridges are categorised as eskers, and are marked with lines following the ridge crest.
- **Fluvial channels:** troughs in the landscape, often with clear meandering features. They are marked with lines in their channel troughs.

As this kind of geomorphological mapping using LiDAR elevation data and aerial photos is subject to subjective choices by the cartographer, dilemmas regarding how to interpret a landform are common. Several interpretation dilemmas were encountered during the detailed mapping, with the most common ones being mentioned briefly below:

- Ribbed moraine ridges often appear as a conjoined chain of mounds rather than with a flat ridge crest (Dunlop and Clark, 2006; Aario, 1977b), whilst hummock mounds appear as single mounds in the landscape. These two landforms were often found in close proximity to each other, often with smooth transitions, which made deciding where ribbed moraine ridges ended and hummock mounds began a challenge. To solve this challenge, the landform definitions described above were followed strictly.
- Fluvial channels crossing the valley floor or other flat areas often leave traces resembling rides and troughs in the landscape. These can often be morphologically similar to ribbed moraine ridges, especially when oriented in the same transverse ice flow direction as ribbed moraines and possibly also in close proximity to ribbed moraine fields. There is therefore a possibility that such features were either interpreted as ribbed moraine ridges, or that unclear ribbed moraines were mistaken for such fluvial features and not included in the datasets.

In addition, elevation profiles are gathered across the mapped fields of the detailed map to further analyse how the fields are situated in the landscape. This is done using the "profile tool" plugin in QGIS. The elevation profiles were then plotted as line plots and compared visually.

3.2 Fieldwork and sediment analysis

A total of 4 days were spent in the southeast part of the detailed study area, with the goal of making observations which could be used for ground truthing of the detailed map. This was done by visiting strategic viewpoints in the landscape to get overview of ribbed moraine fields, and by traversing several ribbed moraine fields to identify the general morphological and sedimentological composition of ribbed moraines in this study area. In addition, ribbed moraine fields were investigated for fluvial influences to identify possible traces of subglacial water presence. In a step to study this, sediment samples were gathered, as the degree of sorting in sediment samples can often be related to their depositional environment (Boggs, 1995).

The area visited lies in the eastern part of the Vestre Slidre municipality, between the small town of Heggenes and the Langsua national park (Figure 2). This area has good road connections in the form of private gravel roads accessible by paying a toll fee, and therefore a car was used as a mode of transport through most of the area. In addition, bikes and foot travel were used for parts of the study area away from the road and in protected areas such as nature reserves and national parks. As one of the main goals of the field trip was to undertake ground truthing of already mapped areas, finding viewpoints and walking trails around the mapped areas was prioritised. 6 viewpoints on hilltops and slopes were used to get a general overview of the area and to identify landform and landscape features for closer investigation. These viewpoints were Gravfjellet, Synhaugen, Skåltjernknatten, Kjølastølen, Haldorbu and the Storeskag parking (Figures 2, 14). Longer walks and bike trips were made in the ribbed moraine fields in the Trollåsen and Fjelldokka areas, with several other shorter trips made to viewpoints and other interesting features. (Figures 2, 14).

21 sediment samples were gathered during the field trip at various locations. All samples were gathered outside of protected areas such as national parks and nature reserves. Wherever possible, sediment samples were taken from existing road cuts and gravel quarries for simplicity reasons and to comply with local regulations. All samples were taken by digging a hole with a cleaned, vertical back wall. The back wall was first used to identify possible sedimentary features such as any larger layering, before a sediment sample was extracted form it. At some locations several samples were taken, either in the same hole at different heights in the sediment column or at different holes in the same slope. Sediment samples were gathered predominantly in the Trollåsen valley at Skatrudstølen (10 samples) and Langetjernet (4 samples) as well as near Robølstølen (1 sample), Storeskag (4 samples) and Olægeret (2 samples) (Figures 2, 14).

The Sediment samples were analysed through a sieving process to obtain their grain size distribution. Grain size distributions can be used to estimate a deposition process of the sediment sample in conjunction with analysis of the sedimentological structure of the in situ sediment. This is possible due to different deposition processes deposit sediment with different levels of sorting. A very well-sorted sediment sample may contain almost exclusively one or two grain size categories, whilst an unsorted sediment sample may contain shares of almost all grain size categories. The sediment in our study area is expected to be mostly unsorted, as this is the common grain size distribution for sediment that is deposited by glaciers, ie. the common distribution for glacial till (van der Meer et al., 2003). In addition, some sorted samples are expected where fluvial processes are thought to have deposited sediment, as fluvial deposition is known to give very sorted sediment in many cases (Boggs, 1995).

The sediment samples were dried in open containers in a lab drying cabinet before sieving in order to achieve accurate results. The drying cabinet temperature was set to 60°C, and the sediment was dried until no visible moisture could be seen in the containers when stirring in the soil. Criteria for seeing visible moisture were visible water droplets, visibly darker soil patches and/or clumped soil. The drying process took between 8 and 20 hours. The Wentworth scale (Wentworth, 1922) was used to quantify sediment sorting. This scale divides the sediment into several different named categories with a set grain size interval for each category (Table 3). The grain sizes decrease logarithmically, resulting in the scale covering a large span of grain sizes effectively.

Sieving was carried out with 9 sieves of different mesh sizes, with sieve sizes corresponding to the Wentworth scale between the categories "pebble" and "coarse silt" (see Table 3). Sieves were mounted on top of each other consecutively from fine mesh at the bottom to large mesh at the top, with a collection container underneath the column. The sample was weighed before adding it to the sieve column from the top. A lid is placed on the column, and it is mounted in a vibration machine with a timer, in this study set to 15 minutes. The column is then dismantled one sieve by one starting from the top. Any larger organic content (e.g. roots) is extracted from the sample at this stage.Each of the sieve's contents are emptied into a container on a scale, and each sediment load for each sieve was then weighed. All weighed sediment shares are then added to a sample bag, which is weighed at the end of the process. The recorded weights are then calculated into percentages of the total sample weight before sieving, and then drawn into a cumulative plot.

The difference between the total sample weight before and after sieving gives an indication of the accuracy of the sieving process. If substantial amounts of the sample is lost during the sieving process, this indicates errors during either sieving or weighing of the samples. An error threshold is therefore set, and samples are deemed unusable if the difference between total sample weight before and after sieving is larger than 5%. This was not the case for any of the 21 samples analysed in this study.

Table 3: *Table showing grain distribution classes based on Wentworth (1922). The phi-values use a logarithmic scale with the base 2, and are used along the x-axis of the grain size distribution plots of each sample.*

Wentworth size class	**Wentworth size grade**	**Grain size** [mm]	**Sieve size** [μm]	**Phi-value of sieve**
Gravel	Cobble + boulder	>16	16000	-6 and below
	Large pebble	8 - 16	8000	-4
	Small pebble	4 - 8	4000	-2
	Granule	2 - 4	2000	-1
Sand	Very coarse sand	1 - 2	1000	0
	Coarse sand	0.5 - 1	500	1
	Medium sand	0.25 - 0.5	250	2
	Fine sand	0.125 - 0.25	125	3
	Very fine sand	0.063 - 0.125	63	4
Mud	Silt + clay	<0.063	Rest of sample	5 and above

3.3 Modelling the hydraulic potential

3.3.1 Theory

The physical relation that was used as a basis for modelling hydraulic potential in this study was first defined by Shreve (1972), and states that the hydraulic potential in a subglacial drainage system can be expressed as:

$$\phi = \rho \cdot g \cdot z_b + P_w \tag{1}$$

where ϕ is the hydraulic potential, g is the gravitational acceleration, z_b is the basal topography elevation and P_w is the water pressure in a subglacial channel. For modelling purposes, knowing the water pressures in a subglacial channel network requires a relatively comprehensive combination of physical formulas, of which several variables will be unknown and have to be estimated, introducing large potential for errors. The water pressure can however instead be simplified by stating that the water pressure in a subglacial drainage system will be equivalent to the pressure exerted by the ice above the channel. The assumption in this is that the subglacial drainage channel is filled completely and continuously. The water pressure can therefore be described through the pressure exerted by the ice above the subglacial channel, which gives this modified equation:

$$\phi = \rho_w \cdot g \cdot z_b + \rho_i \cdot g \cdot z_i \tag{2}$$

where ρ_i is the density of ice and z_i is the ice thickness above the channel. Thereby, the water pressure is simplified, returning the hydraulic potential in pressure units. The equation can however also be rearranged to represent the hydraulic head in terms of water column height, giving the following equation:

$$H = z_b + z_i \cdot \frac{\rho_i}{\rho_w} \tag{3}$$

Shreve (1972) also noted that, even if this formula is set up for a subglacial drainage channel, it can be used for calculations throughout the bed of the ice sheet if enough care is taken. This has resulted in the formula above being widely used to estimate hydraulic potential beneath a wide variety of glaciers, from which in turn probable drainage channel paths can be calculated, as will be described later.

Several authors investigated the initial assumption of the formulas set up by Shreve (1972). The initial assumption that the water pressure in subglacial channels is equal to the ice overburden pressure was tested in field experiments through pressure gauges situated in drainage channels. The water pressure in subglacial channels were found to fluctuate heavily throughout each season (Engelhardt and Kamb, 1997; Kamb, 2001; Wright et al., 2016). These deviations from the idealised situation can be quantified through a so-called flotation factor, or flotation ratio. The flotation factor is defined as the ratio between the subglacial water pressure and ice overburden pressure

(Clarke, 2005). It is a dimensionless, empirical number which is added to the water pressure part of the hydraulic head equation:

$$H = z_b + F \cdot z_i \cdot \frac{\rho_i}{\rho_w} \tag{4}$$

For use in ice sheet modelling over several seasons, the flotation factor represents an average fill height of the subglacial channels beneath the ice over time. Different studies have made different assessments of realistic values to use for ice sheet modelling over long time periods. In models of the hydrology of the present-day Antarctic ice sheet (Livingstone et al., 2013a) and the last North American ice sheet (Livingstone et al., 2013b), a flotation factor of 1 was chosen. This was justified through in situ measurements by (Kamb, 2001) showing average pressure ratios of between 0.95 and 1, and it was therefore deemed satisfactory to use a flotation factor of 1 for purposes of modelling ice sheets over large time spans.

A model of the subglacial hydrology of the Fennoscandian ice sheet by Shackleton et al. (2018) instead decided to use a factor of 0.925. This study used findings from several in-situ studies that had been published since Livingstone et al. (2013a,b) as a basis for this decision. Shackleton et al. (2018) averaged in situ measurements of subglacial water pressures by four different studies and calculated a mean flotation factor value of 0.9241. Shackleton et al. (2018) further justified the choice of flotation factor by modelled findings in studies by Banwell et al. (2013) and Lindbäck et al. (2015) showing that a factor of 0.925 was optimal for the hydraulic modelling of ice sheets over more than one season. A modelling sensitivity analysis surrounding the flotation factor in the study by Shackleton et al. (2018) found that the flotation factor was a sensitive parameter, but that 0.925 was an optimal value. Since this study by Shackleton et al. (2018) includes references to a large amount of the latest research on the subject, this study will also adopt an flotation factor of 0.925. To test the sensitivity of this parameter, this study will however also test other flotation factors briefly.

By calculating the hydraulic head over a large area of the landscape, it is also possible to calculate probable flow routes of the water and probable areas where water would have collected under the ice. As the calculated hydraulic head can be visualised like a pressure "landscape" that the water follows, just like rivers follow the minima of the present day topography, possible flow routes and subglacial lakes can be calculated using simple algorithms designed for above-ground hydrological calculation.

To calculate the flow paths of probable flow channels, two algorithms were applied to the raster grid. Firstly, a flow routing algorithm was applied to every cell of the raster. Several algorithms can be used to calculate the flow routing, but the simplest and most widely used calculates the gradient from one cell to all its surrounding cells, saving the direction with the highest gradient as the direction water will flow in the output raster. This gives a grid of the area with directions that water is calculated to choose from each of the cells. From this, a flow accumulation algorithm can be applied. This algorithm calculates flow paths from the directions supplied by the first algorithm, calculating how many cells flow into any given cell. This then gives flow paths across the whole grid, with every grid cell having a flow path assigned to it. In addition, a threshold value of how many cells must drain into a stream is set, acting as a minimum river "size" to be displayed in the output. From this, drainage basins can also be calculated using an algorithm that groups all cells that drain into a certain stream together and visualises these cells as one area.

However, the flow accumulation algorithm cannot handle so-called "sinks" in a raster grid. A sink in a raster grid is a cell that is surrounded by cells with higher values on all sides, i.e. a cell with all flow directions calculated by the flow direction algorithm pointing towards it. This causes stream paths calculated by the flow accumulation algorithm to stop once they reach a "sink" cell (or group of such cells), as there is no flow direction exiting the cell, suddenly causing calculated streams to end. As an analogy to a real-life landscape, if an area is lower than all its surrounding areas, normally water would collect in this area, forming a lake which covers all lower-lying cells. The same approach can be used before calculating flow paths with a flow accumulation algorithm, preventing any streams from suddenly ending in the middle of the raster grid. An algorithm for "filling" such sink cells and areas can be applied to the raster grid before the flow accumulation process, filling any sink areas so that the flow accumulation can be calculated realistically.

When modelling subglacial hydrology, these sinks represent possible positions of subglacial lakes, as in reality, water would be dammed up in areas which have lower water pressures than all surrounding areas of a raster grid. In contrast to normal hydrological modelling, this step is not just a pre-processing step used to correct any errors in the landscape DEM used, but a separate method for finding subglacial lake positions. An additional method for identifying where the subglacial bed may be affected/influenced by water is to check where there are areas of no gradient between raster grid cells. This approach is described by Clarke (2005), who defined the so-called "ponding condition" as areas where $\nabla H = 0$, i.e. where there is no gradient of the hydraulic head. If this ponding condition is applied to a raster grid of the hydraulic head where sinks are already filled in by an algorithm, all identified sink areas would also show as areas where water would not have a gradient, and therefore be areas of ponding. In this study both an algorithm for filling sinks as well as a modified ponding condition was used to identify areas of water presence at the glacial bed. As this study is not just interested in identifying areas where water is either dammed up or there is absolutely no water, but also in areas where there may be larger amounts of slow-flowing water, the ponding condition is modified to identify areas where the head gradient is below a certain threshold. This modified method can therefore identify areas of slow water flow, rather than just areas where there is "still" water where water is dammed completely.

3.3.2 Data

As mentioned in Section 3.3.1, the flotation factor and the properties of ice and water are considered constant in space and time in this model. The two variables of the hydraulic head equation (Equation 4) where spatial variation is important however, are the basal topography and the ice sheet thickness. As there are no physical records of either of these variables, they have to be estimated using models and indirect indications and data. Estimates of both of these variables are acquired from an existing ice sheet model of the last Fennoscandian glaciation. The model by Patton et al. (2016, 2017) models the extent, shape, flow and dynamics of the Fennoscandian ice sheet from 30 kya to 8 kya.

Ice sheet thickness, basal topography elevation and initial topography elevation data from this ice sheet model was kindly provided by Henry Patton from the University of Tromsø. This data is provided as point data in a 10x10 km grid oriented approximately northeast. Gridded data is provided for basal topography elevation and ice sheet thickness in the time frame of 25 kya to 8 kya in 500 year time steps, giving a total of 34 time steps for each dataset.

As one of the goals with this model is to downscale this ice thickness and basal topography elevation data from the 10x10km grid provided to a finer grid size, additional data for the downscaling process is needed. Downscaling is done as the aim of the model is to yield insights at a high enough resolution to investigate ribbed moraine fields and associated landforms as well as the possible development of the subglacial water flow, which would not be visible at such a high grid size.

The variable from the hydraulic head equation (Equation 4) which can be acquired at a finer grid resolution is the basal topography, which for modelling purposes is assumed to be equivalent to the present-day topography corrected for the isostatic adjustment. A gridded DEM of the present-day topography can therefore be used as a basis for downscaling of the ice sheet data. A DEM at a grid resolution of 100x100 meters is used in the model. Therefore, the DEM dataset "DTM50" (Table 2) is resampled to a 100x100 meter configuration and used as a basis for downscaling the other datasets. The grid size and properties of this new 100m resolution DEM (from now on described as DTM100) will be used as a standard for all output data of the model.

3.3.3 Implementation and analysis

To be able to model the hydraulic head at the desired resolution from the low resolution ice height and bed elevation, two main pre-processing steps were undertaken to prepare this data for modelling. The pre-processing consisted of simultaneously re-aligning the ice sheet data to a target grid orientation as well as downscaling the data from a 10x10km resolution to a 100x100m resolution (Figure 4).

To use the DTM100 dataset as a basis for downscaling the ice sheet data as mentioned in the section above, the 10x10km basal topography elevation was subtracted from the 10x10km initial topography elevation for each of the 34 time steps. This gave a 10x10km gridded dataset of the isostatic depression of the landscape for each time step used in the model by Patton et al. (2016, 2017). As the isostatic depression of the crust is a gradual and large-scale phenomenon, no sudden changes of the depression in space are expected (Benn and Evans, 2010). In the same style of proceedings, the ice sheet thickness is assumed to vary with the basal topography, whilst the ice sheet surface elevation is assumed to be smooth, with only gradual changes (Shackleton et al., 2018). These resulting datasets were therefore much more suitable for downscaling using interpolation methods than the datasets originally acquired from the ice sheet model. The 10x10km ice sheet thickness dataset was added to the 10x10km basal topography elevation data for each of the 34 time steps, giving a 10x10km ice sheet elevation dataset.

Both the 10x10km ice sheet elevation and the 10x10km isostatic depression datasets could then be downscaled using an interpolation method without adding much uncertainty. For this downscaling, the MATLAB interpolation function "ScatteredInterpolant" was used. This function is normally

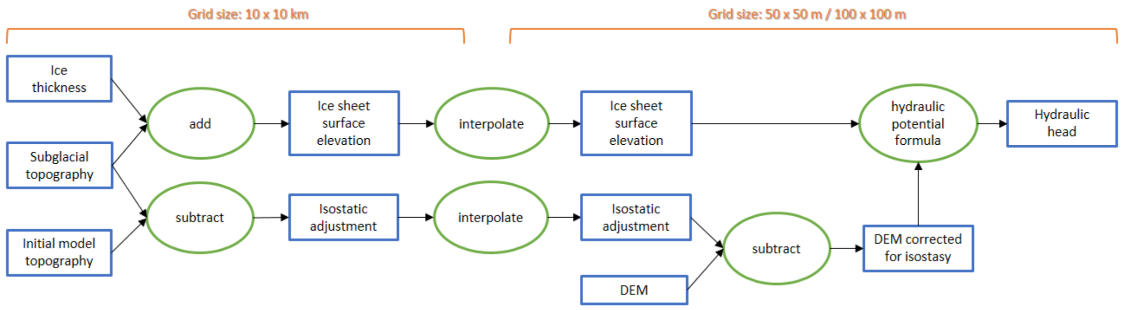


Figure 4: *Flow diagram of the pre-processing leading up to the hydraulic head calculation. Blue boxes represent raster datasets, green ovals represent calculations. Note the orange markers showing the grid sizes of the blue raster datasets.*

used for 2D- or 3D-interpolation of scattered point data, and does not require the input and output data to have the same grid orientation, therefore allowing a rotation of the grid in addition to interpolation between two grid sizes. The function uses a linear interpolation method as default, which is acceptable for our data due to the presumed smoothness of the two datasets which will be interpolated, as mentioned above. The "ScatteredInterpolant" function was used on all time steps of both the 10x10km ice sheet elevation and the 10x10km isostatic depression datasets, interpolating them down to the same grid size and a grid orientation as the DTM100 dataset, which is the coordinate system UTM32/33N, grid size of 100 meters (Figure 4).

Next, the ice sheet elevation and isostatic depression datasets, now available in a 100x100 meter UTM32N/33N raster grid, could be used to calculate the required input parameters of the hydraulic head equation (Equation 4), which are the basal topography elevation and the ice thickness. Therefore, the 100x100 meter isostatic depression dataset was subtracted from the detailed DTM100 dataset to give a new basal topography elevation dataset with 100x100 meter resolution. Then this new basal topography elevation dataset was subtracted from the 100x100m ice sheet surface elevation dataset to give a new 100x100m ice thickness dataset. Both new datasets were then included into the hydraulic head equation (Equation 4) to give a gridded hydraulic head dataset at 100x100m grid size and the UTM32/33N coordinate system (Figure 4). The densities of ice and water were assumed to be constant in these calculations, with values of 917 kg/m^3 used for the density of ice and 1000 kg/m^3 for water.

After calculating the hydraulic head, the next steps focussed on calculating water-specific parameters, attempting to establish positions of subglacial lakes, streams and rivers. To calculate these parameters from the subglacial hydraulic head raster grid, pre-written functions from the MATLAB toolbox "TopoToolbox" were utilised (Schwanghart and Kuhn, 2010; Schwanghart and Scherler, 2014). Using this function collection, sink filling, flow routing, flow accumulation, and several other hydraulic analyses can be run on raster data.

The first calculation step after the hydraulic head had been calculated was to apply the function "fillsinks" to the hydraulic head raster, which fills any sinks in the raster (see Section 3.3.1). After the fillsinks function had been applied, the gradient of the hydraulic head was calculated in each direction of the raster using the MATLAB function "gradient". From these two directional gradients (in north-south and east-west direction, respectively) a directionless gradient is calculated. As the two directional gradients in effect show vector coordinates in north-south and east-west direction, this was achieved by taking the square root of the sum of the gradients squared (Pythagoras). The resulting gradient now represents the length of the gradient vector for each grid cell of the hydraulic head. The process of filling sinks in the hydraulic head raster as well as calculating a new raster file with the gradient of the hydraulic head was repeated for all time steps.

The hydraulic head raster was also used to calculate possible subglacial stream paths using the TopoToolbox module. This was achieved by first converting the hydraulic head to a flow object (FLOWobj) which calculates the flow routing for the hydraulic head raster, before applying the flow accumulation function “flowacc”. The resulting outputs were then exported to a GeoTIFF format, using the same geographic reference information as the DTM50 DEM raster, and the procedure is repeated for all time steps.

To analyse the modelled hydraulic gradient and compare it to the areas mapped in the regional mapping, the resulting gradient raster DEMs were added to QGIS. By overlaying the mapped fields and areas of low hydraulic gradient, the two datasets can be manually compared. In addition, the calculated gradient data can also be compared to the mapped areas using quantitative methods. Using the zonal statistics tool in QGIS, the mean value of the hydraulic gradient raster as covered by a certain polygon can be calculated. This is done for all mapped polygons of the 3 landform area categories mentioned in Section 3.1.2. After the calculation is complete, the mean hydraulic gradient value of each mapped polygon is plotted in a box plot in MATLAB and sorted by category. This gives 3 box plots showing the distribution of the mean gradient values of all mapped areas. In addition, the distribution of the hydraulic gradient values of the whole regional area are also plotted in a box plot to provide a basis for comparing the distributions of the different mapped areas against the regional study area as a whole.

3.3.4 Uncertainties and limitations

Hydraulic modelling of ice sheets as implemented in this study has several uncertainties and error possibilities associated with it. These can be roughly divided into uncertainties in the physical approximations underlying the model and uncertainties in the input data.

A clear uncertainty in the physically based formula by Shreve (1972) is the already described determination of a fitting flotation factor (see Section 3.3.1). In addition, it is presumed that the ice sheets of the last ice age had varying temperature conditions at the glacial bed with mountain areas assumed to be mostly cold-based and therefore de-watered through parts of the glaciation. This is not taken into account in this model, as no certain extent of cold-based areas under the Fennoscandian ice sheet exists to this date. This study’s model must therefore be viewed in light of recent research regarding cold ice extent under the ice sheet, especially as both the regional and detailed study areas cover mountainous areas and high-mountain plateaus that are likely to have had cold-based conditions under part of the last glaciation (Olsen et al., 2013).

There are also several uncertainties which can originate from the input data. The largest uncertainty is in the ice thickness data, which is acquired from ice sheet reconstructions based on ice sheet models. The ice sheet model used as a basis for the model of subglacial hydraulics in this study is a physically based model (Patton et al., 2016), and the ice thickness calculated by this ice sheet model is therefore directly dependant on the accuracy of the physical relations and constraints that form the basis of this model. This in turn means that this study's model of the subglacial hydraulic conditions is highly dependant on the quality and accuracy of the underlying ice sheet model.

However, this study is only interested in ice height elevation data for a small part of the centre of the ice sheet where the ice is suspected to be relatively flat and smooth. This is well-reflected in the ice heights from the ice sheet model by Patton et al. (2016, 2017). As the ice surface gradient is one of the main controlling factors on the subglacial hydraulic gradient (Shackleton et al., 2018), the ice height data is therefore not expected to introduce much error into the model of the subglacial hydrology. The uncertainties of the ice height data is one that needs to be kept in mind, but we can still model a useful glacial hydrology for our area as long as the ice elevation is smooth and gradual.

The other main uncertainties that can originate from the input data are related to the glacial bed elevation data. As we are using a high-resolution DEM for the glacial bed in relation to the down-scaled low-resolution ice thickness data, the ice front will not be detailed and realistic. This is due to the level of detail of the ice height data not increasing during downscaling of the dataset. The DEM used as a basal topography also includes some features which are not ideal for use as a basal topography in the form of countless flat lake surfaces which would have of course been filled with ice during the last ice age. As lake bathymetry data is not available for almost any lakes in our regional study area, this is also not something that can realistically be corrected before modelling. Therefore, the presence of completely flat lake surfaces in the DEM will have to be taken into account when analysing the resulting hydraulic head and hydraulic gradient. The DEM dataset of the present-day topography will also include sedimentary landforms and landscape features deposited during the glaciation of the last ice age, such as glaciofluvial deltas for example. As there is no simple way of removing these from the present-day DEM used as input data, this needs to be taken into account when viewing the data.

In addition, the resolution of the input DEM will affect the amount of detail that can be seen in the grids of the model results. At high spatial resolutions, the large amount of small changes in the DEM of the present-day topography will also create a large amount of changes in the hydraulic gradient. A resolution of 10x10m or 50x50m for example, available through the DEM datasets "DTM10" and "DTM50", would cause a large amount of noise in subsequent results when viewed at the scales of both the detailed and regional study areas. Such high resolutions would also add noise to subsequent processing steps, such as calculations of hydraulic gradient or of flow paths, reducing its applicability for subsequent analysis. In addition, processing times would be greatly increased due to the large increase in grid sizes throughout the whole modelling process. A grid size of 100 x 100 meters is therefore preferred in this study as it reduces both noise in the resulting grid and computation time, whilst still achieving considerably higher detail than previous studies such as Shackleton et al. (2018).

4 Results

4.1 Regional mapping

4.1.1 Observations from the map

The landform fields mapped in the regional study area are shown as polygons in Figure 5. Several general observations can be drawn from the polygons of this regional map. Firstly, ribbed moraine fields and hummocky/ribbed fields are present in many sizes and forms, and are often found in valleys and lower-lying terrain. Long trails of ribbed moraine and/or hummocky/ribbed fields are found in relatively narrow valleys, forming ribbed moraine ribbons and tracks, as also observed by Dunlop and Clark (2006). Hummocky/ribbed fields always cover more area than the ribbed moraine fields contained in them. Following the field definitions used during mapping (Section 3.1.2), this indicates that all ribbed moraine fields have some degree of hummocks and/or unclear ribbed morphology around them. Ribbed moraine fields sometimes covering large shares of the hummocky/ribbed fields, like in the southeast of the study area near Hamar, and sometimes ribbed moraine fields are not present in hummocky/ribbed fields at all. Streamlined fields are mostly larger than the hummocky/ribbed fields, and are seemingly often present at higher elevations than neighbouring hummocky/ribbed fields and ribbed moraine fields. There is often a close spatial connection between the streamlined fields and the hummocky/ribbed fields, with neighbouring areas often having common borders. Ribbed moraine fields and streamlined fields however never share borders.

Several general observations were also made during the mapping process. These are observations that were noted in and around many of the mapped fields, and are therefore too detailed to be visible in Figure 5. These additional observations are listed below.

- Ribbed moraine ridges have many different morphologies and sizes throughout the regional study area. Even ribbed moraines in fields of close proximity often have widely varying forms, sizes and wavelengths. Ribbed moraine fields also have different amounts of hummocks in their fields, and different degrees of streamlining.
- There are sometimes smooth transitions between hummocky/ribbed fields and streamlined fields and features. Different transitions are visible; sometimes at the sides of hummocky/ribbed fields or sometimes at the start or end of fields. Sporadic streamlined features are also found inside the hummocky/ribbed fields, often overprinting ridges or hummocks. No specific spatial patterns for these transitions were identified during mapping.
- Very often, ribbed moraine ridges were found only on the valley edges of narrow glacial valleys. These ribbed moraines often transition into what seems like water channels coming down the valley sides. In addition, the middle of the valley is normally clearly impacted by erosion from present-day rivers, cutting the ribbed moraine fields in half.
- On extensive flat areas as well as in and around ribbed moraine and hummocky/ribbed fields, it is common to find a lot of glaciofluvial traces. Both eskers and fluvial channels flowing on, between and around ribbed moraines and hummocks can be observed. This can be seen

to alter several ribbed moraine ridges, with the consequence that there is often a smooth transition between typical ribbed areas and glacially-induced water channels. The water flow may have been both subglacial and/or proglacial, but it is not caused by recent processes.

- There are some areas in the regional study area that have a high influence of bedrock outcrops, with smaller till surfaces in between these. One of the largest areas with these characteristics are the hills between Begnadalen, Randfjorden and Etnedalen in the southern end of the study area, with similar types of areas found in the southwestern and northeastern edges of the study area. In these areas, the till surfaces between the countless bedrock outcrops very often contain streamlined features and also sometimes hummocky or ribbed features. The bedrock outcrops also contain geological lineations however, with layering, faults and folds visible. This results in a hard-to-define mix of geological features with traces of subglacial landforms such as flutes, hummocks, ribbed features and drumlins in between them, making these areas very challenging to classify into the defined categories. As the uncertainty linked to classifying these areas was deemed to be too high to achieve a trustworthy mapping result, these mixed areas were omitted from the map.

4.1.2 Comparison to previous map of ribbed moraine distribution

The last comprehensive map of ribbed moraine distribution in southern Norway was compiled by Sollid and Sørbel (1994). Their published map visualisation is not very detailed in today's mapping standards. Figure 6 compares the polygons of the ribbed moraine fields and hummocky/ribbed fields mapped in this study to the map compiled by Sollid and Sørbel (1994). The digitised map from the 1994 article was imported to a map program and was georeferenced approximately. This georeferencing is somewhat uncertain, and deviations from the optimal overlap between the image and the map in the background should be expected. Note that Sollid and Sørbel use ribbed ridge symbols to mark ribbed moraine fields, and that uncertainties due to symbology should be taken into account when observing the comparison.

When observing the comparison, large differences can be immediately noticed (Figure 6). In the southern part of the study area, almost none of the fields mapped in this study are present in the map by Sollid and Sørbel (1994). The largest differences can be seen on both sides of Lake Mjøsa. On the east side of the lake, the mapped areas around the greater Hamar area and also the mapped areas up towards Moelv are not included in the map by Sollid and Sørbel (1994). On the west side of the lake, this also applies to the mapped areas around Gjøvik and down to the southern edge of the study area. Near Dokka and Torpa there is one marked field in the map by Sollid and Sørbel (1994), but from here and towards the northern end of the Mjøsa Lake, several more areas were found in this study that were not included in the older map. In addition, the area around Rena and both north and south in that valley have mapped ribbed and hummocky areas in this study, but not in the older map. On the other hand, there are two marked areas in the map by Sollid and Sørbel (1994) on just west of this area, which are not mapped in this study. A small area around Heidalen in the northwest of the study area is also not included into the map by Sollid and Sørbel (1994), along with several areas dotted around the study area.

On the other hand, the area surrounding and including the detailed study area (around the Langsua

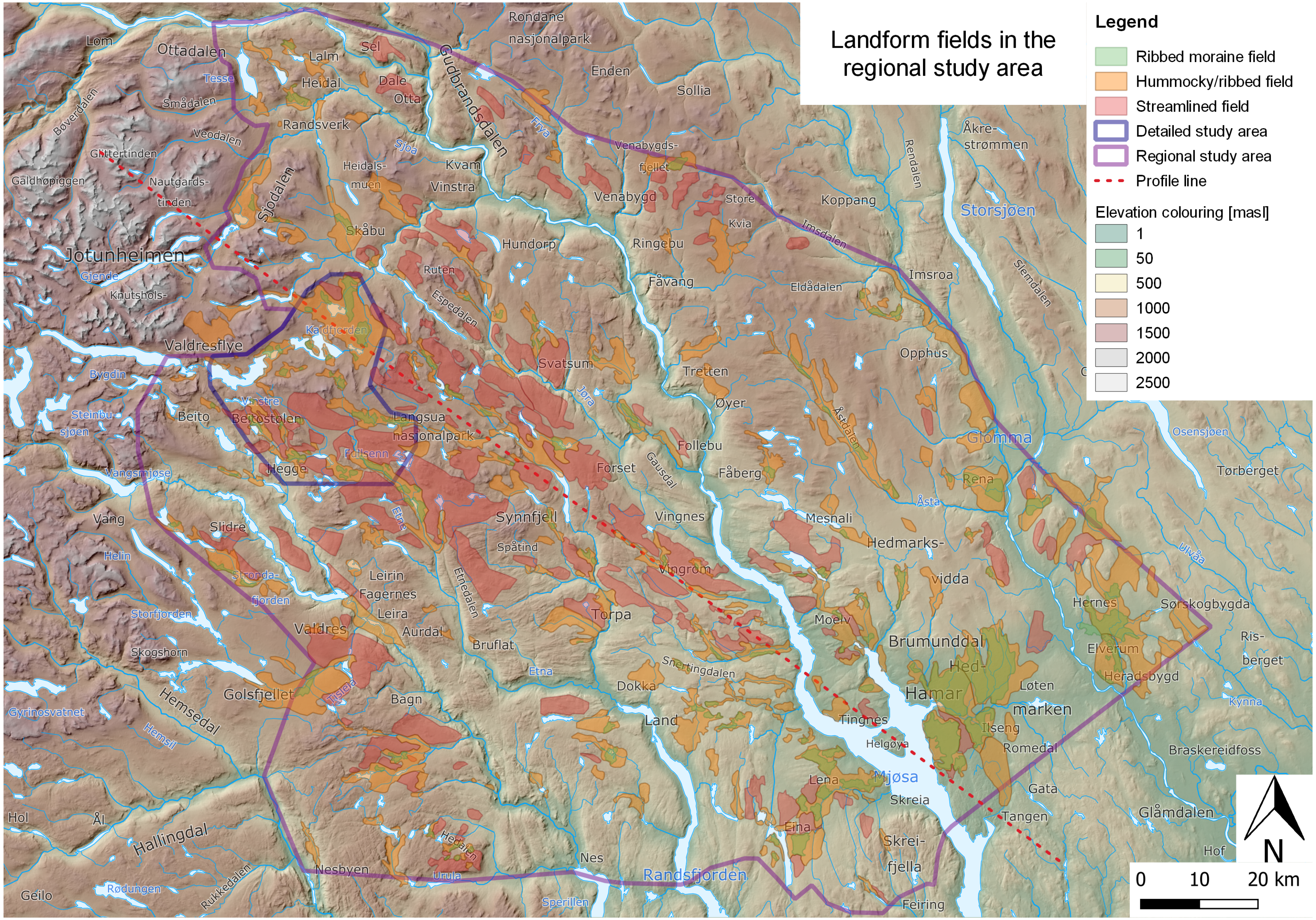


Figure 5: *Map of landform fields identified in the regional study area. In addition, the transect line along which the field elevations were plotted by (Figure 7) is also shown. The background DEM with elevation colouring is the DEM dataset "DTM10" form the Norwegian Mapping Authority (see Table 2). The place names, rivers and lakes in the background are part of the dataset "Norgeskart" by the Norwegian Mapping Authority (see Table 2).*

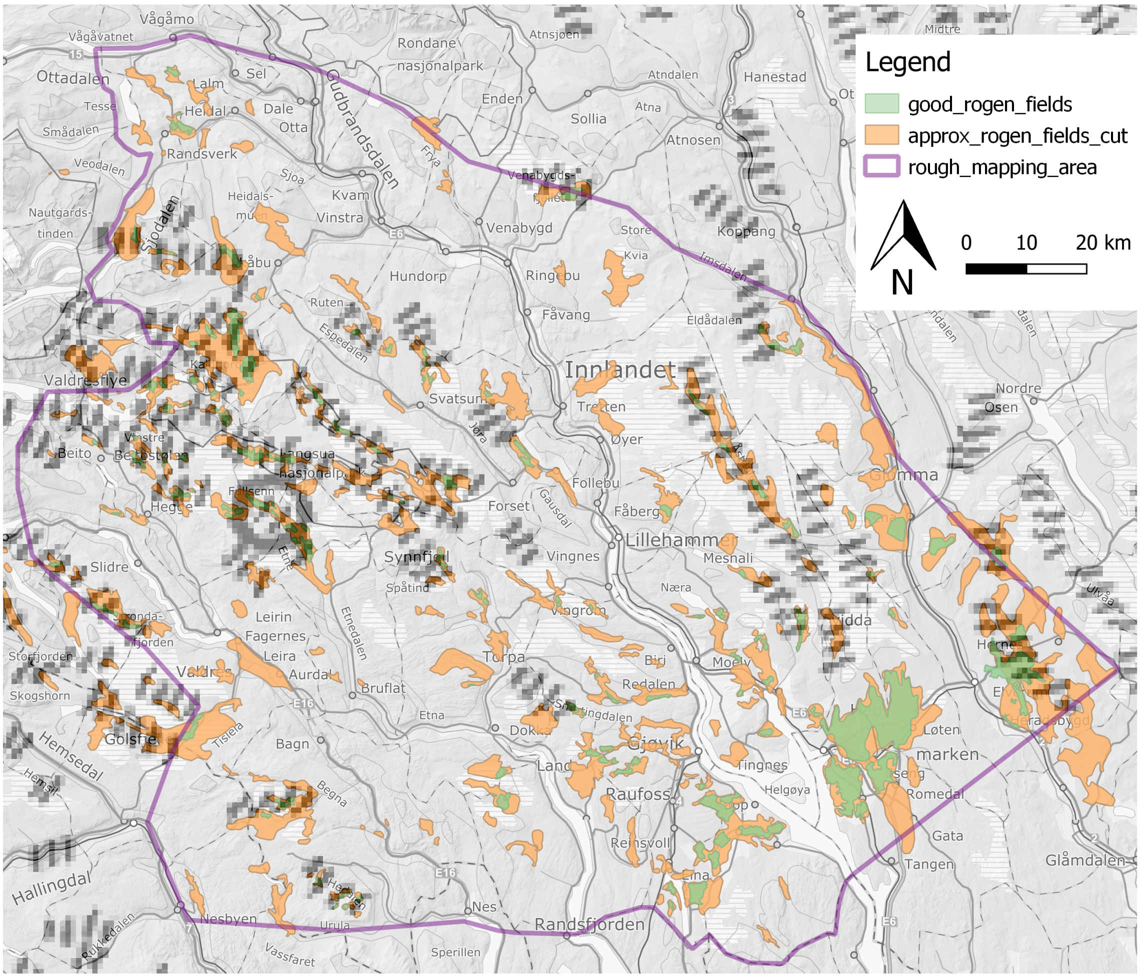


Figure 6: *Map showing the ribbed moraine fields and hummocky/ribbed fields mapped in this study in contrast to the ribbed moraine fields shown in Sollid and Sørbel (1994). Ribbed moraien fields are marked with groups of black lines in the map compiled by Sollid and Sørbel (1994) which is overlain over the regional study area. The background map is a greyscale version of the map dataset "Norgeskart" by the Norwegian Mapping Authority (see Table 2).*

national park) is extensively included in the map by Sollid and Sørbel (1994), as well as the Huldreheimen, Synnfjell, Valdresflye and Sjodalen areas. These also fit well with the approximate hummocky/ribbed fields mapped in this study.

4.1.3 Distribution of areas by elevation

One step in evaluating the relation of ribbed moraines and associated landforms was determining in what elevation intervals the mapped landform fields occur. Figure 7 shows the plot of the median, maximum and minimum elevations of each mapped field polygon. Ribbed moraine fields (Figure 7A) consistently cover only small elevation intervals, with a few exceptions. Only about 5 ribbed moraine fields cover an elevation interval of more than 200 meters, with many covering less than 50 meters in elevation.

In contrast, hummocky/ribbed fields (Figure 7B) cover much larger elevation intervals than the ribbed moraine fields, with many fields covering elevation intervals of more than 200 meters, and even several fields covering more than 500 meters. The same applies to streamlined fields (Figure 7C), which also cover significantly larger elevation intervals than the ribbed moraine fields. Streamlined fields also cover slightly larger elevation intervals than hummocky/ribbed fields. Streamlined fields have a large range of elevation intervals can be seen to cover elevation intervals of everything between 40 and 650 meters.

The differences in elevation intervals between the three field types is also very apparent when the average elevation interval is calculated. Ribbed moraine fields were found to have and average elevation interval of 72 meters, whilst hummocky/ribbed fields and streamlined fields have elevation intervals of 175 and 260 meters respectively.

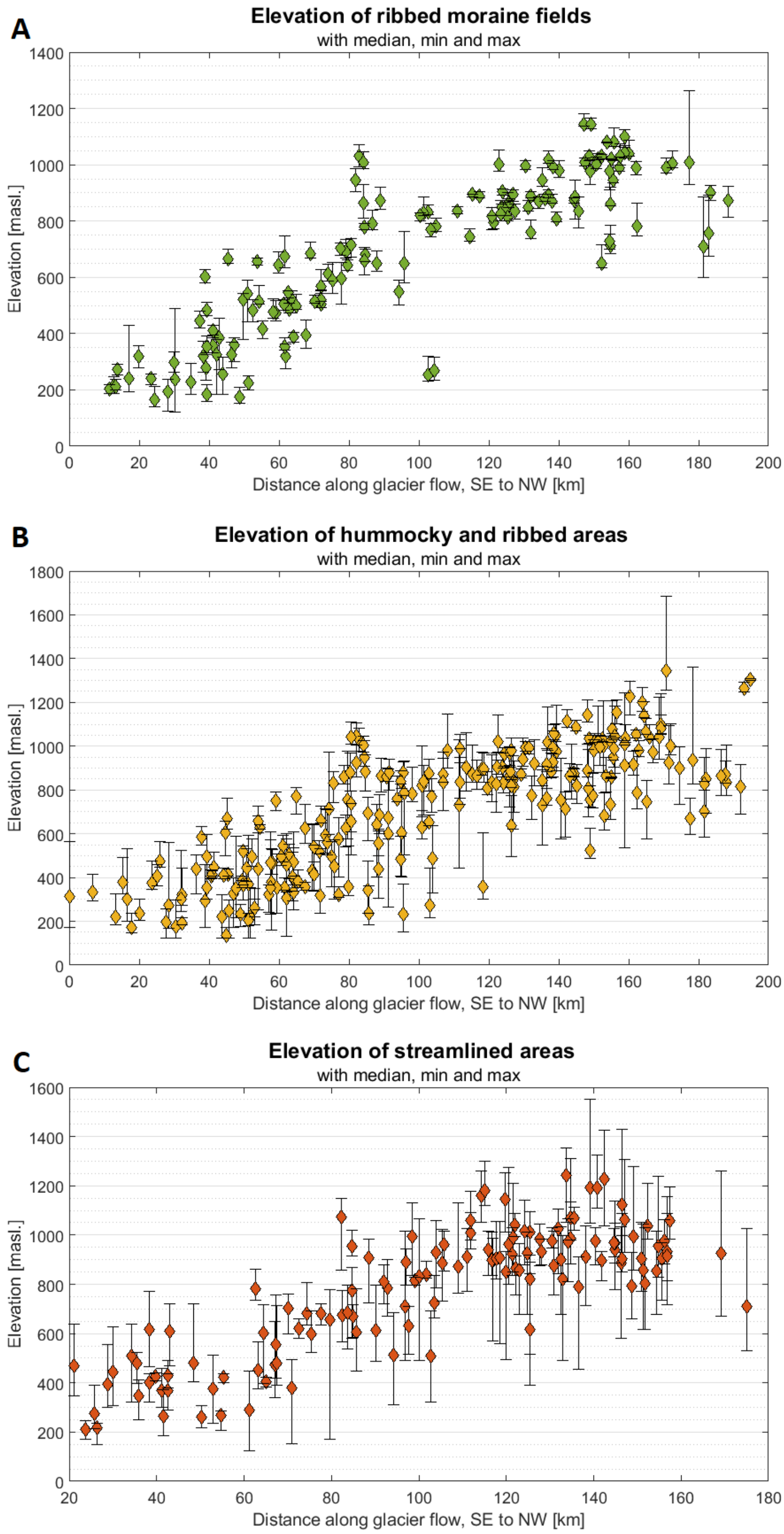


Figure 7: *Plot of the median, minimum and maximum elevation for the 3 landform categories mapped in the regional study area (A - ribbed moraine fields, B - Hummocky/ribbed areas, C - Streamlined areas). The elevation values are plotted for each mapped field polygon along a 200km profile through the study area.*

4.2 Hydraulic modelling

4.2.1 Hydraulic gradient trends over time

The hydraulic gradient of the larger regional study area (Figure 8A), shows a very even trend through the time steps. There is little change between the time steps, except for slightly higher gradient values for the 11 kya time step. The average gradient for the majority of the time steps modelled is around 0.03 m/m (equal to a 3% grade). The three other box plots of the hydraulic gradient in the mapped landform field polygons of the regional mapping (Figure 8A,B,C) also shows a stable gradient development through the time steps. The time steps have 11 kya and 12 kya have slightly raised gradient values also in these plots.

Ribbed moraine fields are situated in areas with significantly lower hydraulic gradient values than the other two mapped field types. In relation to the box plot of the whole regional mapping area, the ribbed moraine fields consistently have a median gradient 0.01-0.015 m/m less than the median of the whole area. Even though this only constitutes a difference in slope of 1-1,5%, this is still significant considering the interquartile range of only 4% for the regional study area. In addition, the median can be seen to approximately follow the lower percentile of the regional study area, and all outliers are below the upper percentile of the regional study area, again confirming that the gradient values of the ribbed moraine fields are significantly lower than the average gradient in the regional area.

The mapped hummocky/ribbed fields and the streamlined fields both have higher medians and larger ranges than the ribbed moraine fields. The medians of the hummocky/ribbed fields and streamlined fields are also much closer to the median of the distribution of the regional study area in general. However, their distribution doesn't cover nearly as much gradient interval as the whole study area, which indicates that these landforms have a specific elevation interval where they are commonly found as well as elevation intervals where they are uncommon.

To summarise, the ribbed moraine fields show a consistently smaller spread of average gradient values than both the streamlined and hummocky/ribbed fields, and a consistently lower values in relation to the regioanls study area as a whole.

4.2.2 Hydraulic gradient across the regional study area

The hydraulic gradient raster map of the regional study area (Figure 9) shows unevenly spread areas of low hydraulic gradient throughout the landscape. Several areas show widespread low gradients, like the Hamar-Elverum area, Golsfjellet, an area south of Gjøvik and several other areas. Most of the landscape has widespread smaller patches of low gradient, whilst some parts of the landscape have very few areas of low gradient, such as around Bruflat and in the Vinstra-Otta-Heidal area. Most ribbed moraine fields can be seen to be situated in areas of low hydraulic gradient, though there are outliers, especially in the northern end of the study area.

Note that all present-day lakes also have low hydraulic gradients in this raster dataset. As mentioned in Section 3.3.4, this occurs due to the input DEM to the model not including lake

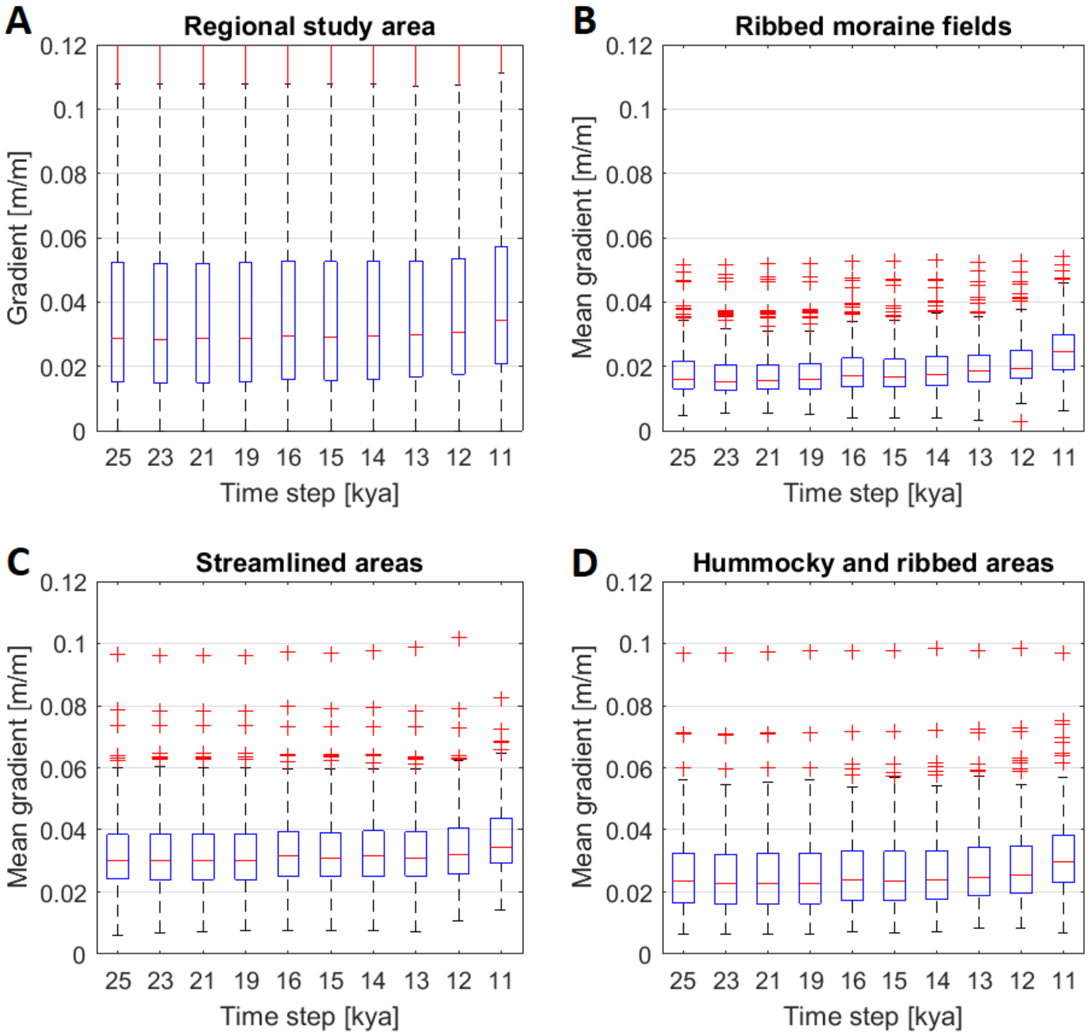


Figure 8: *Box plots of the modelled hydraulic gradient in the regional area over time. A shows the overall distribution of the hydraulic in the regional study area. B shows the hydraulic gradient in the mapped ribbed moraine fields of the regional study area. C and D show the same for streamlined and hummocky/ribbed fields respectively. The red lines represent the median value, the blue box represent the interquartile range spanning between the 25% and 75% quartile, the black dotted lines represent the whiskers (1.5 times interquartile range +/- quartile) and the red points show outliers.*

bathymetry, but rather the lake surfaces. This causes all lake areas to receive a low hydraulic gradient, as they are completely flat in the input data. The hydraulic gradient is not 0 at these positions however, due to the slope of the ice above. Areas where the hydraulic gradient is 0 represent areas where the model calculated and filled sinks, and therefore represent the suspected positions of subglacial lakes. Larger areas of 0 gradient can be found at a few prominent areas, such as in our detailed study area near Kaldfjorden and at 3-5 further positions to the north and northeast, as well as by Golsfjellet, near Reinsvoll in the south and in the Hamar-Elverum corridor.

4.2.3 Hydraulic gradient and flow paths across the detailed study area

The map of the hydraulic gradient and sinks in the detailed study area (Figure 10) shows a prominent sink by Kaldfjorden and Hersjøen. In addition, several sink areas that were not very visible in the regional view become visible in this detailed view, such as the southeastern edge of the Vinstre lake and at several spots by Trollåsen and towards Fjelldokka. Most ribbed moraine fields in the detailed study area can also be seen to be situated inside of areas of low gradients, though not in sink areas. The Yddeåne ribbed moraien field as well as some other small ribbed moraine fields have somewhat higher gradient values.

The modelled subglacial water flow paths in the detailed study area (Figure 11) shows subglacial drainage in 2 main directions. In the top half of the detailed study area the calculated flow direction can be seen to go from west to east. The flow follows a main flow path coming from the northwest of the study area and switching to a southeasterly by the eastern study area boundary. In the southern half of the study area the water can be seen to flow approximately southeast, with almost all streams originating from inside the study area.

Sinks and areas of low gradient stay stable in their position over time, but change in size. As a consequence, only the raster grid for the time step 16 kya is shown in this results section. The evolution of sinks and gradient over time can therefore be found in Appendix 1. Flow paths also change a limited amount over time, and also only the 16 kya time step is shown here. Modelled flow path evolution over time can be found in Appendix 2.

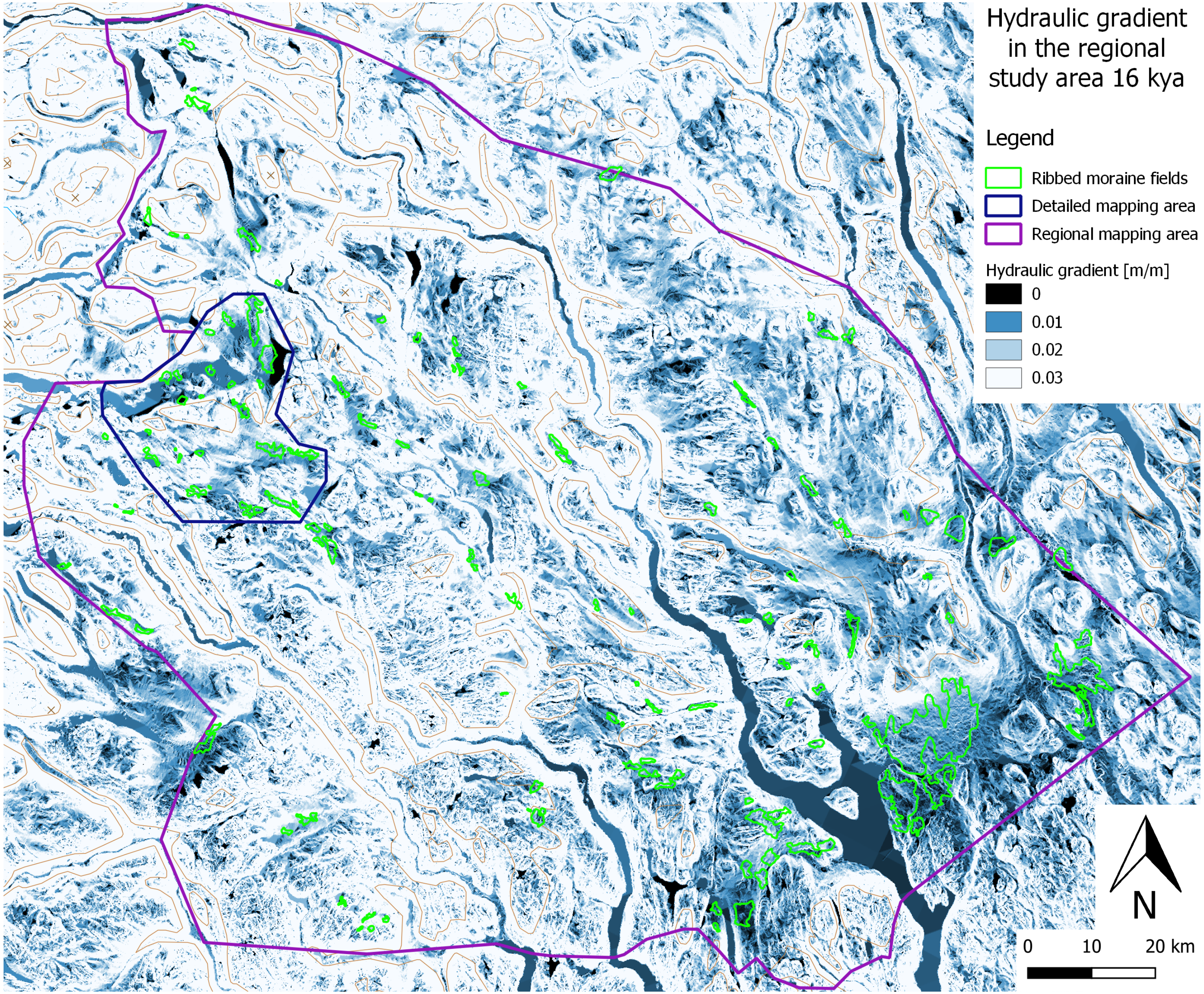


Figure 9: *Map showing areas of low hydraulic gradient for the modelled time step 16 kya in the regional study area. Ribbed moraine fields are also included for comparison. Note that areas where present-day lakes are situated do not have realistic hydraulic gradient values. The brown lines represent elevation contour lines at 500m intervals. The contour lines are part of the map dataset "Norgeskart" by the Norwegian Mapping Authority (see Table 2).*

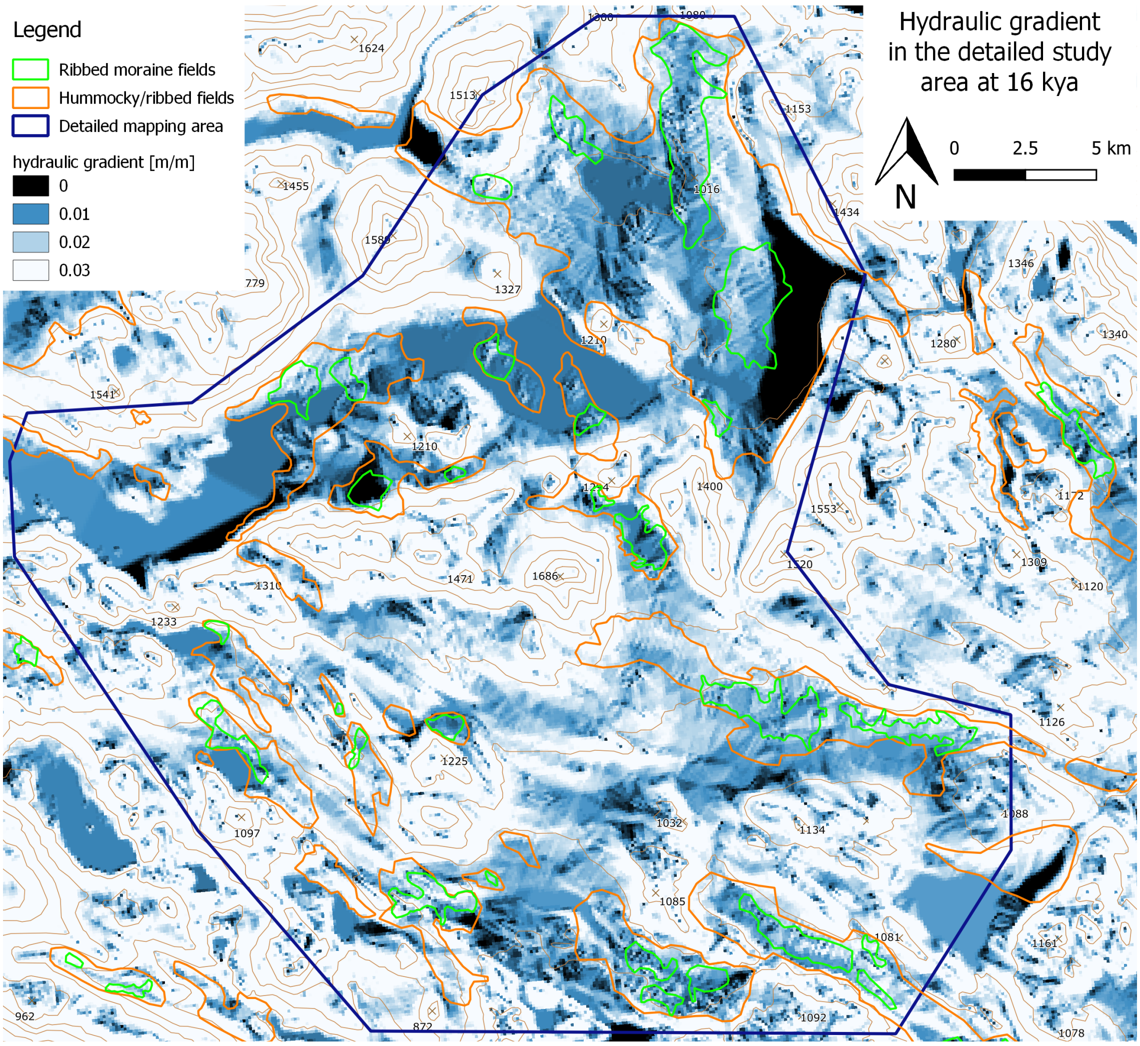


Figure 10: *Map showing areas of low hydraulic gradient for the modelled time step 16 kya in the detailed study area. Ribbed moraine fields and hummocky/ribbed fields are also included for comparison. Note that areas where present-day lakes are situated do not have realistic hydraulic gradient values. The brown lines represent elevation contour lines at 100m intervals. The contour lines and elevation points are part of the map dataset "Norgeskart" by the Norwegian Mapping Authority (see Table 2).*

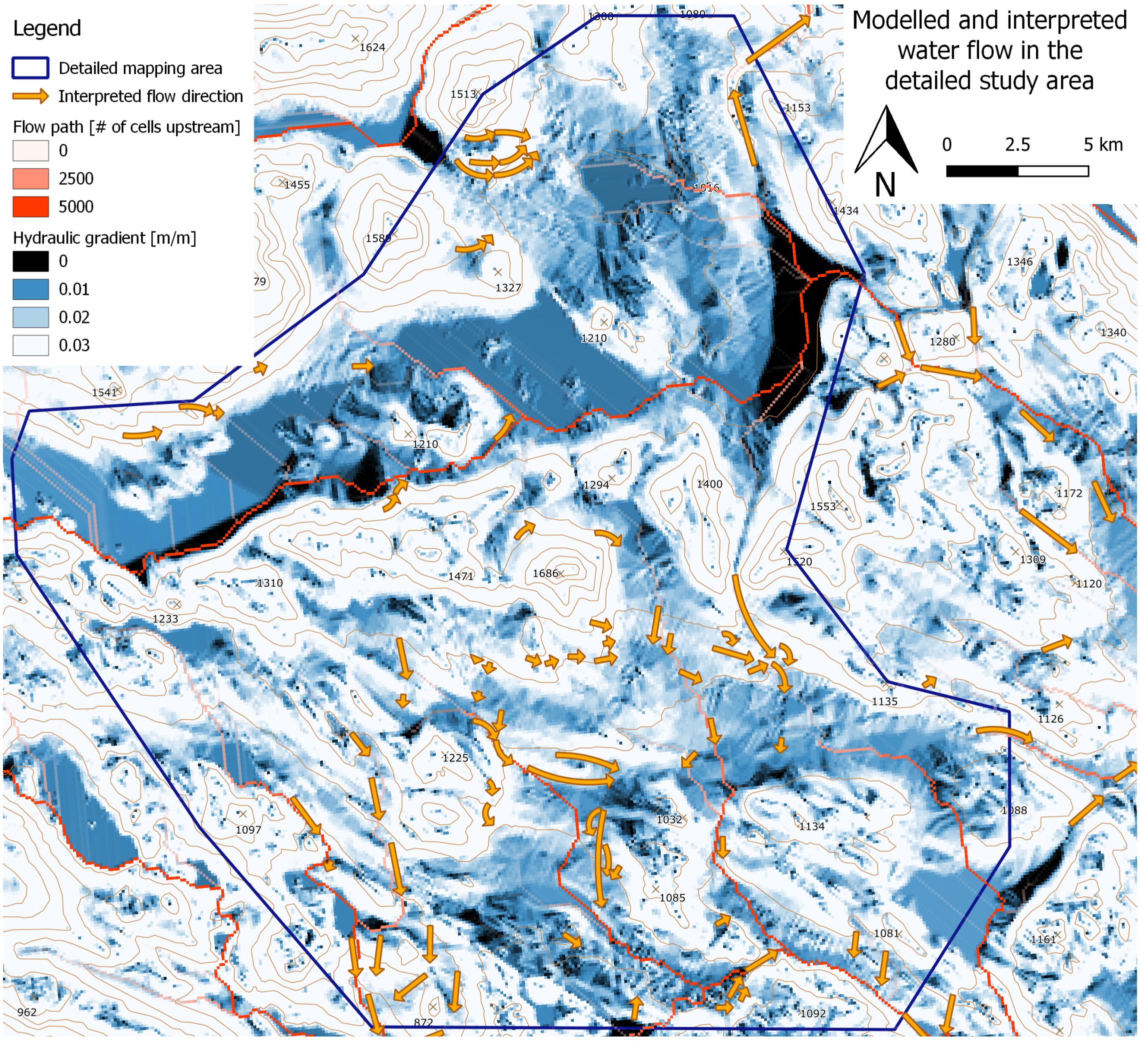


Figure 11: *Map showing areas of low hydraulic gradient as well as modelled and interpreted flow paths for subglacial drainage in the detailed study area. Modelled flow paths (in red) are calculated form the modelled hydraulic head of the time step 16 kya. The colour intensity indicates how many pixel cells the flow path drains. Interpreted flow paths are channel paths from the detailed maps (Figures 12, 13) that have been simplified for better understanding and have been assigned a interpreted direction (see Section 5.3.2). The contour lines and elevation points are part of the map dataset "Norgeskart" by the Norwegian Mapping Authority (see Table 2).*

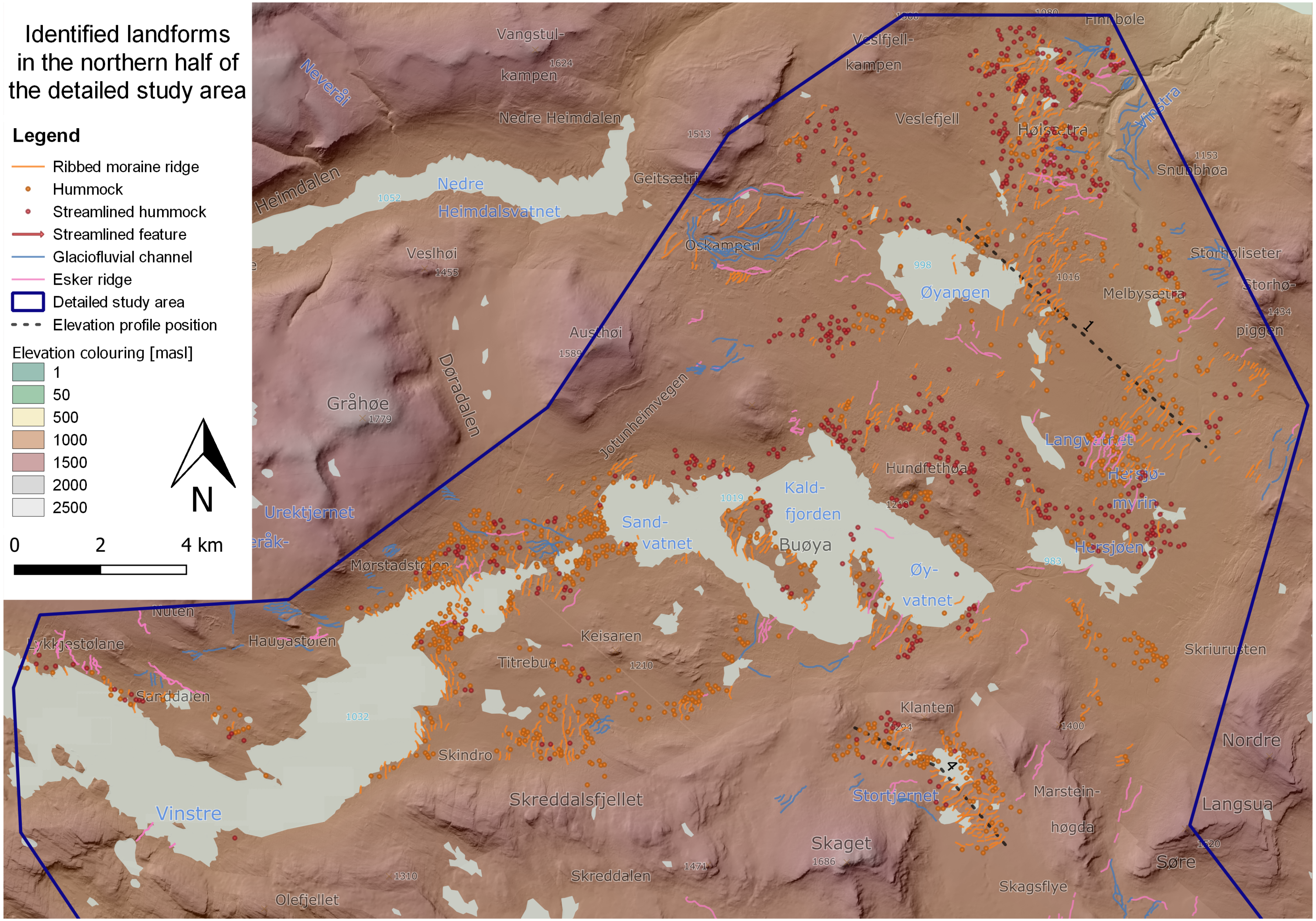


Figure 12: *Mapped landforms in the northern half of the detailed study area. The background is comprised of a hillshade of the DEM "DTM1", a hillshade and coloured version of the DEM "DTM10" as well as layers of names and lakes. The name and lakes layers are part of the dataset "Norgeskart" by the Norwegian Mapping Authority (see Table 2).*

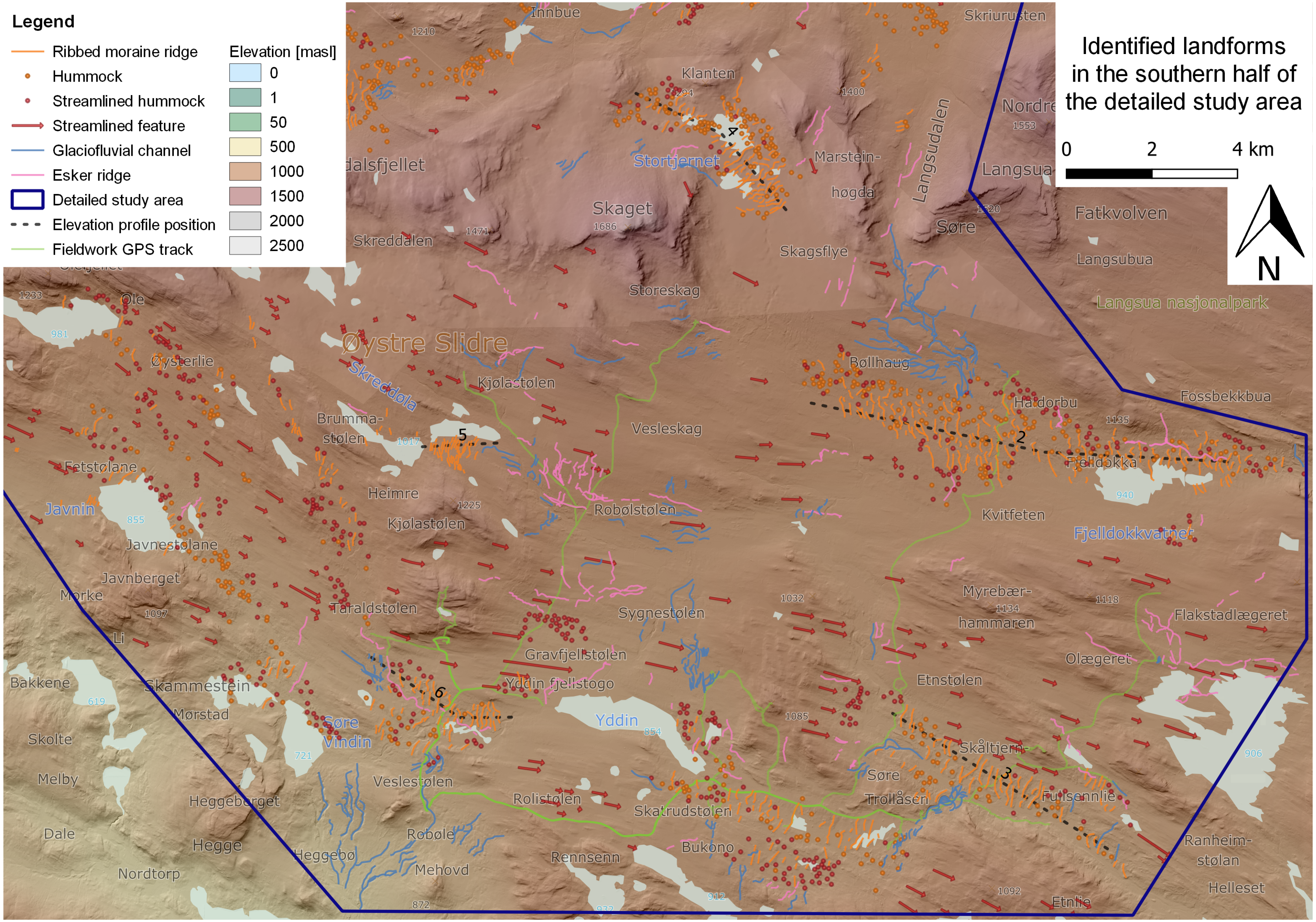


Figure 13: *Mapped landforms in the southern half of the detailed study area. Elevation profile transects and GPS tracks of the conducted fieldwork are also shown. The background is comprised of a hillshade of the DEM "DTM1", a hillshade and coloured version of the DEM "DTM10" as well as layers of names and lakes. The name and lakes layers are part of the dataset "Norgeskart" by the Norwegian Mapping Authority (see Table 2).*

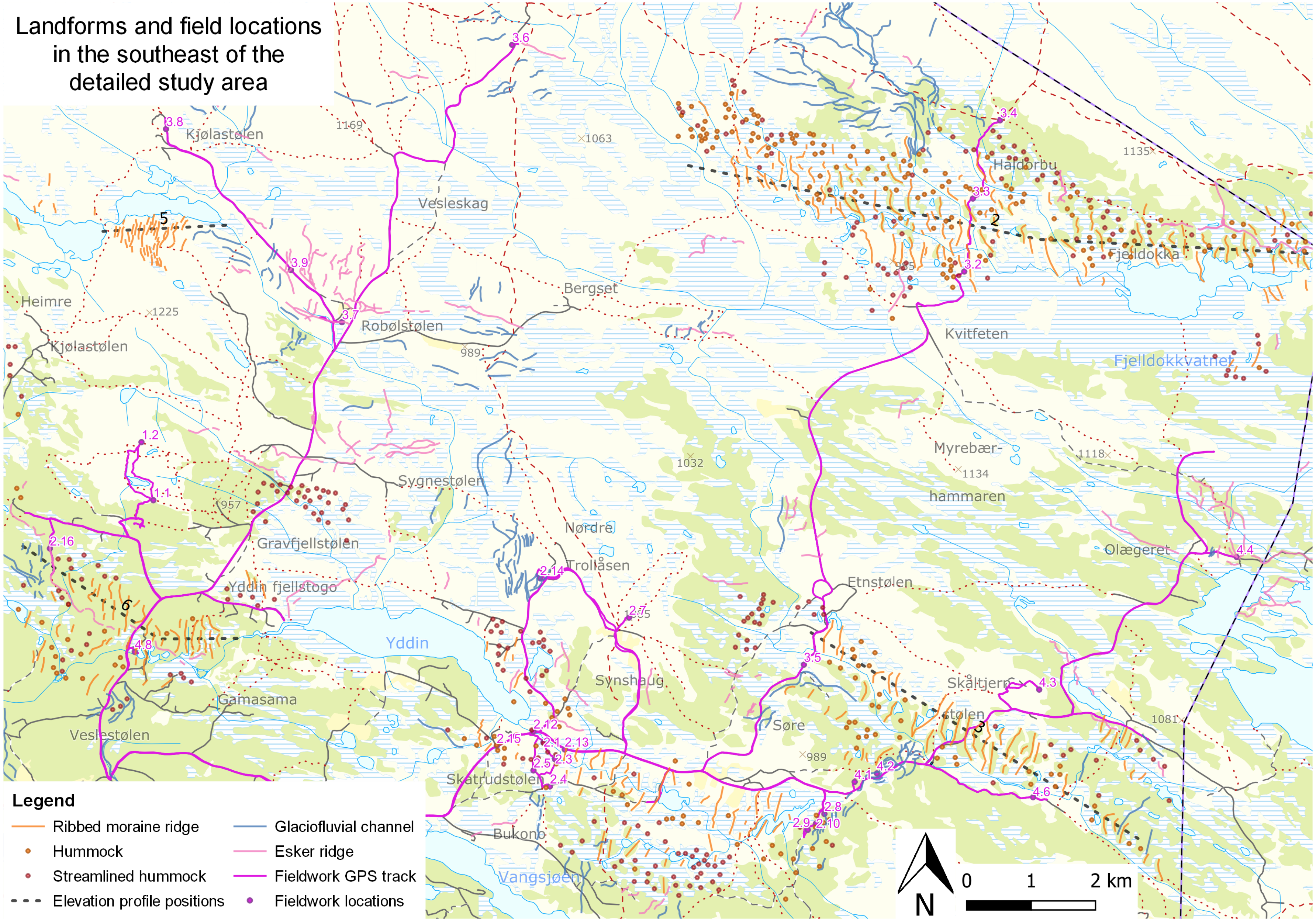


Figure 14: *Map showing landforms and field locations in the southeast of the detailed study area. Elevation profile transects and GPS tracks of the conducted fieldwork are also shown. The background map is part of the topographic map dataset "Norgeskart" by the Norwegian Mapping Authority (see Table 2).*

4.3 Fieldwork and detailed mapping

The following section will describe the observations made during mapping of the detailed study area, as well as observations made during the fieldwork in the southern portion of the detailed study area. Grain size distributions of sediment samples gathered in conjunction with this fieldwork will also be described in this section. The landform maps of the detailed study area can be viewed in Figures 12 (northern half of the study area) and 13 (southern half of the study area). A detailed view of the southeastern portion of that map which includes field locality positions, can be found in Figure 14.

4.3.1 Fjelldokka and Storeskag

From views over the area from Storeskag and Haldorbu one could observe a substantial ribbed moraine field in the Fjelldokka area. The field extends from just below Storeskag towards the start of a more confined valley in the east, a length of about 11km. The field contains ribbed moraines and hummocks, with hummocks and ridges towards the edges of the field often featuring streamlined features on their tops and ridges crests. The elevation profile through the field (Figure 15) shows a gradual slope to the east, falling around 50 meters. In the profile, 5-10 meter high mounds are visible when the profile crosses the ribbed moraines. The moraines in the eastern end of the profile have a slightly more pointed shape than those in the rest of the profile.

From traversing the field on the path to Haldorbu, the morphology of the ribbed moraines in the field was investigated close up. The first thing that was observed when arriving in the ribbed moraine field was that there were trees growing only on the ribbed moraines. This may be a consequence of the areas between the ridges being very wet and swamp-like, together with the fact that this area is right at the treeline elevation, making the trees even more sensitive to unfavourable conditions (Bryn and Potthoff, 2018). One of the main observations that was made is that all ribbed moraine ridges had large shares of boulders both on and between the ridges (Figure 16). The boulders had different sizes covering all dimensions up to big slabs of rock and no clear form. Another important observation that was made in the field was the discovery of bedrock sticking up in a flat area in the middle of the ribbed moraine field (Figure 17), marked as location 3.3 in Figure 14.

The ribbed moraine field at Fjelldokka appeared impacted by water flow, especially the western half of the field. Here, water channels were observed coming down from the mountainside and from the higher lying Skagsflye area, flowing into the ribbed moraine field at approximately a right angle. However, no clear exit point for the water could be seen. The water channels on the mountainside run parallel to the elevation contour lines before turning and descending towards the ribbed moraine field. This indicates that these channels formed either subglacially, or as lateral supraglacial channels before turning and flowing subglacially through the ribbed moraine field. In the hummocky area on the far west side of the field, towards Skagsflye, there were also subtle traces of water impacting the landscape. Water seems to have run down from the north through the Skagsflye area, fed also by water streams from the west at Storeskag. Even though the traces are not very clear, these water flows seem to run east towards the Fjelldokka ribbed moraine field, with traces suggesting some parts possibly branching south towards the Etnestølen/Skåltjern area

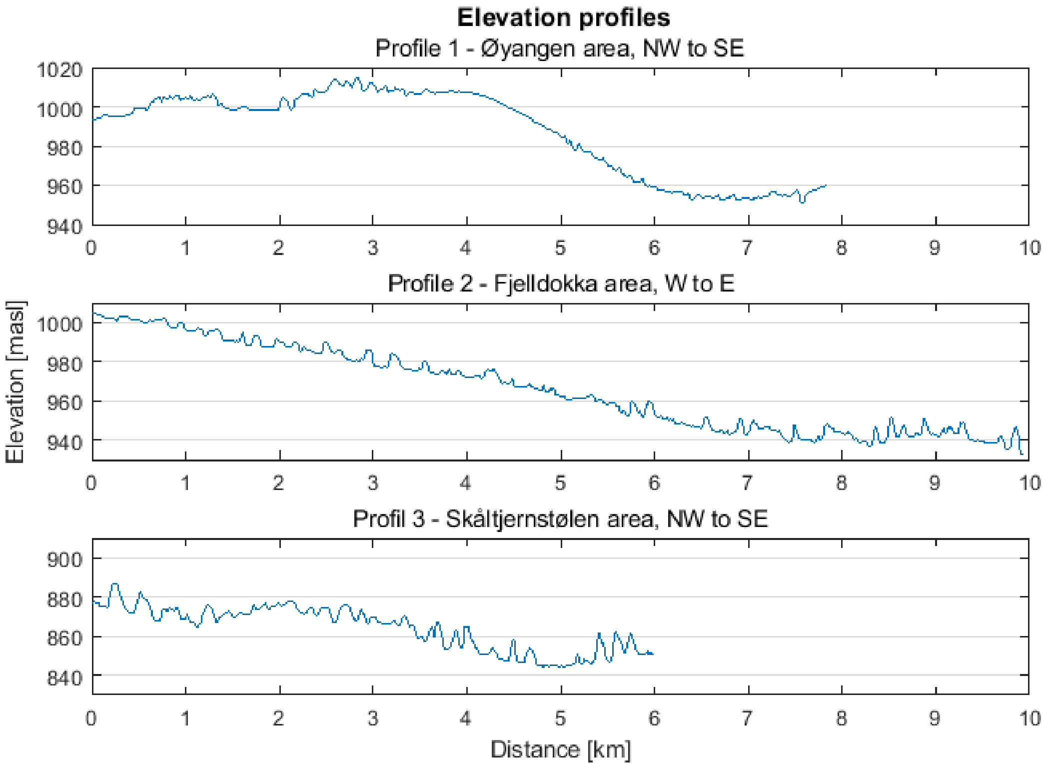


Figure 15: *Elevation profiles through the ribbed moraine fields of Hersjøen-Øyangen, Fjelldokka and Skåltjernstølen. See the detailed landform maps (Figures 12, 13) for the location of the profile lines.*

Figure 16: *Picture of large boulders on ridges in the Fjelldokka area. Note the very large block on the ridge in the middle of the picture. Observe also the edge of the ribbed moraine field in the distant right side of the picture. Image location: Figure 14, location 3.3, picture taken towards southeast*

Figure 17: *Picture of a flat bedrock outcrop in a flat part of the Fjelldokka area. Note a second outcrop with two rocks on it in the upper left of the image. The ridges in the background are ribbed moraine ridges and hummocks. Image location: Figure 14, location 3.3, picture taken towards southeast*

at some point in time. In the eastern half of the field, one esker was identified, running along the northern edge of the field in between ribbed moraine ridges and hummocky mounds.

At Storeskag (Figure 14, location 3.6), the hillside appeared to have been affected by water channels and also one ridge which may resemble an esker. A total of four sediment samples were taken from different sediment layers near the top of the outcrop to investigate this ridge at location 3.6. The grain sizes of the four samples differ substantially, showing varying degrees of sorting (Figure 18C). Sample 3.6A is highly sorted and is mostly composed of very fine sand, whilst sample 3.6B is relatively sorted with high shares of medium and coarse sand. Samples 3.6C and 3.6D are less sorted than the other samples but not unsorted. Sample 3.6D is mostly composed of very fine to coarse sand, with little coarser shares present, whilst 3.6C is mainly composed of coarse sand and above. This generally fits with the observations from the map that there are clear fluvial influences in this slope, as these sorted sediment samples indicate fluvially deposited material.

4.3.2 Fullsenn

The farmstead "Olægeret" beside lake Fullsenn lies between the Fjelldokka and Skåltjern areas. The hills around lake Fullsenn only have around 50-100m higher elevation than the lake level, and the landscape can be described as relatively flat and smooth. The area is dominated by streamlined terrain in the form of many flutes and drumlins, which can be clearly identified around the edges of the lake. In addition to the streamlined terrain, a large amount of esker ridges can be found on the northwest side of the lake right by the farmstead. No ribbed or hummocky features were identified in this area at all, and almost no fluvial channels either.

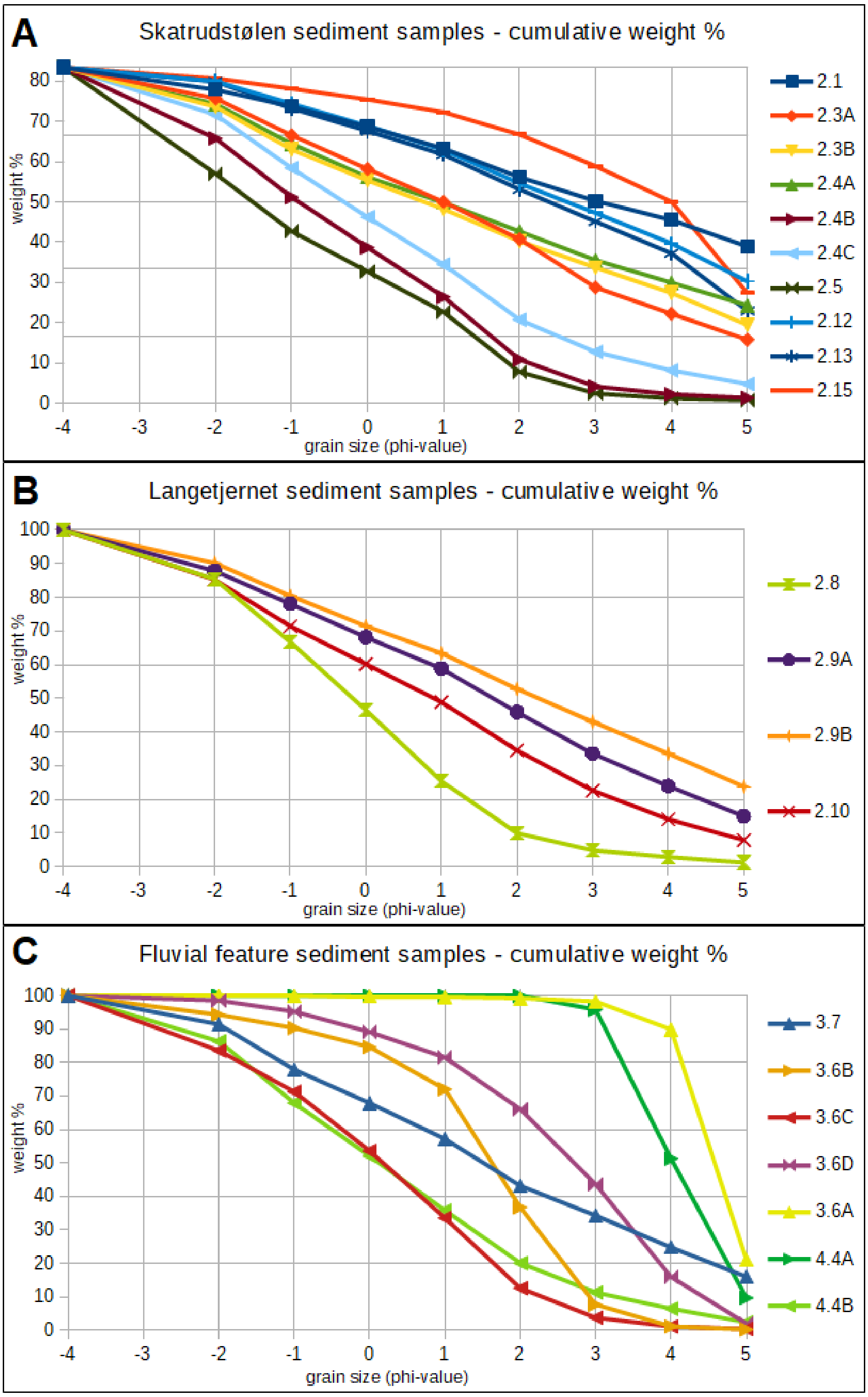


Figure 18: *Cumulative grain size distribution of sediment samples gathered during fieldwork. See table 3 for x-axis scale explanation.* ***A*** *- Sediment samples from near Skatrudstølen on the western end of the Trollåsen area.* ***B*** *- Sediment samples from near Langetjernet on the eastern end of the Trollåsen area.* ***C*** *- Sediment samples from 3 locations where glaciofluvial landforms (eskers and channels) were identified during fieldwork and mapping. These are taken at Røbølstølen (3.7), Olægeret (4.4A,B) and Storeskag (3.6A,B,C,D)*

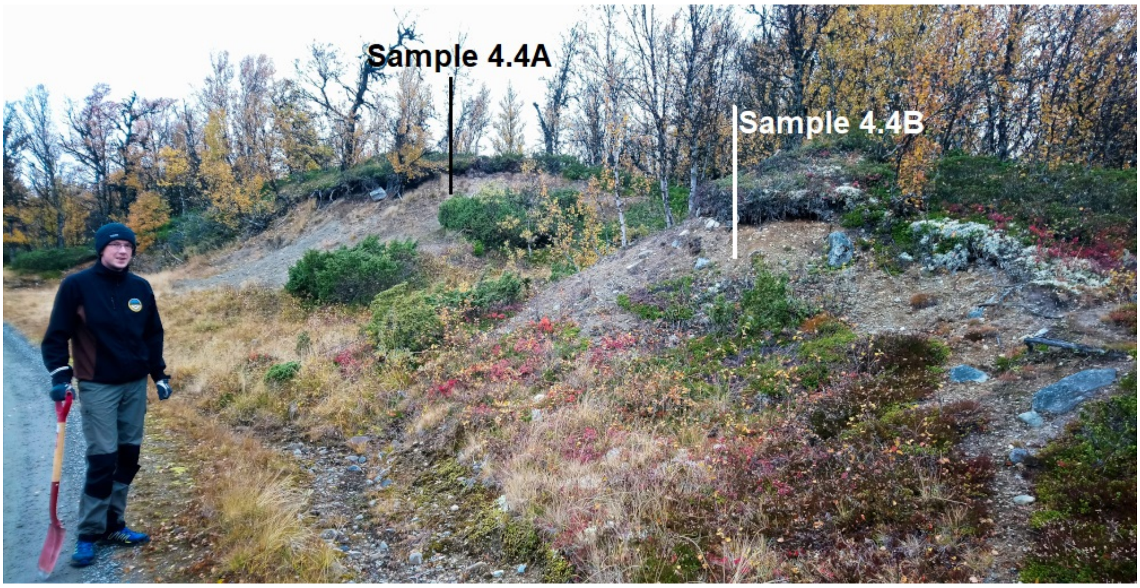


Figure 19: *Photo of an esker ridge in the Fullsenn area, just east of the Olægeret Farmstead, with sediment sample positions marked. Photo position: Figure 14, location 4.4, picture taken towards northwest.*

Two sediment samples were taken at an esker ridge outcrop beside the dirt road leading east of Olægeret, approximately 0.5km east of the crossroads (Figure 14, location 4.4). The first sediment sample was taken near the top of the outcrop (Figure 19). The second sample was taken around 20 further along the esker in a smaller outcrop right beside the road, not as high up as the first sample (Figure 19). As can be seen in the grain size analysis (Figure 18C), the first sample, 4.4A, was well sorted, containing a majority of 2 sample sizes, namely fine and very fine sand. Small shares of silt or clay as well as medium sand were also present. The second sample, 4.4B, however, has a wide variety of grain sizes present and is therefore very poorly sorted. This unusual composition for an esker ridge was also observed while gathering the sample, with larger stones observed when digging the sediment sample hole. This poor sorting and high share of coarse grains does not seem to represent esker material, which may be explained by the fact that the second sediment sample was gathered near what seemed to be the base of the ridge. It is therefore possible that the sample was gathered in a till ridge present in the landscape before the esker was deposited on it at this location.

4.3.3 Skåltjernstølen

Viewed from the top of the Synhaugen and Skåltjernknatten mountains, the valley by Skåltjernstølen features prominent ribbed moraine field. The field stretches around 15km down-valley from Etnestølen, of which about 10km is outside of the study area. The detailed mapping showed that the ribbed moraine field is not completely continuous down the valley however, with several breaks of a few hundred meters length along its extent. The elevation profile through the upper 6 km of the field (Figure 15) shows an uneven mix of larger mounds of around 10 to almost 20 meters, and many smaller mounds starting at around 2 meters. The field contains some irregular hummocks, especially towards the Trollåsen area, but what is striking is the very close connec-

Figure 20: *Photo of the Skåltjernstølen ribbed moraine field from the Skåltjernknatten mountain. Photo position: Figure 14, location 4.3, picture taken southwards.*

tion between the ribbed moraine ridges and the streamlined terrain around them. Transitions to streamlined terrain could be seen at the northwestern end of the field, along most of the northern edge of the field, and by the study area border also in between groups of ribbed moraines. In this southern area, the ribbed moraine field appeared to be almost split in two by a drumlin or a similar glacial lineation feature, with one ribbed part extending up to the Skåltjern lake and the other one clinging to the Etne river. At Etnestølen, there is an apparent transition from glacial lineations to streamlined hummocks in the hillside down from Synhaugen, before transitioning further to streamlined ribbed moraines. In addition, bedrock was observed near ribbed moraines at two separate locations. The first observation is located near Etnestølen (Figure 14, location 3.5) and the second observation was made in an irregular hummock very close to the farm "Rognsfeten" (Figure 14, location 4.6).

When driving down the road towards Skåltjernstølen from Søre Trollåsen, the road follows a large canyon-like feature in between the two valleys. In the canyon just beside the road, there are elongated areas of boulder fields in an otherwise till-covered landscape (Figure 21). On closer inspection the boulder field was also found to have several rounded boulders and many more signs of rounding. When observing aerial photos and LiDAR DEM clear meandering channel forms could also be identified here, yet there is no water flowing here today. Therefore, this large channel system must have previously been a main drainage point for the Trollåsen area and, considering the size of this channel feature, also more of the landscape upstream of Trollåsen. Even though it was attempted to investigate, it was not possible to find indications in the surroundings whether this channel had been created subglacial or out in the open. Subglacial formation is likely considering that water does not flow here today and that the area resembles a catchment boundary between water flow towards the Yddin lake in the Trollåsen area and the river Etne in the Skåltjernstølen area. This also fits with the observation of other fluvial traces in the Skåltjernstølen area, with water also seemingly having flowed the ridge north of Synberget from Trollåsen towards Etnestølen in addition to this big channel further east. One possibility is that water first flowed over this ridge before it sought out the more favourable route later, excavating the larger channel further east when water flow started to increase during the deglaciation. In addition, smaller water traces were also found coming down beside the Etne river and into the area in the northwest as well as into the area by the Skåltjern and Gudleikstjern lakes.

Figure 21: *Panorama photo of the boulder field in a fluvial channel between the Skåltjernstølen area (towards the right) and Trollåsen area (towards the left). Note that many boulders have somewhat rounded edges, indicating that they have been affected by fluvial processes. Photo position: Appendix 2, position 4.2, picture taken westwards.*

4.3.4 Trollåsen

The Trollåsen area contains one ribbed moraine field stretching from the eastern end of the Yddin lake and about 6km eastwards. At its widest, the field stretches across approximately 2km. The ribbed moraines here are surrounded by a large amount of hummocks, with a majority of the hummocks and ribbed moraine ridges showing signs of streamlining on their crests and tops (Figure 24).

At the eastern end of the Yddin lake by Skatrudstølen, there are several features of a more hummocky nature in addition to the ribbed moraine ridges found here. A few of the hummocks have streamlined crests, but most have an irregular shape. A total of 10 sediment samples were taken in this area. Samples 2.12, 2.13 and 2.15 were taken in road cuts through hummocks and a ribbed moraine along the main gravel road crossing the area from east to west. All three samples were gathered near the top of the ridge or hummock. Samples 2.1 and 2.3A and 2.3B were excavated from the top of 2 hummocks just south of the road (Figure 24). Samples 2.4A, 2.4B, 2.4C and 2.5 were taken in two small abandoned gravel quarries in the area. The grain size analysis of the samples shows a similar distribution for all the samples from Skatrudstølen (Figure 18A). No pronounced sorting is visible, with the cumulative lines sloping gradually for all samples, and many of the samples show almost identical distributions. Samples 2.3A, 2.3B and 2.4A show a very similar distribution, starting at around 20-30% silt and clay (phi 5) and climbing approximately linearly from there. Samples 2.1, 2.12 and 2.13 (blue lines in Figure 18)also show similar trends, with the lines almost overlapping in the upper 2/3 of the plot. In the finer-grained area the samples differ slightly, starting at between 30-50% silt and sand (phi 5). Samples 2.4B, 2.4C and 2.5 all have much lower shares of fine grained material, but start to pick up shares at around fine sand (phi 3) and medium sand (phi 4), and rising quickly after that. All of the samples in the Skatrudstølen area can therefore be described as unsorted, fitting with the general grain size distribution for till.

In the very eastern part of this ribbed moraine field, just southeast of the lake, meandering ridges and several hummocks were observed. A total of four sediment samples were gathered in this area. Three samples, 2.8, 2.9A and 2.9B were taken from two large gravel quarries in the area, whilst sample 2.10 was taken from a road outcrop. The grain size distribution of these samples (Figure 18B) is very unsorted, with samples 2.9A, 2.9B and 2.10 showing almost linear cumulative curves. Sample 2.8 is slightly more sorted, with fewer small grain sizes present than large ones. These grain sizes fit well with the distribution that was also seen by the eastern end of the field, and resembles the distribution of till. Sample 2.8 can be decrbed as slightly sorted indicating that parts of the sediment may have been deposited in water. The meandering ridges in the eastern end of the field (Figure 14, near location 2.10) could be both ribbed moraine ridges which were possibly affected by water flow after their formation, or they could be caused by several parallel fluvial channels cutting into the till surface and leaving ridge-like features behind. This also fits with the large fluvial channel just east of the is area which leads to the Skåltjernstølen area, which seems to be the main water exit point for the Trollåsen field. In addition to these large water traces, there are smaller fluvial channels and eskers entering the area from the southern edge of the field, as well as eskers and channels just north of the Yddin Lake.

4.3.5 Yddeåne

The Yddeåne ribbed moraine field is relatively small and confined compared to the other fields. It lies in between what seems to be hills of bedrock on three sides, with the ribbed moraine field "squeezed" in between these, with the western half of the field lying in gently sloping terrain, falling towards the south. The Yddeåne field has a close proximity to streamlined terrain which can be observed both north, southeast and west of the area.

During the field trip, the area was viewed from the top of the Gravfjellet mountain to get an overview of the area (Figure 14, location 1.1). Streamlined forms around the ribbed moraine field were clearly visible from Gravfjellet, but the ribbed moraine ridges were less visible due to the area having dense forest cover. When travelling through the area by road however, the ribbed moraine ridges and hummocky forms were clearer, especially around the Vidflå river (Figure 14, location 4.8) which snakes its way through the ridges. The elevation profile through the area (Figure 22) shows occasional mounds of around 7 to 10 meters, with much smaller mounds in between these at different spacing. Some of the large mounds are wider, and some are pointier. In addition, the general elevation trend of the landscape in between the mounds also varies, falling sharply in the west, before rising again in the middle. The general trend then falls again before rising to a flatter area in the east.

The Yddeåne area has large impacts of water channels and eskers, altering some of the ribbed moraine ridges. Just south of the area, very large water channels in a southerly direction can be found. Substantial glaciofluvial traces run through the Yddeåne area, running in a north-to-south direction and not following the present-day elevation contour lines. In addition, a substantial esker was identified running northwest to southeast in the area (Figure 14, location 2.16), which is a different direction to the glaciofluvial channels which can be observed.

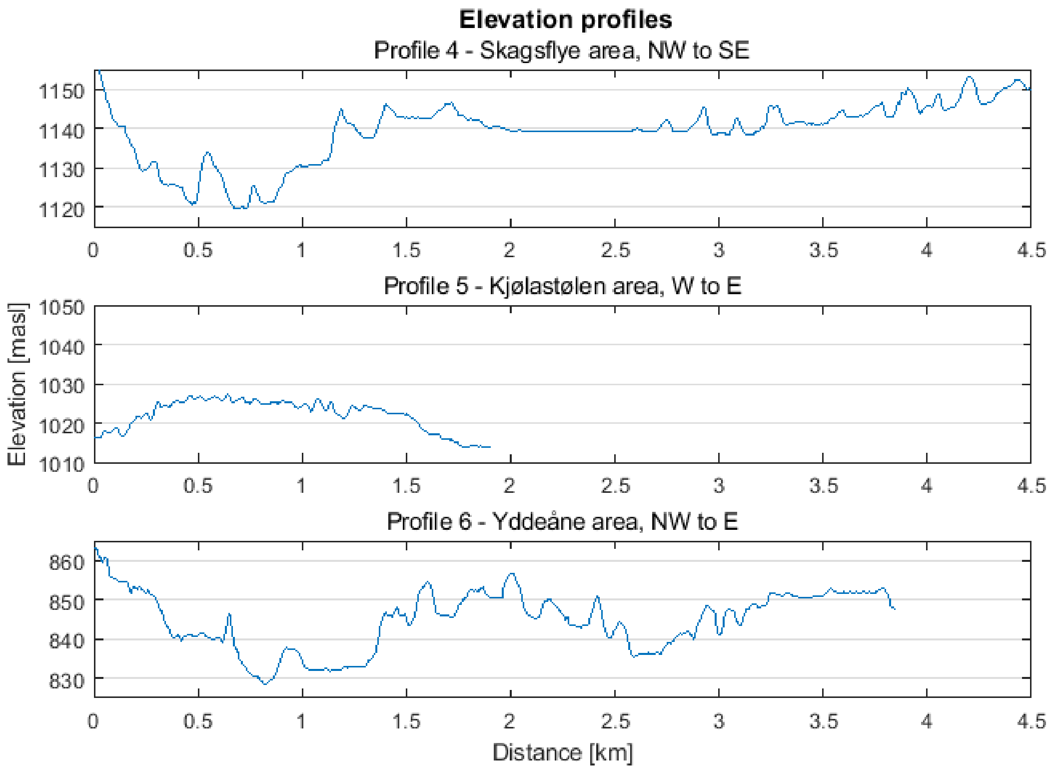


Figure 22: *Elevation profiles through the ribbed moraine fields of Yddeånne, Kjølastølen and Stortjernet. See the detailed landform map (Figure 13) for the locations of the profile lines.*

4.3.6 Kjølaåne

The Kjølaåne area will from now on be used to describe the general area between the north side of the Yddin lake and around the farmsteads of Syngestølen, Robølstølen, Berset, Vesleskag and Kjølastølen, i.e. approximately the area that the Kjølaåne river passes through (Figure 14). The Kjølaåne area was viewed from the hilltops of Gravfjellet and Synhaugen, and partially also from viewpoints along the roads crossing through this area. This area is flat, sloping gently from the Vesleskag mountain in the north down towards Lake Yddin in the south (Figure 23). The area is mainly characterised by streamlined features showing the ice flow direction of the last ice age.

In addition, the area has clear glaciofluvial impacts in the form of large channels and many esker ridges. The eskers especially, but also to some degree the channels, have different directions and cross each other. This makes it challenging to interpret the water flow directions, as they seem to have changed over time. However, it appears that the water mainly flows from northwest to southeast, seemingly originating from the area of the Kjølen lakes near Kjølastølen and flowing down past Robølstølen. This flow direction seems to have had many water inputs also from the Vesleskag area, as many esker ridges were found on this slope towards Robølstølen. Between Robølstølen and Bergset, the fluvial traces are less evident, with a west-east flow direction visible as well as a southward branch. From here, glaciofluvial channels point in a north-south direction, seemingly leading the water towards the east end of the Yddin lake and therefore to the Trollåsen field. In contrast, esker traces seem to lead towards the west end of the Yddin lake and therefore the Yddeåne field. The water may also have flowed by Bergset and down to Etnestølen and the

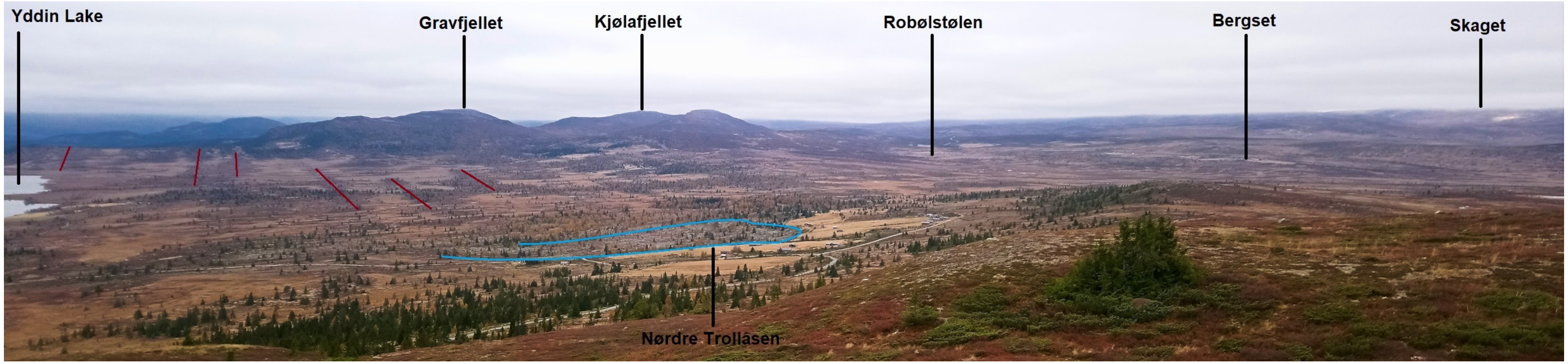


Figure 23: *Panorama picture of the Kjølaåne area from the Synhaugen mountain. Note the streamlined features pointing towards the camera from between Yddin and Gravfjellet (marked with red). Also note the boulder field visible just above Nørdre Trollåsen (marked with blue), as well as the horizontal lines above this field which represent fluvial channels after flow from right to left in this image. Photo position: Figure 14, location 2.7, photo taken towards northeast*

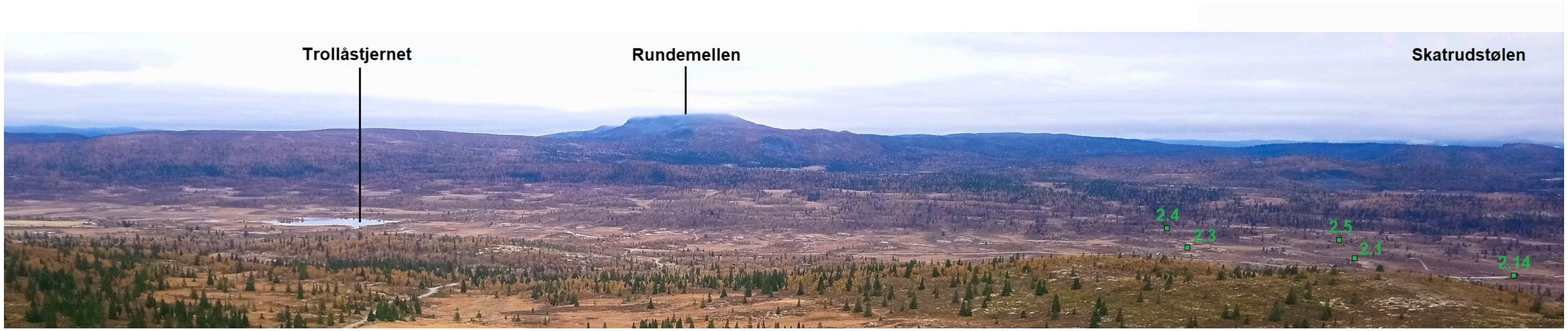


Figure 24: *Panorama picture of the Trollåsen area from the Synhaugen mountain. The position of several sediment samples are marked in green. Note the ribbed moraine ridges between the sample positions and the Trollåstjernet lake in contrast to the hummocks between the lake and the Rundmellen mountain. Photo position: Figure 14, location 2.7, photo taken towards south.*

Figure 25: *Photo of the boulder slabs near Nørdre Trollåsen in the Trollåsen area. The boulder slabs can be seen to be stacked chaotically and unnaturally in the slope, indicating they have been glaciofluvial altered. Photo position: Figure 14, location 2.14, picture taken northwards.*

Skåltjern field at some point, even though there are far less traces in this direction.

Towards the eastern end of the Yddin Lake and Trollåsen field, a extensive field of large boulders was observed in the gentle slope up to Nørdre Trollåsen (Figure 23; Figure 14, location 2.14). In the boulder field, depressions resembling channels were observed pointing down-slope. Further up the hill, bedrock was visible, with boulder slabs loosened from the bedrock outcrop (Figure 25). Below this area, fluvial channels and some esker ridges enter the Trollåsen area. This seems to have been the path of water under pressure, and is interpreted as a path of intense subglacial water flow.

At Robølstølen, one sediment sample was collected near the top of a large esker ridge outcrop (Figure 14, location 3.7). The ridge is around 15 meters high and 50 meters wide at this location, and has been cut at 2-3 locations due to human activity in the form of gravel quarries, showing distinct layering. The grain size distribution shows little sorting of the sample, with an almost linear cumulative curve showing that the sample contains very even shares of the different grain sizes. This does not fit well with the grain size distribution expected, but this is due to the sample containing sediment from several sorted layers of the sediment column.

4.3.7 Kjølastølen - Javnberget - Olevatnet

The area situated in a triangle shape between Kjølastølen, Javnberget and Olevatnet (Figure 13) has several similarities to the Kjølaåne area. The area is relatively flat, sloping towards south/southwest and has a lot of streamlined features. But unlike the Kjølaåne area, this area has both individual ribbed moraines and small groups spread throughout most of the area, as well as an abundance of hummocks, the majority of which have a streamlined top. There are some glaciofluvial channels or eskers, most of them appearing towards the Yddeåne area.

Just south of Kjølastølen and the Lake Søre Kjølen on the hillside up to the Kjølafjellet mountain,

Figure 26: *Photo of the Kjølastølen ribbed moraine field south of the Søre Kjølen Lake. The picture faces the Kjølafjellet mountain and was taken from the Kjølastølen farmstead. Photo position: Appendix 2, position 3.8, picture taken southwards.*

ridges were observed in the landscape (Figure 26, 14, south of position 3.8). When an elevation profile across the area was made, only mounds between 1 and 4 meter height could be identified (Figure 22). The ridges can also be seen to be in a sloped area, and are oriented approximately down slope.

4.3.8 Vinstrevannet and Kaldfjorden

The large area surrounding the Vinstre and Kaldfjorden lakes contains several ribbed moraine fields (Figure 12). The decidedly largest field is situated between the two lakes and also stretches along the southeastern shore of the Vinstre lake and the northern shore of the Kadfjorden lake. Other fields can be found on the northwestern shore of the Vinstre lake, such as on the elevated innland area between the lake just south of the Keisaren hill, on the Buøya Island in the middle of the Kaldfjorden lake, as well as the the Innbutangen peninsula protruding into the Kaldforden Lake. Many hummocks can be found in and around all of the ribbed moraine fields, with only a few of these showing any streamlining features. Streamlining is however common outside of these fields, with glacial lineations found around the whole area.

The ribbed moraines and hummocks by the shores in both the Vinstre and Kaldfjorden lakes often stretch into the lakes. Hummocks and ridges therefore protrude above the water surface, forming many small islands. This indicates that there may also be ribbed moraines under the water surface that don't protrude out of the water. This is especially relevant as both the Vinstre and Kaldfjorden lakes are dammed and their water levels regulated for hydropower. This has probably raised the water level of the lakes considerably, especially the Kaldfjorden lake. Unfortunately the first available aerial photography in the area through the web portal "Norge i Bilder" is from 1963 (See Section 3.1.1), and in this image the dams are already in place and water already covers any present features. The ribbed moraine field south of the Keisaren Hill (Figure 12) has slightly more streamlined ridges and is also affected by glaciofluvial processes in an east-west direction.

Fluvial traces in the form of both channels and eskers are common mainly in the northern part of the area, seemingly flowing down from Valdresflya and the Gråhøe mountain. There are also some traces pointing downwards into the southern part of the Kaldfjorden lake, probably originating from the hills of Skreddalsfjellet. There are no clear fluvial traces of the water exiting the area again, but this may have happened in the southeastern part of Kaldfjorden towards Hersjøen or north of this at Merravikhalsen.

4.3.9 Hersjøen and Øyangen

The area around the lakes of Hersjøen and Øyangen in the north of the detailed study area is wide, flat and plain-like (Figure 12). The borders of the area are characterised by the relatively smooth valley sides of the surrounding mountains. Only a few smaller hills separate this area from the neighbouring Kaldfjorden lake.

Ribbed moraine of this area are less distinct in their morphology than in most other parts of the detailed study area. They are also not grouped as distinctly into fields as in other parts of the study area, with many single ridges spread throughout the area in addition to some groups. Several groups of dense, small hummock-like features are also present in much of this area. These were too small and plentiful to be marked as hummocks. Further, there are several areas of chaotic hummocks, ridges, fluvial channels and eskers that were challenging to map and classify.

The elevation profile from the Øyangen Lake to the Vinstra river shows two main elevation steps at which mounds are present. By the Øyangen Lake in the northwest of the area, the first 2km along the profile showing a relatively rough surface with no distinct mounds visible. Between 2 and 3.5 km of the profile, mounds of 5-8 meters height can be observed with close spacing between them. After this, the profile slopes down several tens of meters, staying smooth for the first part of the slope. In the bottom part of the slope, from about 5km and onward, the profile shows smaller mounds. The part of the profile between 2 and 3.5 km seem to be the part that resembles ribbed moraines the most, whilst the first and last parts of the profile show less characteristic elevation distributions, especially the northwestern part.

Ambiguous and hard-to-classify landforms were identified just north of Hersjøen, extending north along the Vinstra river. Ridges in this area are not as distinct or large as seen in other areas, often with thinner ridge crests and very anastomosing forms. The same smaller ridges can also be seen in the southwestern part of the elevation profile. Most of these ridges are short, but several are longer, and therefore seem to fit better to an esker morphology rather than a ribbed moraine morphology. Some other parts of these anastomosing ridges also resemble fluvial channel morphology in the form of parallel fluvial channels rather than a ribbed moraine morphology. Several of the ridges found in the area are also streamlined or seem flattened in some form, appearing lower than ribbed moraine ridges seen in other parts of the detailed study area.

Streamlined landforms are frequent throughout the landscape, and are also found in small scale on ridges and hummocks. The ice flow direction can be seen to be going in a southwesterly direction in this area, corresponding to the ice flow direction seen in most of the rest of the detailed study area.

Lastly, there is also a large impact of water in the area. Large amounts of water traces enter the area in the west, likely originating from the Heimdalen valley. This water seems to flow chaotically down to the Øyangen Lake, passing through an area with trasnverse ridges. One of these ridges is especially large, and may possibly be a terminal moraine of a glacier tongue that once came out of Heimdalen. It is therefore likely that these water traces are proglacial traces rather than subglacial traces, although the subglacial option can not be excluded. In the central and northern part of the area, esker ridges are more common than fluvial channels. In the middle of the area, esker ridges can be seen to point more in a southwesterly direction, whilst they point mainly in a northeasterly direction in the southeastern part of the area. Fluvial channels can again be seen in the mountainsides in the east of the area, and a substantial amount of channels can be seen exiting the area in the northeast. This also seems to be the main exit point for the water from this area.

4.3.10 Stortjernet

The Stortjernet lake area stretches from the western end of the Fjelldokka area northwards around the mountain "Skaget", which is the highest mountain inside the study area (Figure 12). The valley is at a pretty high elevation, and acts as a mountain pass between the wide valley in the north around the Kaldfjorden Lake and the flatter area in the south towards the Fjelldokka area and Yddin Lake. The ribbed moraine field at Skagflye is compact in size and contains mostly ribbed moraine ridges, with fewer irregular and streamlined hummocks on the sides of the field. The location is interesting, as the ridges change orientation slightly throughout the field, following the ice flow traces around the Skaget mountain. The profile through the ribbed moraine field around the Stortjernet lake (Figure 22) shows a depression in the landscape on the northwestern end of the profile, while the southwestern 2/3 of the profile is relatively flat. There are mounds of 4-15 meters height throughout the profile, except for a 0.5 km stretch in the middle where the profile crosses the Stortjernet lake. The mounds have irregular wavelengths and heights of 4-15 meters. The area shows signs of water flow in the mountainsides around the field, with few identified inside the field.

4.3.11 Identified ribbed moraine types

Using the classification from Dunlop (2004), the ribbed moraines types mapped in the detailed study area can be summarised to mostly resemble anastomosing and hummocky ribbed moraines (Figure 27). Groups of lumpy, minor, blocky/angular and both downstream and upstream curving ridges were also found in several fields, with no clear pattern to their distribution. Individual broader ridge types can also be found, but these are often very unclear in this study area and were therefore not always included in the map. The other forms described in Dunlop (2004) were not observed in the detailed study area. Note that longer ridges in the hummocky ribbed moraine category of this classification will be marked as ribbed moraine ridges in the detailed maps, whilst shorter ridges will be mapped as hummocks, according to the mapping rules set up in Section 3.1.3.

4.3.12 Summary

To summarise, the main observations made during mapping, fieldwork and from the grain size distributions of the sediment samples are listed below.

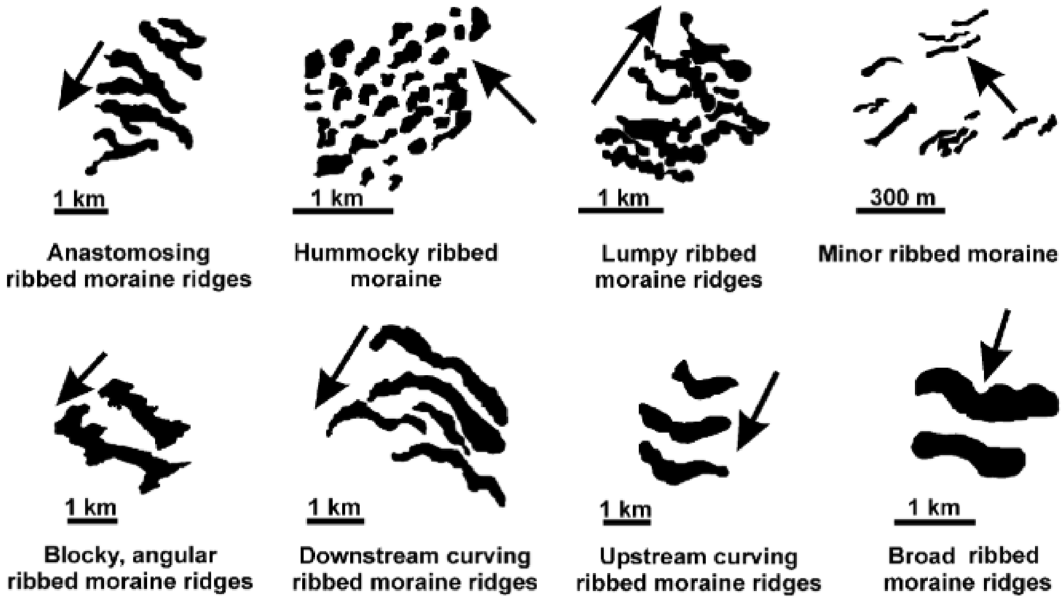


Figure 27: *Ribbed moraine morphology categories as proposed by Dunlop (2004), with only categories identified in this study shown. (modified from Dunlop and Clark, 2006)*

- Ribbed moraine fields are present in flat parts of the landscape.
- Ribbed moraine fields have lots of hummocks in and around them.
- Hummocky bedforms were found to have forms ranging form almost completely round to more elongated in a transverse direction, or more streamlined in the ice flow direction. Often, several hummocks seem to form lines, almost resembling ribbed moraine ridges, and other times ribbed moraines seemed to be comprised of several morphed hummocks.
- Many ribbed moraine ridges and hummocks have streamlined traces imprinted on their highest points. Some ridges and hummocks show a complete, but superficial streamlining.
- Purely streamlined areas are widespread throughout the area and commonly have some eskers and glaciofluvial channels visible in them.
- Ribbed moraine ridges of less clear morphologies were found in some areas, like the Hersjøen-Øyangen area. These sometimes resemble parallel fluvial channels or unclear esker ridges rather than ribbed moraines.
- There are many glaciofluvial channels in the area, and these show a clear directional trend. Glaciofluvial traces south of the Stortjernet area and the Skaget mountain point roughly southeasterly, whilst they point northeasterly in the areas of Vinstrevannet-Kaldfjorden and Øyangen-Hersjøen.
- Sediment samples show a clear trend for the grain size distribution of ribbed moraine ridges and hummocks, with all of these samples showing grain size distributions which fit roughly with the distribution common for till. Sediment samples taken from areas where fluvial landforms and features were identified commonly had visibly sorted grain size distributions in at least one of their samples.

- At 3 positions in the Fjelldokka and Skåltjernstølen fields, bedrock was found in close proximity to ribbed moraines and hummocks.

5 Discussion

5.1 New spatial data and a need for renewed mapping

One of the main results produced by this study, the regional map of ribbed moraines fields, hummock/ribbed fields and streamlined fields, shows substantial differences to an existing map of the ribbed moraine distribution in Southern Norway compiled by Sollid and Sørbel (1994). While the maps match well in some areas, they disagree in many other. This result is unexpected, and the first part of this discussion will investigate the reasons for these differences. Two main reasons are suspected to have contributed to the differences between the maps.

Firstly, the focus and configuration of the study by Sollid and Sørbel (1994) has likely influenced the quality of the landform map. The study by Sollid and Sørbel (1994) compiled maps of several landforms, amongst others the ribbed moraine distribution. The landform distributions shown in Sollid and Sørbel (1994) are extracted from regional geomorphological maps published between 1977 and 1991 by other authors. It is therefore not given that landforms were mapped using the same techniques and definitions in all of the regional geomorphological maps landform extent was extracted from.

Secondly, the different data sources utilised to compile the previous map and the map of this study will affect the amount of landforms that are able to be detected in each study. The geomorphological maps used to compile the landforms distribution maps in Sollid and Sørbel (1994) is based largely on aerial photos, while the present study has utilised high-resolution LiDAR DEM data. LiDAR DEM data at high resolution also shows the form of the landscape when visualized using hillshading, but only requires a computer with a geographic information system program such as QGIS which was used in this study. Aerial LiDAR scanning can generally achieve very precise distance measurements (Hodgson and Bresnahan, 2004).

While the use of aerial photos is a very good tool for many mapping applications, such as topographic an land cover maps, they can introduce a substantial mapping bias into geomorphological maps. A high resolution LiDAR DEM has a significant advantage over mapping using aerial photos, as LiDAR scanning allows for removal of vegetation from the data through post-processing (Zhang et al., 2003). Aerial photos show vegetation patterns and ground colours, a trait which is very useful for most mapping purposes, but not necessarily for geomorphological applications. As geomorphological maps almost exclusively attempt to map the form and shape of landforms and landscape features, seeing the vegetation cover above these forms is often a distracting factor during mapping which can introduce bias. Vegetation cover may hide away ground features, especially in forests, or it may seem to indicate or amplify features that may not be present or may be less dramatic in reality. In contrast, large vegetation such as trees and bushes can accurately and effectively be filtered from high-resolution LiDAR data, revealing the ground form below (Zhang et al., 2003). As a LiDAR DEM hillshade also does not show ground colours, the only landscape property visualised in LiDAR DEMs is the true form of the landscape, allowing for geomorphological mapping in a pure form. As LiDAR DEMs therefore effectively eliminate mapping bias caused by both vegetation and ground colour, they are highly practical for use as a main data source for geomorpholocial mapping, and can also effectively be used for mapping in conjunction with aerial photos or other map data.

The large difference between the ribbed moraine distributions between the present study and the previous map compiled by Sollid and Sørbel (1994) is likely to a large degree caused by the difference in available map data between the two studies and the large advances that high-resolution LiDAR DEM data is bringing to geomorphological mapping. This may also explain why the area of Langsua/ect is mapped as well as it is, while fields situated in lowlands are less similar. The Langsua area is situated at or above the treeline, with landforms more visible in the aerial photos used as a basis for mapping the landform maps compiled by Sollid and Sørbel (1994), whilst lower-lying areas have thicker vegetation cover, reducing mapping accuracy using aerial photos.

The difference in mapped ribbed moraine fields between the regional mapping done in this study and previous mapping compiled by (Sollid and Sørbel, 1994) shows the need for an updated map of the ribbed moraine distribution in southern Norway. This study therefore recommends a renewed mapping campaign of ribbed moraines and other associated bedforms in Southern Norway. The surveying of most of Norway using high resolution LiDAR scanning technology is underway, and is planned to be completed in 2022 (Norwegian Mapping Authority, 2019d). This will result in a new national DEM dataset "DTM1" at 1x1 meter resolution, covering most of Norway (see Section 3.1.1). Any new mapping campaign of ribbed moraines and other landforms in southern Norway should make use of the new DEM dataset "DTM1" from the Norwegian Mapping Authority.

5.2 Ribbed moraine definitions and mapping ambiguities

Several ambiguous ridge landforms were identified in the detailed study area, causing challenges during the mapping process. Most of these features were marked as ribbed moraine ridges nevertheless, as the definition of a ribbed moraine ridge is kept purposefully simple in this study. Their form, interpretations and implications will however be elaborated here.

One of the ribbed moraine fields with ambiguous ridge forms is the Kjølastølen field. As recognised both during mapping and in the elevation profile, these ridges are shorter in height than those seen otherwise in the detailed study area, and are situated on a low slope. To try and discern if these ridges are typical of ribbed moraine morphology or not, the dimensions of the ridges were investigated through the elevation profile and detailed map data. This investigation found wavelengths of approximately 60 meters and ridge heights of 1-4 meters. When comparing these values to the dimensions found by Dunlop and Clark (2006) it was found that the ridge heights and wavelengths are at the lower end of the observed dimensions, but not below these (Table 1, Section 2.3). Using the classification by Dunlop (2004), these therefore fit in the category "minor ribbed moraines". The slope for this area was calculated to be approximately 5% (or 3°), and further investigation showed that the slope was similar to that of the Yddeåne area (also 5%). In conclusion, the Kjølastølen field is found to be a valid ribbed moraine field, and is subsequently also marked as such in the maps compiled in this study.

Another large group of ambiguous ridges were also found in the Hersjøen-Øyangen area. In addition to other unclear landforms and features in the area, several ridges inside ribbed moraine fields resembled groups of parallel esker ridges and/or fluvial channels (Section 4.3.9). These ridges were partly marked as ribbed moraine ridges and partly as esker ridges in the detailed landform map, depending on the interpretation of their morphology. The interpretation of these differences is however problematic, yielding uncertain classification results. The origin of the different ridges and other features in the Hersjøen-Øyangen area therefore remain ambiguous, complicating the glacio-historical interpretation of this area.

The findings highlights a continued challenge in the study of ribbed moraines. As there is no consensus on the formation principles of ribbed moraines, there is also no consensus regarding a defined morphology. This lack of consensus results in most studies working on a basis of loose definitions and/or referring to commonly-quoted morphological observations by other studies to explain the ribbed moraine morphology. This bears the danger that site-specific morphologies or generalised observations surrounding ribbed moraines are accepted as proven without having been thoroughly investigated, such as the inaccurate or unrepresentative accounts of ribbed moraine characteristics uncovered by Dunlop and Clark (2006). Especially transitional or ambiguous forms are therefore challenging to address when mapping and interpreting ribbed moraine distribution and transitions to other landforms. In addition, site-specific and loose definitions of morphological terms can ultimately lead to situations where studies think they are discussing the same situation or features when they are in fact discussing different situations or features.

For the above reasons, the present study has resorted to using a highly simplified working definition to detect and map ribbed moraine ridges in the detailed landform map. Following this definition, all ridges transverse to the ice flow which do not resemble other mapped morphologies were marked as ribbed moraine ridges (Section 3.1.3). This definition has worked well during detailed mapping in this study area and has proven to be easy to use for this purpose. Applying it has, for example, revealed single ridges outside the vicinity of ribbed moraine fields throughout the study area, which would not have been picked up if a traditional definition would have for mapping. Some conflicts arose during mapping and interpretation, such as the one in the Hersjøen-Øyangen area, but these were restricted to few occurrences.

This study therefore recommends the use of simple working definitions such as the one used in this study for future mapping of ribbed moraines. These have less danger of excluding transitional and ambiguous ridges or single ridges which may be important to understanding ribbed moraine distribution and formation processes.

5.3 Model evaluation and comparison to mapped glaciofluvial features

During this study, a model of the subglacial hydrology of the last Fennoscandian ice sheet was constructed using a DEM of present-day topography and a low resolution ice sheet thickness dataset. Both hydraulic head, hydraulic gradient, subglacial lake positions and subglacial flow were calculated for the regional study area, with a strong focus on areas of low hydraulic gradient (which includes sink areas). This section will firstly compare this model to another model of the subglacial hydrology of the last Fennoscandian ice sheet and then investigate model uncertainties that were detected in the results. A stable trend over time identified in the model results will be discussed. Flow paths of subglacial streams will be interpreted from glaciofluvial traces identified in the detailed study area, before being compared to modelled flow paths to further investigate the accuracy and applicability of the model.

5.3.1 Stability in the model results

A strong stability of the calculated gradient over time was observed, both in the gradient box plots (Figure 8), but also in the maps of low gradient areas, sinks, and modelled flow paths over time (Appendix 1 and 2). In each of the 4 gradient box plots (Figure 8), almost all time steps have the same gradient distribution, only changing significantly at the time step 11 kya and also slightly at 12 kya. In the gradient and sink raster data sets of all time steps (Appendix 1), areas of sinks and low gradient stay in very similar positions, although especially sinks vary in size over time, and smaller differences are visible in the gradient. The same is true for the modelled flow paths (Appendix 2), which are also surprisingly stable over the modelled time period.

This stability in the modelled hydraulic data is expected to be a consequence of the properties of the input ice height data. As the input ice height data is the result of a modelled ice sheet reconstruction, it has certain limitations as mentioned in Section 3.3.4. The property of this modelled data that is expected to be causing the stability is the fact that the slope of the modelled ice height data stays almost constant throughout the bulk of the glaciation, and changes in slope only occur in the model towards the last parts of the deglaciation. As the gradient is 10 times more reliant on the ice surface slope than on the slope of the basal topography (Shackleton et al., 2018), an approximately stable surface slope over time together with an approximately stable basal topography slope over time will result in stable gradient values over time.

The stable gradient over time due to little slope change in the input ice surface elevation data visualises a clear limitation to this modelling attempt, as the model depends on uncertain estimates of the ice sheet elevation (as described in Section 3.3.4). Higher variation in the hydraulic variables than suggested by the model used in this study is expected under neath ice sheets due to limited in situ measurements under present-day ice sheets and glaciers (Wingham et al., 2006; Lindbäck et al., 2015). The ice sheet elevation input data is however the best option for input data for this type of modelling at the moment, and we would thus need a newer and more accurate ice sheet model to acquire better ice sheet input data for this type of modelling.

5.3.2 Interpretation of identified glaciofluvial traces

The glaciofluvial traces identified in the area are not present throughout the whole area, only appearing in some parts of the landscape, often in groups of several traces. As they are not connected as fluvial traces are today, describing where the water flowed is a challenging. It is however possible to approximate the subglacial flow patterns from an interpretation of glaciofluvial traces.

As described throughout Section 4.3, glaciofluvial traces of different form and size were identified connecting several ribbed moraine fields in the detailed study area. In the southeastern part of the detailed study area (Figure 13), fluvial traces were for example identified entering and exiting the Fjelldokka, Skatrudstølen, Trollåsen and Yddeåne ribbed moraine fields fields. In addition, distinct fluvial traces were found at Storeskag, in the Fullsenn area, and throughout the whole Kjølaåne area. These traces, as well as others identified in the detailed study area, are shown as simplified arrows showing their expected flow direction in Figure 11. When all observations and interpretations are accumulated, the main water flow direction can be seen to go in a southeasterly direction, approximately the same as the ice flow direction. This also corresponds roughly to the direction from the Jotunheimen mountains and towards the Mjøsa area (Figure 2).

Not all channels can be confidently assigned a specific glaciofluvial process, as it is far from evident whether a glaciofluvial channel is formed subglacially, proglacially or laterally to the glacier ice. Channels running in directions where water does not run today may be a consequence any of the three of the processes above (Fredin et al., 2013). However, one indication for what kind of channel has been identified is their placement in regard to present-day slopes. If a channel is situated on a slope side, it must have been formed either subglacially of laterally. Several parallel channels in a slope are typical of lateral channels, but can also occur subglacially (Fredin et al., 2013).

The approximate stage of the glaciation when these glaciofluvial traces were formed can however be determined through knowledge of the deformation caused by ice flow. Where present, the form and shape of the majority of these traces are relativly pristine, and they are often found to cut through the other glacial landforms present. This indicates that they were formed when ice movement was slow or stopped, and that no large ice flow occurred after their formation. This in turn indicates that most of the glaciofluvial traces identified in the area are from the late part of the deglaciation, when the ice sheet is thought to have been stagnant and strongly melting, with the latter also potentially explaining the origin of the large amounts of water that passed through the detailed study area. If these traces had been formed in the early deglaciation stages, when Scandinavia was still largely covered by ice and there was probably still a flow of ice in this area (Hughes et al., 2016), these landforms would have probably been deformed by the ice movement (Benn and Evans, 2010).

5.3.3 Comparison to modelled flow paths

The water flow interpreted from the mapped glaciofluvial channels fits well with the flow calculated from the modelled hydraulic gradient (Figure 11). The modelled flow paths show the same general trends as the interpreted flow paths across the detailed study area, with flow paths showing the same flow directions as the interpreted flow.

Most of the modelled flow paths for the time steps investigated show very similar flow path positions (Appendix 6) due to the stable gradient evolution described in Section 5.3.1. On the other hand, modelled flow paths sometimes take surprising routes in relation to what was expected from the interpreted flow paths. One of the main surprises is that water from Fjelldokka is modelled to flow through the Fullsenn area and onwards to the Etne valley in the southeastern corner instead of exiting the eastern end of the Fjelldokka area. In addition, several of the modelled flow paths have a parallel displacement to the interpreted flows inferred from the mapped glaciofluvial channels.

When comparing the modelled flow to the interpreted flow, it is important to remember that more variability in hydraulic head, and therefore also hydraulic gradient and flow paths, is expected to be higher over time than was achieved in this study 5.3.1. In addition, the parallel displacement as well as some surprising flow directions may be caused by our interpreted flow directions showing the flow at a later time during the deglaciation which was not modelled in this study.

Thus, the relatively good fit between interpreted flow paths from mapped glaciofluvial features and flow paths calculated from modelled subglacial hydraulic head indicates that the model is reliable, even at the high resolution utilised here. The minor deviations between the differently derived path approximations shows the limitations of the model inherited from the limitations of the ice sheet thickness input data, as well as the limited time intervals modelled in this study in relative to when most water traces in the landscape are believed to have formed. To summarise, using models of subglacial hydrology at high resolution can be used to identify flow paths which can be connected to flow traces in the landscape. This approach leads to an improved understanding of the subglacial hydraulic system of the last ice sheet. Therefore, this type of modelling can be used actively to better understand the subglacial hydrological systems of the last ice age.

5.3.4 Model evaluation

A study by Shackleton et al. (2018) modelled subglacial water flow and storage in a similar fashion, but focused on the whole glaciated area of both the Fennoscandian ice sheet and the Barents Sea ice sheet. Shackleton et al. (2018) also used input data in the form of ice thickness and basal topography from Patton et al. (2016, 2017), the same source as this study. Shackleton et al. (2018) used an output grid resolution of 500x500 meters, i.e. 25 times larger than that used in this study. In addition, the study only regarded water storage in subglacial lakes and filtered out subglacial lakes smaller than 2 km^2 to avoid excessive noise and interpolation errors.

This study shows that the modelling approach of Shackleton et al. (2018) can be used to create a high-resolution subglacial hydrology model from a normal topographic DEM through downscaling of low-resolution ice sheet surface elevation and isostatic adjustment data. This down-scaling approach does not require filtering to avoid interpolation error for the central part of the ice sheet that is modelled in this study. The reason for this is that the only two datasets that are interpolated during down-scaling, the ice sheet surface elevation and isostatic adjustment grids, are expected to be smooth and only gently sloping for all modelled time steps in this area (see Sections 3.3.4, 5.3.1), and are therefore not expected to induce any error into the model.

As mentioned in Section 3.3.4, this study finds that present-day lake areas have low hydraulic gradients, due to the absence of lake bathymetry data for the present lakes. Areas under present-day lakes would probably still have areas of low gradient but, depending on the lake bathymetry, probably in more confined parts of the present-day lake extent. Fennoscandian lakes are known to be deep due to glacial processes and overdeepening (Fredin et al., 2013). However, lakes situated in flatter landscapes on mountain plateaus are likely not that deep (Fredin et al., 2013), likely causing larger areas of low gradient for these. This is expected to be the case in our detailed study area, as the rolling landscape of this area will probably not have caused the formation of deep lakes.

It is important to consider the uncertainty associated with the flotation factor in these model results also outside of a 10km buffer from the ice front. It is already known that subglacial channels are not always filled to the equivalent water pressure of the ice overburden pressure, as visualised in the empirical flotation factor. As described in Section 3.3.1, the flotation factor was selected based on a detailed consideration of literature spanning in situ measurements of subglacial water pressures as well as modelling studies. This field of study is still under active investigation however, and it is therefore crucial to consider a wide range of research, including the newest measurements, when selecting a flotation factor for future ice sheet hydrology models.

At the time steps 12 and 11 kya, the ice front is near enough to the bulk of the study area that the ice surface slope in the model input data starts changing. This affects the hydraulic gradient at these time. 11 kya time step for example, the ice front in the modelled data had reached the Hamar/Mjøsa region. Meierbachtol et al. (2013) found that pressure balances in subglacial channels and water cavities would hardly be stable over time near the ice front. The study estimated that the flotation factor only approaches 1 outside of a perimeter of approximately 10km from the ice front. This means that pressure conditions at the ice sheet base are not at levels which satisfy the assumptions for the hydraulic head equation within 10km of the ice front. Therefore, the modelling gradient near the ice front at 11 kya is uncertain, and the gradient distribution at this time step has less confidence.

To summarise, ice sheet thickness data from recent ice sheet modelling reconstruction downscaled using present-day topography DEMs can be used to model high resolution subglacial hydrology to identify realistic sink and flow path positions with distinct, but reasonable uncertainties and limitations. Uncertainties mainly stem from limitations in the input ice sheet thickness data, as well as a few defined limitations from the input basal topography.

5.4 Till composition and thickness in ribbed moraine fields

The general composition of the sediments in the detaield study area was as expected in both visual field observations and in the sediment samples. Very unsorted till consisting of grain sizes of all classes is present throughout most of the landscape. Boulders are also common in the sediment and are irregularly placed throughout the it. Fluvially deposited sediment is found in identified fluvial features and landforms.

However, in the Fjelldokka field several very large boulders and slabs were identified (Figure 16). These measured as much as 10 meters in their longest axis and are clearly visible in aerial photos. They were identified both on and around ribbed moraine ridges and hummocks. They seemed to be less present in between the ridges and in other flat parts of the landscape. Unfortunately, cuould not be determined if these rocks correspond with the bedrock underneath or not. Therefore, it is not possible to establish if they were eroded from between the ribbed moraine ridges or if they may originate from further away, for example the large Skaget mountain which is around 8 km away. If they were eroded from between the ridges, this may indicate a process like the one suggested by Sarala (2006, see Section 2.4), whilst a deposition of rocks with a further travel distance may indicate basal melting in the ribbed moraine field (Benn and Evans, 2010). Determining the origin of these rocks and slabs could therefore be a subject of investigation in future studies.

In addition to finding large boulders and slabs in the Fjelldokka area, bedrock outcrops were found in close vicinity to the ribbed moraine field in both the Fjelldokka and Skatrudstølen. These three observations indicate that the minimum till thickness needed to form ribbed moraines and also hummocky features may not be very large. Observations of till thicknesses in literature are rare, and little quantitative data regarding till thicknesses have been collected. An exception to this is a seismic survey that found till thicknesses of only "a few meters" in between ribbed moraine ridges in Borgström and Wastenson (1983), and a study using Ground Penetrating Radar (GPR) to investigate till in ribbed moraine fields on the Canadian Shield which could not determine the depth to the bedrock due to permafrost conditions, but found till thicknesses of at least 20 meters (Stokes et al., 2008).

Even though very few observations of till thicknesses in ribbed moraine fields have been made, they may still be of substantial importance to understanding ribbed moraine formation. Till thickness may, for example, be one of the boundary conditions for ribbed moraine formation, potentially controlling the transition between the formation of streamlined terrain, hummocks and ribbed moraine ridges. The Bed Ribbing Instability Explanation (BRIE) suggested by Dunlop et al. (2008), uses till thickness as one of the variables for their instability model of the till-ice interface. The till thicknesses selected for testing their model were however based on the simple assumption that till thickness is approximately half of the ridge height. Using the average ridge heights found in Dunlop and Clark (2006), a till thickness range of 0.5 to 30 meters is therefore used to test their model. This assumption is not based on measurements of the till thickness however, but is based on the idea that the wavelength of ribbed moraines correlates with the till thickness, an assertion that has never been tested. Therefore, having quantitative data regarding the till thickness in ribbed moraine fields would allow for testing of the BRIE. In addition, it would also allow for analysis regarding the influences of till thickness on other formation hypotheses, such as the till fracture hypotheses suggested by Kleman and Hättestrand (1999) and Sarala (2006), or those investigating the role of extensive or compressive flow on ribbed moraine formation (Stokes et al., 2008).

Many more observations than the three point observations made in this study would be necessary to be able to quantify potential boundary conditions for ribbed moraine formation till thicknesses. The need for a larger quantity of sedimentological investigations of ribbed moraine ridges to advance the research field has been pointed out by Dunlop and Clark (2006) and others. A good way to obtain a larger quantity of ground structure data is to use geophysical survey methods such as Ground Penetrating Radar (Davis and Annan, 1989). Stokes et al. (2008) successfully applied geophysical survey methods in the form of GPR surveys to investigate sediment composition and structures in ribbed moraine in Dubawnt Lake Ice Stream on the north-western Canadian Shield. As radar speeds of loose sediment and hard bedrock are very different causing good reflections in GPR data (Davis and Annan, 1989), this would be a good tool for determining till thickness.

GPR would be an especially fitting tool for further investigation of this study's detailed study area, as most ribbed moraine fields that were mapped have very good road access. There are also plenty of opportunities for traditional sedimentological investigations using excavation sites in the area, which can be used to verify the GPR surveys. Road accessibility and a number of small gravel quarries make the area suitable for excavations, but as around half of the area is protected as either a national park or a nature reserve (Putniņš and Henriksen, 2017) care needs to be taken to avoid these areas and obtain appropriate permits.

To summarise, determining the till thickness using GPR surveys could be very useful for further investigations into several hypotheses regarding ribbed moraine formation. Independently of the hypothesis investigated, a better understanding of till thicknesses and sedimentary structures of ribbed moraine ridges would contribute to the study of unconsolidated sediment and their deformation under glaciers and ice sheets.

5.5 Continuum indications

Through both the regional and detailed mapping, several key observations of the distribution of different landforms and landform fields were made.

One of the most distinct observations is that there is a close connection between ribbed moraines and hummocks. This was observed in the regional landform map (Figure5), where a vast majority of ribbed moraine fields have a buffer of hummocky/ribbed field around them (Sections 4.1.1), indicating a strong connection between these two field categories. In addition, hummocks were also found extensively in and around ribbed moraine fields in the detailed study area (Figure 12, 13), with the same observation also being made during the regional mapping (Section 4.1.1).

Another important observation from the detailed area is that hummocks often have streamlined tops just like many of the ribbed moraine ridges (Section 4.3.12). Most of these hummock forms are therefore interpreted to be formed subglacially together with the ribbed moraines, and will from now on be referred to as hummocky bedforms. As mentioned in Section 4.3.12 these hummocky bedforms were found to have forms ranging from almost completely round to more elongated in a transverse direction, or more streamlined in the ice flow direction. In addition, several hummocky bedforms often seemed to form lines, almost resembling ribbed moraine ridges, and other times ribbed moraines seemed to be comprised of several morphed hummocks.

Hummocky bedforms were also found to have localised transitions between streamlined areas and hummocky/ribbed areas. The most distinct transitions found in the detailed study area were observed in the western Fjelldokka area, the northern Yddeåne field and several locations in the Kjølastølen - Javnberget - Olevatnet area (Figure 13). In the regional area, hummocky/ribbed fields and streamlined fields often share borders (Figure 5), which may also indicate a transition between these fields and the landforms defined therein.

In the regional study area, many areas outside of the fully streamlined areas also contian streamlined features, as they are often found on both hummocks and ribbed moraines as well as in areas with only smaller till patches between bedrock (Section 4.1.1). It therefore seems some degree of streamlining is widespread throughout the whole landscape, and streamlining is common also in areas which predominantly contain other landforms.

Observations of transitions between transverse bedforms and longitudinal bedforms are by no means a new discovery, with many previous studies having noted similar connections. Lundqvist (1969 as cited in Lundqvist, 1989) defined the term "Rogen moraine" as transverse ridges with visible transitions to drumlins. Aario (1977b) identified a continuum between landform assemblages of flutings via drumlins to what was termed a "hummocky active-ice assemblage". This last assemblage consisted of ribbed moraine ridges and hummocks in various transitional forms. Also the study by Dunlop and Clark (2006) identified many transitions between both glacial lineations such as drumlins with ribbed moraine fields as well as overprinting of the different landforms in different configurations. These connections and continuum's have several times been suggested to form due to either the same processes or complementing processes, even thought the processes often were not specified (Aario, 1977a; Lundqvist, 1989). Ely et al. (2016) investigated and quantified the form and shape transitions between different glacial bedform to determine which bedform categories actually formed continuum's and subsequently could be formed by the same processes. Ely et al. (2016) found 3 distinctly separate continuum's, one consisting of ribbed moriane, one of glacial lineations and one of flute forms (Section 2.4). Ely et al. (2016) also found populations of quasi-circular bedforms that the study believed could be a transitional form between transverse features and lineations, with future research advised on these forms.

This study has identified a clear continuum between hummocky bedforms and ribbed moraine ridges. This study therefore suggests that hummocky bedforms could be a transitional form also to different glacial lineations, as suspected by Ely et al. (2016). Transitions between hummocky bedforms and glacial lineations of different size and form were also identified in several locations in both the regional and detailed study areas. However, a form and shape continuum between lineations and hummocky bedforms was not as evident as the continuum of the same forms to ribbed moraines, and this study can therefore not say with certainty that there is one single overarching continuum from ribbed moraines via hummocky bedforms to glacial lineations.

This study therefore recommends a quantification of the form and shape of hummocky bedforms to close the knowledge gap described in Ely et al. (2016) regarding their role in a possible continuum. Such a quantification campaign could be easily caarried out in Southern Norway in conjunction with a new mapping campaign of ribbed moraines based on new high resolution LiDAR DEM data, as mentioned in Section 5.1.

5.6 Ribbed moraine formation and subglacial water presence

5.6.1 Low hydraulic gradient areas and ribbed moraine fields

This study has found that ribbed moraines are consistently present in areas of low hydraulic gradient in the landscape. This is identified in both the quantitative analysis of the distribution of the hydraulic gradient in mapped ribbed moraine fields (Figure 8B; Section 4.2.1), and the manual spatial comparison of mapped ribbed moraine fields and areas of low hydraulic gradient (Figure 10). Some outliers are present , but these likely originate from both mapping and modelling uncertainties. In terms of mapping uncertainties, the mapped ribbed moraine fields are categorised by similar morphology in the form of groups of transverse ridges, but it cannot be proven that they are formed by the same process (Sections 3.1.2). Modelling uncertainties may also identify some areas with artificially high gradients (see Section 3.3.4). The vast majority of ribbed moraine fields cover areas of low hydraulic gradients through all time steps.

Areas of hummocky/ribbed fields were also found in a certain hydraulic gradient interval, but their distribution spans a much larger interval than ribbed moraine fields (Figure 8D, Section 4.2.1). The spatial distribution of hummocky/ribbed fields in the detailed study area (Figure 10) shows mostly similar development, but also shows that hummocky/ribbed fields are always situated around ribbed moraine fields (also visible in Figure 5), and often partially overlap low hydraulic gradient areas. Here, it is important to remember that the hummocky/ribbed field category is a diverse category spanning many unclear landforms, such as single transverse ridges and hummocks, but also transitional forms between channels, esker ridges and ribbed moraines, that could not confidently be categorised as ribbed moraines. These forms can be formed by different processes. Therefore, the fact that hummocky/ribbed fields do not consistently have low hydraulic gradients does not exclude the hummock bedforms included in that field category from forming in areas of low gradient.

In addition to the ribbed moraine fields being consistently present in areas of low hydraulic gradient, they are also found to be consistently present in areas of small elevation intervals (Figure 7A; Section 4.1.3). This indicates that almost all of the ribbed moraine fields occur in relatively flat areas with low slopes. This finding is also confirmed by the elevation profiles taken through the most prominent ribbed moraine fields in the detailed study area (Figures 15 and 22, Section 4.3.12). Few outliers present in this distribution are expected to originate from the same mapping uncertainties mentioned earlier. In addition, several of the ribbed moraine fields mapped in the southeastern part of the regional study area cover large, continuous areas, and it is therefore not surprising that they also span larger elevation intervals throughout these larger fields. Hummocky/ribbed fields on average also cover considerably larger elevation intervals than ribbed moraine fields, but not as large as the mapped streamlined fields (Figure 7; Section 4.1.3).

Finding ribbed moraine fields in areas with low hydraulic gradient and in flat areas is in accordance to what is expected. Central southern Norway is known to be the position of the southern end of the Fennoscandian ice sheet ice divide (Olsen et al., 2013; Sollid and Sørbel, 1994). The ice sheet surface is therefore believed to have been relatively flat and only gently sloping in this area (Olsen et al., 2013; Patton et al., 2016). An ice sheet surface with little slope situated over an area of flat topography will also cause low hydraulic gradients over this flat basal topography.

5.6.2 Water presence at the glacial bed

The results of the hydraulic modelling show clearly that ribbed moraines are present in areas of low hydraulic gradient. The modelling also shows that the ribbed moraine fields likely keep their low hydraulic gradient over the time period modelled in this study, except for the very last phase of the deglaciation (Figure 8, Sections 4.2.1 and 5.3.4). This study can therefore, with high levels of certainty, conclude that water would have collected under the ice sheet in the areas where ribbed moraine fields are found today.

This statement is however only valid if the glacial bed is warm-bedded over the modelled time period. Parts of the ice sheet bed are expected to have been cold-based during parts of the glaciation, but the extent in time and space is still a subject to active discussion (Olsen et al., 2013).The extent of cold-based areas below the ice sheet are justified and inferred through landscape features that show signs of preservation throughout the whole last glaciation. The features of this discussion are Tors and Blockfields, and are found in select areas of Fennoscandia, but none are present in our study area. Blockfields, the most common of the two features, are typically found in the high mountain areas of Norway and Sweden, such as the Jotunheimen mountains, which are at higher elevation than this study's area of interest (Olsen et al., 2013). In addition to Tors and Blockfields, ribbed moraines have also been used to infer cold-bedded conditions as described in Kleman and Hättestrand (1999). This connection assumes a specific formation process for ribbed moraine formation (Section 2.4) which is far from accepted in the academic discussion (Dunlop and Clark, 2006; Benn and Evans, 2010). In addition, no specific evidence for this formation process of ribbed moraines was identified in this study. Thus, this study will assume that the ice sheet in our study area was warm-based for substantial parts of the time period modelled in this study (23-22 kya), at least in the flatter valleys where ribbed moraines were identified. Observed widespread streamlining across the study areas also indicates that the ice sheet was warm-based at some point in time, as streamlined forms are associated with warm-based glacial beds (Benn and Evans, 2010).

Water plays a key role in the interaction between glacial ice and the underlying unconsolidated sediment (van der Meer et al., 2003; Benn and Evans, 2010; Iverson et al., 2007). Areas of low hydraulic gradient at the glacial bed under warm-based conditions will cause water to saturate the underlying unconsolidated sediment (Benn and Evans, 2010; Iverson et al., 2007). Larger amounts of water in the sediment will undoubtedly also change the conditions at the till-ice interface, and possibly trigger changes in the interaction between till and ice. This study therefore suggests that changes in the interaction between till and ice due to water saturation of the till triggers ribbed moraine formation.

5.6.3 Possible implications for ribbed moraine formation

Several other ribbed moraine formation hypotheses have previously suggested that subglacial water presence may have affected the formation of ribbed moraines and other associated bedforms, although not necessarily triggered by changed till-ice interaction:

- Sollid and Sørbel (1984, 1994) suggested that ribbed moraines formed in pockets of unfrozen water that were left in landscape depressions during a downwards freezing process of the ice sheet. This downwards temperature regime change of the ice sheet from cold to warm-based is expected to have happened sometime before the last glacial maximum, preserving the ribbed moraine throughout most of the ice age.

- Stokes et al. (2008) found that ribbed moraines in Northern Canada may be caused by a sudden change in ice dynamics due to ice stream shut-down causing a change from extensive to compressive ice flow. The study mentions two processes which may have caused compressive flow during ice stream shutdown, one being that partial freezing of the bed during late deglaciation stages may cause high friction areas and therefore compressive flow. However, the favoured process by Stokes et al. (2008) is a de-watering of the glacial bed due to a change in subglacial drainage system from linked-cavity-like drainage to efficient channels, causing friction and compressive flow.

- Dunlop et al. (2008) acknowledged the effect of water on the subglacial till when testing the BRIE model of ribbed moraine formation by instabilities at the till-ice interface. Dunlop et al. (2008) however only used an indirect analogy for the bed drainage in the form of an effective pressure variable in his model. The model and testing of it undertaken by Dunlop et al. (2008) are however very theoretical, and use generalised ranges for the tested parameters. They therefore do not achieve a straightforward answer regarding the accuracy of the BRIE for replicating ribbed moraine formation.

The idea described by Sollid and Sørbel (1984, 1994) does not state a specific formation process, and is therefore hard to evaluate as a hypothesis in light of this study's results. Their suggestion does not disagree with the findings of this study, and such a downwards temperature regime change scenario is possible, especially if widespread cold-based conditions under the ice sheets are presumed.

The suggestion by Stokes et al. (2008) would fit with the hydraulic gradient results of this study which show that water was present in the ribbed moraine fields of our area. This would allow for a transition to a more effective drainage system during the deglaciation. However, their formation suggestion does not fit with other results of this study. The widespread streamlining of ribbed moraine ridges and hummock crest in our study area, for example, does not seem compatible with a formation of the ribbed moraines at the very end of the deglaciation during an ice stream shut-down. Faster ice flow over the ribbed moraines and also large parts of the remaining landscape, as identified in this study, opposes the idea of ribbed moraine formation during a last slow-down of the glacial ice. In addition, their formation suggestion does not fit with the large glaciofluvial channels observed entering and exiting ribbed moraine fields in our study area. If these channels are a consequence of more efficient flow during ice stream shut-down, this would have led a lot of water into the ribbed moraine field areas. Efficient water flow leading large amounts of meltwater in and out of these areas does not seem compatible with compressive flow forming ribbed moraine ridges.

The investigation of the BRIE model by Dunlop et al. (2008) could fit with the results of this study, as the BRIE model was tested for varying degrees of bed drainage through an indirectly related variable. However, the BRIE is a theoretical model which to date is not tested thoroughly enough to be able to entirely confirm that it is the correct formation mode of ribbed moraines, as this would require knowing the approximate physical parameters (such as pressure conditions and till rheology) in the subglacial environment at ribbed moraines formation (Dunlop et al., 2008).

Nonetheless, areas of low gradient and subsequent water-saturated till at the glacial bed may fit with an adjusted instability hypothesis similar to the one tested in Dunlop et al. (2008). An instability forming both ribbed moraines and hummocky bedforms could be triggered by changes to the till-ice interface due to water presence under the ice sheets. Such an instability could allow for the continuous development of ribbed moraines and hummocky bedforms in areas of low hydraulic gradient under the ice sheet. Hummocky bedforms are interpreted to also be a consequence of water-saturated till at the glacial bed even though they do not consistently show low gradient inside them. Mapping ambiguities surrounding hummocky bedforms and other unclear features (Section 3.1.2, 5.6.1) are suspected to have expanded the hummocky/ribbed fields category beyond where it shows a consistent connection to low gradient areas. Due to time constraints, it was not possible for this study to test this notion, and it is therefore recommended for future research in conjunction with more general investigations into hummocky bedforms and their relation to ribbed moraines and other bedforms.

To summarise, this study deems it likely that water-saturated till presence at the glacial bed may be the triggering factor for instabilities at the till- ice interface, forming ribbed moraine ridges and hummock bedforms. This due to the observed continuum between ribbed moraines and hummocky bedforms in the study area, the consistent presence of ribbed moraine fields in areas where low hydraulic gradients and therefore water-saturated till, and the inadequate match of other formation hypotheses which include subglacial water presence to the collective results of this study.

5.6.4 Interpretation of subglacial flow through ribbed moraine fields

Large glaciofluvial traces have been found entering and exiting ribbed moraine fields in the detailed study area (Section 4.3.12), indicating that large amounts of water passed through these fields at some point in time. Modelling of subglacial streams confirmed that subglacial water prefers to flow through ribbed moraine fields between these entry and exit points (Section 5.3.2). This seems contradictory to the conclusion drawn on Section 5.6.2 where water is mainly present at the glacial bed in unconsolidated sediment through saturating the subgalcial till. However, a modelling study by Walder and Fowler (1994) suggests that a dense network of broad, shallow, anamostosing canals will form in the sediment if subglacial water pressures rise well above overburden pressures. This may be similar to that identified by King et al. (2004), who found a dense network of shallow channels or a similar morphology in unconsolidated sediment at the onset of the Rutford Ice Stream in Antarctica using seismic surveys. The anomaly identified in the study was over 1km long and mostly around 200 meters wide, and was calculated to have a water depth of less than 1 meter (King et al., 2004).

This study therefore suggests that larger amounts of water identified to have entered and exited the ribbed moraine field may have increased the water pressures, changing the hydraulic conditions from a mode of water presence in the underlying till to a dense network of water channels flowing between the previously formed ribbed moraines. Such a situation is expected to have occurred during the later stages of the deglaciation, when the melting of the ice sheet also reached the central parts of the ice sheet including the study areas (Fredin et al., 2013). This water is expected to have flowed efficiently through the landscape in subglacial channels, whose traces were identified entering and exiting the areas. When the water entered the ribbed moraine fields with low hydraulic gradients and subsequent high water pressures, this may have caused a more spread, slow flow. This would explain why the ribbed moraine fields do not show many fluvial alterations.

This would explain the streamlining traces found on countless ribbed moraine ridge crests and hummocky bedform tops. These may have been formed due to ice flow during this spread, channelised mode of water flow in the ribbed moraine areas. Due to the water situated between the ribbed moraine ridges, the ice will only have been able to streamline the upper portion of ribbed moraines and hummocky bedforms. This would additionally also explain the complete, but superficial streamlining observed on individual ribbed moraine ridges and hummocks outside of ribbed moraine fields (Section 4.3.12), such as throughout the Kjølastølen - Javnberget - Olevatnet area (Section 4.3.7). As individual, more spread ridges and hummocks likely did not experience spread slow flow as in the larger ribbed moraine fields with low hydraulic gradients, they will have received traces of streamlining from post-formation ice flow on their sides as well as their ridge crests.

To summarise, increased subglacial water flow in and out of ribbed moraine areas occurred during the late deglaciation and after ribbed moraine formation. Due to increased subglacial water pressures and volumes, water flow spread out in the ribbed moraine fields, causing slow water flow between ribbed moraine ridges and hummocky bedforms. This spread and slow water flow did not greatly alter the sediment in the ribbed moraine fields. Ribbed moraines and hummocky bedforms are only have streamlined ridge crests and tops due to water present between them, while single, more spread ridges and hummocks are superficially streamlined across their complete height.

6 Conclusions

To investigate ribbed moraines and their formation, this study has mapped bedform fields in a regional study area as well as individual bedforms and glaciofluvial traces in a detailed study area. Furthermore, a high-resolution model of the subglacial hydrology was constructed to calculate areas of low hydraulic gradient, areas of sinks indicating subglacial lakes and modelled subglacial flow paths in the study areas.

Regarding ribbed moraines, this study can conclude that:

- Throughout the study, a widespread and distinct continuum in size, shape and location has been identified between ribbed moraine ridges and hummocky bedforms. Furthermore, a continuum from hummocky bedforms to glacial lineations has been partially identified, and is anticipated, but not confirmed, to form a complete continuum from ribbed moraines via hummocky bedforms to glacial lineations.
- Ribbed moraine fields were found to be consistently located in areas of low modelled hydraulic gradient. Ribbed moraines are also consistently situated in flat areas in the landscape.
- This study has subsequently found that water would collect under the ice sheet in present-day ribbed moraine fields, saturating the subglacial till. Interactions at the till-ice interface would change due to water saturation and could potentially be a trigger for the initiation of the ribbed moraine formation process.
- An instability process (similar to that investigate din Dunlop et al., 2008) could facilitate the previous conclusion of changed conditions at the till-ice interface controlling ribbed moraine formation. This study therefore suggests that ribbed moraine ridges and hummock bedforms may be the result of a till-ice instability process initiated and/or facilitated by water presence at the glacial bed.
- During the late deglaciation and after ribbed moraine formation, increased amounts of subglacial water flowed through ribbed moraine fields. Water entered and exited the fields through efficient subglacial channels, but flowed slowly in the ribbed moraine fields, spread between the ribbed moraine ridges and hummocks.

In addition, this study can also state that:

- The subglacial hydraulic model constructed in this study successfully utilises a present-day DEM and downscaled ice thickness data to produce high-resolution subglacial hydraulic head outputs. Furthermore, modelled subglacial flow paths fit well with flow directions interpreted from glaciofluvial traces, showing the applicability of modelling subglacial hydrology at this resolution. The model has distinct and easily identifiable limitations.
- Large differences in the ribbed moraine distribution between a previous study and the present study are attributed to the large advantages of new high-resolution LiDAR DEMs utilised in the present study. A new mapping campaign of ribbed moraines and associated bedforms in Southern Norway using these DEMs is recommended to avoid dependencies on incomplete data for future research on ribbed moraines.

- Ambiguous definitions of ribbed moraines and associated bedforms are problematic during mapping and interpretation of results in light of existing studies. Simplified, purely morphological definitions should be used to avoid mapping bias and to assist advancing the research field.
- Flat bedrock outcrops observed in ribbed moraine fields indicate low till thicknesses between ribbed moraine ridges. Till thicknesses in ribbed moraine fields have hardly been investigated, but may yield valuable findings for research on ribbed moraine formation. Surveys of till thickness using Ground Penetrating Radar are therefore recommended.

References

Aario, R. (1977a). Associations of flutings, drumlins, hummocks and transverse ridges. *GeoJournal*, 1(6):65–72.

Aario, R. (1977b). Classification and terminology of morainic landforms in Finland. *Boreas*, 6(2):87–100.

Aylsworth, J. and Shilts, W. (1989). Bedforms of the Keewatin ice sheet, Canada. *Sedimentary Geology*, 62(2-4):407–428.

Banwell, A. F., Willis, I. C., and Arnold, N. S. (2013). Modeling subglacial water routing at Paakitsoq, W Greenland. *Journal of Geophysical Research: Earth Surface*, 118(3):1282–1295.

Benn, D. and Evans, D. J. (2010). *Glaciers and glaciation*. Routledge.

Boggs, S. (1995). *Principles of sedimentology and stratigraphy*. Prentice Hall New Jersey.

Borgström, I. and Wastenson, L. (1983). *Geomorfologiska kartbladet 17 C FUNÄSDALEN: Beskrivning och naturvärdesbedömning*. Naturvårdsverket.

Bouchard, M. A. (1989). Subglacial landforms and deposits in central and northern Quebec, Canada, with emphasis on Rogen moraines. *Sedimentary Geology*, 62(2-4):293–308.

Boulton, G. (1987). A theory of drumlin formation by subglacial sediment. In *Drumlin Symposium. Balkema, Rotterdam*.

Bryn, A. and Potthoff, K. (2018). Elevational treeline and forest line dynamics in Norwegian mountain areas–a review. *Landscape Ecology*, 33(8):1225–1245.

Carter, S. P., Blankenship, D. D., Peters, M. E., Young, D. A., Holt, J. W., and Morse, D. L. (2007). Radar-based subglacial lake classification in Antarctica. *Geochemistry, Geophysics, Geosystems*, 8(3).

Clarke, G. K. (2005). Subglacial processes. *Annu. Rev. Earth Planet. Sci.*, 33:247–276.

Davis, J. L. and Annan, A. P. (1989). Ground-penetrating radar for high-resolution mapping of soil and rock stratigraphy. *Geophysical prospecting*, 37:531–551.

Dunlop, P. (2004). *The characteristics of ribbed moraine and assessment of theories of their genesis.* PhD thesis, University of Sheffield.

Dunlop, P. and Clark, C. D. (2006). The morphological characteristics of ribbed moraine. *Quaternary Science Reviews*, 25(13-14):1668–1691.

Dunlop, P., Clark, C. D., and Hindmarsh, R. C. (2008). Bed ribbing instability explanation: testing a numerical model of ribbed moraine formation arising from coupled flow of ice and subglacial sediment. *Journal of Geophysical Research: Earth Surface*, 113(F3).

Ely, J. C., Clark, C. D., Spagnolo, M., Stokes, C. R., Greenwood, S. L., Hughes, A. L., Dunlop, P., and Hess, D. (2016). Do subglacial bedforms comprise a size and shape continuum? *Geomorphology*, 257:108–119.

Engelhardt, H. and Kamb, B. (1997). Basal hydraulic system of a West Antarctic ice stream: constraints from borehole observations. *Journal of Glaciology*, 43(144):207–230.

Etzelmüller, B., Romstad, B., and Fjellanger, J. (2007). Automatic regional classification of topography in Norway. *Norwegian Journal of Geology/Norsk Geologisk Forening*, 87.

Fisher, T. G. and Shaw, J. (1992). A depositional model for Rogen moraine, with examples from the Avalon Peninsula, Newfoundland. *Canadian Journal of Earth Sciences*, 29(4):669–686.

Fredin, O., Bergstrøm, B., Eilertsen, R., Hansen, L., Longva, O., Nesje, A., and Sveian, H. (2013). Glacial landforms and Quaternary landscape development in Norway. In Olsen, L., Fredin, O., and Olesen, O., editors, *Quaternary Geology of Norway*, pages 5–27. Geological Survey of Norway Special Publication, 13, Trondheim.

Hättestrand, C. (1997). Ribbed moraines in Sweden — distribution pattern and palaeoglaciological implications. *Sedimentary Geology*, 111(1-4):41–56.

Hättestrand, C. and Kleman, J. (1999). Ribbed moraine formation. *Quaternary Science Reviews*, 18(1):43–61.

Hindmarsh, R. C. (1998a). Drumlinization and drumlin-forming instabilities: viscous till mechanisms. *Journal of Glaciology*, 44(147):293–314.

Hindmarsh, R. C. (1998b). Ice-stream surface texture, sticky spots, waves and breathers: the coupled flow of ice, till and water. *Journal of Glaciology*, 44(148):589–614.

Hindmarsh, R. C. (1998c). The stability of a viscous till sheet coupled with ice flow, considered at wavelengths less than the ice thickness. *Journal of Glaciology*, 44(147):285–292.

Hindmarsh, R. C. (1999). Coupled ice-till dynamics and the seeding of drumlins and bedrock forms. *Annals of Glaciology*, 28:221–230.

Hodgson, M. E. and Bresnahan, P. (2004). Accuracy of airborne lidar-derived elevation. *Photogrammetric Engineering & Remote Sensing*, 70(3):331–339.

Hughes, A. L., Gyllencreutz, R., Lohne, Ø. S., Mangerud, J., and Svendsen, J. I. (2016). The last Eurasian ice sheets–a chronological database and time-slice reconstruction, DATED-1. *Boreas*, 45(1):1–45.

Iverson, N. R., Hooyer, T. S., Fischer, U. H., Cohen, D., Moore, P. L., Jackson, M., Lappegard, G., and Kohler, J. (2007). Soft-bed experiments beneath engabreen, norway: regelation infiltration, basal slip and bed deformation. *Journal of Glaciology*, 53(182):323–340.

Kamb, B. (2001). Basal zone of the West Antarctic ice streams and its role in lubrication of their rapid motion. *The West Antarctic ice sheet: behavior and environment*, 77:157–199.

King, E. C., Woodward, J., and Smith, A. M. (2004). Seismic evidence for a water-filled canal in deforming till beneath Rutford Ice Stream, West Antarctica. *Geophysical Research Letters*, 31(20).

Kleman, J. and Hättestrand, C. (1999). Frozen-bed Fennoscandian and Laurentide ice sheets during the Last Glacial Maximum. *Nature*, 402(6757):63–66.

Lindbäck, K., Pettersson, R., Hubbard, A. L., Doyle, S. H., van As, D., Mikkelsen, A. B., and Fitzpatrick, A. A. (2015). Subglacial water drainage, storage, and piracy beneath the Greenland ice sheet. *Geophysical Research Letters*, 42(18):7606–7614.

Livingstone, S., Clark, C., Woodward, J., and Kingslake, J. (2013a). Potential subglacial lake locations and meltwater drainage pathways beneath the Antarctic and Greenland ice sheets. *Cryosphere*, 7(6):1721–1740.

Livingstone, S. J., Clark, C. D., and Tarasov, L. (2013b). Modelling North American palaeo-subglacial lakes and their meltwater drainage pathways. *Earth and Planetary Science Letters*, 375:13–33.

Lundqvist, J. (1989). Rogen (ribbed) moraine—identification and possible origin. *Sedimentary Geology*, 62(2-4):281–292.

Lundqvist, J. (1997). Rogen moraine — an example of two-step formation of glacial landscapes. *Sedimentary Geology*, 111(1-4):27–40.

Martinsen, O. J., Nøttvedt, A., and Pedersen, R. B. (2008). Norway rises from the sea. In Ramberg, I. B., Bryhni, I., Nøttvedt, A., and Rangnes, K., editors, *The making of a land: geology of Norway*, chapter 14, pages 442–479. Norwegian Geological Association, Trondheim.

Meierbachtol, T., Harper, J., and Humphrey, N. (2013). Basal drainage system response to increasing surface melt on the Greenland ice sheet. *Science*, 341(6147):777–779.

Minell, H. (1980). The distribution of local bedrock material in some moraine forms form the inner part of northern Sweden. *Boreas*, 9(4):275–281.

Möller, P. (2006). Rogen moraine: an example of glacial reshaping of pre-existing landforms. *Quaternary Science Reviews*, 25(3-4):362–389.

Möller, P. and Dowling, T. P. (2015). The importance of thermal boundary transitions on glacial geomorphology; mapping of ribbed/hummocky moraine and streamlined terrain from LiDAR, over Småland, South Sweden. *Gff*, 137(4):252–283.

Möller, P. and Dowling, T. P. (2018). Equifinality in glacial geomorphology: instability theory examined via ribbed moraine and drumlins in Sweden. *GFF*, 140(2):106–135.

Norwegian Mapping Authority (2019a). Høydedata og terrengmodeller for landområdene. `https://www.kartverket.no/data/Hoydedata-og-terrengmodeller/`. Last viewed 03.06.2020.

Norwegian Mapping Authority (2019b). Kartverkets sentralarkiv for flyfoto og satellittbilder. `https://www.kartverket.no/geodataarbeid/Flyfoto/Sentralarkiv-for-flyfoto`. Last viewed 26.02.2020.

Norwegian Mapping Authority (2019c). Nasjonalt program for omløpsfotografering. `https://www.kartverket.no/geodataarbeid/Flyfoto/Nasjonalt-program-for-omlopsfotografering/`. Last viewed 26.02.2020.

Norwegian Mapping Authority (2019d). Om nasjonal detaljert høydemodell (ndh). `https://www.kartverket.no/Prosjekter/Nasjonal-detaljert-hoydemodell/om-nasjonal-detaljert-hoydemodell/`. Last viewed 03.06.2020.

Olsen, L., Sveian, H., Bergstrøm, B., Ottesen, D., and Rise, L. (2013). Quaternary glaciations and their variations in Norway and on the Norwegian continental shelf. *Quaternary Geology of Norway*, 13:27–78.

Patton, H., Hubbard, A., Andreassen, K., Auriac, A., Whitehouse, P. L., Stroeven, A. P., Shackleton, C., Winsborrow, M., Heyman, J., and Hall, A. M. (2017). Deglaciation of the Eurasian ice sheet complex. *Quaternary Science Reviews*, 169:148–172.

Patton, H., Hubbard, A., Andreassen, K., Winsborrow, M., and Stroeven, A. P. (2016). The build-up, configuration, and dynamical sensitivity of the Eurasian ice-sheet complex to Late Weichselian climatic and oceanic forcing. *Quaternary Science Reviews*, 153:97–121.

Peterson, G., Johnson, M. D., and Smith, C. A. (2017). Glacial geomorphology of the south Swedish uplands–focus on the spatial distribution of hummock tracts. *Journal of Maps*, 13(2):534–544.

Putniņš, A. and Henriksen, M. (2017). Reconstructing the flow pattern evolution in inner region of the Fennoscandian Ice Sheet by glacial landforms from Gausdal Vestfjell area, south-central Norway. *Quaternary Science Reviews*, 163:56–71.

Sarala, P. (2006). Ribbed moraine stratigraphy and formation in southern Finnish Lapland. *Journal of Quaternary Science: Published for the Quaternary Research Association*, 21(4):387–398.

Schwanghart, W. and Kuhn, N. J. (2010). TopoToolbox: A set of Matlab functions for topographic analysis. *Environmental Modelling & Software*, 25(6):770–781.

Schwanghart, W. and Scherler, D. (2014). TopoToolbox 2–MATLAB-based software for topographic analysis and modeling in Earth surface sciences. *Earth Surface Dynamics*, 2(1):1–7.

Shackleton, C., Patton, H., Hubbard, A., Winsborrow, M., Kingslake, J., Esteves, M., Andreassen, K., and Greenwood, S. L. (2018). Subglacial water storage and drainage beneath the Fennoscandian and Barents Sea ice sheets. *Quaternary Science Reviews*, 201:13–28.

Shreve, R. (1972). Movement of water in glaciers. *Journal of Glaciology*, 11(62):205–214.

Siegert, M. J. (2000). The identification, examination and exploration of Antarctic subglacial lakes. *Science Progress (1933-)*, pages 223–242.

Sigmond, E. M. O. (1992). Bergrunn Norge med havområder, 1:3 000 000. *Nasjonal Atlas for Norge, Norges Geologiske Undersøkelse.*

Sollid, J. and Torp, B. (1984). Glasiogeologisk kart over Norge, 1:1 000 000. *Nasjonal Atlas for Norge, Geografisk Institutt, Universitetet i Oslo.*

Sollid, J. and Trollvik, J. (1991). Oppland Fylke, Kvartærgeologi og geomorpfologi, 1:250 000. *Institutt for Naturgeografi, Universitetet i Oslo.*

Sollid, J. L. and Sørbel, L. (1984). Distribution and genesis of moraines in central norway. *Striae*, 20:63–67.

Sollid, J. L. and Sørbel, L. (1994). Distribution of glacial landforms in southern Norway in relation to the thermal regime of the last continental ice sheet. *Geografiska Annaler: Series A, Physical Geography*, 76(1-2):25–35.

Stokes, C. R., Lian, O. B., Tulaczyk, S., and Clark, C. D. (2008). Superimposition of ribbed moraines on a palaeo-ice-stream bed: implications for ice stream dynamics and shutdown. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, 33(4):593–609.

Thoresen, M. (1990). Quaternary map of Norway, scale 1:1 million. *Geological Survey of Norway.*

Trommelen, M. S., Ross, M., and Ismail, A. (2014). Ribbed moraines in northern Manitoba, Canada: characteristics and preservation as part of a subglacial bed mosaic near the core regions of ice sheets. *Quaternary Science Reviews*, 87:135–155.

van der Meer, J. J., Menzies, J., and Rose, J. (2003). Subglacial till: the deforming glacier bed. *Quaternary Science Reviews*, 22(15-17):1659–1685.

Vorren, T. O. and Mangerud, J. (2008). Glaciations come and go. In Ramberg, I. B., Bryhni, I., Nøttvedt, A., and Rangnes, K., editors, *The making of a land: geology of Norway*, chapter 15, pages 480–533. Norwegian Geological Association, Trondheim.

Walder, J. S. and Fowler, A. (1994). Channelized subglacial drainage over a deformable bed. *Journal of Glaciology*, 40(134):3–15.

Wentworth, C. K. (1922). A scale of grade and class terms for clastic sediments. *The journal of geology*, 30(5):377–392.

Wingham, D. J., Siegert, M. J., Shepherd, A., and Muir, A. S. (2006). Rapid discharge connects Antarctic subglacial lakes. *Nature*, 440(7087):1033–1036.

Wright, A. and Siegert, M. (2012). A fourth inventory of Antarctic subglacial lakes. *Antarctic Science*, 24(6):659–664.

Wright, P. J., Harper, J. T., Humphrey, N. F., and Meierbachtol, T. W. (2016). Measured basal water pressure variability of the western Greenland Ice Sheet: Implications for hydraulic potential. *Journal of Geophysical Research: Earth Surface*, 121(6):1134–1147.

Zhang, K., Chen, S.-C., Whitman, D., Shyu, M.-L., Yan, J., and Zhang, C. (2003). A progressive morphological filter for removing nonground measurements from airborne lidar data. *IEEE transactions on geoscience and remote sensing*, 41(4):872–882.

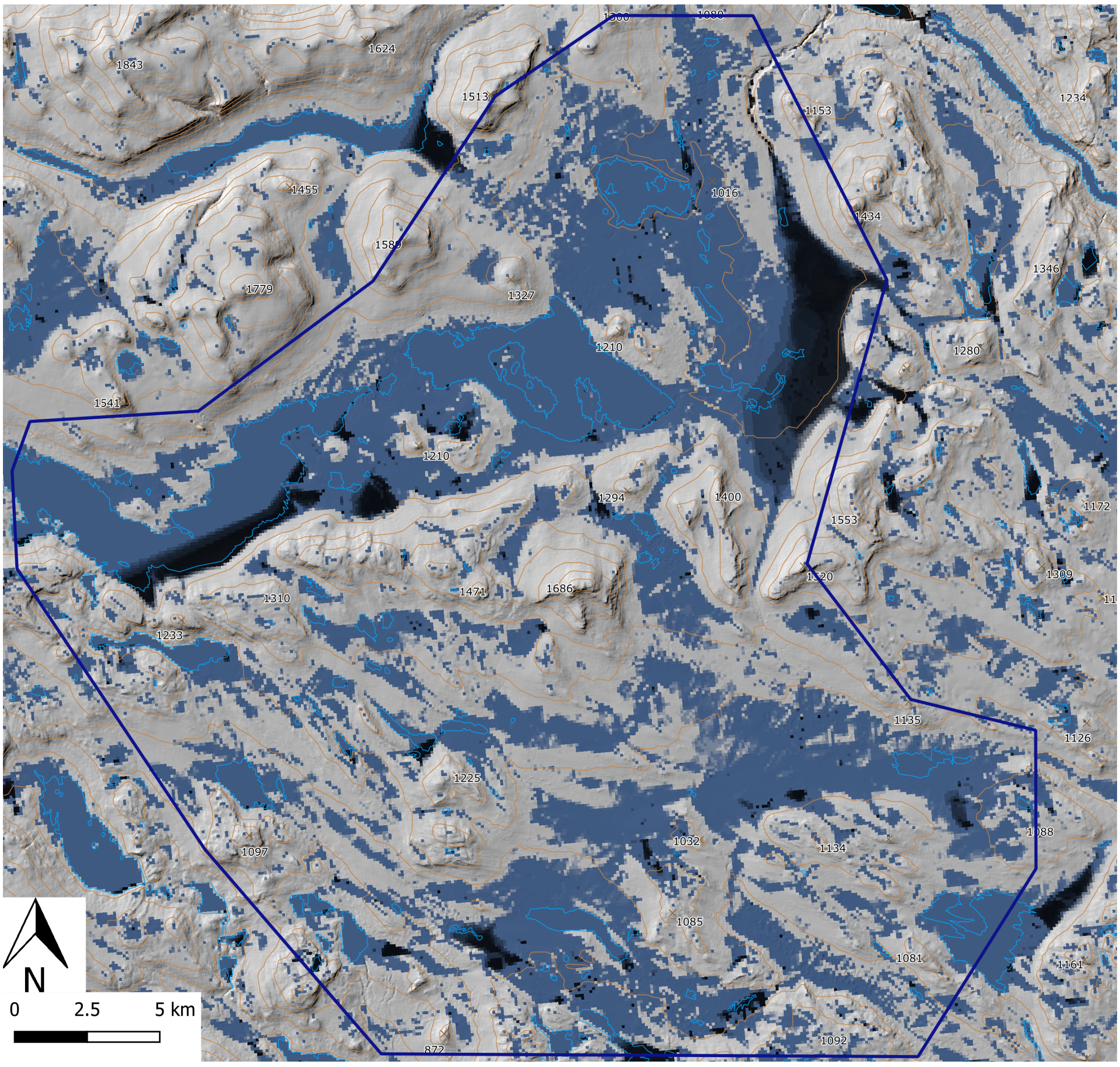
Appendix 1 - Areas of low gradient and sinks over time

Map of low gradient areas (below 0.02 m/m gradient, in dark blue) and sinks (black) for all modelled time steps in the detailed study area (blue line).

Areas of low gradient are marked in blue, with a very dark blue pixel colour indicating that all time steps had a gradient of less than 0.02 m/m at that location, and lighter shades marking less time steps at low gradient.

Sinks are marked in grey, with a black pixel colour indicating that all time steps had a sink present. Shades of grey indicate less time steps with sink presence.

In addition, elevation contour lines are shown in brown, elevation points are shown with numbers, and lake outlines are shown in light blue. These are part of the map dataset "Norgeskart" by the Norwegian Mapping Authority (see Table 2).



Appendix 2 - Modelled flow paths and sinks over time

Map with overlay of the modelled subglacial water flow paths (red) and sinks (black) of all modelled time steps in the detailed study area (blue line).

Flow paths of all time steps are marked in red. The intensity of the red colour shows the number of upstream cells draining through these flow paths (see scale in legend for colour intensity interval).

Sinks are marked in grey, with a black pixel colour indicating that all time steps had a sink present. Shades of grey indicate less time steps with sink presence.

In addition, elevation contour lines are shown in brown, elevation points are shown with numbers, and lake outlines and extents are shown in light blue. These are part of the map dataset "Norgeskart" by the Norwegian Mapping Authority (see Table 2).