Mapping of Quaternary Geomorphology in Southern Dalarna: a LiDAR Study

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Abstract

The Quaternary has been a period that has seen a fluctuation in glaciation, in Sweden, for 2.5 million years, with the last glaciation vanishing around 9.6 cal kyr BP. Left behind are glacial landforms that can help us understand the behavior of the ice and the processes which shape our landscape. Earlier works has set out to map these landforms and to determine the history of the ice. Since the advent of LiDAR, mapping these features has become easier and more precise, and they can be used to make detailed maps. Since it is a relatively new tool, the extent of mapped features is limited. The purpose of this study is to map glacial landforms in southern Dalarna, central Sweden, where no LiDAR mapping has been done before, and to further connect what is found to earlier works. What glacial landforms are prominent in the area and what are their extent? To find out, mapping was undertaken in QGIS using LiDAR data; where shapefiles (lines and polygons) came to represent the mapped landforms. Lineations, meltwater channels, eskers and murtoos fields became the four feature categories which were mapped. The extent of the mapped features, is used to draw conclusions regarding their quantity and extent and to further connect them to earlier works, such as an ice-margin map over the deglaciation of Fennoscandia. Meltwater channels are abundant but their spread was limited to a few areas. Eskers have a high spread but were few in number, while sometimes being very large in regards to their length. Murtoos fields are few in number but are prone to cover large areas in the few places where they appear. The most mapped feature is glacial lineations, which were spread out in almost every part of the study area and were high in quantity. Using the general orientation of the lineations, a comparison could be drawn between the lineations and the ice-margin map over the deglaciation of Fennoscandia. The comparison showed that the ice-margin map agreed with the mapped lineations. The landforms found also tells of a rapid deglaciation and the ice being warm bottomed.

1. Introduction

The Quaternary Period has been a period of varied climate with a significant fluctuation between warmer and cooler temperatures. The period which has been dubbed the “ice age”, hosted glaciations and deglaciations in Northern Europe for more than 2.5 Million years. This fluctuation in glaciation continued all the way to the early Holocene (Batchelor et al., 2019) and is therefore a part of our recent history in geological terms. To understand this part of history is to understand how the glaciers behave and how they shape the land we live on. To study the ice’s movement, expansion and retreat one can look at the different landforms that the glacier has left behind. Previously, the mapping of these features, has been a process of tedious work where the mapping was undertaken by studying aerial photographs, satellite imagery, and topographic maps, which are difficult to interpret. With the advent of LiDAR, the process of mapping has become more accessible and faster to carry out (Johnson et al., 2015). Processing the LiDAR data through a GIS-software, reveals the expansive patterns the ice has left behind, and in the wake of LiDAR, new glacial landforms has been discovered, such as Murtoos (Ojala et al., 2019). Studies has already set out to map glacial features in Sweden using LiDAR, but since it is a recent technology, the extents of mapped areas are limited. There is still plenty of land, and features, that are not mapped in Sweden. The region Dalarna, which is located in central Sweden, has been mapped in some parts, such as the geomorphologic map over the Siljan area (Smith and Peterson, 2014). The south of Dalarna has not been mapped using LiDAR, and since it is an area that has been ice free for just about ten thousand years (Stroeven et al., 2016), it begs the question; which glacial landforms are prominent in the area?

1.1. Aim

This study sets out to map glacial landforms in an area in Southern Dalarna and connect it to the geomorphologic map of the Siljan area, produced by Smith and Peterson (2014).

1.2. Research Questions

- Which glacial landforms are prominent in the study area?
- What is the geographical spread of the landforms?
- Does the glacial lineation orientation align with the predicted ice margin?
- What does the landforms found say about the ice?

1.3. Latest Glaciation in Sweden

Sweden has been ice-free for most of the Holocene, but looking back at the larger part of the Quaternary, the country has been more or less covered in ice many times. Before the deglaciation of Fennoscandia (22-9.7 cal kyr BP) and sometime during the deglaciation, the ice sheet covering Sweden was more akin to what can be seen on Greenland and Antarctica today (Stroeven et al., 2016) (Figure 1). Before the retreat of ice, during, the Last Glacial Maximum (LGM), the ice sheet stretched all the way to the northern parts of Germany and Poland, and reached eastward to engulf the Baltics and the northwestern parts of Russia (Figure 1). After the LGM, the ice retreated until it was entirely gone around 10 cal kyr BP (Stroeven et al., 2016) (Hughes et al., 2015). In between LGM and the end of the glaciation, a cooler episode occurred in the northern hemisphere which lasted between about 12.9-11.7 kya. That episode is called the Younger Dryas cold event (YD) (Johnson et al., 2019) (Carlson, 2013).

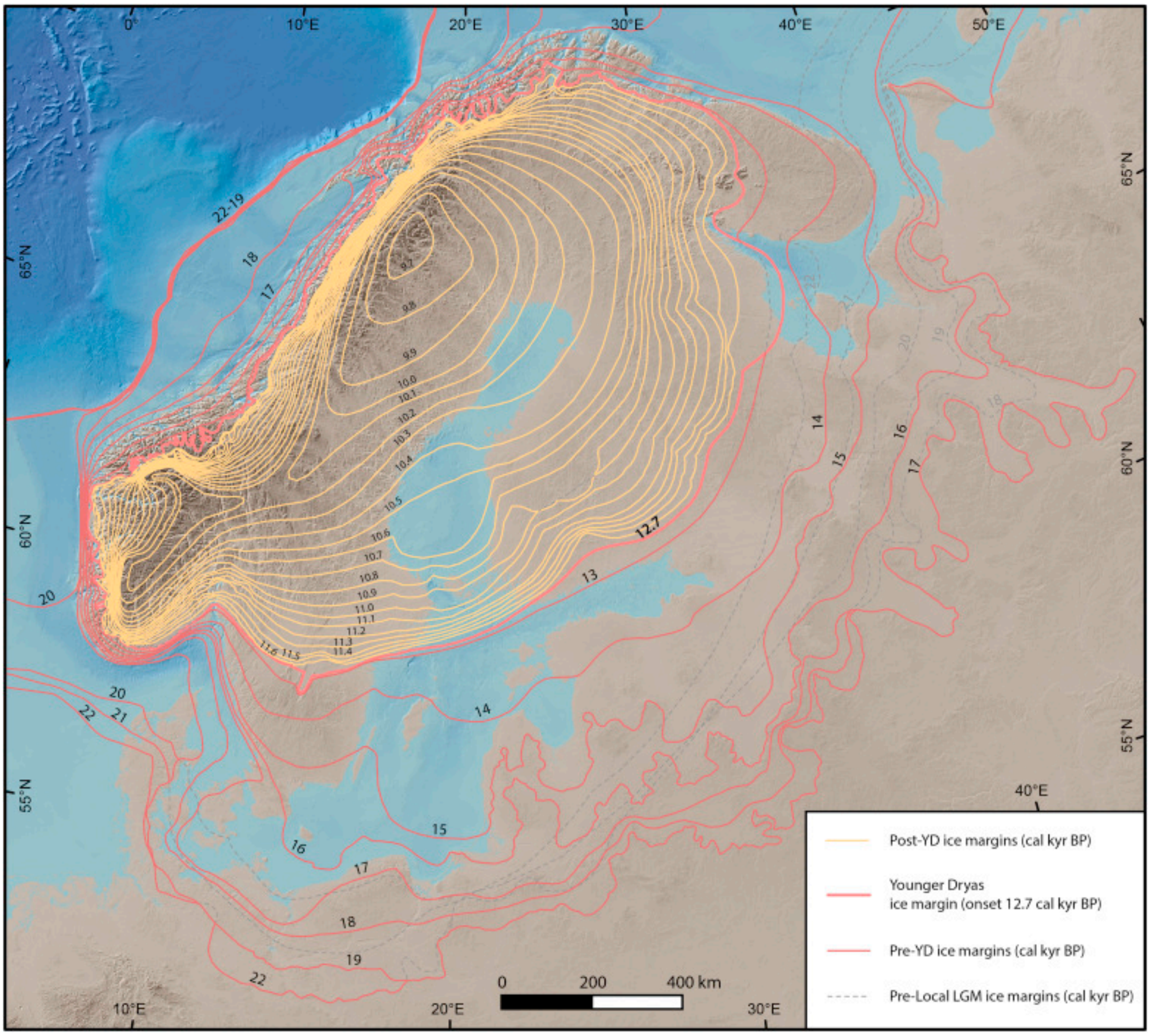

Figure 1: From "Deglaciation of Fennoscandia", by A. P. Stroeven et al 2016, Quaternary Science Reviews, Volume 147, p. 105, © 2015 A. P. Stroeven et al Published by Elsevier Ltd.

1.4. Glacial Landforms

Gravity is the main factor contributing to ice movement regarding glaciers and Ice-sheets. The movement of the ice will have an effect on the ground beneath it, creating glacial landforms. They are created by erosion, deposition, and even by deformation. The landforms created beneath the ice are called subglacial landforms. As glaciers and ice sheets are also reservoirs of water, the meltwater produced will also affect the ground and leave landforms behind, such as meltwater channels or eskers, which are both landforms created by warm based glaciers (Peterson, 2021).

1.5. LiDAR

Light Detection and Raging or LiDAR is a remote sensing system based on airborne laser scanning. The components consist mainly of a laser, scanner and GPS receiver which are attached primarily to an airplane or helicopter, but also drones for higher resolution in smaller areas. The type of LiDAR, which is important for this study, is topographic LiDAR. It uses near-infrared light when scanning the area and the product of this process are data points which can be converted to a digital elevation model. One can essentially see through the trees to get a clearer picture of the ground. (NOAA, 2021). Through LiDAR, one can pick out formations in the landscape which are not easily seen in mere aerial photography or even satellite imagery. There is LiDAR data for almost all of Sweden and at this point and the collection of that data started in 2009. (Johnson et al., 2015).

1.6. Earlier Works

As mentioned earlier, mapping glacial landforms using LiDAR data has been done in several parts of Sweden. A few examples are the mapping of glacial geomorphology between lake Vänern and Vättern (Öhrling et al., 2020), the geomorphologic study in the South Sweden Uplands, focusing on hummock tracts (Peterson et al., 2017) , the geomorphologic map of Jämtland (Blomdin et al., 2021), and also the geomorphologic map of the Siljan area (Smith and Peterson, 2014). The latter one is of importance to this study due to its mapped area sharing border with the planned area of mapping. It also lies in a generally close proximity to the study area of this project.

The mapping of the Siljan area was carried out in 2014 and the map was on a scale of 1:100,000 and covered an area of 2500 km^2. The landforms that were included were ribbed moraines, drumlins, crag-and-tails, eskers, ice-marginal-moraines, glaciofluvial delta surfaces, lateral meltwater channels, proglacial channels, highest coastline, and aeolian dunes (Figure 2) (Smith and Peterson, 2014).

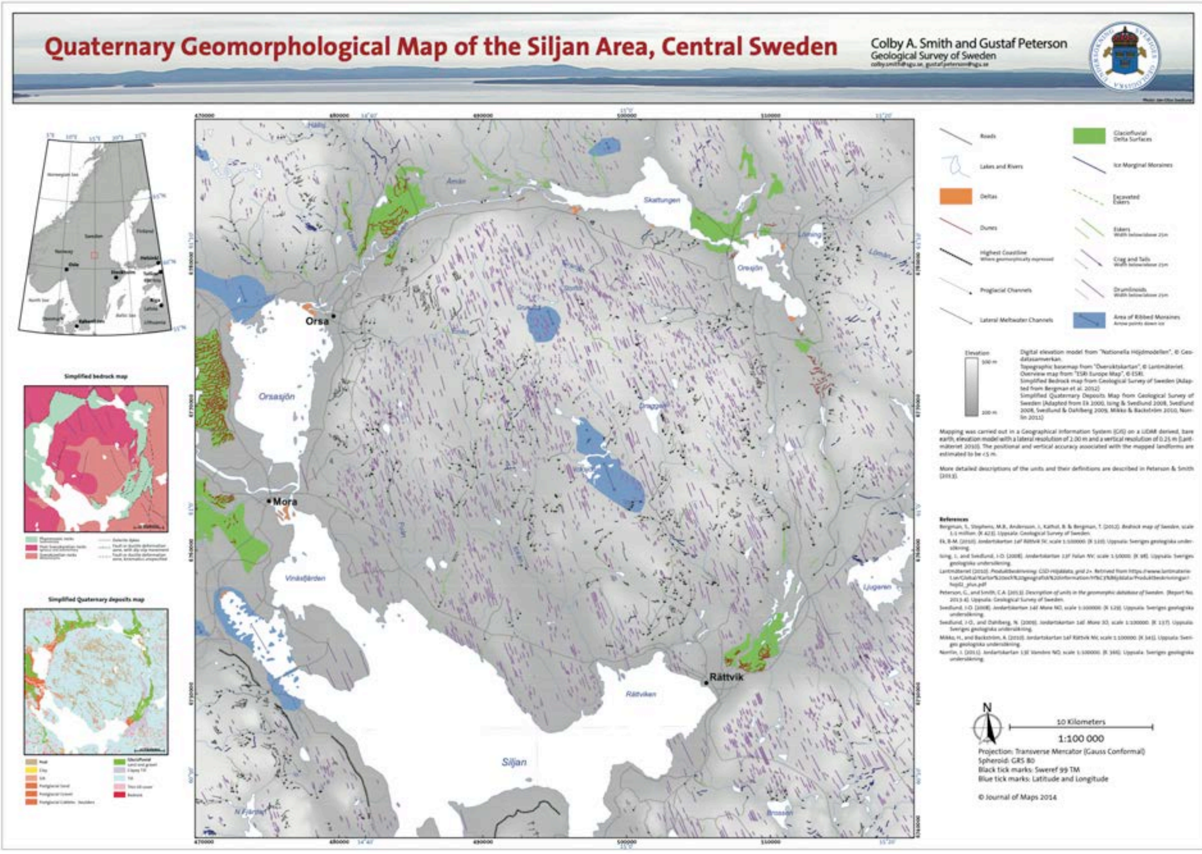

Figure 2: Mapped geomorphologic features in the Siljan area. From "Quaternary geomorphology of the Siljan area, central Sweden", by C. A. Smith and G. Peterson 2014, Journal of Maps, Volume 10, p. 521-528, © 2014 Colby A. Smith

1.7. Site Description

Figure 2 shows how the map extends southeast of Siljan in its lower right corner. That is where the Siljan map (2014), and this study, intersect. In Figure 3, lake Siljan can be seen in the northwestern corner of the study area. The area, which is located in Southern Dalarna, extends from Siljan in the northwest, Falun in the east and Borlänge in the south. The area became ice free somewhere between 10.6-10.5 kya after YD and is therefore marked with a rapid deglaciation compared to parts of Sweden lying to the south of the study area (Stroeven et al., 2016). Looking at Figure 3, the features which are prominent are; the river Dalälven, which flows from the western part of the map. It extends to the southeast and flows through Borlänge in the south and furthermore intersects with lake Runn in the southeast. The northern half of the area is somewhat uniform compared to the south. A mostly forested land dotted by lesser lakes is presented in the north and is contrasted with urbanized areas and prominent bodies of water in the south. The soils map provided by SGU (2020) reveals that the primary soil type is till but the area also contains an abundance of rocky outcrops. The lowland that follows Dalälven has the primary soil type; glacial silt (SGU, 2020).

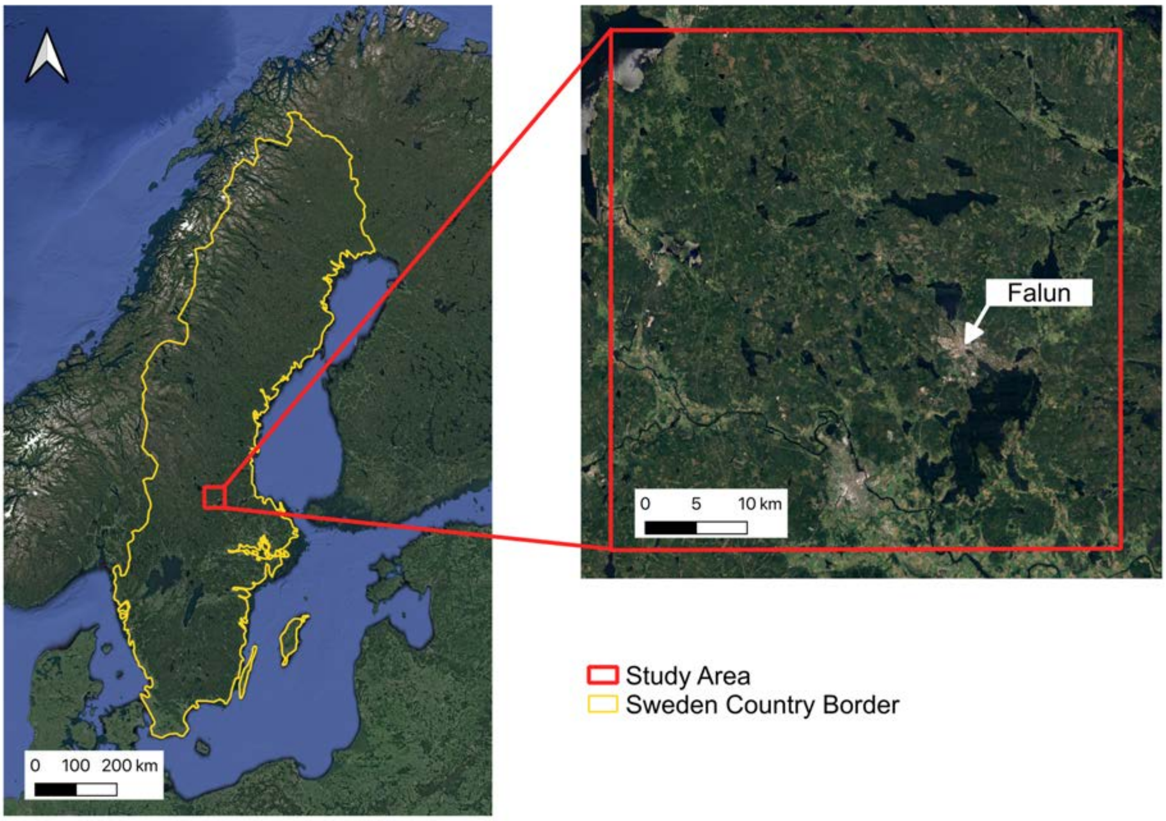

Figure 3: Map of Sweden presenting the study area in Southern Dalarna, central Sweden, which has an area of around 2600 km^2.

2. Method

The methodology of the study included data acquisition, mapping in QGIS3.10 and complimentary literature reading.

2.1. Data Acquisition

Maps that were used for the mapping were extracted from QGIS' built in browser bar. These include a satellite map, a soil map and two different LiDAR maps, which showed the terrain slope and terrain shadow. The elevation map was provided by Lantmäteriet through the Geographic Extraction Tool. To have a reference to earlier mapping, shape files of mapped features, and grid lines, was provided by Gustaf Peterson Becher at SGU.

2.2. Mapping

2.2.1. Glacial lineations

At the beginning of the mapping, the first step taken was to identify glacial lineations and their different forms. Glacial lineations are a form of subglacial landforms which forms in the direction of the flowing ice (Peterson et al., 2017). To limit the scope of the mapping, different landforms, which are forms of glacial lineations, where all grouped into the category "Lineations". These include crag and tails, drumlins, streamlined bedrock, striations and undifferentiated glacial lineations (Stroeven et al., 2016). As glacial lineations represents the flow direction of the ice (Peterson et al., 2017) it makes sense to group them into one category. The symbol that represents a lineation is a straight purple line (Figure 4C & 4D)

While mapping lineations, the map used was mainly the terrain slope map. This is because it was, subjectively, more difficult to spot some lineations in the terrain shadow map.

As seen in Figure 4, the lineations follow a general direction, which further gives a clue that the shapes seen are in fact glacial lineations, since they form in a straight line perpendicular to the ice-margin (Stroeven et al., 2016). Another technique, which was used sparingly, was to lay the soil map (SGU, 2020) with 50% opacity over the LiDAR map in use. This combination enforces the hypothesis that the shape noted was a glacial lineation. Although the constituents of drumlins are diverse, some are formed by glacial material being packed up against solid bedrock (Stokes et al., 2011). In the soil map, bedrock is represented in red as can be seen in Figure 5.

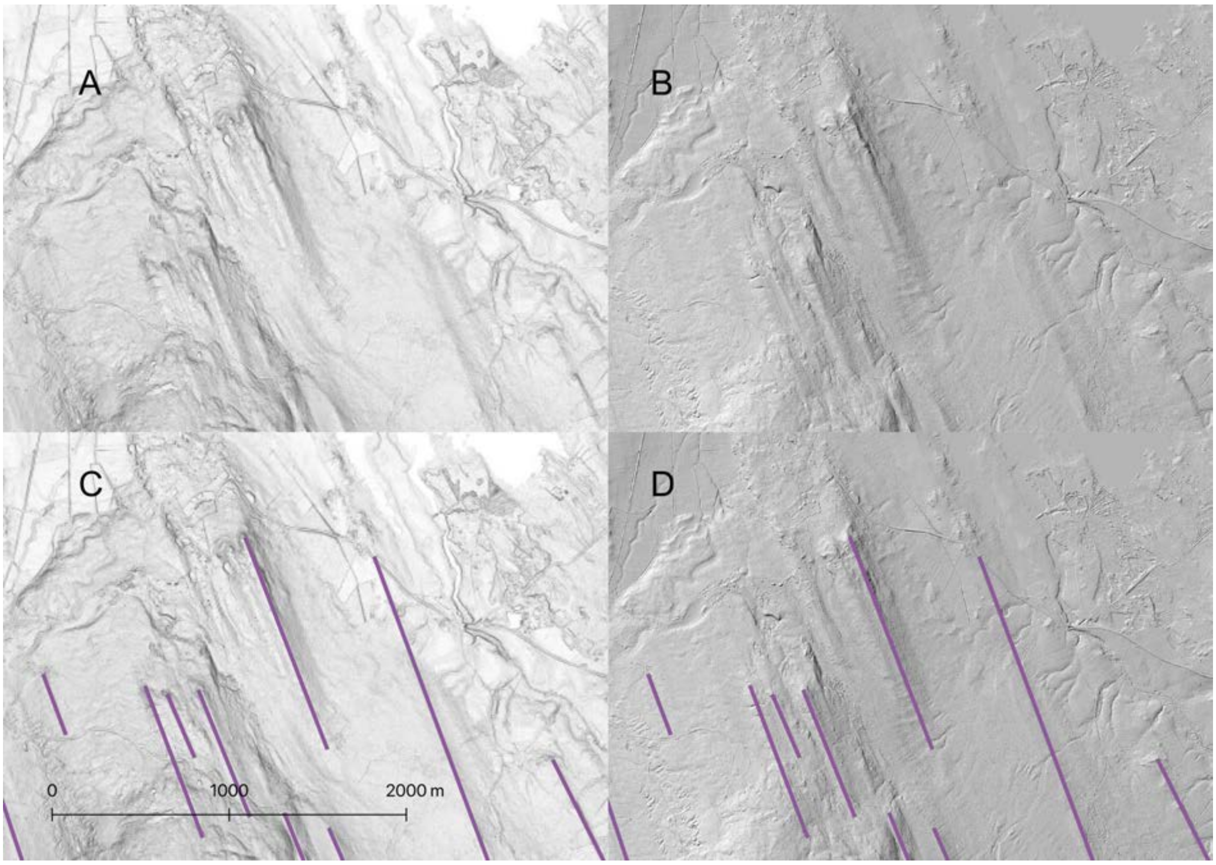

Figure 4: Shows a part of the mapped area with prevalent glacial lineations which has a general direction of NW-SE. (A) is the raw terrain slope map. (B) is the raw terrain shadow map. (C) is the terrain slope map with mapped lineations. (D) is the terrain shadow map with mapped lineations. The LiDAR data is provided by SLU, 2022.

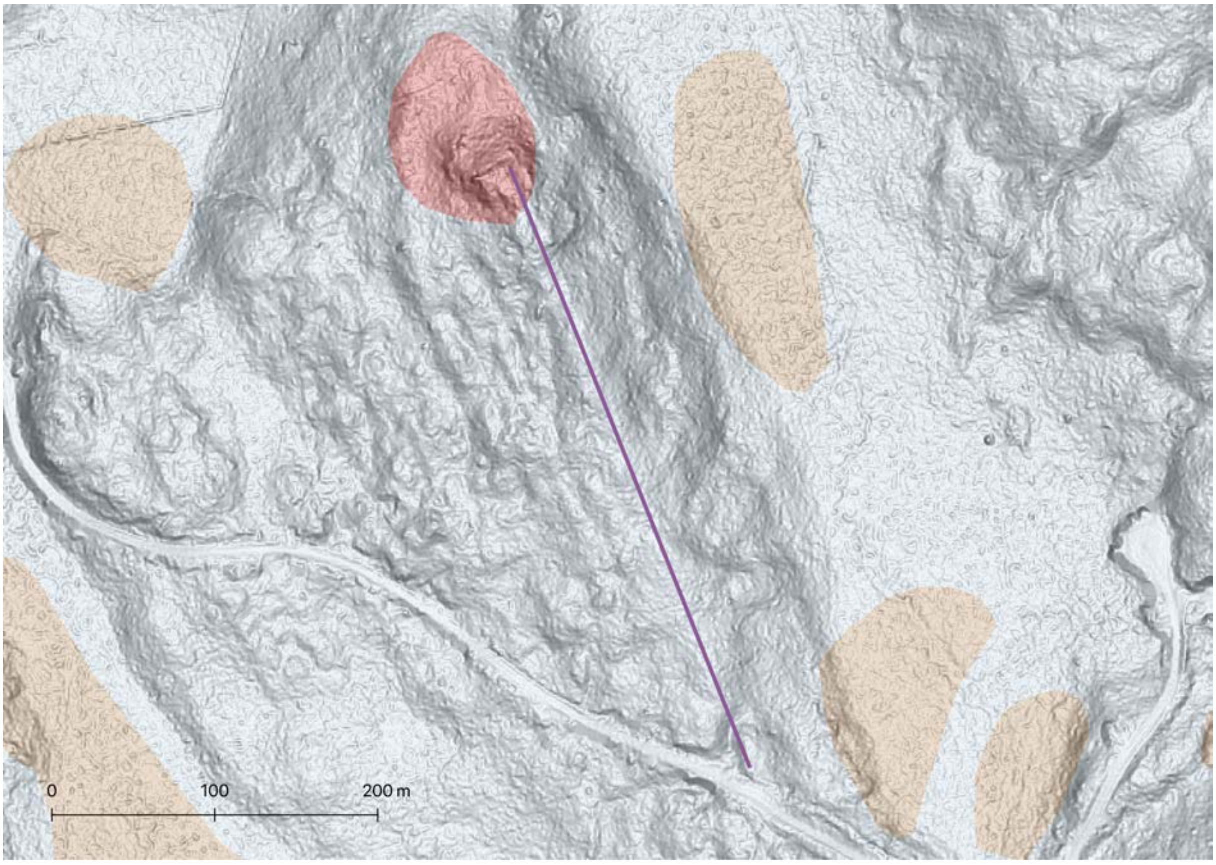

Figure 5: Drumlin from the mapped area seen through the terrain slope map with a soil map (SLU, 2022) overlay of 50% opacity. Mapped with a straight purple line, which shows a NW-SE direction. The LiDAR data is provided by SLU, 2022.

2.2.2. Meltwater Channels

Mapping meltwater channels coincide a bit with mapping glacial lineations due to the channels flow direction being in a somewhat perpendicular direction to the glacial lineations. This can be seen in Figure 6 where the flow direction is roughly NE-SW, the symbol for the mapped channels are blue lines. Why meltwater channels tend to have a perpendicular direction to the lineations is due to the ice storing meltwater in the bottom and when the water gets released, it flows with high energy along the ice margin, being a good indication for where the ice margin has been located (Stroeven et al., 2016). It is also a general occurrence that several channels are grouped together in a bigger field regarding the mapped area. This is therefore a good way to tell the different landforms apart and to easily spot the meltwater channels. If some meltwater channels are difficult to determine, looking for adjacent fields of meltwater channels can help to indicate if it is a meltwater channel or not.

While the slope map work well for mapping meltwater channels, the terrain shadow map made it easier to determine if a declination or an elevation was visible, making it easier to dictate the boundaries of a certain channel.

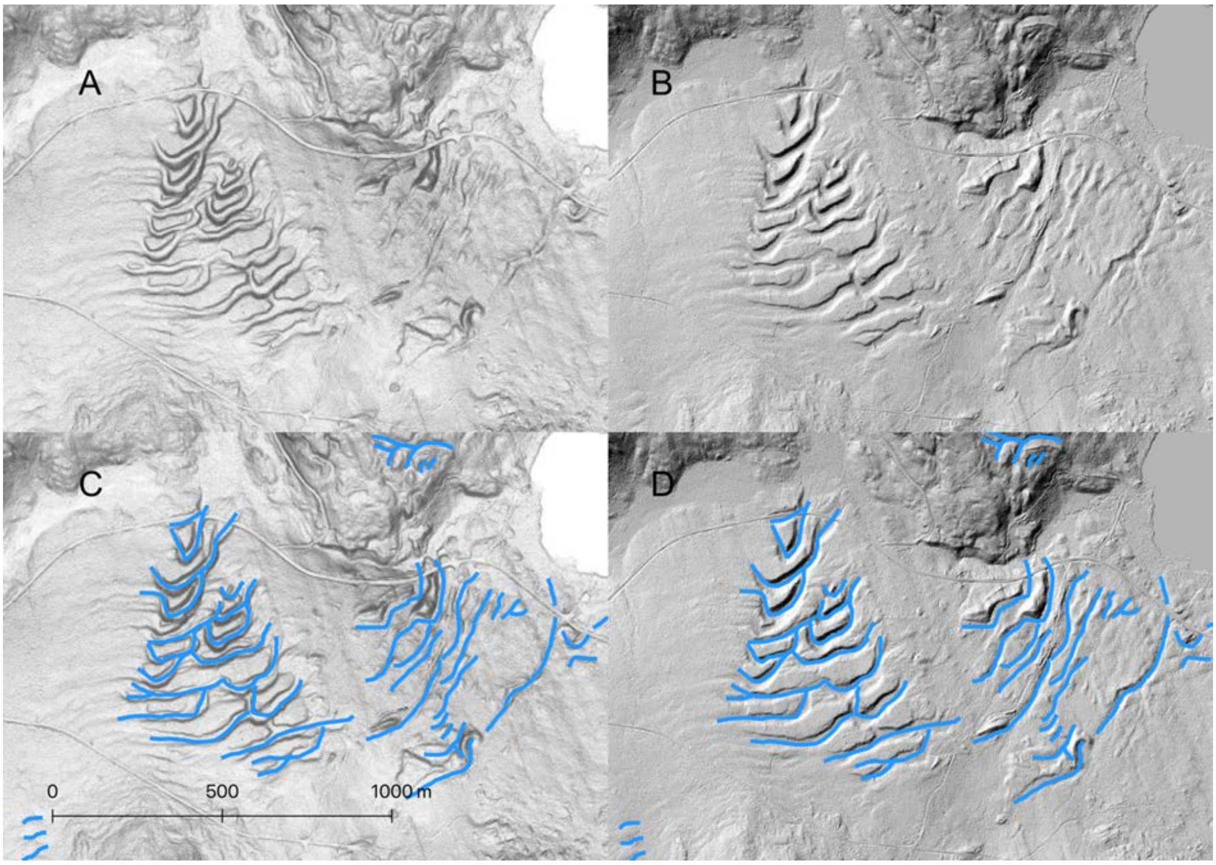

Figure 6: Shows a part of the mapped area with an abundance of meltwater channels where the general flow direction is NE-SW. (A) is the raw terrain slope map. (B) is the raw terrain shadow map. (C) is the terrain slope map with mapped meltwater channels. (D) is the terrain shadow map with mapped meltwater channels. The LiDAR data is provided by SLU, 2022.

2.2.3. Eskers

Eskers form in meltwater tunnels beneath the ice, where water is flowing, which will eventually be filled up by coarse grained glaciofluvial sediment. This form expansive ridges which can extend for hundreds of kilometers and reach heights of tens of meters (Stroeven et al., 2016). Compared to lineations, eskers form more irregular patterns than that of the lineation’s straight lines, as seen in Figure 7 compared to Figure 4.

While mapping the eskers, the symbol used were green lines. The landform was recognizable in both the terrain inclination map as well as in the terrain shadow map. To verify the eskers, the soil map was used more frequently than before due to eskers mostly being composed of glaciofluvial sediments compared to earlier landforms which were mostly made up of till.

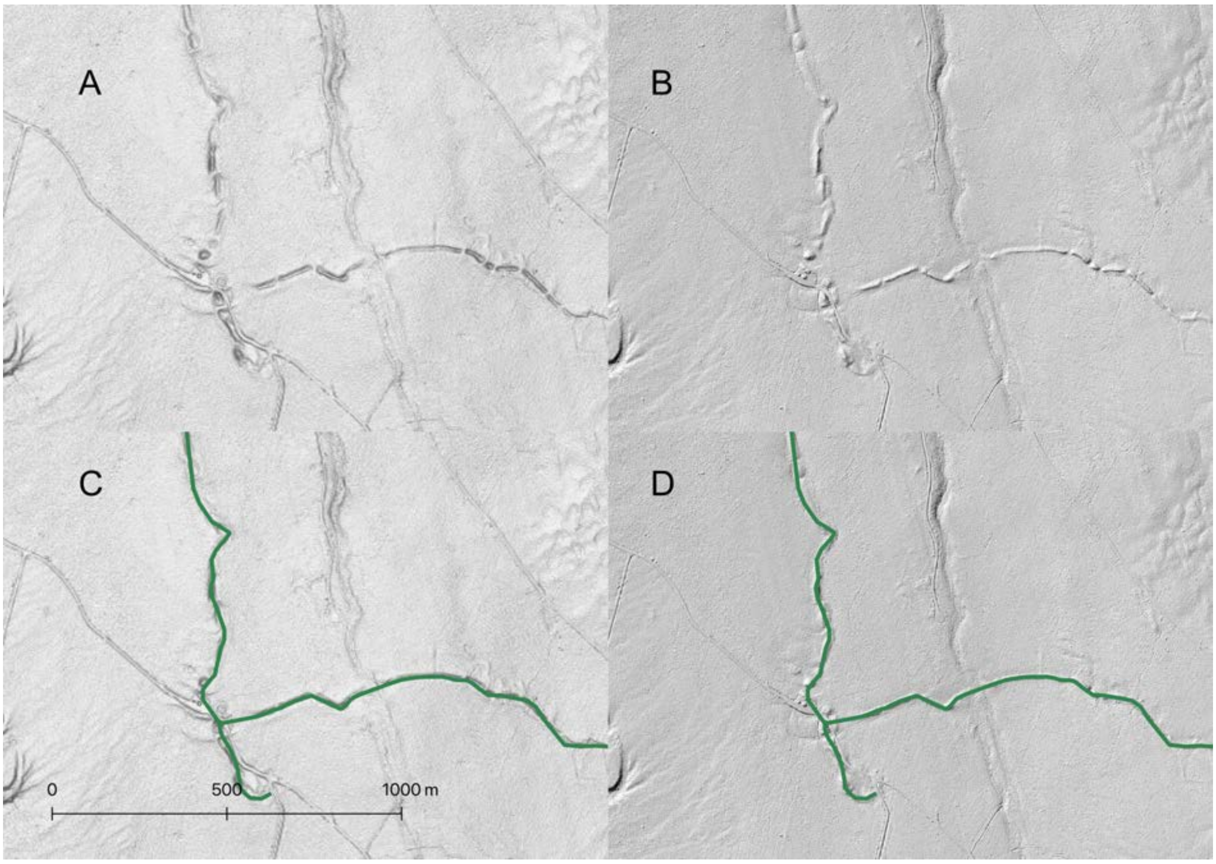

Figure 7: Part of the mapped area showing a sizeable esker extending outside of the images in both northern and eastern directions. (A) is the raw terrain slope map. (B) is the raw terrain shadow map. (C) is the terrain slope map with mapped esker. (D) is the terrain shadow map with mapped esker. The LiDAR data is provided by SLU, 2022.

2.2.4. Murtoos

'Murtoos' are a rather newly discovered type of glacial landform. They are believed to have formed subglacially during a time of rapid deglaciation when a lot of meltwater can be transported to the bed of the glacier. The excessive meltwater creates a field V-shaped hills, seen in figure 8, which are primarily made up of loose diamictons (Ojala et al., 2019) (Ojala et al., 2021).

While mapping murtoos, the symbol used was a blue polygon (Figure 9). To find the murtoos fields the V-shapes were a prevalent feature to look for as seen in Figure 8. While they could be seen in the terrain slope map, they became clearer while using the terrain shadow map.

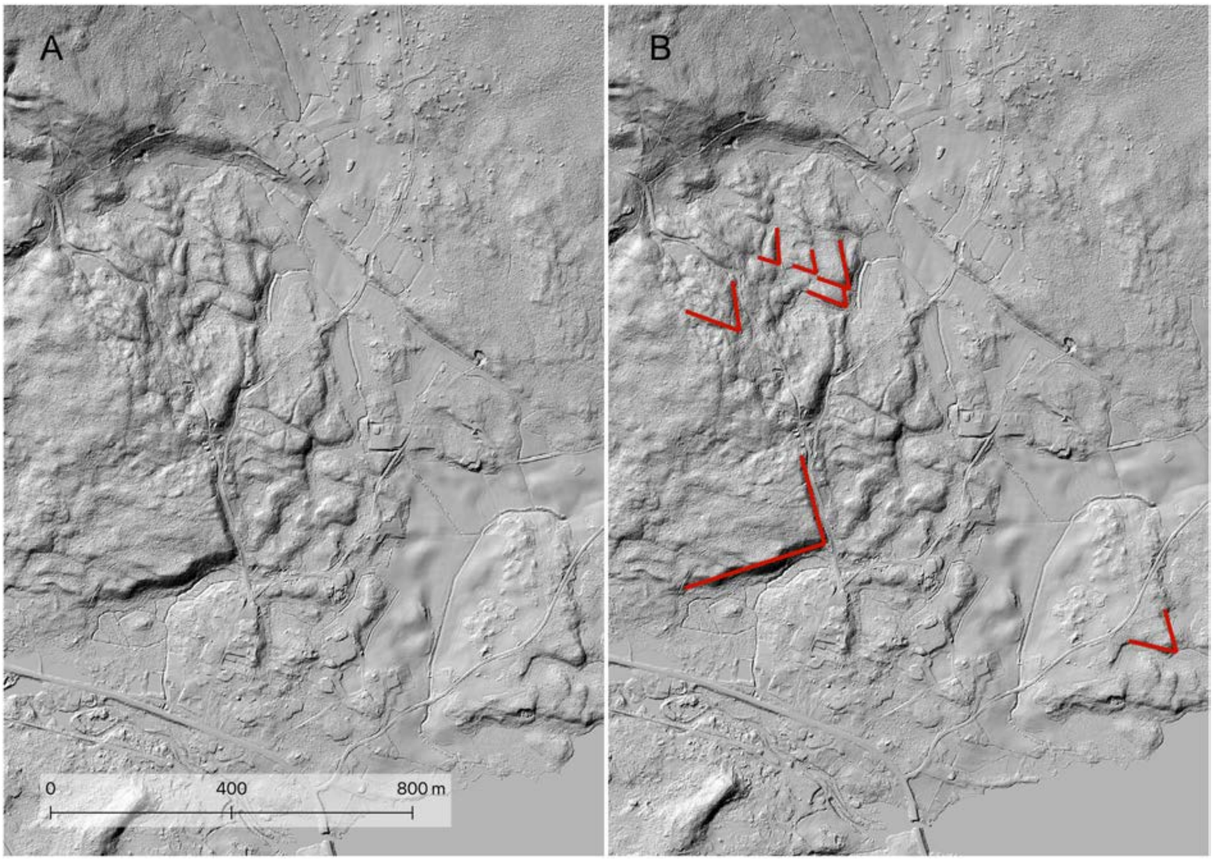

Figure 8: Part of the mapped area showing a field of Murtoos'. (A) is the unaltered terrain slope map. (B) is the terrain slope map with a few of the discernable V-shapes being mapped using red lines. The LiDAR data is provided by SLU, 2022.

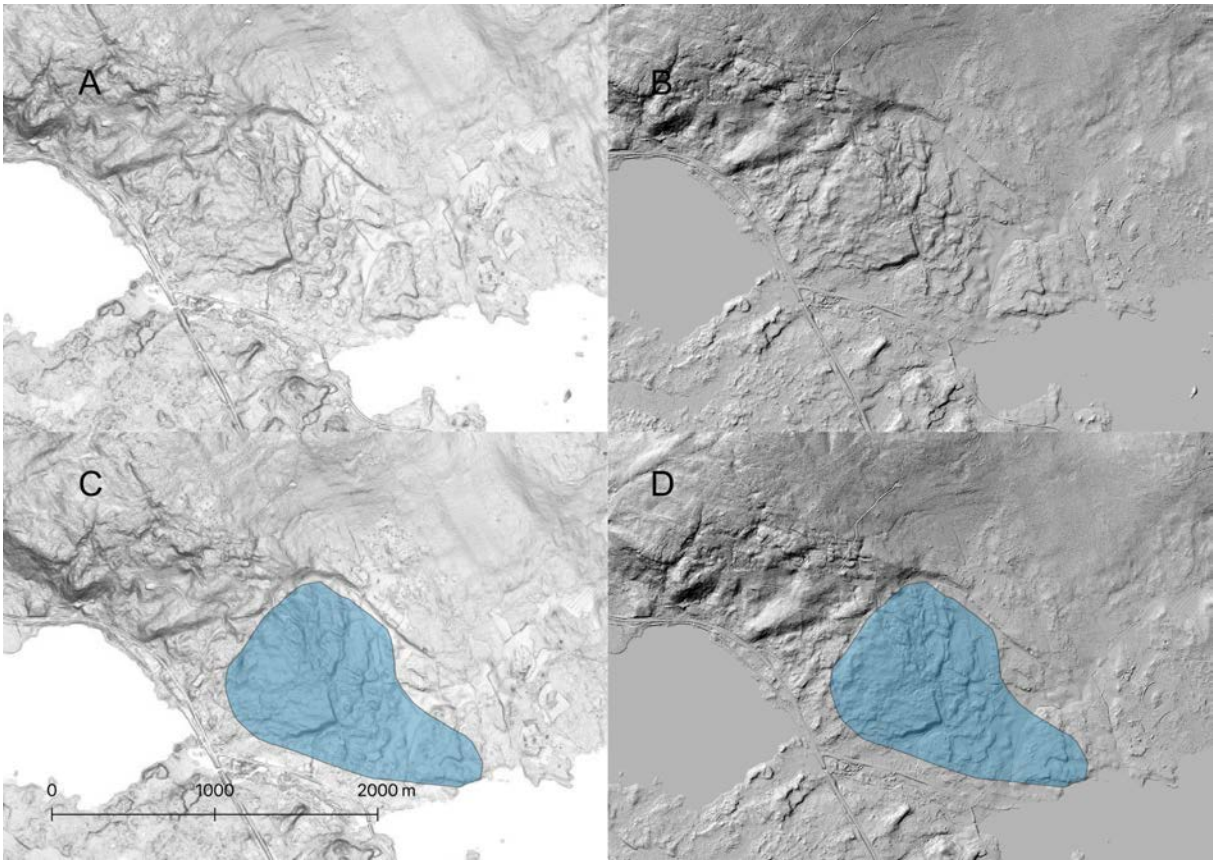

Figure 9: Part of the mapped area showing a field of Murtoos' between two lakes. (A) is the raw slope map. (B) is the raw terrain shadow map. (C) is the terrain slope map with mapped murtoos. (D) is the terrain shadow map with mapped murtoos. The LiDAR data is provided by SLU, 2022.

3. Results

Figure 10 represents the final product of the mapped geomorphologic features. The base map used is the terrain shadow map. To get a clear picture of the topographic height, the terrain shadow map is set to 63% opacity with a height model, created from elevation data, Grid 2+, provided by SLU (2019), as underlay. Falun and Borlänge are mapped out to get a pair of reference points compared to figure 10 and to make it clear where significant urban areas are located. The Landforms are presented as shapefiles with clear colors, where lineations are purple lines, meltwater channels are blue lines, eskers are green lines, and murtoos fields are blue polygons. The blue in meltwater channels is a brighter blue compared to that of Murtoos Fields. The feature which is found the most in the study area is the lineations (Table 1), followed by meltwater channel, esker, and the least abundant feature, murtoos field.

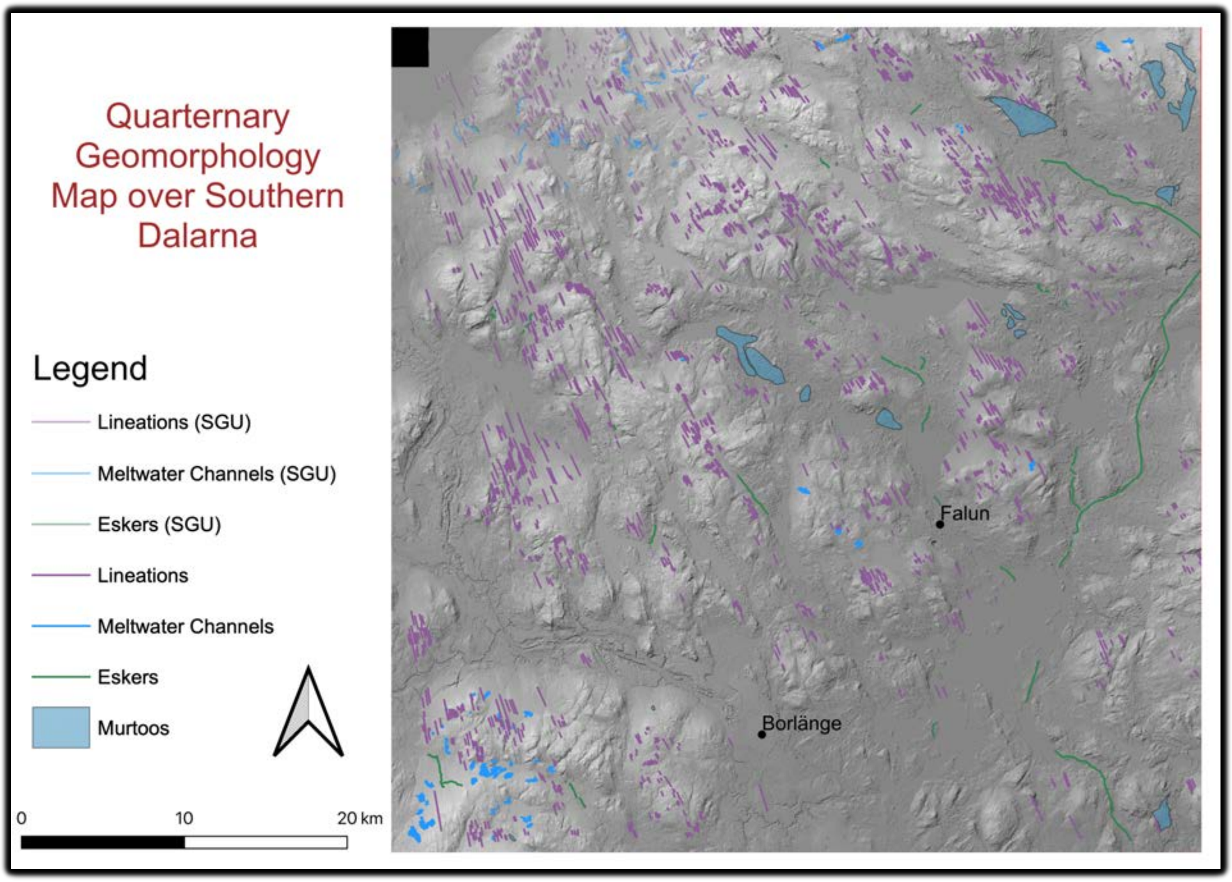

Figure 10: Final map over the study area with all mapped features included. The map also includes mapped features from Smith and Peterson (2014) in the northwestern corner. These features have the same color as the features mapped in this study but with an opacity of 50%. The LiDAR data is provided by SLU, 2022.

Table 1: The mapped amount of each landform based on data from the landform's respective attribute tables.

Landform	Lineations	Meltwater-Channels	Eskers	Murtoos-Fields
Mapped amount	1946	331	59	20

While Figure 10 includes all the mapped features and their spread, Table 1 is included to make the spread clearer. Black lines & polygons on a white background reveals the distribution in a clear way as seen in Figure 11. The distribution of glacial landforms in the study area follows: Lineations are found in the entire study area but with higher concentrations residing in the northernmost 2/3 of the study area. There is also a high concentration in the southwestern corner of the study area. Meltwater channels do not enjoy the same spread as lineations and are reserved to a thick cluster in the southwestern corner but also spread out sporadically in the eastern part. Eskers are found in the entire study area, but lack the abundance that lineations have. The most standout feature among the Eskers is the large eastern one which is spreading out along the eastern border for more than 55 km and continues on outside the study area. Murtoos fields are primarily found in the northern part of the study area, with the highest concentrations in the center of the study area and the northeastern part.

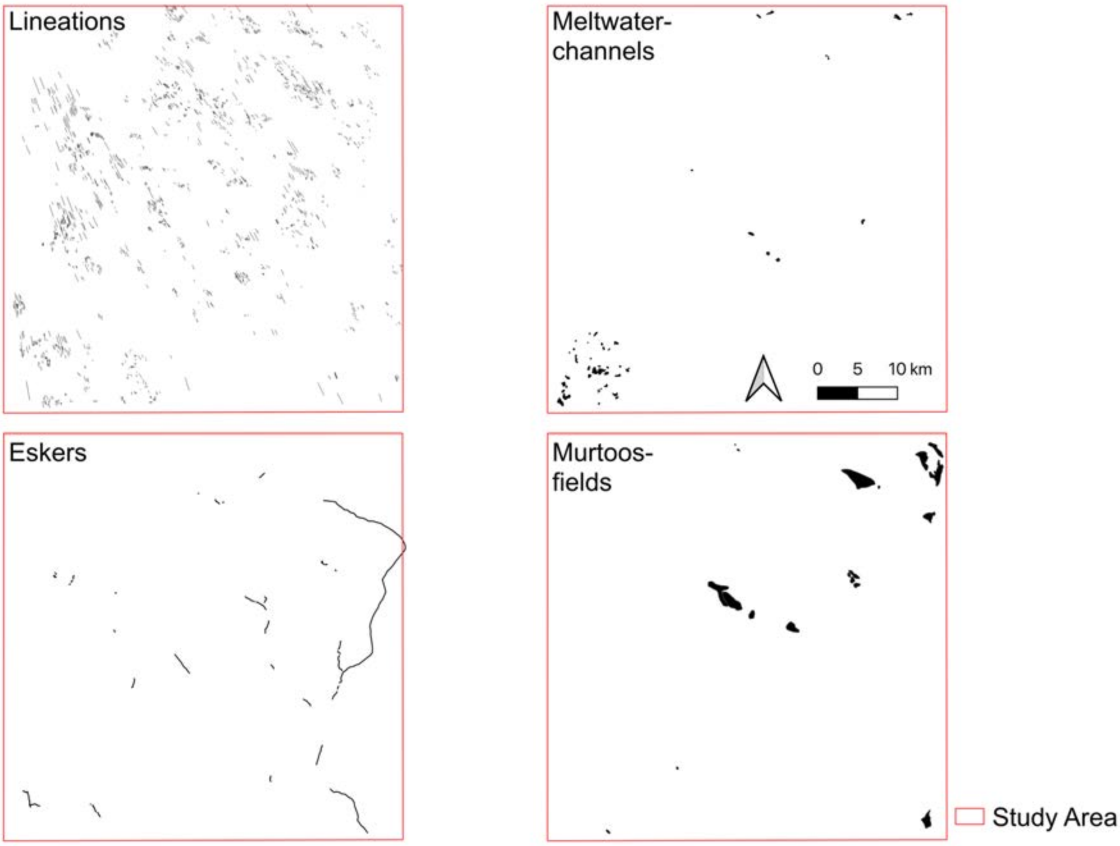

Figure 11: The entire mapped area presenting the distribution of the four different glacial landforms. The landforms are black on a white background in order to make the distribution clearer.

Calculating the direction of direction of each lineations, reveals the general direction. This is presented in a rose diagram in Figure 12 which paints a clear picture of the behavior of the lineations. The vast majority of the lineations are in a NW-SE direction, with some outliers bordering on a N-S direction.

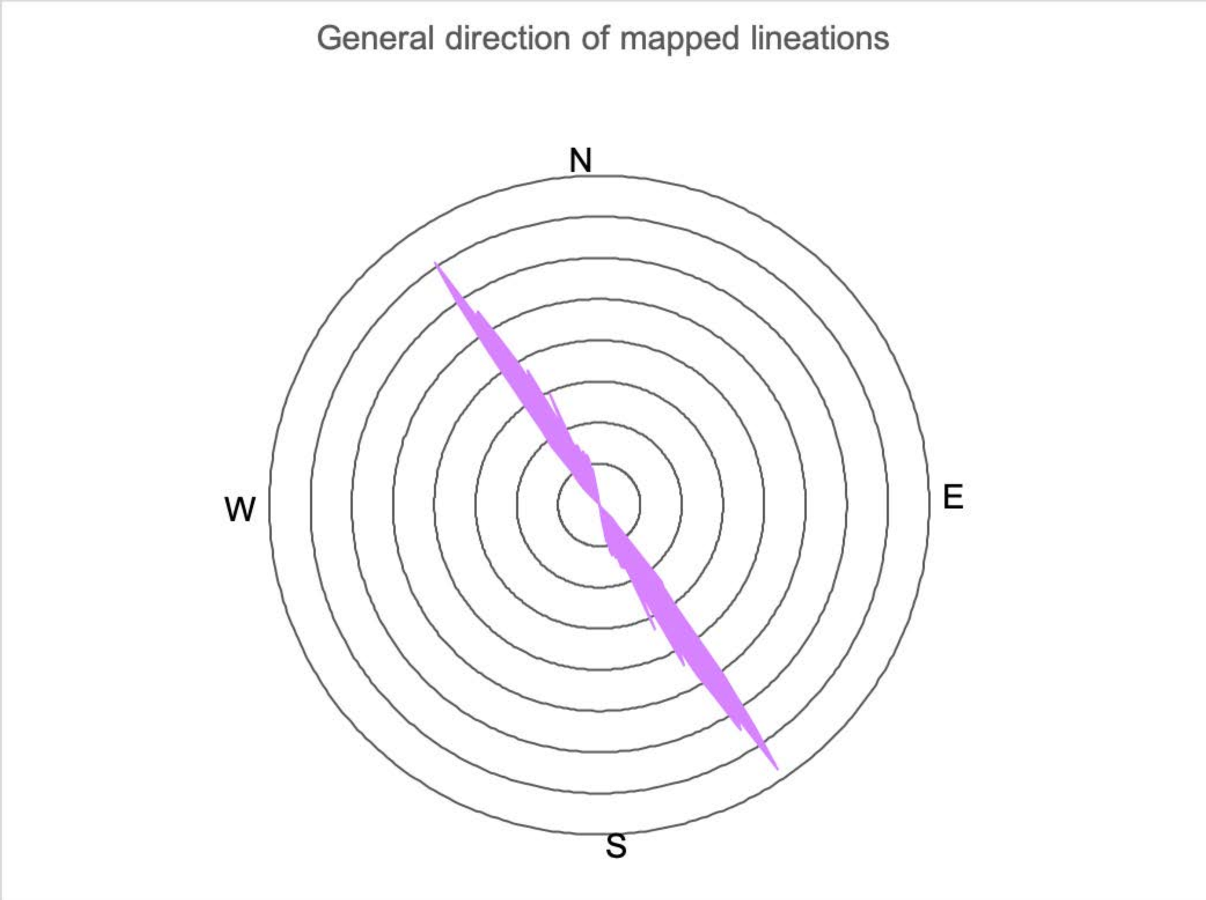

Figure 12: Displays the orientation of the glacial lineations, with a vast majority oriented NW-SE direction.

4. Discussion

When observing the results, it becomes clear that lineations are an especially striking feature left behind by the ice (Figure 10 & 11) (Table 1). It can be found in almost every part of the mapped area except for urban areas and areas directly adjacent to streams and other bodies of water (Figure 10). This mimics what has been found in earlier studies. In Smith and Peterson (2014), glacial lineations can be found in most of the mapped Siljan area (Figure 2) and they are in abundance.

Meltwater channels are less abundant than lineations (Table 1), as mentioned previously. This might not be all that surprising when considering how they are made. Based on the map of the deglaciation of Fennoscandia (2016), the ice retreated rapidly in the study area, which might be the reason for the abundance of meltwater channels in some areas of the map (Figure 10 & 11). This being places where lots of meltwater was expelled and carried out rapid erosion.

While not being nearly as prominent as lineations or even meltwater channels, eskers might still be considered a prominent presence in the study area (Figure 10 & 11) (Table 1). The discontinuity of some eskers seems to coincide with other esker's discontinuities (Figure 10) and could be extending a lot further than their representations in the maps (Figure 10 & 11). This indicates that some of the eskers found in the area are one of the same and might actually extend for hundreds of kilometers as proposed by Stroeven et al (2016). Although being relatively few (Table 1), the size of the eskers makes them a remarkable presence in the area (Figure 10 & 11).

The least abundant landforms presented in Table 1 are murtoos fields. The abundance is clearly affected by the decision to map the fields as polygons (Figure 8), where if the individual V-shapes would have been mapped instead, the amount would most likely have been much higher. Looking at figure 10 & 11 will however show that murtoos fields occupy everything from small (30 000 m^2) to large (up to 6 km^2) areas where they are found. This is very interesting regarding the fact that the murtoos' are newly discovered landforms (Ojala et al., 2019) and one would think that they would have been discovered sooner. But as the landform is difficult to discern without LiDAR data, it might not be as surprising. This is worth considering even though they have a significant presence when revealed through LiDAR mapping (Figure 8, 9, 10). Previous works, in other areas, has also mapped some murtoos fields as hummocky moraine or dead ice moraine in the past (Ojala et al., 2019). Looking at the map (Figure 10) reveals the murtoos fields to be concentrated to valleys between hills. The reason could be that the meltwater seeks it way to lower elevation, and in a sense behaving like a river under the ice. It could also be that the murtoos needs a lot of glacial material to form. Higher elevations in the area tends to support rocky outcrops to a greater extent.

Ojala (2019) explains that murtoos' are a good indication of rapid deglaciation as they are, allegedly, formed through large amount of meltwater finding its way to the bottom of the ice. This reinforces the map over deglaciation of Fennoscandia (Stroeven et al., 2016) as it shows a relatively fast deglaciation over this study's research area. This is also something that might explain the lack of end moraines in the study area as they form where there is an interruption in ice margin retreat and this not being the case here (Stroeven et al., 2016).

As glacial lineations forms in the direction of the ice flow (Peterson et al., 2017) it stands to reason that the lineations should be perpendicular to the ice margin presented by Stroeven et al (2016) (Figure 1). Analyzing the general direction of the ice margin over the study area (Figure 1 & 3), the direction is in a SW-NE extent. In the western part of the study area, the ice margin slightly levels out to a W-E extent. Figure 12 further reinforces the connection between the mapped lineations (Figure 10 & 11), and the ice margin map (Stroeven et al., 2016) (Figure 1), as it shows a perpendicular direction to the ice margin. Figure 12 shows a clear orientation which coincide with the reconstructed ice margin (Figure 1). The few outliers which shows a borderline N-S direction (Figure 12) can be clearly connected to the lineations found in the southwestern corner of the map (Figure 10) which further aligns it with the ice margin (Figure 1). The obvious problem with this conclusion stems from the fact that the ice-margin map was drawn up using lineations as a reference. It is therefore no surprise that the lineations mapped in this study, aligns with the ice margin map of Stroeven (2016). One thing it can say is that mapping of lineations using LiDAR gives similar result as traditional mapping of lineations. It speaks of the accuracy of the tool, but it is not surprising when the accuracy has been seen before in earlier works.
The high amount of glacial lineations (Table 1) and alignment with the ice margin (Figure 1 & 12) tells a story that the ice has been melted in the bottom, and this is supported by the presence of eskers and murtoos (Stroeven et al., 2016).

While one of the study's aims were to carry out an accurate mapping of the glacial landforms, the human bias cannot be overlooked. As mentioned in the methods, the process of mapping is a rather subjective endeavor. As the mapper, I might see features where someone else might not and vice versa. Seeing features that are not present is especially true when the mapping has been carried out for some time. As one starts to see patterns in the features mapped, confirmation bias can serve to make one see things that might or might not actually be there. Furthermore, it is critical to look out for pitfalls such as deforestation or anthropogenic activity, which had me scratching my head several times, until I looked at a satellite map, revealing it to be some form of human activity. Nonetheless, the map was thoroughly studied for many hours over several weeks, and as I was aware of many traps one might fall into, the map came out quite accurately in my opinion.

5. Conclusion

The glacial landforms of notability are: Glacial lineations, meltwater channels, eskers and murtoos'. Lineations being the most numerous and spread out landform, covering most of the area, might adhere to the broad categorization of the landform but also by the landform being prominent overall in areas of rapid deglaciation. Meltwater channels presents a small spread, mostly found in the southwest, but are numerous in the few places where they were discovered. Eskers show a high spread, being found in most of the area but mainly in the east. The amount present is however low compared to previously mentioned landforms. The extent of individual eskers varies from small (a few hundred meters) to large (tens of kilometers). Murtoos fields are few in number but often covers a large area where they are present. Their spread is varied but are mainly concentrated to the center and the northeast of the study area.

When analyzing the general direction of the lineations, it shows that the lineations are overall perpendicular to the ice margin provided by Stroeven et al (2016) but this is not surprising as the ice-margin map was drawn up using lineations. The landforms also tell us that the ice was melted in the bottom.

Future studies might want to narrow increase the categories of the landforms to get a more developed insight to the glacial landforms found in this study area. The inclusion of more glacial landforms, which has been neglected in this study, might also broaden the understanding of the study area.

6. Acknowledgements

First and foremost, I would like to thank Jakob Heyman for being a good advisor and being present when his help was needed. I want to thank Mark Johnson for opening my eyes to the exciting world of geomorphology. A special thanks to Gustaf Peterson Becher at SGU for providing me with maps and shapefiles from his previous works. Moreover, I would like to thank Liane and Martin, but also the rest of my classmates for giving me valuable critique. Lastly, I would like to thank Hanna for always being there for me no matter how durable or brittle the rock is that we stand upon.

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