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The mapping and study of glacial geomorphology near Piteå, Northeastern Sweden

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Abstract

Since the beginning of the 20th century numerous mapping projects regarding glacial geomorphology in different regions of Sweden have been published, with methods advancing from in situ field observations to modern remote sensing systems that are currently used to map the surface of Mars. What all these have in common however is the intention to lay ground for a better understanding of the glacial history, and the dynamic processes that shaped the landscape during past glaciations.
With the more recent availability of LiDAR derived elevation models mapping of small-scale landforms, such as De Geer moraines and smaller glacial lineations, has been made possible, furthering the use of remote sensing and GIS for detailed mapping of local geomorphology.
This mapping project explores the use of LiDAR as a mapping tool in pursuit of identifying glacial landforms in and around the Swedish city Piteå, an area previously known to have smaller scale landforms and a dynamic glacial and post glacial geological history.
The mapping was done in QGIS 3.10.14, with four sets of data being used in total.
Results showed that there are predominantly three types of glacial landforms in the studied area, glacial lineations, De Geer moraines, and post glacial shorelines. The predominant facing NW direction of the lineations and moraine ridges and the earlier shorines appearing along elevated features agree with what is previously known about the ice movement in the area. The method of using high resolution LiDAR elevation models also proved to be a time efficient method of geomorphological mapping, making it possible to identify small scale landforms.

Keywords: Glacial Geomorphology; Piteå; LiDAR; QGIS; Digital Elevation Model; glacial lineations; De Geer moraines; postglacial shorelines.

Sammanfattning

Sedan början av 1900-talet har många kartläggningsprojekt över glacial geomorfologi i olika delar av Sverige publicerats, där metoderna har gått från att vara fältobservationer till nutidens karteringsmetoder som också används för geomorfologisk kartläggning på Mars. Den gemensamma avsikten har dock varit att förstå regional is- rörelse och de dynamiska processer som kom att forma landskapet under den senaste deglaciationen. Den senaste tidens tillgänglighet av LiDAR producerade höjdmodeller har också möjliggjort en mer detaljerad kartläggning av småskaliga landformer såsom De Geer-moräner och mindre glaciala lineations. Det här kartläggnings projektet utforskar användningen av LiDAR som ett kartläggningsverktyg med målet att identifiera glaciala landformer i- och omkring Piteå, som är tidigare känt för att ha småskaliga landformer och en dynamisk glacial och postglacial geologisk historia.
Kartläggningen utfördes i QGIS 3.10.14, med fyra olika dataset.
Resultatet av karteringen visade att det huvudsakligen finns tre typer av glaciala landformer i det studerade området, dessa är lineations, De Geer-moräner och postglaciala strandlinjer. Att glaciala lineations och morän- ryggarna huvudsakligen har en nordvästlig riktning, samt att de postglaciala strand- linjerna ofta uppträder längs upphöjd terräng överensstämmer med vad som tidigare är känt om is- rörelsen i området. Användning av LiDAR-höjdmodeller visade sig också vara en tidseffektiv metod för geomorfologisk kartläggning, och den höga upplösningen möjliggjorde en mer detaljerad kartläggning av småskaliga landformer.

Nyckelord: Kvartär Geomorfologi; Piteå; LiDAR; QGIS; Digital Elevation Model; glaciala lineaions; De Geer moräner; postglaciala strandlinjer.

Contents

1. Introduction

During the last phase of the Pleistocene epoch, northern Europe, like most of the northern hemisphere, experienced a large-scale deglaciation marking the end of the Weichselian glacial cycle (Svendsen et al., 2004). In Fennoscandia, this meant a complete disappearance of the inland ice, which left an impact on the landscape with glacial landforms and deposits reflecting the dynamic processes and changes that took place (Stroeven et al., 2016). The identification and study of these landforms and deposits gives us an insight of their formation and a broader understanding of regional ice movement and the dynamic environment at the time (Śledź et al., 2021).

While remote sensing has been in use for more than century, the recent advancements and availability of data has resulted in major improvements in the mapping of geomorphology (Verstappen, 2011; Chandle et al., 2018), with high resolution aerial imagery being used to map the surface of the earth in great detail, and in recent years also the surface of Mars (Rangarajan et al., 2018).

Light detection and ranging (LiDAR), which is another method of remote sensing, also opens up the possibility of mapping geomorphology by providing high resolution digital elevation models (DEMs) over larger areas (Johnson et al., 2015). The method is being used by The Swedish Geological Survey (SGU) at the present, where most of the glacial geomorphology in south and central Sweden has been mapped using LIDAR derived DEMs (Peterson & Smith, 2013). The mapping of northern Sweden with the use of LiDAR has however been much more limited.

The aim of this thesis is to (i) map glacial landforms around Piteå in northeastern Sweden, where mapping with LiDAR data has not been done, to better understand the regional ice movement, and (ii) explore the usage of LiDAR derived DEMs for geomorphological mapping.

2. Background

2.1. The Late Weichselian glaciation and its traces in Sweden

The most recent glacial period, known as the Weichselian glacial cycle, lasted until around 9-10 ka (Stroeven et al., 2016), marking the end of the Pleistocene and the beginning of the present interglacial period. The age of the Eurasian glacial maximum has been determined for the the Early Weichselian period to be 100–80 ka, Middle Weichselian period 60–50 ka, and the Late Weichelian period 25–15 ka (Svendsen, 2004), covering most of northern Europe at its maximum reach (Rinterknecht, 2018). Due to the erosive nature of ice sheets, many of the glacial landforms that can be observed today were created during the Late Weichselian period, and only a limited number of landforms have been determined to be from the Early- and Middle Weichselian (Mangerud, 2004). Therefore, making interpretations based on landforms from Early and Middle Weichselian more difficult. These are a few of the commonly appearing glacial landforms that have previously been studied in Sweden:

2.1.1. Eskers

Eskers form in ice- walled channels or subglacial tunnels where there is a flow of water and where glaciofluvial sediments, mainly sand and gravel, deposit in ridge- like structures (Knight, 2009). These are present in most of Sweden and vary in facing direction depending on regional ice flow (Hättestrand, 1998).

2.1.2. Lineations

Glacial lineations, which include crag and tails, drumlins, flutes, and mega-scale lineations are elongated subglacial landforms typically made in softer sediments (Szuman et al., 2021), however these can also form in bedrock. The nature of their formation reflects the direction of the final ice flow, and their length varies from shorter m- scale lineations to km- long mega scale lineations.

2.1.3. Moraines

Ice marginal moraine

Ice marginal moraines are landforms that have been deposited at the margin of the ice sheet and shaped by deforming processes. The material is either formed by a thickened wedge, dumped where there is a steep debris charge glacial margin, or where there is glaciotectonic deformation as the result of stress (Kruger et al. 2015).

De Geer moraines

Since the discovery of De Geer moraines in 1889, numerous hypotheses have been made concerning their genesis. And while several mechanisms could contribute to their formation it is generally accepted today that they form at a submerged ice margin during annual winter re-advance (Bouvier 2015; Hämberg 2021), where deposited material is pushed into a ridge. De Geer moraines consist mainly of coarser material, and this is likely due to water washing away finer material during sea level regression, following postglacial land uplift. They are predominantly located below The Highest Coastline (HK) and appear in majority in Norrbotten County, Västerbotten County, and southcentral Sweden (Hättestrand 1998; Bouvier 2015).

Ribbed/Rogen moraines

Ribbed moraines commonly appear as a series of ridges aligned perpendicular to ice flow and are sometimes characterized by being drumlinised (Hätterstand & Kleman, 1999). There are several hypotheses explaining the formation of ribbed moraines, but it is generally believed that these form subglacially (Dunlop & Clark, 2006). It is commonly theorized that the moraines could be reshaped pre- existing ridges (Möller, 2006), that they form by the folding and stacking of pre- existing slabs (Shaw, 1978; Lindén et al., 2008), or by the fracturing of a pre-existing till sheet, because of changing basal conditions (Hättestrand, 1998).

Veiki moraines

These types of moraines are characterized by “rim ridges” and have mostly been studied in parts of northern Scandinavia, also forming what is known as a hummocky moraine landscape (Hoppe, 1957). The theories behind the genesis of these moraines vary but it is generally agreed that these are till-covered-ice-walled lake plains (Lagerback et al. 1988).

2.1.4. Postglacial shorelines

Local change in sea level or shoreline displacement can be caused by two interactive movements; crystal uplift or decompression and global eustatic sea- level rise or lowering (Påsse & Daniels, 2015), and both occurred during the deglaciation of Sweden. Sweden, like other regions covered by the inland ice during the last glaciation, is still going through a post glacial rebound, which is seen along The Highest Coastline (HK). The Highest Coastline is a reference to the maximum reach of the Baltic Sea at the end of the last deglaciation (SGU, 2015), and can be determined by the reach of past shorelines.

2.2. Previous work

2.2.1. Previous mapping of Quaternary geomorphology in Sweden

Gustaf Frödlin (1916) was one of the first people to document the composition and orientation of some of the fluvial- glacial deposits in central Sweden, and before that Arvid Högbom (1906) published one of the first geomorphological maps over Norrland County. However, it is likely that the study of glacial landforms, their genesis, and composition goes back much earlier than that.

In more recent times, the development of remote sensing has allowed mapping of geomorphology to be done using detailed imagery over large areas. An example of this is aerial photos being used by Hättestrand (1998) to map and study the prevalence of glacial lineations, moraines, eskers, and meltwater channels in central and northern Sweden. A report published by Naturvårdsverket (1982) describes the mapping done by aerial photos taken between 1963-1980, some monochromatic and some later examples multichromatic. In the report the resolution is mentioned as a limiting factor complicating the mapping of smaller landforms. Furthermore, several publications were made between 1970-1990 studying the mountainous landscape and glacial geomorphology of north- western Sweden and the northmost Lapland region (Hättestrand, 1998), though limited to smaller areas.

Since then, there has been significant progress in the usage of remote sensing as a mapping tool. Today, unmanned aerial vehicles (UAV) can be used to develop cm-scale orthomosaic and digital elevation models (DEM) over smaller scaled areas making highly detailed mapping possible (Śledź et al. 2020). A recent example is the use of orthorectified aerial imagery to map boulder spread in Uppland, eastern Sweden, a glacial erosion that is the result of abraded bedrock being ripped by the Fennoscandian ice sheet (Hall et al., 2020).

2.2.2. LiDAR as a mapping tool

While LiDAR was first introduced in the 1960´s the method of mapping with LiDAR derived data has only been in use for about a decade, providing high resolution digital elevation models (DEMs) and digital terrain models (DTMs) by aerially scanning a surface (Mehendale & Neoge, 2020). This not only opens up the possibility to study larger landforms in greater detail, but also smaller landforms, such as De Geer moraines and glacial lineations, that are more difficult to recognize in aerial imagery (Johnson et al., 2015). This method of mapping has been used by SGU, where identification and mapping of glacial geomorphology in mainly south and central Sweden (Fig. 1) has been done by using LiDAR derived grid 2+ elevation models (Peterson & Smith, 2013), the models being provided by the Swedish national mapping agency Lantmäteriet. The geomorphological map is available in SGU´s open map service *Kartvisaren* (Sveriges Geologiska Undersökning, https://apps.sgu.se/kartvisare/). The mapping project is ongoing, and as seen in Fig. 1, a large portion of northern Sweden is currently unmapped.

Figure 1: Regions (green) where glacial geomorphology has been mapped by Sveriges Geologiska Undersökning using LiDAR elevation models, named "Kvartär geomorfologi" and available in the map service Kartvisaren.

3. Study area

Piteå, which is located in north eastern Sweden, is a part of the Norrbotten County and borders the Baltic Sea (Fig. 2), geographically also known for its archipelago. The area is part of the Svecofennian orogeny and consists of mainly old granitic bedrock; rocks of more sedimentary origin are found closer to the coastline, and are also characteristic for the regional Bothnian Bay (Piteå Kommun, 2012). In case of Quaternary deposits the area is dominated by till, outwash and fine grained sediments. While the till above the Highest
Coastline (HK) has more fine sediments and is useful for agriculture, the till below has fewer fine sediments due to fluvial processes washing it away during land uplift.

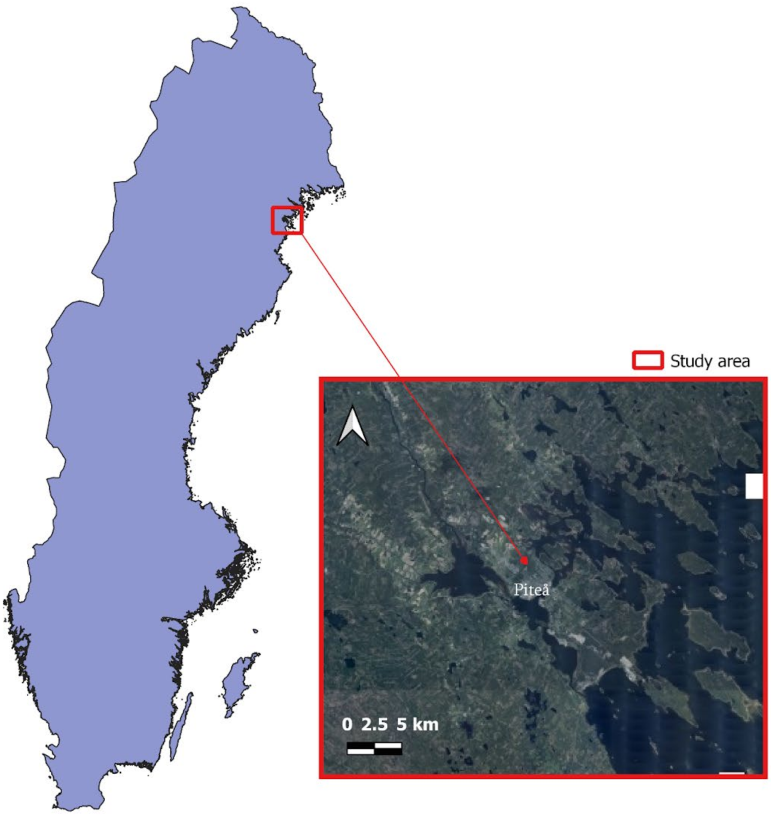

Figure 2: Piteå, Norrbotten County. Made with QGIS 3.10.14

4. Method

4.1. Data

To map the geomorphological features in this project two datasets and two open web services were used.

4.1.1. Digital elevation model (DEM)

Digital elevation models provide a topographic representation of a surface, excluding other objects such as vegetation and buildings. Today the data is commonly collected by either satellite/aerial imagery or AirborneLiDAR, however it is also possible to do so by field measurements. The product is a raster layer that can be used for various GIS applications.

A LIDAR derived DEM with the resolution 2 m/pixel was used in this project to identify glacial landforms in the terrain. The elevation models are available to download from the database of Swedish University of Agricultural Sciences (Sveriges lantbruksuniversitet, https://zeus.slu.se/get/?drop=), and the collection of data has been done by Lantmäteriet. Additionally a hillshade was applied for ease of identification.

4.1.2. Quaternary deposits

Information about Quaternary deposits is often sourced by aerial imagery and field reconnaissance, and the area of use and application is broad. To correlate glacial landforms with likely Quaternary material in the study area data over Quaternary deposits was downloaded from SLU´s database. The information has been gathered by The Swedish Geological Survey (SGU) and comes in scale 1:25 000, 1:200 000, 1:250 000, 1:750 000, and 1: 1 000 000. The downloaded data is then applicable in the form of a vector layer.

4.1.3. WMS

The Web Map Service application allows finished maps over geospatial data to be used in any GIS software, by access to the remote server that hosts it. The service was used to apply an orthophoto with the resolution 0,4 m/pixel. This option was preferred over downloading orthophotos, due to the file size. A terrain- shade map with the resolution 1 m/pixel was also applied by using WMS for higher detail. Both of these were provided by Lanmäteriet.

4.1.4. Kartvisaren SGU

The open map service *Kartvisaren* was also used for further identification and verification of glacial deposits. The information provided in the service is gathered by Sveriges Geologiska Undersökning (SGU) and maps over regional bedrock and Quaternary deposits were applied for comparison (Sveriges Geologiska Undersökning, https://apps.sgu.se/kartvisare/)

Table 1: Name of data, type of file, resolution, source, and source URL of the datasets used in the GIS mapping of glacial landforms near Piteå.

Name	Type of file	Resolution	Source	URL
Höjddata, Grid 2+ 2019 TILES	tif	2 m/pixel	Lantmäteriet, SLU LiDAR	https://zeus.slu.se/get/?drop=
Jordarter 1:25 000 - 1:100 000 latest	shp	_	Lantmäteriet, SLU	https://zeus.slu.se/get/?drop=
Ortofoto färg 0,4 m upplösning	WMS	0,4 m/pixel	Lantmäteriet	http://maps.lantmateriet.se/ortofoto/wms/v1.3?version=1.1.1
Terrängskuggning	WMS	1 m/pixel	Lantmäteriet LiDAR	http://maps.lantmateriet.se/capabilities/hojdmodell/wms/v1.1?version=1.1.1

4.2. Mapping

The mapping of glacial landforms was done by using the GIS software QGIS version 3.10.14, with the coordinate system EPSG:3006 - SWEREF99 ™. The acquired layers “Jordarter_1:25000-1:100000_latest”, “Terrängskuggning”, and “Ortofoto_färg_0,4_m_upplösning” were ready to use upon downloading. For the DEM layer “Höjddata, Grid 2+ 2019 TILES” the function “Hillshade” in QGIS was used to make elevation features more prominent, and the azimuth was set to different values to experiment with the shade from different angles.

The identification of different glacial landforms was based on SGU´s description of units in their geomorphic database (Peterson & Smith, 2013), where image examples of glacial landforms in DEMs are given. A new shapefile layer was then created for each type of landform identified. Interpretations of the ice sheet movement were then made and compared to earlier literature and landform mapping in northern Sweden.

5. Results

Three types of glacial landforms which were found to be most common in the study area have been mapped (Fig. 3). These are glacial lineations, De Geer moraines, and post glacial shorelines that are no longer in contact with a body of water. An esker and landforms appearing to be hummocky moraines were additionally identified and mapped.

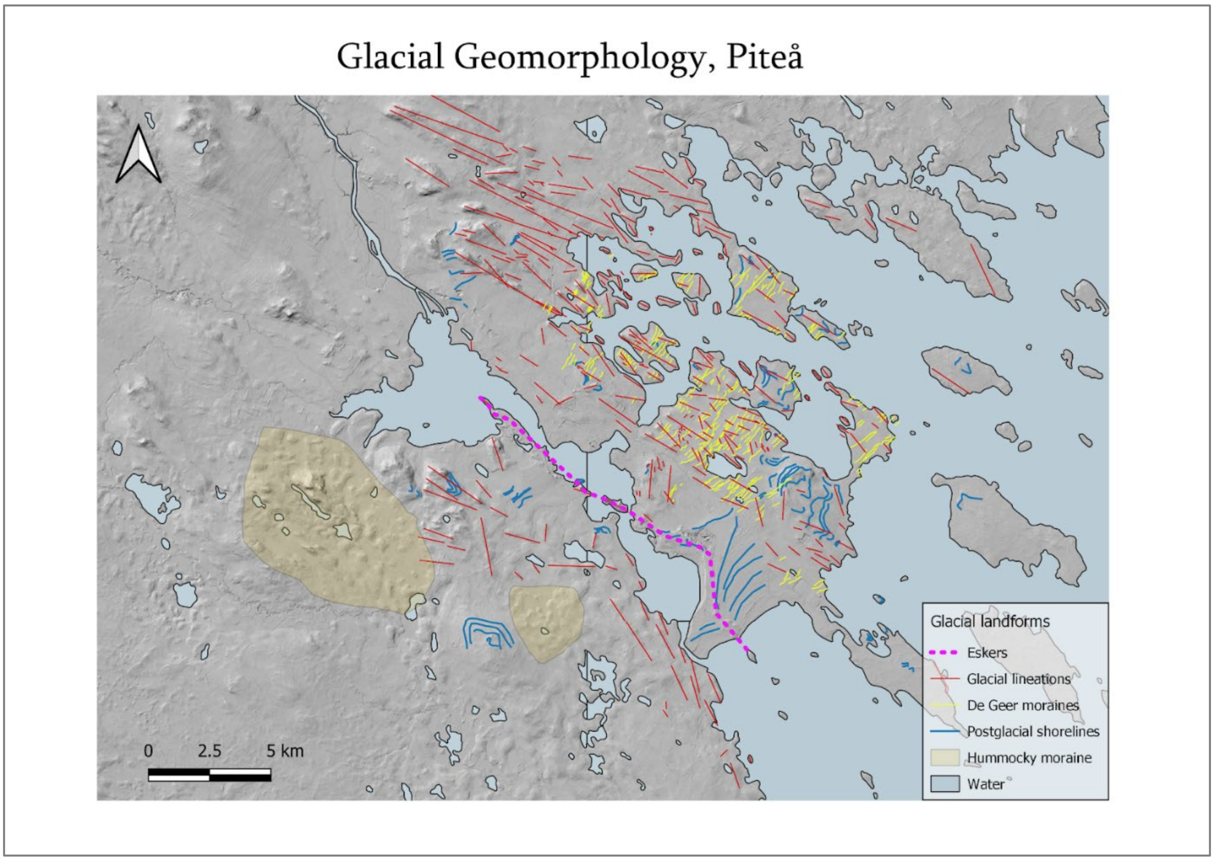

Figure 3: All mapped glacial landforms displayed over a DEM layer (WMS), with the resolution 1m/pixel. Glacial lineations marked in red, De Geer moraines in yellow, post glacial shorelines in blue, eskers in purple, and hummocky moraine as shaded polygons. The mapped features are selected examples. Made with QGIS 3.10.14.

5.1. Glacial lineations

The mapped glacial lineations near Piteå appear to vary in size (Fig. 4), with shorter lineations being more common closer to the coast and on small islands, and more extensive lineations appearing further inland (Fig. 3), however the average length was measured to be 1-1,5 km. It is worth mentioning that while some of the shorter lineations could be >50 m, some of the more extensive ones measured up to 5,5 km in length. They are fairly dispersed along the coast, and likewise further inland, and have a main orientation towards NW, however some variation in orientation occurs.

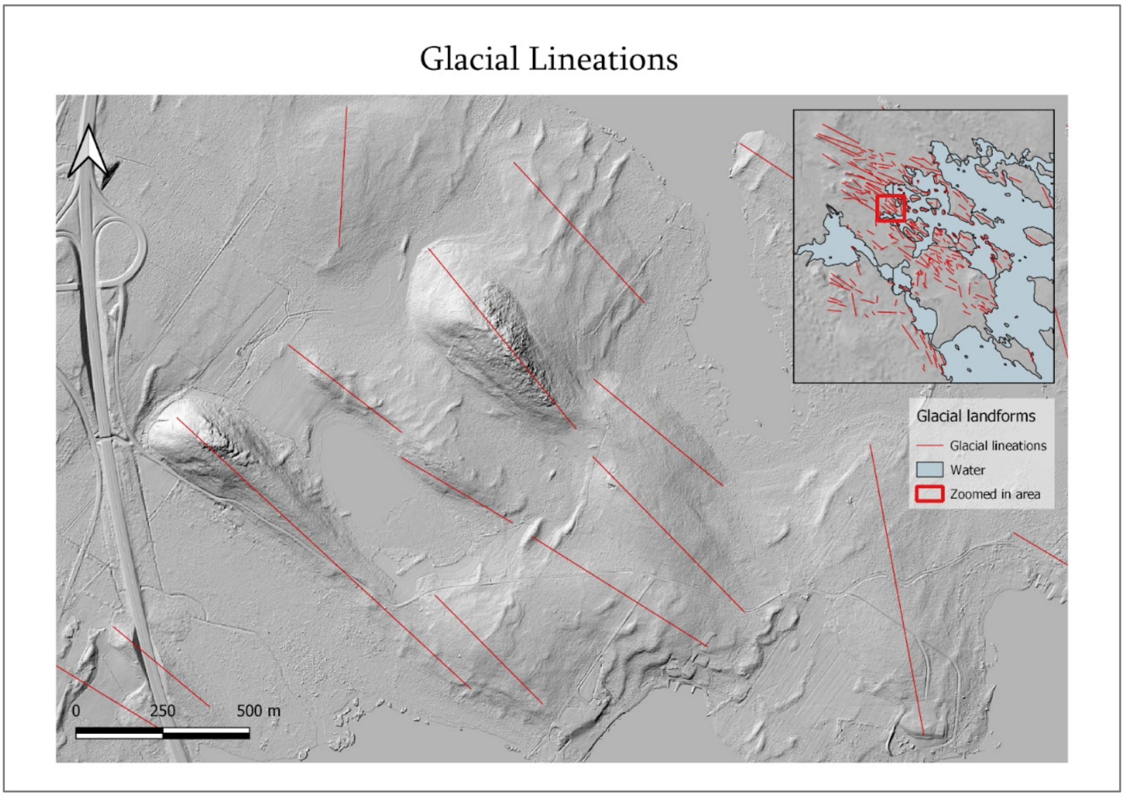

Figure 4: Mapped glacial lineations near Piteå, displayed over a 1m/pixel DEM layer (WMS). The lineations predominantly face NW, and have an average measured length of 1-1,5km. The mapped features are selected examples. Made with QGIS 3.10.14.

5.2. De Geer moraines

The De Geer moraines are fairly short and thin, with no major variation in width or ridge-form (Fig. 5). They appear to be widely dispersed over the study area and can in a few places be seen crossing over glacial lineations (Fig. 6a). Nevertheless, the moraines appear to be less frequent closer to the coastline, especially in areas largely dominated by postglacial shorelines (Fig. 6b), something that could be due to coastal erosion.

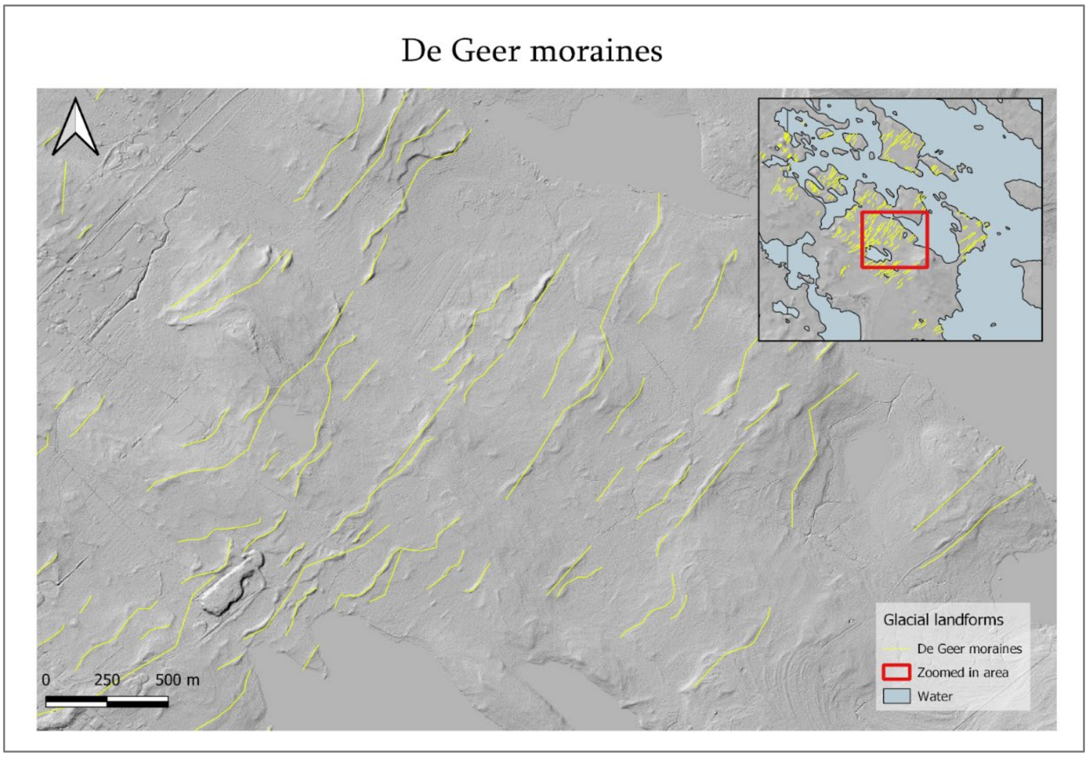

Figure 5: Mapped De Geer moraines near Piteå, displayed over a 1m/pixel DEM layer (WMS). The moraine ridges are fairly short, thin, and are oriented NE-SW. The mapped features are selected examples. Made with QGIS 3.10.14.

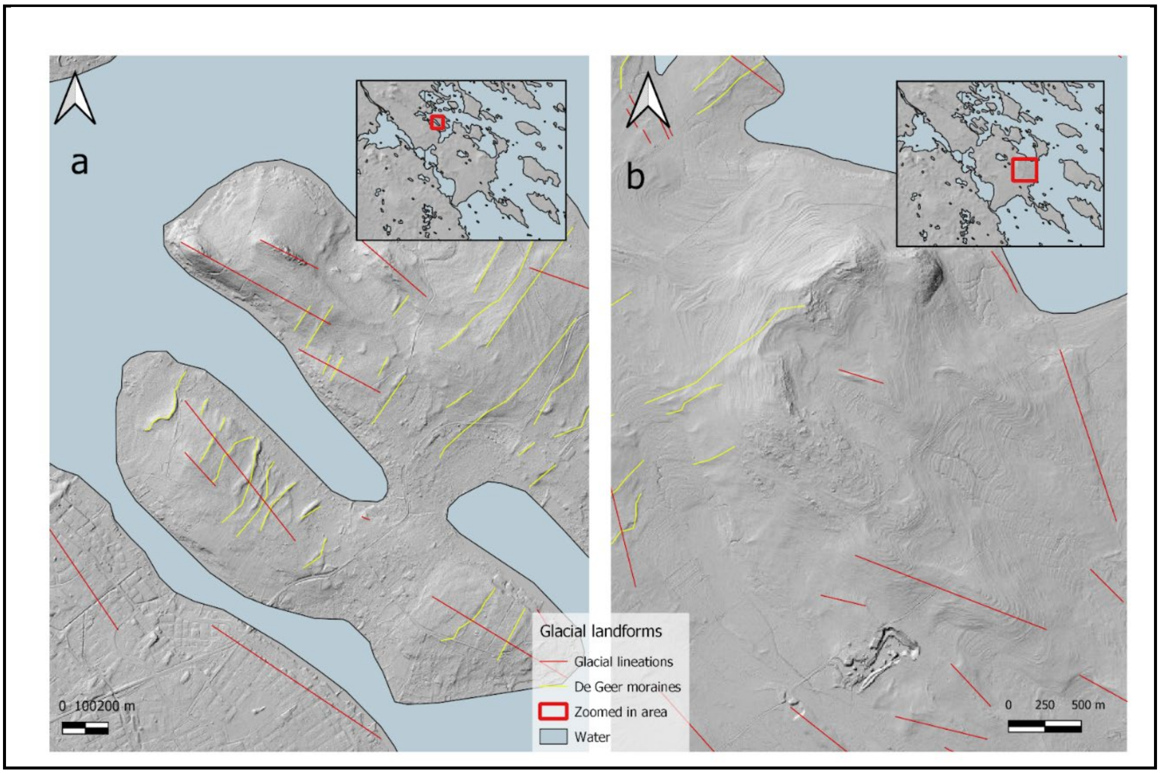

Figure 6: De Geer moraines crossing smaller scale lineations (a), an area near the coast which has almost no moraine ridges (b). Displayed over a 1m/pixel DEM layer (WMS). Made with QGIS 3.10.14.

5.3. Postglacial shorelines

The postglacial shorelines are dispersed over the region and vary in length, shape, and the size of the areas which they cover (Fig. 7). The shorelines commonly appear where the terrain is elevated (Fig. 8a), and some can be seen in the DEM extending the reach of present shorelines at specific locations (Fig. 8b), while others appear to be scattered further inland (Fig. 3).

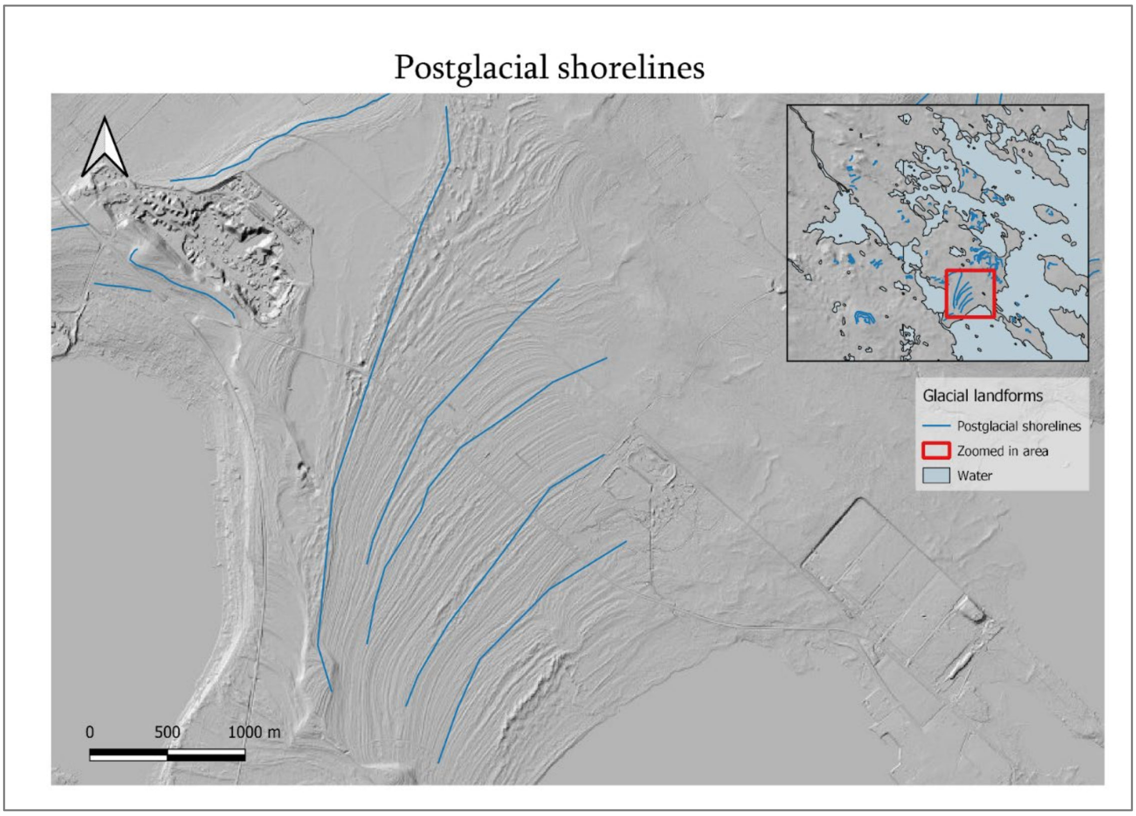

Figure 7: Mapped shorelines near Piteå, displayed over a 1m/pixel DEM layer (WMS). The shorelines are no longer in contact with a body of water. The mapped features are selected examples. Made with QGIS 3.10.14.

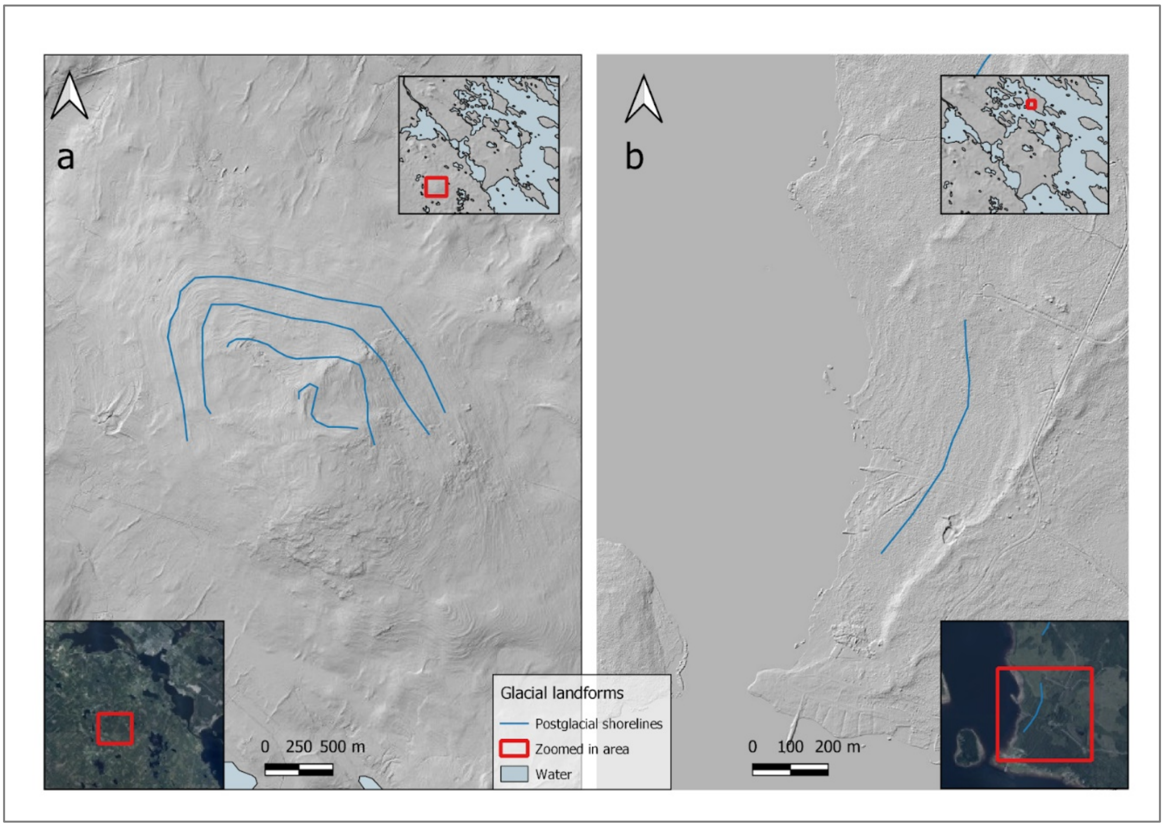

Figure 8: Postglacial shorelines appearing along an elevated feature (a), postglacial shorelines extending the reach of a present shoreline (b). Displayed over a 1m/pixel DEM layer (WMS). Orthophotos with the resolution 0,4m/pixel are included for reference. Made with QGIS 3.10.14.

5.4. Eskers

One esker was identified in the study area (Fig. 9), with an orientation towards NW.

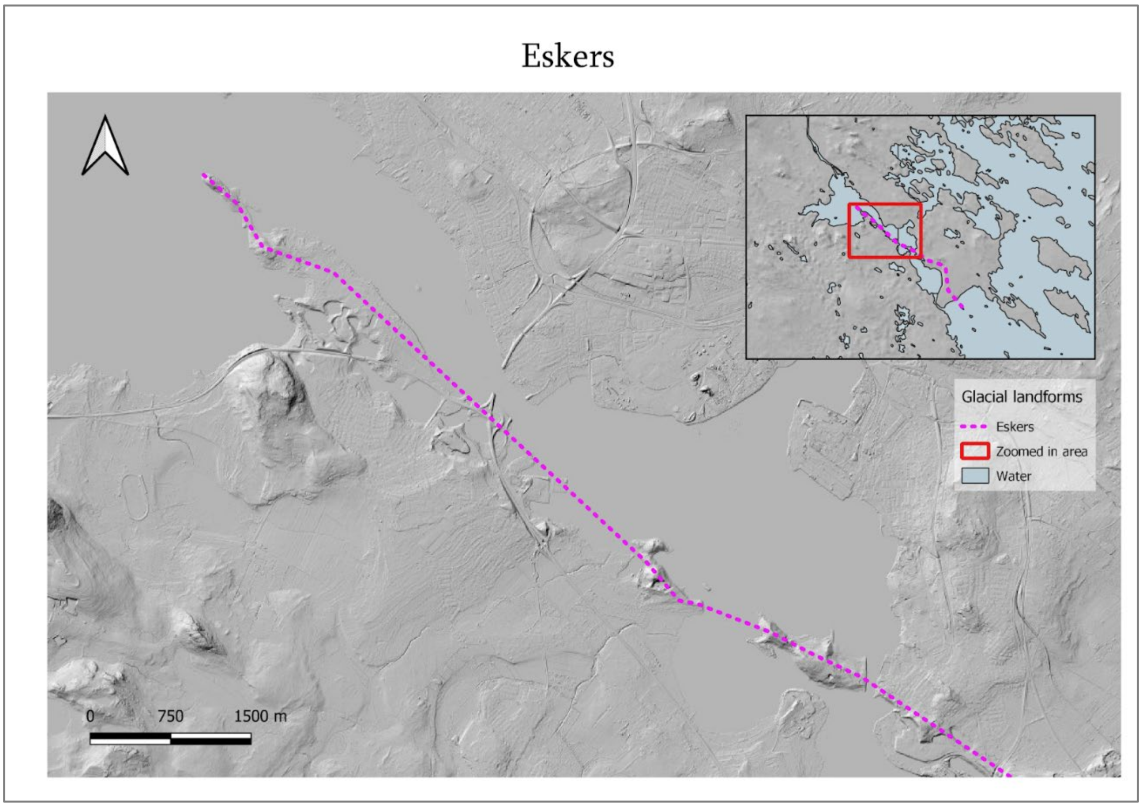

Figure 9: One mapped esker near Piteå, displayed over a 1m/pixel DEM layer (WMS). Made with QGIS 3.10.14.

5.5. Hummocky moraine

Hummocky moraine was identified southwest of Piteå by the ripple- like form, having similarly sized and shaped mounds (Fig. 10). The hummocky moraine continues outside of the mapped area and also appears further inland (Fig. 11).

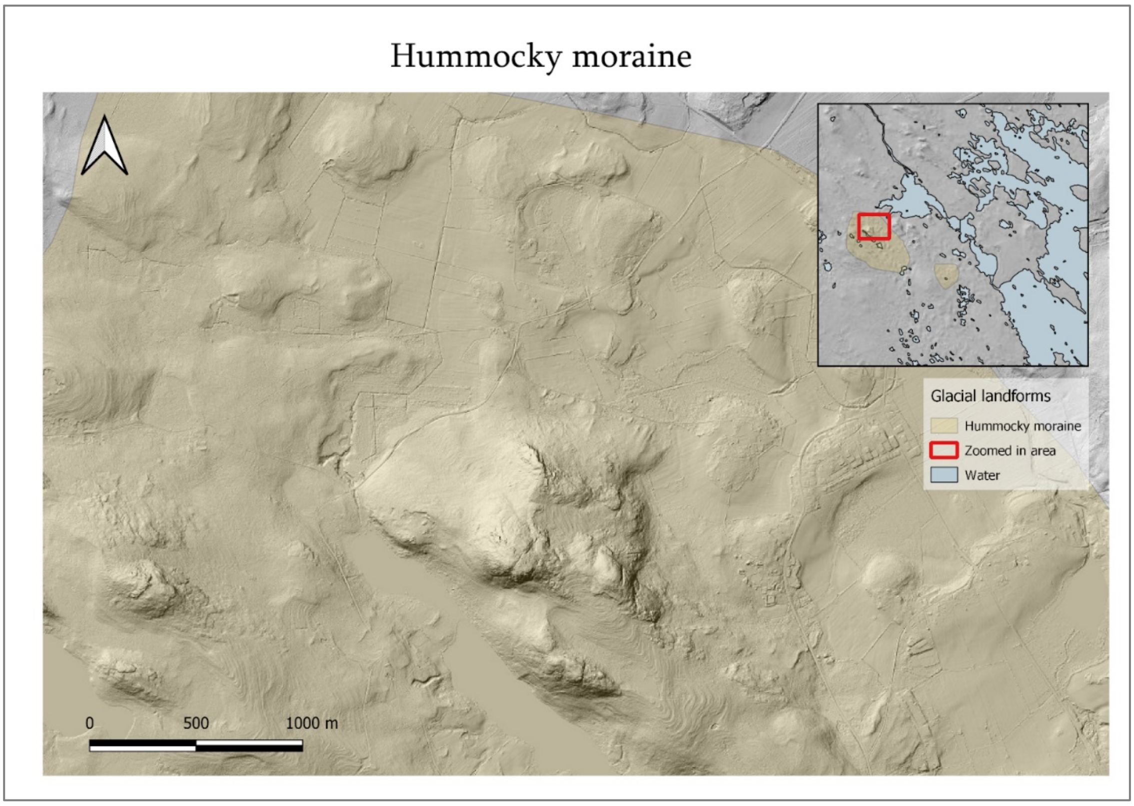

Figure 10: A close up of one of the two mapped areas that appear to show hummocky moraine, displayed over a 1m/pixel DEM layer (WMS). The mapped features are selected examples. Made with QGIS 3.10.14.

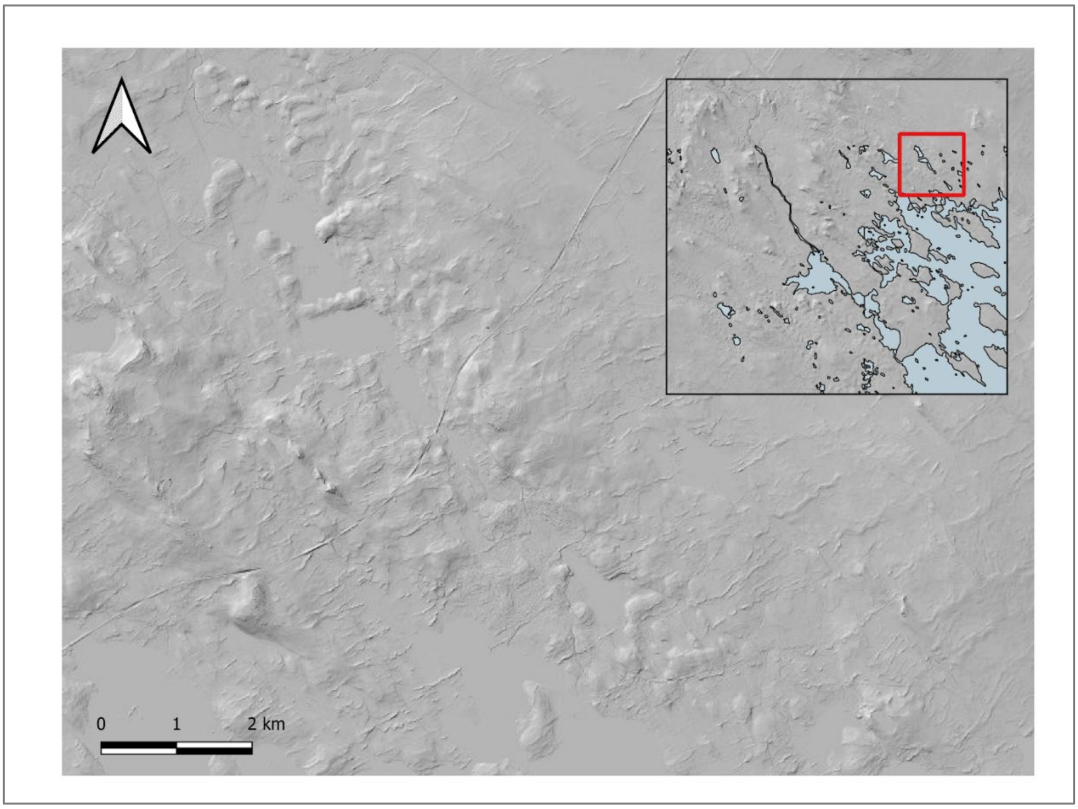

Figure 11: Hummocky moraine further inland that was identified but not mapped. Displayed over a 1m/pixel DEM layer (WMS). Made with QGIS 3.10.14.

6. Discussion

6.1. Glacial geomorphology near Piteå

The mapping in this study demonstrated that lineations, De Geer moraines, and post glacial shorelines are the most prevalent glacial landforms near Piteå. Areas with hummocky moraines were also identified, however mainly outside the study area. Additionally an esker was identified and mapped.

The prevalence of Dee Geer moraines in the region has previously been studied (Lindén & Möller; Hättestrand 1998), and the reason for their general distribution might, according to Bouvier (2015), be due to the low relief. However Hättestrand (1998) points out that the interior of the northeastern coast is an exception as the relief is higher in the region. Bouvier (2015) also mentions that the De Geer moraines in central Sweden appear to sometimes "cross" drumlins and ribbed moraine, indicating that they must have formed later than the other landforms, a similar pattern appears near Piteå where some of the ridges can be seen crossing glacial lineations (Fig. 6a).

One esker could be identified in the study area (Fig. 9), which is oriented NW, indicating a meltwater route from northwest. The esker is broken up, which is likely due to coastal erosion, and it is therefore hard to determine how far inland it extends.

Two areas with what appears to be hummocky moraine have been mapped near Piteå (Fig. 10). All the hummocky moraine in the region has not been mapped however, as it would have required more time to make a detailed geomorphological map this far, but they may be of interest for future mapping and study of regional glacial geomorphology. It should be mentioned that these hummocky moraines also resemble ribbed moraines to some degree, however they do not appear as well defined as in other places in Sweden. It could therefore be said that these appear "less developed".

6.2. The regional advance and retreat of the Scandinavian ice sheet

The predominant NW orientation of the glacial lineations in the area tells us that there has likely been an ice flow from northwest during deglaciation, when rapid warming led to ice sheet withdrawal. Because of the variation in length, it can be theorized that ice flow was more rapid further inland (Stokes & Clark, 2002), where the lineations are more extensive. Additionally, the variation in orientation indicates a variation in flow direction. An explanation for this could be that the lineations in the region have formed at different times (Hättestrand, 1998), with lineations that took longer time to form also eroding slower, thus remaining despite a change in ice flow direction. A majority of the moraine ridges are oriented NE-SW (Fig. 5), and with the assumption that De Geer moraines form at the ice margin, which is typically perpendicular to ice flow, this would also be an indication of an ice flow predominantly from northwest.

Some of the De Geer moraine ridges in the area also appear to be more prominent than others, these could be annual and interannual ridges (Möller 1962; Bouvier 2015). The stronger ones likely formed by winter ice margin advance, while the less prominent ones may have formed due to calving or minor summer advance. While the average spacing between the annual ridges was not a main focus in this project, previous studies have estimated it to be around 500-700 m (De Geer 1940; Bouvier 2015), this would agree with Stroeven et al. (2016) who estimated an ice retreat rate of 600-800 m/year in this region.

6.3. Sea level change

Because of the elevated shorelines, it is known that the area studied was previously covered by the Baltic Sea, like most of the eastern Swedish coastline, and has only reached today's level due to the isostatic rebound that started during deglaciation. This is also apparent when mapping glacial landforms. De Geer moraines form under the water surface at the ice margin (Hämberg, 2021), indicating that Piteå was submerged by the end of the Weichselian glaciation. Postglacial shorelines can be found along elevated terrain practically everywhere in the study area; this is an indication of a sea level regression due to crustal uplift, where the isostatic uplift has been faster than the global sea level rise (Påsse & Daniels, 2015). Furthermore, the reach of the shorelines reveal where the terrain was not submerged by the end of the deglaciation, as the maximum reach of the Baltic Sea in Norrland County (Ångermanland) was about 300 m above the present sea level (SGU, 2020).

6.4. LiDAR

Using LiDAR derived DEMs to map glacial geomorphology proved to be efficient with the accesses to 1 m/pixel resolution. It was noted by Hättestrand (1998) that the difficulty to identify De Geer moraines in aerial photos because of their small scale led him to identify these by earlier publications of quaternary deposits in Sweden. This is not an issue when using LiDAR derived DEMs, where the removed vegetation, such as forested regions, gives a clear model of the bare ground. Consequently, the high resolution elevation data proved to be especially useful when mapping small scale landforms such as De Geer moraines and smaller lineations in the study area. The method of mapping also proved to be time efficient. It is therefore easy to understand how the advances in remote sensing, and the availability of LiDAR derived DEMs, have impacted the mapping of geomorphology.

6.5. Improvments

Throughout the project, time has been the main restricting factor. The greater the area and the more detailed the mapping is the more time it requires. The postglacial shorelines were the last to be mapped and therefore appear scarcer. Similarly, there are De Geer moraines in the area that have not been mapped due to a lack of time. The maps in *Results* therefore demonstrate selected examples of each identified group of glacial landforms in the region. Because of this, an improvement is further detailed mapping of glacial landforms near Piteå, with greater focus on postglacial shorelines. An additional improvement could be a detailed mapping of the hummocky moraines that appear more frequently a bit further away from Piteå.

Conclusion

- Three major types of glacial landforms were identified and mapped near Piteå; glacial lineations, De Geer moraines, and postglacial shorelines.
- In addition to the more common glacial landforms, one esker was identified, and two areas with hummocky moraines were mapped.
- The lineations had an average measured length of 1-1,5 km, increasing in average size further inland. Like the esker, the lineations face NW, which agrees with what is previously known about the direction of the ice movement in the area.
- The presence of De Geer moraines is an indication of Piteå being submerged by the end of the deglaciation, as these form at a glaciers' grounding line. Another possible explanation to their presence in this part of northeastern Sweden could be due to low relief in the region.
- The earlier shorelines that are dispersed over the region also show the sea level regression that followed due to crustal uplift, and although the mapped area was limited these can often be found below the Highest Coastline (HK).
- Using high resolution LiDAR elevation data proved to be an efficient method for time effective mapping, making even small-scale landforms in the study area easily identifiable, and thus highly detailed mapping possible.
- The mapping in this project does not include all the landforms in the study area due to time being a limiting factor, an improvement could therefore be further identification of glacial landforms if that would be the aim.

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