Geomorphology in Borås-Kinna-Ulricehamn area, southwestern Sweden

Stina Wessberg

Bachelor of Science thesis

University of Gothenburg

2023

Abstract

A geomorphological map of southwestern Sweden is presented in this thesis. 12 different landforms were mapped using a 2 m resolution digital terrain model from LiDAR. The focus of the map is on glacial geomorphology however two non-glacial landforms were also included. Two former ice-dammed lakes were also reconstructed in this project, they were estimated to have lasted between 95-135 and 70-100 years respectively. The glacial landforms found in the study area reveal a deglaciation likely governed by an active warm-based glacier. Glacial lineations indicate ice flow direction towards the southwest. The hummocks in the region where often found in connection with eskers, some of the hummocks appear to be lying on top of the eskers while others appear overlain by eskers. This could imply multiple processes behind the formation of hummocks. Lastly the most common trends for the fracture valleys were between NNE-SSW to ENE-WSW.

Sammanfattning

En geomorfologisk karta av sydvästra Sverige presenteras i denna uppsats. 12 landskapsformer karterades med en digital terrängmodell med 2 m upplösning från LiDAR. Kartan fokuserar på glaciala landskapsformer, två icke-glaciala landskapsformer är dock också inkluderade. Två isdämda sjöar var också rekonstruerade i detta projekt, dessa uppskattas ha varat i mellan 95–135 and 70-100 år respektive. De glaciala landskapsformer som hittades i studieområdet avslöjar en deglaciation som styrs av en aktiv varmbottnad glaciär. Glaciala lineationer indikerar ett isflöde mot sydväst. Många rullstensåsar upptäcktes i närheten av moränbacklandskap i området, vissa av moränkullarna verkar ligga över rullstensåsarna medan andra moränkullar verkar befinna sig under rullstensåsarna. Till sist, de vanligaste orienteringarna för sprickdalarna var i mellan NNÖ-SSV och ÖNÖ-VSV.

Table of Contents

1. Introduction

Mapping of geomorphological landforms and features has a long history that has undergone many developments going from a purely field-based approach to using aerial photographs and satellite imagery and to more recently using high resolution remotely sensed data such as the national 2-meter resolution elevation model (NH) derived from Light Detection and Ranging (LiDAR) (Knight et al., 2011; Peterson et al., 2017). With today's improved technology we can create geomorphological maps with great detail.

Glacial geomorphological mapping has been done in Sweden for over 100 years, with different scales and coverage (Öhrling et al., 2020), more detailed geomorphological maps have been made in surrounding regions of this study area (Figure 1) by Peterson et al. 2017 of the south Swedish uplands and Öhrling et al. 2020 of the area between lake Vänern and lake Vättern.

Regional glacial geomorphological maps are important not only for academic use to help better understand the formation and evolution of glacial landforms but also for societal use such as natural hazard assessments and civil engineering (Peterson et al., 2017; Chandler et al., 2018).

Figure 1. Overview map of the mapped area for this project, in southwestern Sweden.

1.1 Geology of southwestern Sweden

The bedrock in southwestern Sweden is polymetamorphic and has been formed and reworked by several orogenesis, first the Gothian orogeny around 1.7 to 1.5 Ga, followed by the Hallandian orogeny ~1.46 to 1.4 Ga and most recently the Sveconorwegian orogeny ~1.1 Ga (Åhäll et al., 2008).

By the end of Neoproterozoic era around 550 Ma the bedrock had been eroded down to a low relief plain known as the sub-Cambrian peneplain (Grendaitė et al., 2022). Sedimentary rocks such as limestone, shale and sandstone were deposited on top of the peneplain during the Paleozoic era. Following the Paleozoic era, the Mesozoic era's climate was warm and humid leading to deep weathering of the exposed sub-Cambrian peneplain as well as the Paleozoic sedimentary rocks that were mostly weathered away (Elvhage et al., 1987).

1.2 Glaciation

During the Pleistocene, glaciers advanced and retreated several times over the Swedish landscape in the multiple glacial periods. Little evidence can be found from the earlier glaciations in the southern Swedish landscape, where most glacial landforms are a record of the latest glaciation, the Late Weichselian glaciation (Peterson et al., 2017; Lundqvist, 2004, p. 401).

The Weichselian glacial period began around 115 ka and reached maximum glaciation three times with two interstadials at 195-93 ka and 85-74 ka (Lokrantz & Sohlenius, 2006). The full extent of the first two glaciations during the early Weichselian is still uncertain (Lundqvist, 2004, p. 402-403). The last glaciation covered Sweden in ice from the middle Weichselian to the beginning of the late Weichselian, reaching its maximum glaciation around 21 ka and extending as far south as northern Germany (Lokrantz & Sohlenius, 2006). During the deglaciation several readvances and stillstands took place, leaving the southwestern Sweden ice free at around 14 ka (Peterson et al., 2017).

1.3 Purpose of report

- Provide a detailed geomorphological map of glacial landforms to better understand the glacial history of the study area.

- To recreate ice-dammed lakes within the study area and make an estimation for how long they could have lasted.

2. Method

2.1 Mapping

The mapping of landforms was performed on ESRI ArcGIS® ArcMap 10.7 using a digital terrain model (DTM) with a 2 m resolution derived primarily from LiDAR scanning (Lantmäteriet, 2019). Five hillshades were created with different azimuths of 315, 0, 30, 90 and 270 to help improve interpretations of different features. Surficial deposits data from SGU was also used to improve interpretations. The landforms were mapped at altering scales of 1:15 000, 1:30 000 and 1:60 000 depending on the size of the landform.

2.2 Rose diagrams

Software program Stereonet 11 was used to create rose diagrams for the azimuth distribution of the glacial lineations and fracture valleys. The azimuth of the glacial lineations and fracture valleys were measured and calculated on ArcGIS.

2.3 Reconstruction of ice-dammed lakes

The reconstruction of ice-dammed lakes was made on ArcGIS using the DTM. Estimations of the shapes and sizes of ice-dammed lakes were made using the top elevation of meltwater channels to get the elevation and thereof the extant of the ice-dammed lakes.
The longevity of the ice-dammed lakes was estimated using ice retreat rates that were calculated from the De Geer moraines found in the mapped area as well as deglaciation timelines from Stroeven et al. 2016 and Anjar et al. 2014. The ice retreat rates were than compared to the length of the lakes to get a rough estimate of how long they might have lasted.

3. Results

A total of 2774 features were mapped in this project and presented in the map below (Figure 2). Four rose diagrams were made (Figure 5(A-D)) and two ice-dammed lakes were reconstructed (Figure 6(A-C)).

3.1 Mapped landforms

12 different landforms were mapped, Table 1 show the number of features for each landform. The focus of the map is on glacial landforms, however fracture valleys and raised bogs were also included.

Table 1: The total sum of features mapped as well as the individual count for all landforms.

Landform	Features (n)
Drumlins	92
Crag & tails	248
Stoss-side drumlins	10
Eskers	407
End moraines	16
De Geer moraines	55
Meltwater channels	120
Hummock tracts	77
Deltas	48
Outwash plains	11
Raised bogs	76
Fracture valleys	1614
Total	**2774**

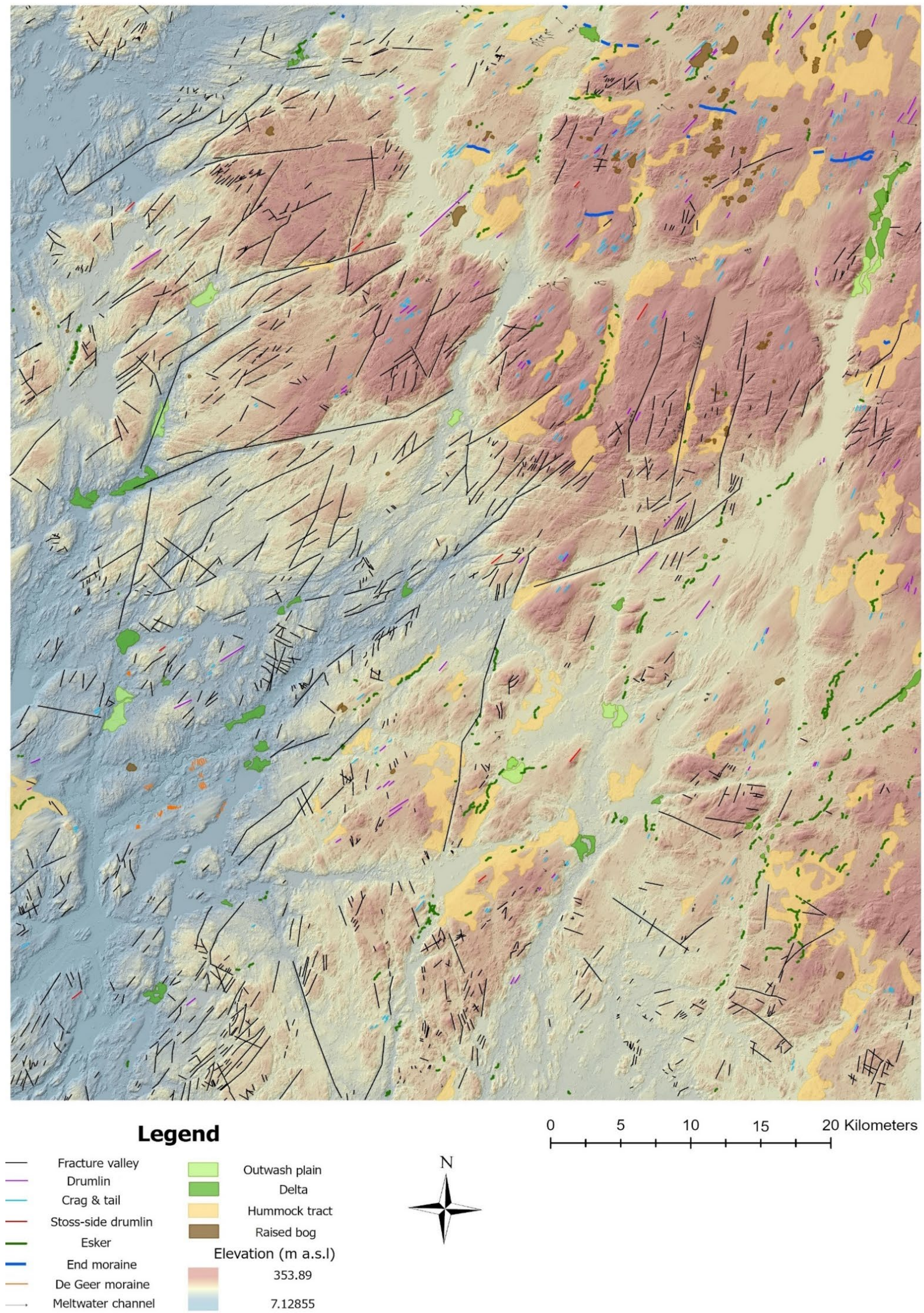

Figure 2. Geomorphological map of southwestern Sweden

3.1.1 Glacial lineations

The glacial lineations that were mapped are drumlins, crag-and-tails and stoss-side drumlins. They are elongated to oval shaped hills that are formed subglacially in the direction of the ice flow (Peterson et al, 2016; Remmert et al., 2022). A total of 350 glacial lineations (Table 1) were mapped and they appear mostly in the middle and eastern part of the mapped area (Figure 2).

Drumlins have long been a source of debate, their genesis is still a mystery without a complete answer, there is evidence for both erosional and depositional genesis (Möller & Dowling, 2018; Stokes et al., 2011).

Crag-and-tails are identified by the presence of a rock knob at the up-ice end of the landform, their genesis can be either depositional or erosional. Depositional crag-and-tails are more common and are formed when the ice moves over the resistant bedrock protuberance at the up-ice end creating a cavity down-ice, which is then filled up by till (Evans & Hansom, 1996) (Figure 3). Erosional crag-and-tail are on the other hand formed when the resistant bedrock at the up-ice end acts as a shield for weathered, less resistant bedrock on the down-ice side protecting it from erosion (Benn & Evans, 2010).

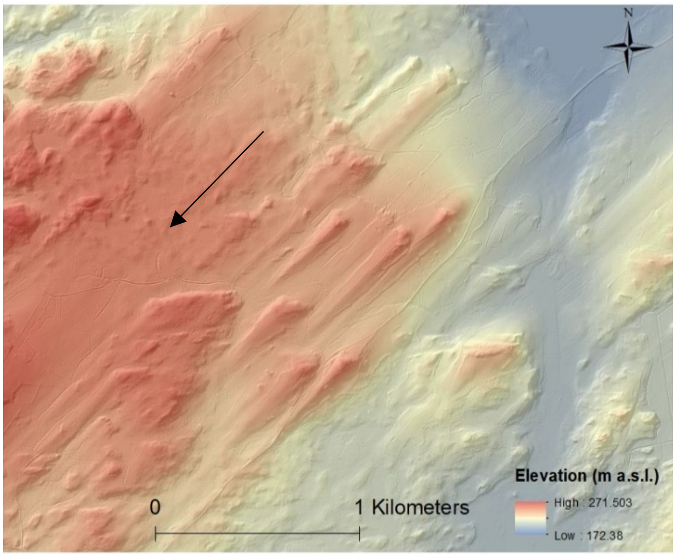

Figure 3. Examples of some depositional crag-and-tails within the study area, with a visible rock knob up-ice and a tail of till down-ice. The black arrow show ice flow direction.

Compared to crag-and-tails, stoss-side drumlins have a resistant rock formation at the down-ice end. The formation of stoss-side drumlins is believed to be primarily depositional. However, findings of exposed sediments that predate the late Weichselian in several stoss-side drumlins would suggest that they are also in part erosional (Remmert et al., 2022).

3.1.2 Esker

Eskers are ridges often found along the sides of valleys, made up of sorted glaciofluvial sediments that were deposited by meltwater flowing through tunnels within the glacier or underneath it, or though channels on top of the ice (Öhrling et al, 2020; Stroeven et al, 2016; Butcher, 2020). Eskers can get up to hundreds of kilometers long and tens of meters high (Stroeven et al., 2016). 407 segments of esker ridges were mapped, most of which are found in the eastern and central area.

3.1.3 End moraine

Ridges formed at the snout of the glacial are known as end moraines or terminal moraines. They are made up of unsorted glacial till and mark former stillstands or readvances (Peterson et al., 2016). Segments of the well-known Trollhättan moraine can be found in the northern part of the study area and further north parts of a lesser-known moraine can also be found (Figure 4(A)). This moraine has been mapped previously by Stroeven et al. 2016 and Öhrling et al. 2020, the later which referred to it as the ‘Remmene moraine’.

3.1.4 De Geer moraine

De Geer moraines are narrow ridges formed during ice retreat at the grounding line of a glacier in subaquatic environments (Bouvier et al., 2015) (Figure 4 (B)). They often occur below the highest shoreline in equally spaced, parallel to subparallel sequences, and believed to be formed annually during winter advances (Öhrling et al., 2020; Bouvier et al., 2015). De Geer moraines are found in the southwest region of the mapped area.

3.1.5 Hummock tract

Hummocks are small irregular hills occurring in clusters surrounded by depressions (Figure 4(C)). An area with hummocks is referred to as a hummock tract and it is often elongated, subparallel to the ice flow direction (Johnson & Clayton, 2003).

There are multiple explanations for how hummock tracts are formed. The most accepted theory is that they are formed through dead-ice processes, where supraglacial debris lying on stagnant ice is let down as the ice melts away (Johnson & Clayton, 2003). There are also several theories that the genesis occurs subglacially, such as the formation of hummocks through subglacial meltwater erosion, the pressing of dead ice on a soft bed or the molding by active ice (Munro & Shaw, 1997; Hoppe 1995; Aario, 1977).

The hummock tracts mapped can be found mostly in the central and eastern part of the map (Figure 2), within the tracts other features can also be found. Many eskers as well as a drumlin and some ribbed moraines were found. The ribbed moraines found in the hummock tract were the only ones found in the entire study area and were therefore not included in the final map as a mapped landform.

3.1.6 Meltwater channel

This erosional landform is formed by meltwater flowing along the ice margin cutting into the ground surface forming channels. These channels are usually tens of meters deep and can get up to hundreds of meters long and form in subparallel, down-slope sequences (Stroeven et al., 2016) (Figure 4(D)). Within the study area meltwater channels are found in the central and eastern part (Figure 2).

3.1.7 Outwash plain

Outwash plains, also known as sandurs, are flat-topped accumulation of glaciofluvial sediments such as sand and gravel (Öhrling et al., 2020;

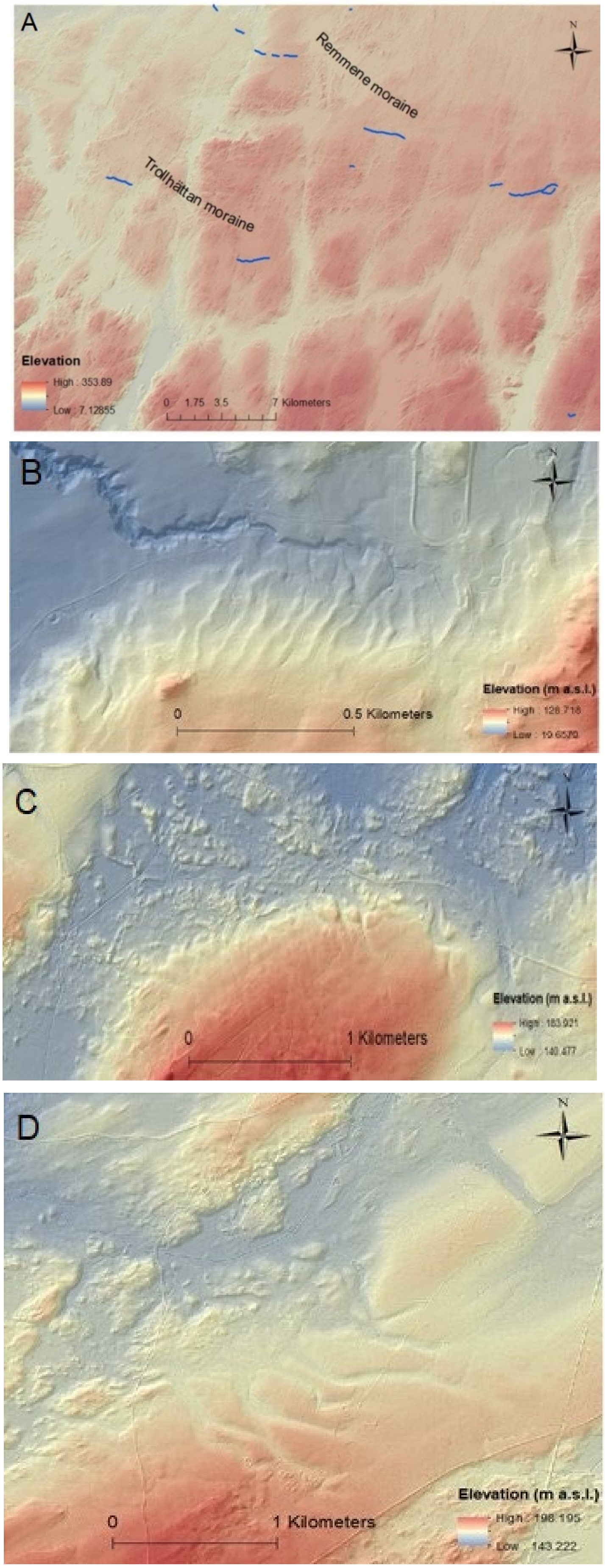

Figure 4. Examples of several features found in the study area. A) End moraines. B) De Geer moraines. C) Hummock tract. D) Meltwater channels.

Peterson et al., 2017). A couple of outwash plains were mapped, found spread out in the study area (Figure 2).

3.1.8 Glaciofluvial delta

During deglaciation, glaciofluvial material is carried out of the glacier by meltwater and deposited in standing water forming glaciofluvial deltas (Peterson et al., 2017). Deltas have flat surfaces and record the water level at the time of formation, some graded to sea level or the Baltic basin's water level while others are graded to ice-dammed lakes from the area (Öhrling et al., 2020). Most deltas found in the area were located along the western side.

3.1.9 Raised bog

Raised bogs are raised, dome-shaped bodies of peat that can reach 10 m in height. They are formed in shallow lakes where accumulations of un-decaying plant materials fill the lake and create a fen. On the surface of the fen more peat is formed and accumulated creating a raised bog (Almquist-Jacobson & Foster, 1995). The development of a raised bog can take several thousands of years, many began forming after the last deglaciation (Peatlands Management Unit, n.d.). Most of the raised bogs mapped were found in the northeastern part of the map, however there were also many smaller bogs found throughout the study area that were not mapped due to time restrictions.

3.1.10 Fracture valley

Fracture valleys are created through deep weathering and erosion of pre-existing faults or joints. They can be found throughout most of the study area. Fewer fracture valleys can be found towards the east with a majority of found along the western and central part of the map.

3.2 Rose diagrams

The rose diagrams for drumlins, crag & tails and stoss-side drumlins show very similar NE-SW trending orientations, only drumlins had one distinct outlier trending in a NW-SE direction (Figure 5(A-C.)). Fracture valleys in the mapped area show more variety in orientations, most trending between NNE-SSW to ENE-WSW, N-S and NW-SE (Figure 5(D)).

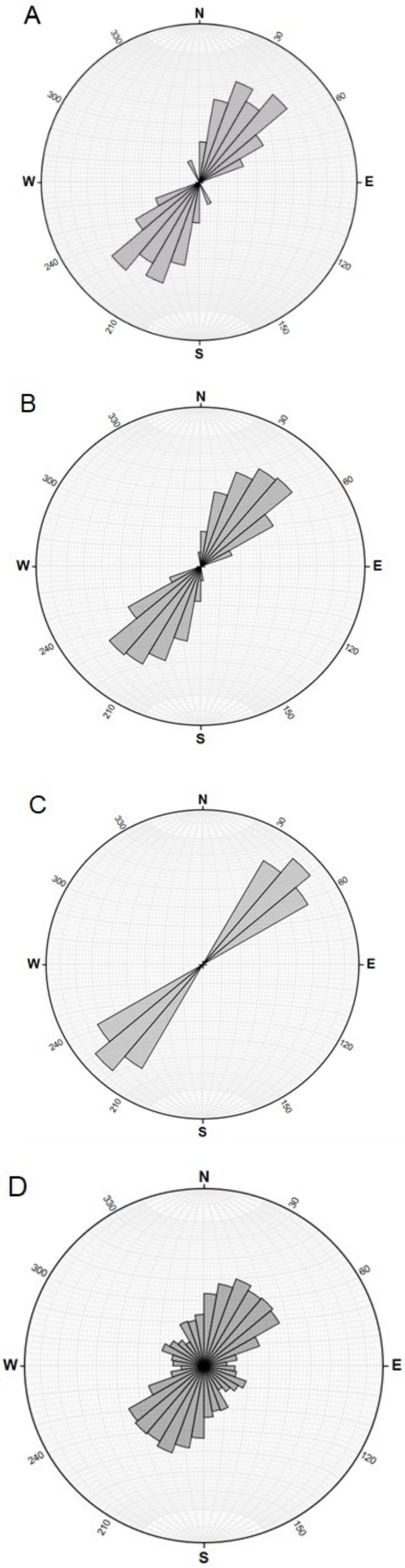

Figure 5. Rose diagrams of orientations for: A) Drumlins, B) Crag-and-tails, C) Stoss-side drumlins and D) Fracture Valleys.

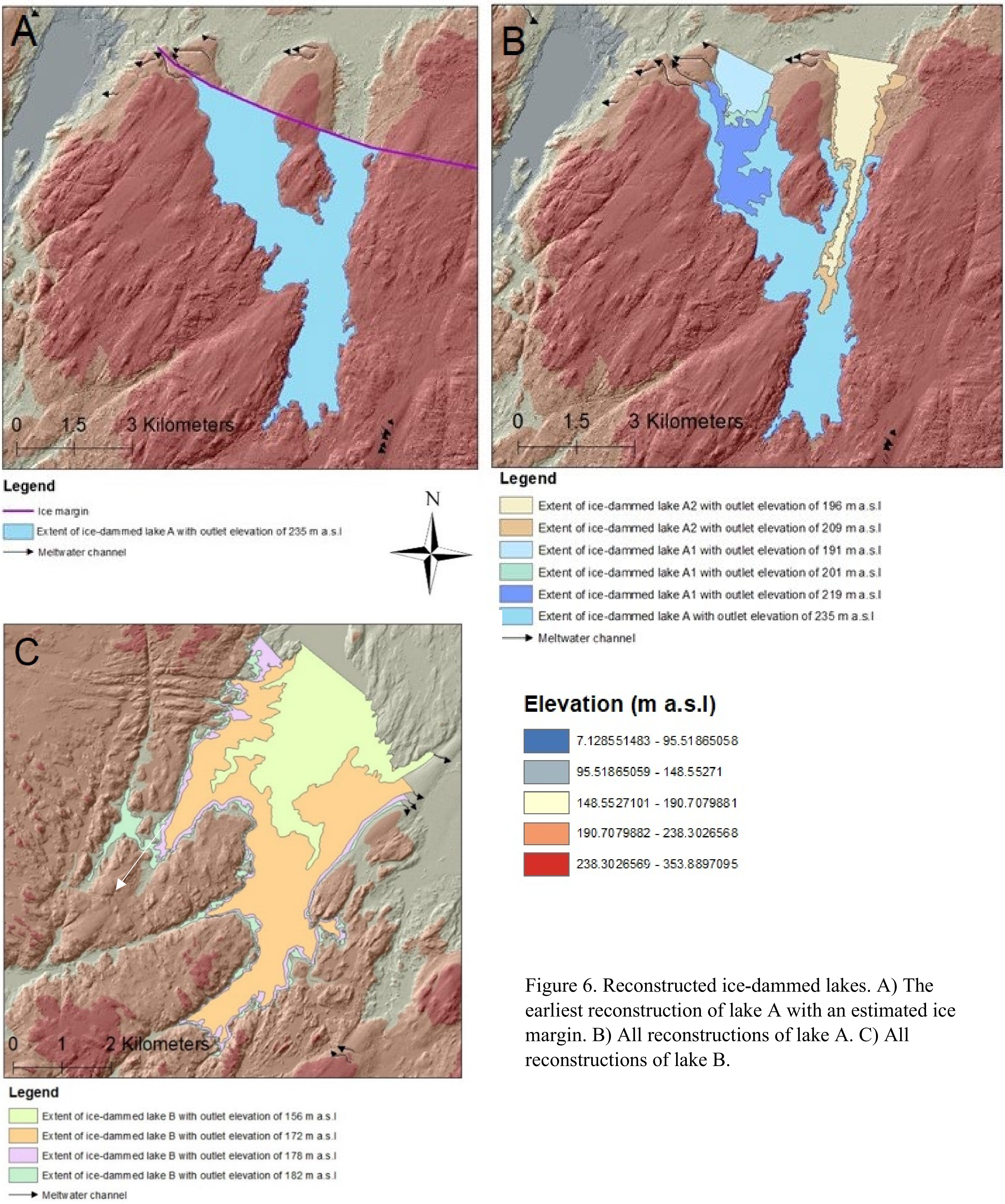

Figure 6. Reconstructed ice-dammed lakes. A) The earliest reconstruction of lake A with an estimated ice margin. B) All reconstructions of lake A. C) All reconstructions of lake B.

3.3 Recontructed ice-dammed lakes

Ice dammed lakes are formed in front of the glacier where their natural drainage is blocked by the ice margin (Benn & Evans, 2014, p. 91). Along the ice margin water can drain from the lake, eroding the substrate forming meltwater channels. Two ice-dammed lakes were reconstructed in this project, referred to as lake A and B (Figure 6 (A-C)). When using the meltwater channels to reconstruct several different stages of the lakes during the ice retreat, you can see that at some point lake A diverged into two separate lakes, lake A1 and A2 (Figure 6(B)). The ice-margin-retreat rate of the area was estimated to be around 75-109 m/yr. With these retreat rates, lake A and B were estimated to have lasted around 95-135 and 70-100 years respectively. At the earliest stage that was reconstructed for lake A and B, they were of similar size, lake A covering and area of 16 km^2 and lake B 17 km^2.

4. Discussion

Many of the glacial landforms such as drumlins, crag-and-tails, eskers, and hummock tracts that were mapped in this area have a similar distribution pattern, with all or a majority of features found in the central and eastern part of the map. The sparsity of features in the western area might be because it’s in large part below the highest shoreline, which could mean that these features don’t occur under the highest shoreline or have been covered by marine sediments. De Geer moraines that are generally found below the highest shoreline were also found in the southwestern part which would further suggest that the western part is below the highest shoreline.

Rose diagrams of the glacial lineations show a unanimous trend towards the southwest which suggest that being the ice flow direction, this would be in agreement with the previous studies by Öhrling et al. 2020 and Peterson et al. 2017 from surrounding areas. The drumlin outlier that trend towards the southeast might have been the result of a readvance or a different ice flow direction due to local topography.

It was likely an active warm-based glacier that moved through the study area, evident by the plentiful distribution of glacial lineations and glaciofluvial landforms such as eskers and deltas. The De Geer moraines found in the area would also indicate an active retreat as winter advances are common with active warm-based glaciers (Benn & Evans, 2014, p. 599).

Many of the hummock tracts mapped were found with eskers in them, indicating the presence of meltwater, some of the eskers appear to be overlying the hummocks. Examining these eskers further to determine whether they are subglacial, englacial or supraglacial could be helpful in figuring out the genesis of those hummock tracts. If they are subglacial, it could indicate a subglacial meltwater erosion genesis for those hummock tracts with the hummocks forming prior to the eskers. The eskers being formed subglacially could possibly be supported by Peterson & Johnson (2018) who interpreted the eskers found within and in proximity of hummock tract in their study area to be subglacial eskers. There was also at least one tract where hummocks seem to be resting on top of an esker, which could indicate the formation of hummocks through dead-ice melting. Finding both hummocks overlain by eskers and eskers overlain by hummocks could mean that there are multiple processes responsible for formation of the hummock tracts in the study area, this would be consistent with previous studies. Peterson & Johnson (2018) and Öhrling et al. (2020) believed the hummock tracts found in their respective study areas to be the result of various processes, including subglacial meltwater erosion and dead-ice melting. As their study areas are in proximity and slightly overlapping with this project’s study area it is also possible to be the case here. A more detailed study of the hummocks in this mapped area and the other features found within them would be necessary to draw further conclusion regarding their origin. For instance, determining if they are erosional or depositional, if there’s a difference in their morphology throughout the area, if the eskers are subglacial, englacial or supraglacial could help give greater insight to how hummocks are formed.

Only two ice-dammed lakes were reconstructed in this project as it was not the main focus of this thesis. It should however be noted that there are likely more former ice-dammed lakes to be found within the study area. Using the roughly calculated local ice retreat rate of 75-109 m/yr, lake A (Figure 6(A)) was estimated to have lasted around 95-135 years. The A1 section of the lake was likely dammed by the ice margin a few years less than section A2 (Figure 6(B)). Lake B was estimated to have lasted about 70-100 years (Figure 6(C)).

Many fracture-valleys were found trending NNE-SSW, NE-SW, ENE-WSW, N-S and NW-SE, these could be possible fracture sets however, to be more certain further analysis of the fractures would be required. To determine how these fracture sets relate to the regional tectonics a more in-depth analysis of the tectonic evolution and the fracture valleys in the study area would be necessary.

There are improvements that could be made, time was limited for this project which resulted in many features not being mapped. With the focus of this project being on glacial geomorphology less time was spent on the non-glacial landforms. Raised bogs were mapped last and there wasn't time to include all of them which could've contributed to their unequal distribution. Going over the study area again would likely result in many more features being mapped. Including some field-based analysis of some of the features could also be helpful to improv the map and its accuracy.

5. Conclusion

- The distribution of glacial landforms indicates that at least some areas of the western side of the study area are below the highest shoreline.
- The glacial lineations reveal an ice flow direction towards the SW.
- The glacier was likely active warm-bottomed as several of the landforms found are often products of such a glacier.
- Hummocks in the area show possible evidence for multiple processes behind their formation.
- The longevity of the reconstructed ice-dammed lakes was estimated to 95-135 and 70-100 years.
- Most of the fracture valleys mapped were trending between NNE-SSW to ENE-WSW.

References

Almquist-Jacobson, H., & Foster, D. R. (1995). Toward an integrated model for raised-bog development: theory and field evidence. *Ecology*, *76*(8), 2503-2516. DOI: https://doi.org/10.2307/2265824

Benn, D., & Evans, D. J. (2010). *Glaciers and glaciation* (2nd ed.). Routledge.

Bouvier, V., Johnson, M. D., & Påsse, T. (2015). Distribution, genesis and annual-origin of De Geer moraines in Sweden: insights revealed by LiDAR. *GFF*, *137*(4), 319-333. DOI:10.1080/11035897.2015.1089933

Butcher, F. (2020, August 18). *Eskers*. AntarcticGlaciers. Retrieved September 2, 2023, from https://www.antarcticglaciers.org/glacial-geology/glacial-landforms/glaciofluvial-landforms/eskers/

Chandler, B. M., Lovell, H., Boston, C. M., Lukas, S., Barr, I. D., Benediktsson, Í. Ö., ... & Stroeven, A. P. (2018). Glacial geomorphological mapping: A review of approaches and frameworks for best practice. *Earth-Science Reviews*, *185*, 806-846. DOI: https://doi.org/10.1016/j.earscirev.2018.07.015

Elvhage, C., & Lidmar-Bergström, K. (1987). Some working hypotheses on the geomorphology of Sweden in the light of a new relief map. *Geografiska Annaler: Series A, Physical Geography*, *69*(2), 343-358. DOI: https://doi.org/10.1080/04353676.1987.11880220

Grendaitė, M., Michelevičius, D., & Radzevičius, S. (2022). A large array of inselbergs on a continuation of the sub-Cambrian peneplain in the Baltic Basin: evidence from seismic data, Western Lithuania. *Geological Quarterly*, *66*(1), 66-2. DOI: http://dx.doi.org/10.7306/gq.1633

Knight, J., Mitchell, W. A., & Rose, J. (2011). Geomorphological field mapping. In *Developments in earth surface processes* (Vol. 15, pp. 151-187). Elsevier. DOI:https://doi.org/10.1016/B978-0-444-53446-0.00006-9.

Lantmäteriet. (2019). Quality description of National Elevation Model: v. 1.4.

Lokrantz, H & Sohlenius, G. (2006). Ice marginal fluctuations during the Weichselian glaciation in Fennoscandia, a literature review. *Geological Survey of Sweden.* Technical Report, TR-06-36.

Lundqvist, J. (2004). Glacial history of Sweden. J. Ehlers & P. L. Gibbard, (Eds.) *Quaternary Glaciations Extent and Chronology - Part I: Europe* (1st ed., pp. 401-412). Elsevier.

Möller, P., & Dowling, T. P. (2018). Equifinality in glacial geomorphology: instability theory examined via ribbed moraine and drumlins in Sweden. *GFF*, *140*(2), 106-135. DOI: https://doi.org/10.1080/11035897.2018.1441903.

Peterson, G., & Johnson, M. D. (2018). Hummock corridors in the south-central sector of the Fennoscandian ice sheet, morphometry and pattern. *Earth Surface Processes and Landforms*, *43*(4), 919-929. Doi: https://doi.org/10.1002/esp.4294

Peterson, G., Johnson, M. D., & 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. DOI: https://doi.org/10.1080/17445647.2017.1336121.

Peatlands Management Unit (n.d.) *What is a raised big?* The Living Bog. Retrieved May 29, 2023, from https://www.raisedbogs.ie/what-is-a-raised-bog/.

Remmert, I., Johnson, M. D., Ström, O. J., Peternell, M., & Becher, G. P. (2022). Seasonal subglacial ponding deposits in a thick till sequence, Dösebacka drumlin, southwest Sweden. *Sedimentary Geology*, *440*, 106241. DOI: https://doi.org/10.1016/j.sedgeo.2022.106241.

Stokes, C. R., Spagnolo, M., & Clark, C. D. (2011). The composition and internal structure of drumlins: complexity, commonality, and implications for a unifying theory of their formation. *Earth-Science Reviews*, *107*(3-4), 398-422. DOI: https://doi.org/10.1016/j.earscirev.2011.05.001.

Stroeven, A. P., Hättestrand, C., Kleman, J., Heyman, J., Fabel, D., Fredin, O., ... & Jansson, K. N. (2016). Deglaciation of fennoscandia. *Quaternary Science Reviews*, *147*, 91-121. DOI: https://doi.org/10.1016/j.quascirev.2015.09.016.

Öhrling, C., Peterson, G., & Johnson, M. D. (2020). Glacial geomorphology between Lake Vänern and Lake Vättern, southern Sweden. *Journal of Maps*, *16*(2), 776-789.DOI: https://doi.org/10.1080/17445647.2020.1820386.