PH.D. THESIS

Sedimentology and Geomorphology of Glacial Landforms in Southern Sweden

Studying the Landscape of a Melting Ice Sheet

Gustaf Peterson Becher

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Gothenburg 2021

Cover illustration:
Illustration by John Bauer (1882-1919) from *Bland tomtar och troll* 1914 (Eng. Among Gnomes and Trolls).
On the cover of this thesis, the meeting, and conversation between the troll and the young boy symbolizes the research process in which the researcher formulates and asks questions to nature. The setting is typical for the forests in which hours have been spent looking for answers during the work on this thesis.
The background is a color stretched elevation model of the Hörda tunnel valley.

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In loving memory of my mother

At last, two or three quiet guests essayed to call in the assistance of a period of severe cold, and from the highest mountain ridges would look in spirit upon glaciers sloping down far into the land, sliding-planes so to speak, provided for heavy masses of primitive rock, which were thus pushed farther and farther down upon the slippery path. These, on the advent of the period of thaw, must needs sink down, to remain lying forever on foreign soil.

Johan Wolfgang von Goethe (1749-1832) in "Wilhelm Meisters Wanderjahre" (von Goethe, 1833, 1885)

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ABSTRACT

Ice sheets are disintegrating due to global warming. One factor controlling ice-sheet behavior is the processes active beneath the ice sheet. In particular, processes connected to glacial meltwater drainage are essential to understand ice-sheets behavior in a warming climate. Investigating sediments and geomorphology of drainage systems below ice sheets is complicated; however, formerly glaciated regions are easily accessible. These regions display landforms and sediments formed by the processes at the ice-sheet bed.

Glacial landforms were mapped in the south Swedish uplands, an area that makes up a large part of the former south-central part of the Scandinavian Ice Sheet. This region was deglaciated during the Bølling-Allerød warm period, before the Younger Dryas cold event. During the Bølling-Allerød, large amounts of meltwater were derived from ice sheets to the world's oceans.

In the form of detailed digital elevation models, new datasets have made it possible to map formerly glaciated regions in unprecedented detail and pinpoint locations for detailed sedimentological work.

The map produced is the first comprehensive inventory of glacial geomorphology produced for the south Swedish uplands. This mapping discovered several new features that are added to the plethora of landforms already known, including radial hummocks tracts interpreted to be tunnel valleys, glaciofluvial meltwater corridors, and a new V-shaped hummock referred to as murtoos.

Hummock tracts within the area demonstrate a heterogeneous hummock morphology. As previously mapped, a lobate band of hummock tracts can be traced through southern Sweden. However, the hummock tracts also display a clear radial pattern of hummock corridors associated with ice flow. Based on the geomorphological and sedimentological analysis, the radial pattern of hummock corridors are interpreted as tunnel valleys or glaciofluvial meltwater corridors and is suggested to reflect strong meltwater activity at the bed of the ice sheet.

The V-shaped hummocks (murtoos) are argued to be a new and distinct subglacial landform with a morphology related to overall ice flow. Based on ice-sheet scale distribution, geomorphological analysis, and sedimentological studies, a formational model is hypothesized. The model is driven by variations in the subglacial hydrological system connected to repeated influx from supraglacial meltwater to the ice-sheet bed within the distributed system.

Tunnel valleys, glaciofluvial corridors, and murtoos are all proposed to be formed in the subglacial hydrological system. The formation of these landforms indicates intense melting at the ice-sheet surface, and this is clearly associated with times of climate warming. The landform connection can be illustrated as a times-transgressive landform system, where murtoos are suggested to form first, followed by TVs, GFCs, and finally, eskers.

Keywords: glacial geomorphology, glacial geology, glacial sedimentology, paleo-glaciology, hummock, tunnel valleys, glaciofluvial meltwater corridors, murtoo, esker, subglacial hydrology, subglacial deformation, subglacial process

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Sammanfattning

Inlandsisar och glaciärer smälter på grund av global uppvärmning. I olika delar av världen påverkar detta en viktig källa för dricksvatten. Kustsamhällen påverkas när havsnivåerna stiger som en konsekvens av avsmältningen. För att bättre förstå hur inlandsisar reagerar när de smälter behöver vi studera de olika processer som påverkar inlandsisarna. De viktigaste processerna för att förstå inlandsisarnas reaktioner sker under inlandsisen. Inte helt oväntat är dessa processer därför ganska svåra att studera under dagens inlandsisar och glaciärer.

Under istiden täcktes stora delar av Europa upprepade gånger av inlandsisar. Inlandsisarna lämnade spår efter sig i landskapet som vittnar om de processer som var aktiva under isen. Dessa återfinns som olika landformer och sediment i landskapet. Genom att studera landskapet som har varit täckt av inlandsisen är det möjligt att öka förståelsen för de processer som är aktiva under inlandsisar och på så vis öka kunskapen om hur de reagerar i ett förändrat klimat.

När den senaste inlandsisen smälte, för cirka 22 000 år sedan, började iskanten röra sig norrut. För ungefär 15 000 år sedan började inlandsisen smälta snabbare på grund av ett varmare klimat kopplat till värmeperioden Bølling-Allerød. Vid denna tid låg iskanten i de södra delarna av Småland och under de kommande 3 000 åren drog sig iskanten norrut genom landskapet. Som en del i den här avhandlingen har stora delar av Småland därför kartlagts med avseende på landformer som bildats under inlandsisen med syfte att öka förståelsen om de processer som är aktiva.

Kartläggningen möjliggjordes av digitala höjdmodeller som avbildar landskapet i en sådan detalj att landformer som bara är några meter stora kan urskiljas. En så detaljerade kartläggning ger också möjligheten att med stor precision välja platser att studera sedimentens egenskaper i dessa landformer. Kartläggningen har resulterat i flertalet nya upptäckter som kan bifogas den kunskap som redan finns. De mest intressanta resultaten inkluderar att de i södra Sverige finns förekomster av tunneldelar, smältvattenkorridorer och en nyfunnen V-formad landform, som kallas 'murtoo'.

Landskapet uppvisar fler landformer än tidigare trott och dessa är kopplade till mycket smältvatten från glaciärerna. Förutom rullstensåsar, vilka bildas i vattenfyllda tunnlar under isen, visar studierna i denna avhandling också att andra, större landformer bildades när inlandsisen drog sig tillbaka. En av dessa landformer är tunneldalar, vilka är stora (upp till 2 km breda) dalgångar i landskapet bildade av smältvatten under inlandsisen. Relaterade landformer, så kallade smältvattenkorridorer, har också bildats. Dessa landformer är rikligt förekommande i hela kartområdet men har tidigare inte återfunnits i Sverige, exempel finns dock från bland annat Kanada, som på många vis har en liknande inlandsishistoria.

Genom att studera tunneldalarnas och smältvattenkorridorernas morfologi samt sedimentens egenskaper tolkas de i denna avhandling som bildade under perioder med stor avsmältning under Bølling-Allerød.

Ett ytterligare spännande resultat är en helt 'ny' landform. Landformen är ny på så vis att den inte tidigare beskrivits, troligtvis kopplat till den ökade detaljrikedomen i de digitala höjdmodellerna. Landformen kan beskrivas som en V-formad kulle, där V:et pekar i den forna inlandsisens rörelseriktning. Landformerna har kartlagts över hela Sverige och Finland. Tillsammans med kollegor i Finland har vi tillsammans valt att kalla dem murtoos. Kartläggningen visar tydligt att murtoos återfinns i områden där inlandsisen smälte snabbt. Dessa landformer uppvisar komplicerade sedimentegenskaper och strukturer som kopplas till variationer i smältvattensystemet under inlandsisen. Tolkningen är att dessa variationer bildas genom att sjöar på inlandsisen, vilka är vanliga bland annat på dagens Grönland, dräneras genom sprickor i isen. Tunneldalar, smältvattenkorridorer och murtoos kan alla kopplas till den betydande avsmältningen under deglaciationen.

List of papers

This thesis is based on the following studies, referred to in the text by their Roman numerals.

I **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), pp. 534–544.[i]

II **Peterson, G.** & Johnson, M. D. (2017). Hummock corridors in the south-central sector of the Fennoscandian Ice Sheet, morphometry and pattern. Earth Surface Processes and Landforms, 43(4), pp. 919–929.[ii]

III **Peterson, G.**, Johnson, M. D., Dahlgren, S., Påsse, T. & Alexanderson, H. (2018). Genesis of hummocks found in tunnel valleys: an example from Hörda, southern Sweden. GFF, 140(2), pp. 189–201.[iii]

IV Ojala, A. E. K., **Peterson, G.**, Mäkinen, J., Johnson, M. D., Kajuutti, K., Palmu, J.-P., Ahokangas, E.& Öhrling, C. (2019). Ice sheet scale distribution of unique triangular-shaped hummocks (murtoos) – a subglacial landform produced during rapid retreat of the Scandinavian Ice Sheet. Annals of Glaciology, 60(80), pp. 115–126.[iv]

V **Peterson Becher, G.** & Johnson, M. D. (2021). Sedimentology of murtoos - V-shaped landforms indicative of a dynamic sub-glacial hydrological system. Geomorphology. 380(107644). 1-16.[v]

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[i] GP, MJ, and CS developed the study. GP performed the mapping, analysis, and map design. GP wrote the manuscript. All co-authors edited and revised the manuscript and approved the final version.

[ii] GP and MJ designed the study. GP performed data preparation. GP and MJ conducted the geomorphometric analysis. GP wrote the manuscript. MJ edited and revised the manuscript and approved the final version.

[iii] GP and MJ formulated the study and performed the field work. GP and MJ analysed the data. GP wrote the manuscript. All co-authors edited and revised the manuscript and approved the final version.

[iv] GP, JM, MJ, JP, KK conceived the study. GP, CÖ, AO, JP, MJ, and EA performed LiDAR screening, measurements and classification. AO, GP, JM, MJ, CÖ, KK analyzed tha data. AO, GP JM, MJ, KK, EA, and JP wrote the paper. All co-authors edited and revised the manuscript and approved the final version.

[v] GP and MJ conceived the study and performed the field work. GP and MJ analysed the data. GP wrote the manuscript. MJ edited and revised the manuscript and approved the final version.

The following papers were published contemporaneously but are not a part of this thesis.

Öhrling, C., Mikko, H., **Peterson Becher, G.** & Regnéll, C. (2020). Meteorite crater re-interpreted as iceberg pit in west-central Sweden. GFF, 00(00), 1–8.

Öhrling, C., **Peterson Becher, G.** & Johnson, M. (2020). Glacial geomorphology between Lake Vänern and Vättern, southern Sweden. Journal of Maps, 16(2), 776–789.

Johnson, M. D., Fredin, O., Ojala, A. E. K. & **Peterson, G.** (2015). Unraveling Scandinavian geomorphology: the LiDAR revolution. GFF, 137(4), 245–251.

Peterson, G. (2015). Landform diversity in LiDAR-derived elevation models, exemplified by an area in central Sweden. GFF, 137(4). 397-397.

Greenwood, S. L., Clason, C. C., Mikko, H., Nyberg, J., **Peterson, G.** & Smith, C. A. (2015). Integrated use of LiDAR and multibeam bathymetry reveals onset of ice streaming in the northern Bothnian Sea. GFF, 137(4), 284–292.

Contents

1 Introduction

The landforms and sediments of the formerly glaciated landscape of southern Sweden offer an opportunity to study the behavior of ice sheets in a warming climate. Southern Sweden was deglaciated during a climatic warm period that resulted in intense melting and rapid ice margin retreat.

Contemporary glaciers and ice sheets are melting due to global warming (Hanna et al., 2008; Schoof, 2010; Rignot, Mouginot and Scheuchl, 2011; Bamber et al., 2013; Zemp et al., 2015). In various regions of the world, increased melting threatens vital freshwater resources (Stern, 2006). It also threatens coastal communities as sea-level rise (Rignot, Mouginot and Scheuchl, 2011; Sachs, 2015), and increased fresh water discharges can play a role in changing ocean circulation patterns (Royer and Grosch, 2006; Holliday et al., 2020). Therefore, it is of great importance to increase the knowledge of glaciers and ice sheets with the overall aim to better understand and predict the effects of global warming on glaciers and ice sheets.

The overall behavior of glaciers and ice sheets is to a large extent controlled by the processes active at their beds, so-called subglacial processes. Subglacial processes depend on the properties of the geological substrate, the glacier ice, and the presence of water at the bed (Clarke, 2005). In particular, the spatial and temporal distribution of meltwater at the bed of ice sheets plays an important role in ice-sheet behavior. Increased meltwater delivered to the bed of ice sheets will alter subglacial processes that in turn influence ice-movement behavior, subglacial hydrology, and bed sedimentology.

Meltwater at the ice-sheet bed controls the motion as it enhances sliding at the ice bed interface and deformation within the geological substrate (Weertman, 1967; Boulton and Jones, 1979; Iverson, 2010). Subglacial processes are considered crucial to understand better how glaciers will react in a warming climate (Alley et al., 2019; Dowdeswell, 2006; Greenwood et al., 2016; Kamb, 1987; Shannon et al., 2013; Bindschadler, 1983; Iverson et al., 2003). Although it is important, the distribution and products of ice-sheet hydrology are perhaps one of the least understood components (Greenwood et al., 2016), connected in part to the difficulty to obtain data on actual conditions on contemporary ice sheets.

Investigating sediments and geomorphology of contemporary ice-sheet beds is complicated for obvious reasons; however, formerly glaciated regions are easily accessible. During the Pleistocene, the northern hemisphere was covered by ice sheets multiple times. The last glacial maximum (LGM, 26.5-19 ka; Clark et al., 2009) of the Scandinavian Ice Sheet (SIS) reached as far south as northern Germany and Poland (Svendsen et al., 2004; Mangerud, 2009; Hughes et al., 2016; Stroeven et al., 2016). During ice-sheet retreat, a landscape emerged, shaped by the ice sheet's processes, and by studying this landscape it is possible to learn about the subglacial processes.

The landscape left behind yields information about different aspects of the ice-sheet's behavior, such as their outline, volume, and dynamics. Studying the glacial sediments and landforms of this landscape makes it possible to infer the active processes, for example beneath the ice sheet during glaciation and deglaciation (Stroeven et al., 2021). However, this can also be used in reverse; by studying specific landforms and their internal structures, it is possible to infer insights on processes active beneath ice sheets to understand better contemporary ice sheets and glaciers (Stokes et al., 2015). Consequently, a better understanding of the genesis and processes connected to the formation of glacial landforms is essential to increase the confidence in ice-sheet reconstructions, glaciological theories, and future predictions on ice-sheet behavior.

As new techniques of observing nature develop, new data can be studied, yielding new hypotheses to be tested and moving science forward. For example, the advent of new LiDAR (Light Detection And Ranging) derived Digital Elevation Models (DEM) has revealed a landscape with a wider variety of glacial landforms than previously known from aerial photos, topographic maps, and field investigations. Increased detail is especially true for landforms in the mesoscale size spectrum (e.g., 1m to 1km), where the smallest is small enough to be difficult to detect from topographic maps and also demanding to notice in the field due to forests and ground vegetation (Johnson et al., 2015). This type of LiDAR DEM has been accessible in Sweden for about ten years making it possible to investigate the landscape in unprecedented detail.

Increased knowledge of the former ice-sheet bed is crucial for many purposes, for example:

- By assuming that former glacial landscapes are analogous to contemporary ice-sheet beds, it is possible to address questions essential to understand the effects of rapid melt seen on contemporary ice sheets today.

- Paleo ice-sheet bed mapping is the base for paleo-glaciological reconstructions (Chandler et al., 2018) and is used to evaluate numerical ice-sheet and climatic models (Patton et al., 2016).
- Observations of former ice-sheet extent and chronology can act as an archive for past large-scale climatic fluctuations (Kleman et al., 2006; Stroeven et al., 2016).
- Fundamental knowledge about glacial deposits makes it possible to undertake questions concerning a plethora of societal needs (i.e., groundwater, aggregates, mineral exploration, physical planning, and more).

1.1 Study Area

The study area lies on the south Swedish uplands and can be loosely defined as the area above 250 m a.s.l. in southern Sweden with its highest point, Tomtabacken, at 377 m a.s.l. (Figure 1.1). Precambrian crystalline rocks make up the area's bedrock which is divided in two provinces; the Sveco-Norwegian gneiss-dominated western province and the eastern province dominated by granite and porphyry, separated by the Transscandinavian Igneous Belt (Wik et al., 2009).

During the Mesozoic Era, climate was warm and humid, and exposed bedrock was deeply weathered within the area. Later, during the late Oligocene and early Miocene Epochs, the area was uplifted, forming the south Swedish Dome (roughly the south Swedish uplands) (Lidmar-Bergström and Näslund, 2002). The area was uplifted again, as well as tilted and eroded, later in Neogene. This event formed the south Småland peneplain (Olvmo et al., 2005). These processes effectively formed the large-scale topography of the south Swedish uplands.

During the Pleistocene, glaciations acted as agents to remove weathered material from the area and reshape the landscape by erosion and deposition from ice sheets.

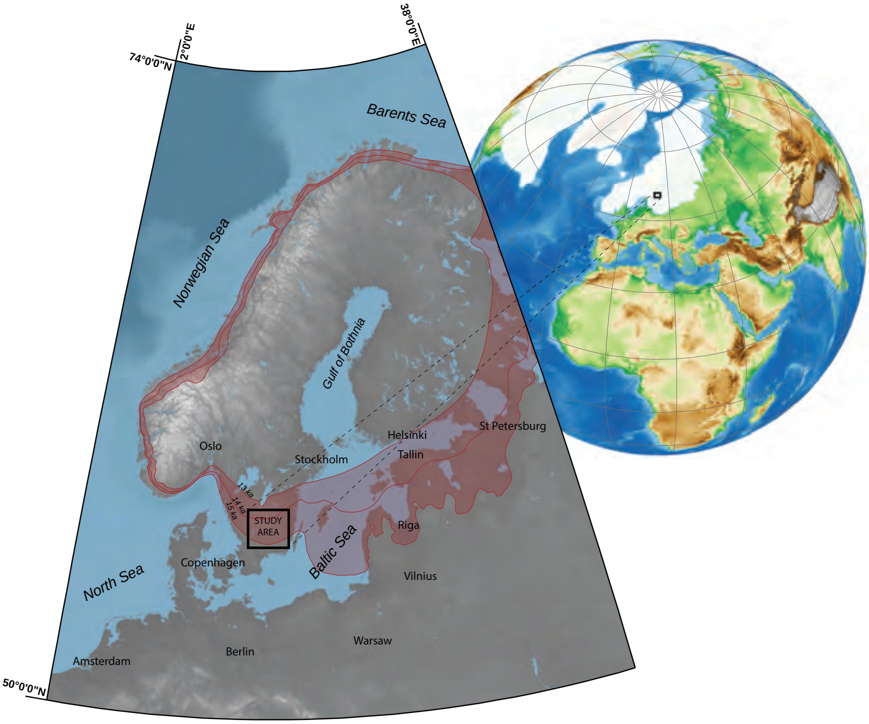

Figure 1.1: Overview map: Northeastern Europe with the study area in a black dotted box. Deglacial isochrones for 15, 14, and 13 ka ago (Stroeven et al., 2016). Elevation data derived from the GEBCO dataset, GEBCO 2014 Grid, version 20150318, www.gebco.net. Globe: Ice-sheet extent during LGM on the northern hemisphere from Batchelor et al. (2019).

2 Background

A complete and thorough background covering all aspects of the glaciations during the Quaternary as well as physical characteristics, processes, and products along with their behavior would be excessive in length. For that reason, this background section should be considered a selection of those aspects that are most important to understand this thesis and to place it in a bigger picture.

2.1 Glacial History

The Quaternary is the current geological period and spans from 2.58 million years ago (Figure 2.1) until the present (Cohen et al., 2013) and is characterized by a generally colder and more variable climate than earlier periods; it is often referred to as 'the Ice Age'. The warmer stages ('interglacials') were perhaps as warm or warmer than today, and during the colder stages, glaciers formed and advanced, and permafrost prevailed over large part of the areas beyond the ice margins (Ehlers, Gibbard and Hughes, 2017). These variations in climate occured over different time scales, from thousands to hundreds of thousands years (Clark, Alley and Pollard, 1999; Lisiecki and Raymo, 2005). The Quaternary Period is divided into the Pleistocene Epoch (2,588 myr to 11.7 ka ago), representing the last period of repeated glaciations, and the Holocene Epoch (11.7 ka ago to present), representing the time after the last glaciation until present (Cohen et al., 2013) (Figure 2.1). During the Pleistocene, Scandinavia was covered by ice sheets multiple times, perhaps as many as 40 (Mangerud, Jansen and Landvik, 1996; Haug et al., 2005). Only a few of these glaciations are present in the terrestrial geological archives, as subsequent ice sheets eroded and remolded the traces of the former ice sheets.

However, scant information available about earlier glaciations is still available where the ice sheet, in places, preserved the landscape as it was frozen to the ground and left no or little trace, this is most evident in the northern parts of Sweden and Finland (e.g., Kleman, 1994; Lagerbäck, 1988).

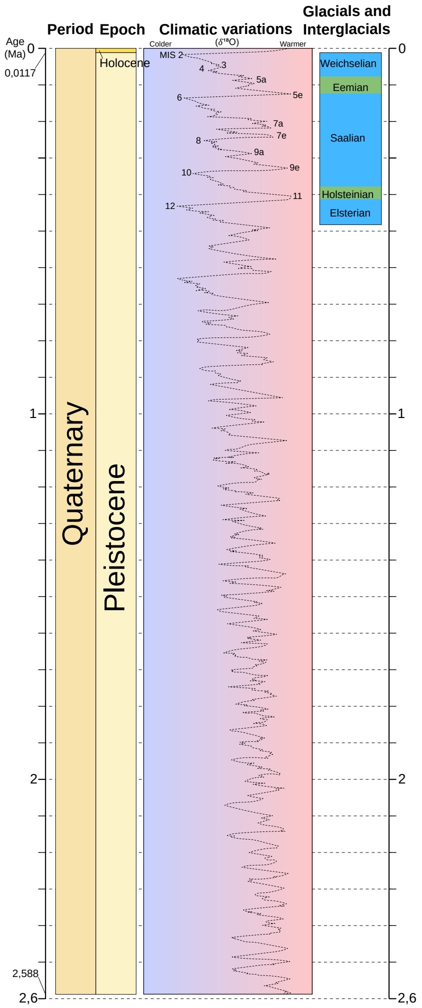

Figure 2.1: Quaternary climate variations, MIS, and glacials and interglacials. Modified from Cohen et al. (2013).

It has been suggested that the thicker drift cover (i.e., glacial sediments) in central and northern Sweden is due to multiple, smaller mountain-centered ice sheets depositing multiple tills, and fewer full-sized SIS with more effective glacial erosion in the distal parts and a frozen-bed central part (Kleman, Stroeven and Lundqvist, 2008). Sometimes, the SIS is called the Fennoscandian ice sheet, however, as not all of the ice sheets originating from the Scandinavian mountains during the Quaternary reached Finland (i.e., Fenno), the term SIS is used throughout this text (Mangerud, 2009). In southern Sweden, preserved older sediments can be found in favorable topographic positions, such as in the lee side or stoss side of bedrock outcrops, in topographic lows, or due to transient subglacial erosion (e.g., Hillefors, 1974; Robertsson, 2000; Möller and Murray, 2015).

The climatic changes during the Quaternary (and older) are divided into Marine Isotope Stages (MIS), where even numbers are cold periods and odd numbers warm, e.g., the Holocene is MIS 1. MIS are based on the variation in oxygen isotopes (δ^{18}O ratio) in marine sediment cores, mainly reflecting the amount of water bound in land ice (Lowe and Walker, 1997).

The oldest preserved glacial sediments in Sweden, as well as in Finland, are dated by pollen and

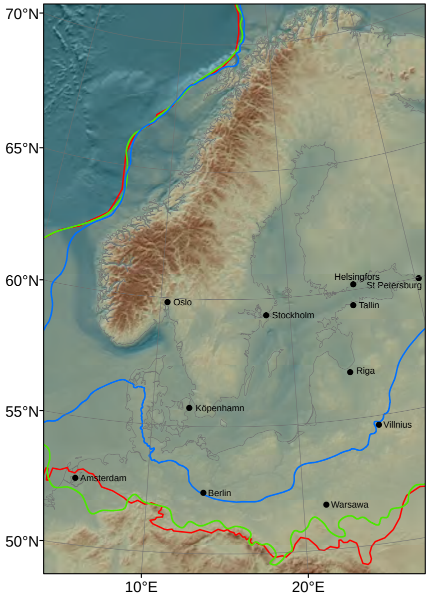

Figure 2.2: Elster (Red), Saale (Green), and Weichsel (Blue) maximum ice sheet extents. Extent reconstructions from Hughes et al. (2016) and Batchelor et al. (2019).

macrofossils, and these are suggested to be from Holsteinian interglacial sediment that overlies Elsterian till (MIS 12, Figure 2.2) (Miller, 1977; Hirvas, 1991; García Ambrosiani and Robertsson, 1998). After the following Holsteinian interglacial (MIS 11, Figure 2.1), a long period of cold climate started, the so-called Saalian glaciation (MIS 10-6). At its maximum extent (MIS 6, Figure 2.2), the Saalian ice sheet reached as far south as Prague (Batchelor et al., 2019). Warming climate caused the ice sheet demise, and the interglacial Eem (MIS 5e, Figure 2.1) commenced, lasting about 15 ka (Andrén et al., 2011). As the climate once again became colder, the last glacial period began, called the Weichselian. The Weichselian glacial period, started at about 115 ka ago (Andrén et al., 2011) and can be divided into at least three different warm and cold intervals (interstadials and stadials, respectively). The largest ice volume during the Weichselian likely occurred during MIS 4 (c. 75–60 ka) and MIS 2 (c. 25–11.7 ka) (Lundqvist, 1981; Mangerud, 1991; Batchelor et al., 2019).

In southern Sweden, the later stages of the MIS 4 ice advance can probably be correlated to what is called the Ristinge advance into Denmark (Figure 2.3A) (Houmark-Nielsen, 2010; Möller et al., 2020). After this, during the warmer MIS 3, the ice retreated into the Scandinavian mountains and left large areas of southern Sweden ice-free (Figure 2.3BC). At around 35 ka ago the ice advanced again (Wohlfarth, 2010) and at around 34 – 30 ka ago it had reached into present Denmark, an advance known as the Klintholm Advance (Figure 2.3D) (Houmark-Nielsen and Kjær, 2003; Houmark-Nielsen, 2010). However, it has been suggested that the south Swedish uplands were never glaciated during the Klintholm advance as the ice sheet advanced as an ice-stream through the Baltic instead, keeping the upland ice free (Möller et al., 2020) (Figure 2.3D). After the Klintholm advance, the ice retreated once more, at least as far north so that parts of southern Sweden were ice free (Figure 2.3E) before the ice sheet advanced again. Finally, the SIS reached the LGM extent at around 22 ka ago (Figure 2.2) (Hughes et al., 2016).

2.1.1 Final Deglaciation

After the LGM, the ice sheet retreated as a response to a warming climate. The first parts of Sweden to be ice free was the Kullen Peninsula in northwestern Skåne at about 17 ka BP (Sandgren et al., 1999; Anjar et al., 2014). The ice margin retreated through southern Sweden, first eastwards and then northwards, and the southern part of the study area was deglaciated at around 16 ka ago (Anjar et al., 2014; Stroeven et al., 2016). Around 15 ka ago the front of the ice sheet halted at the southern part of the study area (Stroeven et al., 2016) (Figure 1.1) during a cold interval (Björck and Möller, 1987). At this time permafrost and frozen-bed conditions in the ice marginal zone are suggested, and therefore led to a slow down at the ice bed interface, leading to thrusting in the ice margin and concomitant transfer of material from the bed into the ice mass, filling and covering it with debris (Möller, 1987, 2010). As the ice moved northwards this material was let down, leaving an area of disorganized hummocky terrain and ribbed moraine (i.e., Åsnen type) (Möller, 1987, 2010).

This zone of hummock tracts form a band through southern Sweden and has been suggested to be roughly age-equivalent to the Gothenburg moraine (Wedel, 1971; Lundqvist and Wohlfarth, 2001; Möller, 2010), most clearly in the western part where moraine ridges can be traced into central Småland (Paper I). However, moraine ridges are in places superimposed on the hummock tracts, suggesting no genetical relationship based on geomorphology (Stroeven et al., 2016, Paper I). The ice left this position at about 15 ka ago (Stroeven et al., 2016), possibly relating to the start of a climatic warm period starting at 14.7 ka ago, known as the Bølling-Allerød interstadial (Figure 1.1). This led to a relatively fast ice-margin retreat northwards, of

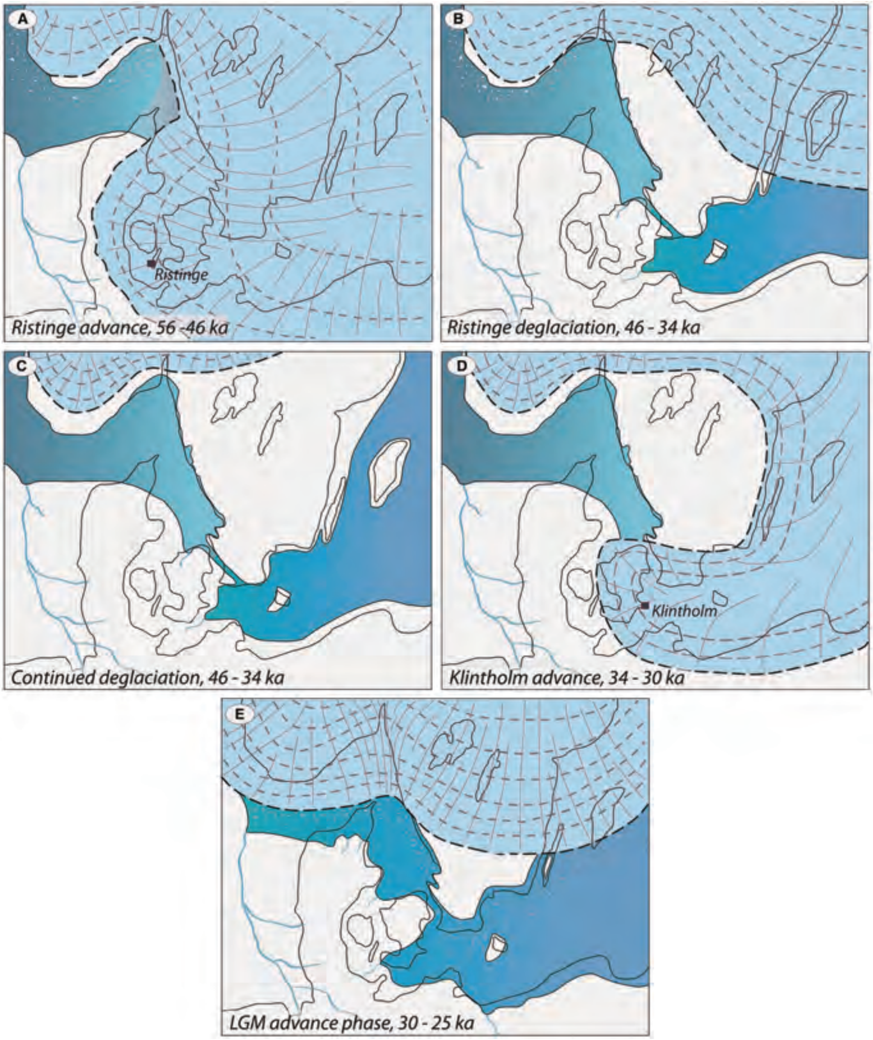

Figure 2.3: Southern Sweden from 56 – 25 ka ago, including the Ristinge, Klintholm, and LGM advances. Modified from Möller et al. (2020).

perhaps as much as 100 m per year (Ringberg, 1987; Stroeven et al., 2016; Avery et al., 2020).

During the Bølling-Allerød interstadial, the ice sheets produced large amounts of meltwater, and the associated rapid sea-level rise seen in the marine isotope record is referred to as Meltwater Pulse 1A (Deschamps et al., 2012; Cuzzone et al., 2016; Brendryen et al., 2020). The enhanced melting of the ice sheet during this period created large amounts of meltwater, much of which was generated at the ice surface and delivered to the bed producing landforms formed by increased activity or discharge in the subglacial environment (Paper II, III, IV, and V). Increased subglacial activity at this time is also suggested to be discernible as thicker varve layers (Avery et al., 2020). Deglaciation continued, and there were multiple standstills or small readvances, visible in the landform record as moraine ridges (Lindén, 1984; Stroeven et al., 2016, Paper I). The most pronounced moraine is the so-called Vimmerby moraine (Agrell, Friberg and Oppgården, 1976), where the ice margin was standing at about 14.5 ka ago (Johnsen et al., 2009). Deglaciation continued until the onset of the Younger Dryas cold period, approximately 60 km north of the study area.

As the ice margin retreated northwards, the Baltic ice lake started to form in the Baltic basin. When the ice margin later passed Mt Billingen at the end of the Allerød, the Baltic ice lake drained into the ocean, lowering the lake level of 5-10 m (Wohlfarth et al., 2007).

At the onset of the Younger Dryas (12.8 ka), the ice sheet advanced in central Sweden forming the so-called Middle Swedish end moraine zone. These moraines can be trace into both Norway and Finland (Hughes et al., 2016). The ice sheet's advance reconnected, again, to Mt Billingen, where it became stationary until the end of the Younger Dryas (11.7 ka) (Wohlfarth et al., 2007). This configuration led to the filling of the Baltic ice lake once again. When the Baltic ice lake drained the second time, as the Younger Dryas ended and the climate warmed, its surface lowered with about 25 m (Jakobsson et al., 2007).

After the Younger Dryas, with the start of the early Holocene warming, the ice margin retreated fast. The chronology of the deglaciation through central and northern Sweden is poorly constrained but suggested to have taken place before 9.5 ka ago, just east of the Sarek mountains (e.g., Karlén, 1979; Regnell, Mangerud and Svendsen, 2019).

2.2 Subglacial Processes, Sediments, and Landforms

2.2.1 Glacial Processes

Ice sheet flow

Glaciers and ice sheets move by the force of gravity from higher to lower elevations and this is also one of their most fundamental characteristics (Benn and Evans, 2010). Glacier motion and velocity is dependent on many factors such as, but not limited to, ice temperature and ice surface slope (i.e., internal processes) as well as factors connected to the bed of the glacier (e.g., frozen or thawed bed, hard or soft bed, subglacial drainage) (Jiskoot, 2011).

The movement of ice sheets occur as a response to gravitation and is facilitated either in the ice, in the bed, or in the ice bed interface and can be divided into three components (Figure 2.4):

Internal deformation, where ice deforms by movement between or within the ice crystals. This is an important process and is most evident in settings with frozen bed conditions, where the movement at the bed is very limited (Figure 2.4) (Cuffey and Paterson, 2010). This is the type of subglacial environment in which older landscapes can be preserved beneath ice sheets (Kleman and Hättestrand, 1999).

More important for geomorphic processes, are two processes at the base of the glacier the glacier (Clarke, 2005). *Basal sliding* is where water at the ice bed interface decreases the friction between the ice and the bed and the glacier slides (Figure 2.4). There is typically a thin film of water produced due to frictional heat between the ice and a solid rock bed. On rough, bumpy beds, sliding is facilitated by melting on the proximal side of bumps and refreezing on the distal side (regelation), or on larger bumps, the ice deforms around the obstacle (enhanced creep) (Weertman, 1967; Cuffey and Paterson, 2010).

Subglacial deformation is where the bed of the ice sheet is deformed and in turn causes ice sheet movement (Figure 2.4). When the bed consists of unfrozen sediments, the bed will deform if the strength of the sediment is less than the stress from the overlying glacier. Typically, deformation occurs when subglacial water-pressures within the sediment are high enough to separate individual grains and decrease the friction (Boulton and Jones, 1979; Alley et al., 1986; Boulton and Hindmarsh, 1987).

Dependent on the properties of the bed (frozen bed, bedrock, or unfrozen sediments) the three components could be active simultaneously (Figure

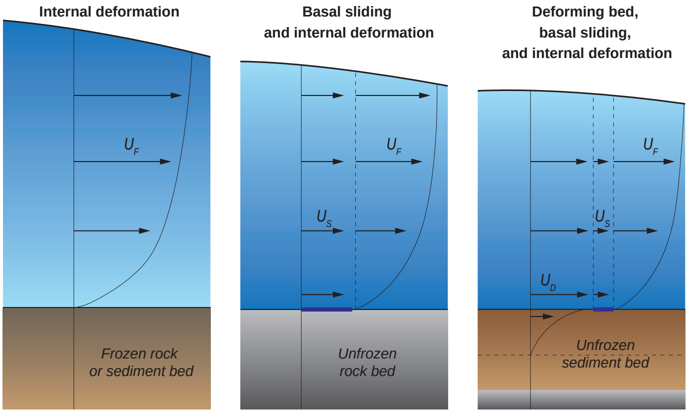

Figure 2.4: Components of glacier motion. A: Internal deformation (U_F). B: Basal sliding and internal deformation (U_S+U_F). C: Deforming bed, basal sliding, and internal deformation (U_D+U_S+U_F). Modified from (Boulton, 1996).

2.4). However, an unfrozen sediment bed does not always indicate deformation (Piotrowski et al., 2001). Piotrowski, Larsen and Junge (2004) propose that the sediment bed could be conceptualized as a mosaic of deforming and stable spots, controlled primarily by variation in pore-water pressure.

If subglacial water pressure is higher than the ice overburden, the ice will decouple from its bed and limited deformation will occur. This will decrease friction and can also lead to enhanced ice velocity (Fischer, Clarke and Blatter, 1999; Kjær et al., 2006; Piotrowski et al., 2006). Moreover, deposition of sorted sediment is likely during such decoupling events (Piotrowski et al., 2006). Therefore, although ice is the primary element of the ice sheet, the subglacial processes operating at the bed are of greatest importance to understand, as they to control the ice sheet's dynamic behavior (Clarke, 2005). In particular, subglacial hydrology is an important factor governing ice-sheet behavior.

Ice Sheet Hydrology

Ice sheets are large temporary reservoirs of water, on a geologic time scale. When ice sheets melt, meltwater processes are important in forming the landscapes left behind, such as the areas of the northern hemisphere covered by Pleistocene ice sheets (Eyles, 2006). The production and evacuation

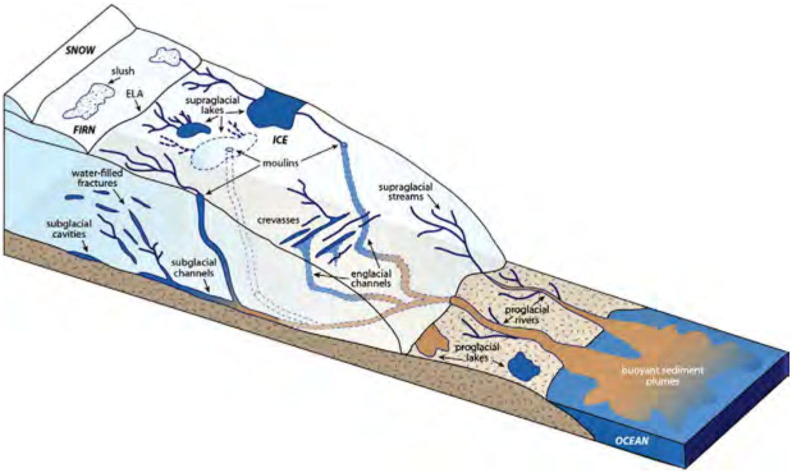

Figure 2.5: Schematic figure of the glacial hydrological system on a terrestrial terminating ice sheet. Modified from Cuffey and Paterson (2010) and Chu (2014).

of meltwater is a spatially and temporally transient mechanism, and is connected to for example, rate of meltwater production, storage potential, and the efficiency of the flow paths. The meltwater system can be divided into three parts; supraglacial, englacial, and subglacial (i.e., above, within, or below the ice sheet) (Figure 2.5).

Supraglacial hydrology: Meltwater is generated at the surface of the ice sheet due to warm air temperatures and solar radiation. As the water is released it can directly flow off the ice sheet in supraglacial streams (Nienow et al., 2017). However, much of this water could also flow into crevasses and moulins, recharging the englacial and subglacial hydrological system (Figure 2.5). On ice sheets in particular, large bodies of water can be ponded and stored at the surface as supraglacial lakes (Box and Ski, 2007) (Figure 2.5). The most efficient delivery of meltwater to the bed is through moulins and crevasses (Smith et al., 2015) but the sudden drainage of supraglacial lakes to the bed is an important point source of water that could influence ice-sheet behavior (Das et al., 2008; Joughin et al., 2013; Greenwood et al., 2016).

Englacial hydrology: Waterflow through ice is theoretically possible within veins between individual ice grains, but this flow is very limited and ice can be practically seen as impermeable (Cuffey and Paterson, 2010). More im-

Figure 2.6: Example of moulin on Kennicott glacier, Alaska. Atna Peak (4,048 m asl) in the back. Note that there is no flow through the moulins as it has not opened all the way down to the glacier bed, as it is early in the melt season. Photo: Gustaf Peterson Becher.

portant is flow through crevasses, englacial conduits, and moulins. Moulins are vertical wells through the ice sheet that connect the surface to the bed (Figure 2.6 and 2.5). These features efficiently deliver water to the bed and are kept open due to frictional heat from the flowing water, meaning that they might deform or even close during periods without discharge (i.e., winter). Where supraglacial lakes occur, the lake water can propagate through hydrofracturing to the bed, with ice thicknesses up to 1 km (Alley et al., 2005).

Subglacial hydrology: Water at the bed is derived either from geothermal or frictional heat, *in situ* melting, or it is delivered through englacial flow paths from the surface. During warm, sunny days (i.e., summer), the supraglacially derived water will be dominant. The hydraulic potential of water in a glacial system is mainly influenced by the bed's topography, the hydrogeology of the subglacial rock and sediment, and the ice sheet's surface, where the ice surface has the strongest influence (Shreve, 1972). Consequently, the water pressure beneath a glacier can be higher than the atmospheric pressure due to the influence of the ice overburden. Therefore, water flow at the bed of glaciers does not always follow the bed topography. This means that water can flow up hill beneath a glacier or ice sheet. When water flows at the bed of the ice sheet, it will heat the overlying ice due to friction. This will produce semi-circular channels (Röthlisberger-channels) in the ice with a dendritic pattern (Röthlisberger, 1972), which is called a channelized system (Figure 2.5). Channels, or canals (Nye-channels), can also form in the bed (Nye, 1973). However, water at the bed also exists as a water film or as water-filled interconnected cavities, and this is referred to as a distributed system (Weertman and Birchfield, 1983; Kamb, 1987) (Figure 2.5).

The waterflow in a channelized system is fast and the pressure is relatively low while a distributed system is characterized by slower water flow and higher subglacial water-pressure (Greenwood et al., 2016). The temporal and spatial variability of these two systems is transient due to the seasonality of meltwater influx. This variability helps determine the evolution of the channels, increased water influx to the bed leads to higher discharge, and higher discharge results in more friction which in turn enlarges the channels (Cuffey and Paterson, 2010). This leads to a more effective drainage and consequently a lower subglacial water-pressure. The subglacial water-pressure has a large impact on the flow velocity as high water pressure reduces friction. Periods of elevated water pressures (i.e., higher than the ice overburden) enhance flow as it lifts the ice from its bed and inhibit friction. Such ice flow can be transient and associated with warm periods or annual melting (Greenwood et al., 2016).

Glacial Erosion

An ice sheet's erosional capacity spans many orders of magnitude (Koppes and Montgomery, 2009). From practically zero where frozen-bed conditions exits, preserving large areas from glacial imprints (e.g., Hättestrand and Stroeven, 2002) to extremely effective, beneath some valley glaciers, forming large U-shaped valleys (e.g., Harbor, 1992) (Figure 2.7). The erosional rate is also dependent on the underlying bedrock structures and topography, where higher erosion rates would occur where the bedrock is fractured or where fast ice flow is funneled in topographic lows (Eyles, 2006).

Erosion of bedrock occurs through either abrasion, where the bed is scraped by a debris-rich ice, or quarrying, where larger pieces are being broken due to differences in pressure on the stoss and lee side of bedrock bumps (Benn and Evans, 2010). Some sediment is needed at or within the ice sole (i.e., pebbles frozen into the ice) to yield an effective erosion. However, as soon as the amount of sediment at the ice bed interface is enough to facilitate deformation and transport within the sediment, the erosion of

Figure 2.7: Example from Yosemite valley in California of a glacially sculpted U-shaped valley. El Capitan (2,307 m asl) and Cathedral Rocks in the forground and Half Dome (2,694 m asl) at the horizon. Photo: Gustaf Peterson Becher.

the bedrock will be suppressed (Alley et al., 2019). This means that effective erosion is dependent on the removal of subglacial sediment, which is effectively done by subglacial streams (Alley et al., 1997).

2.2.2 Subglacial Sediments

The ice sheet produces, transports, and deforms sediment. The presence of flowing water will sort sediments, such as the gravel in eskers that form in tunnels at the ice sheet's bed. Moreover, and perhaps the most important sediment in the context of this work is till. Till is a sediment that is transported and deposited directly by the ice sheet as it erodes, transports, crushes, and deforms the underlying bedrock or sediment (Piotrowski, 2011). Consequently, till generally exhibits a mixture of grain sizes (i.e., diamicton), and it can be formed by at least the following processes (Evans et al., 2006; Piotrowski, 2011; Evans, 2017).

Lodgement is a process where the till is formed by plastering of debris onto the bed by an active and flowing ice (Chamberlin, 1895; Dreimanis, 1988).

Deformation is a process where the till is formed by deformation and subglacial mixing of pre-existing sediments (Elson, 1961).

Melt-out is a process where the till is formed by glacial debris melting out from slow, *in situ* melting of stagnant, debris-rich ice with little or no subsequent transport or deformation (Lawson, 1979; Benn and Evans, 2010).

And finally, *flowage*, a process where glacial sediment is moved as a debris flow. It is not deposited directly by the ice sheet, but is formed due to flow or creep into subglacial lee side cavities (Hillefors, 1973; Lawson, 1979; Dreimanis, 1988).

As mentioned earlier, the presence of till, or other sediments at the bed, produces what is referred to as a 'soft bed' and makes the sliding process more complicated compared to a bedrock bed ('hard bed') (Figure 2.4). Sliding on a soft bed might enhance sliding if the sediment is weak (e.g., water saturated) or reduce sliding if strong (e.g., perfectly drained) (Cuffey and Paterson, 2010) and can vary both spatially and temporally (Piotrowski, Larsen and Junge, 2004). Deformation is a response of the sediment to the shear stress applied from the overlying ice sheet, if the sediment is weaker than the applied stress. The deformation of subglacial sediments acts as a mobile layer beneath the ice-sheet (Boulton and Jones, 1979; Alley et al., 1987).

Increased meltwater input to a soft bed will drive the water into the sediment. This increase in pore-water pressure within the sediment causes decreased shear strength, resulting in sediment deformation (Iverson, 2010; Bougamont et al., 2014; Damsgaard et al., 2016). Moreover, if water discharge increases, as an efficient hydrological system evolves into channels at the ice bed interface, water would flow up towards the bed again, as the pressure is lower, leading to strengthening of the bed. In conclusion, due to high water-pressure, the decrease in friction of sediments at the bed of the ice sheet leads to accelerated ice velocity, and the opposite (low water-pressure) leads to deceleration.

2.2.3 Glacial Landforms

The behavior of an ice sheet affects the landscape and produces landforms. Certain landforms are indicative of specific glacial behavior and by mapping them it is possible to decipher the glacial retreat pattern and history (Kleman and Borgström, 1996; Stroeven et al., 2021). Furthermore, the mapping of these landforms makes it possible to investigate the processes that acted beneath the former ice sheet. To understand the genesis of subglacial landforms, it is important to study the processes of the ice bed interface, as this is the zone where erosion, deposition, and deformation occur (Harbor, 1993).

Subglacial landforms, such as drumlins and striations, record the former direction of ice movement. Striations are centimeter-scale features eroded in bedrock by abrasion from debris-rich ice (Figure 2.8). Drumlins, which are very common in the study area (Paper I), are elongated in the direction of ice flow and common on many glaciated landscapes and are generally described as oval shaped hills oriented along ice flow (Figure 2.9). Their length spans from 250 to 1000 m long and they are up to 300 m wide (Clark, Hughes, Greenwood, Spagnolo and Ng, 2009). The genesis of drumlins is not clearly understood and there is support for both erosional and depositional genesis (e.g., Johnson et al., 2010; Stokes, Spagnolo and Clark, 2011; Möller and Dowling, 2018; Påsse, 1998).

Ribbed moraines occur in the southern part of the study area and are ridges oriented transverse to ice flow. Like drumlins, there are many different suggestions on how they from, although there is a consensus that they are formed subglacially (Hättestrand and Kleman, 1999; Dunlop and Clark, 2006). Suggestions on their genesis are primarily focused on the following; glacial reshaping of pre-existing ridges (Lundqvist, 1989), extension of a frozen bed due to increased ice flow at the bed (Hättestrand and Kleman, 1999), instabilities below active ice (Dunlop, Clark and Hindmarsh, 2008), subglacial meltwater processes (Fisher and Shaw, 1992), and compression

Figure 2.8: Example of striated bedrock in front of a Sierra de Sangra ice cap outlet glacier, Patagonia, Argentina. Ice flow into the picture (blue arrow). Photo: Gustaf Peterson Becher.

Figure 2.9: Oblique aerial photograph of drumlin field outside Umeå, northern Sweden. Blue arrow represents the ice flow towards the southeast. Photo: Gustaf Peterson Becher.

Figure 2.10: Example of sharp crested esker ridge, example from Norrbotten, Northern Sweden. Photo: Gustaf Peterson Becher.

and thrusting of debris rich ice with subsequent melt-out in an ice marginal position (Möller, 1987, 2010; Lindén, Möller and Adrielsson, 2008). The last of these models has been suggested for the genesis of the ribbed moraine in the study area and occur in large parts of the hummocky zone that make up a lobate band through the southern part of the south Swedish uplands (Möller, 1987). Ribbed moraines, as well as drumlins, have been suggested to be equifinal landforms, formed by different processes but resulting in the same shape (Möller and Dowling, 2018).

Eskers are a common landform in the study area and formed by fluvial deposition primarily in subglacial tunnels, and they consist of sorted sediments. They often appear as sharp-crested sinuous ridges (Figure 2.10) in the landscape and reflect the subglacial hydrological system. Eskers are common in landscapes of former warm-based ice sheets and in particular in areas with crystalline bedrock (Eyles, 2006). Crystalline bedrock is impermeable, in comparison to sedimentary bedrock, keeping the subglacial water at the ice bed interface (Clark and Walder, 1994).

Two other features formed by the subglacial hydrological system are tunnel valleys (TV) and glaciofluvial meltwater corridors (GFC). TVs, and especially GFCs, are common in the study area (Paper II). TVs are overdeepend valleys incised into sediment or bedrock by meltwater erosion beneath the ice sheet (Ussing, 1903; Wright, 1973; Piotrowski, 1994; Cofaigh, 1996; Piotrowski, 1997; Hooke and Jennings, 2006; Jørgensen and Sandersen, 2006, Paper III). The term tunnel channel is sometimes used when they are assumed to form in bankfull conditions (Clayton, Attig and Mickelson, 1999). The width of these channels are 1-7 km wide (Kehew, Piotrowski and Jørgensen, 2012; van der Vegt, Janszen and Moscariello, 2012; Livingstone and Clark, 2016). GFCs are elongate tracts of hummocks and often bare bedrock in the glacial landscape formed by the erosion, and perhaps deposition by subglacial meltwater. They are described on areas with crystalline bedrock in Canada (St-Onge, 1984; Brennand and Sharpe, 1993; Rampton, 2000; Utting, Ward and Little, 2009; Dredge, McMartin and Campbell, 2013; Sharpe et al., 2013, 2017; Lewington et al., 2019, 2020) and Scandinavia (Paper I and II).

End moraines are formed as an active glacier constantly delivers material to the front, and, consequently, deposit ridges along its frontal margin. These moraines give information of the ice-sheet margin's shape and position at a time during deglaciation.

Undulating till landscapes, or hummocky tracts, are a prominent feature in the study area, and they commonly are interpreted to have been formed by the collapse of supraglacial debris that overlies dead, or stagnant, ice (Johnson and Clayton, 2003). These landforms are characterized by a chaotic appearance formed by the disintegration of a debris-rich glacier front (Figure 2.11). Many of these landforms appear in the study area where they have previously been mapped as stagnation moraine or dead-ice moraine. But the large variation in morphology of these hummocky landforms indicate that this landform class is very heterogeneous and perhaps sometimes formed subglacially under active ice (Munro-Stasiuk, 2000; Utting, Ward and Little, 2009, Paper III, IV, V).

Figure 2.11: Example of active formation of dead-ice hummocks on the front of a melting glacier snout of Root glacier, Alaska. Mount Blackburn (4,996 m a.s.l.) in the clouds. Photo: Gustaf Peterson Becher.

3 Methods

3.1 Geomorphological Mapping and LiDAR

The study area was mapped for Quaternary geomorphology, focusing on glacial landforms, using a base map derived from airborne LiDAR elevation data. Sweden's national DEM is acquired using LiDAR sensors mounted on the hull of a small airplane. The LiDAR sensor is an active technology that sends and receives a laser swath. By measuring the angle, loss of energy, and the two-way time it is possible to produce a DEM. The LiDAR DEM is delivered with a vertical resolution of 0.25 m and a horizontal pixel-size of 2 m and provides a 'bare earth' view of the landscape as vegetation and buildings can be filtered away (Lantmäteriet, 2020).

Mapping was conducted using the ESRI ArcMap 10.2 on a Wacom® CINTIQ® 27 digital drawing table. The mapped area was screened twice at different scales (1:15,000 and 1:60,000) to ensure recognition of landforms of different sizes. During mapping, multiple hill shades of different illumination angles were used to make sure that features of different orientations are mapped unbiased. The digital data from surficial geology maps (Geological Survey of Sweden) and orthorectified aerial photographs of the area were used to assist with interpretations.

3.2 Geomorphometry, Statistics, and Analysis

Geomorphometry is the quantitative analysis of the earth's surface (Pike, Evans and Hengl, 2009). The mapped landforms were used together with the DEM to produce statistics on the geomorphometry of the data collected during mapping. All data collection and GIS-analyses were performed using ESRI ArcGIS® ArcPython™, ArcMap™ 10.2, Python 3.6.6 and GRASS GIS 7.4.0. All plots and statistical measurements were performed in the R software package version 3.3.2 (GNU GPL).

3.3 Excavations and Sedimentology

The excavations (Figure 3.1) were made using mechanical excavators, a “scientific tool” providing an outstanding opportunity for Quaternary geologists to “liberate them[selves] from the restrictions of natural exposures, and allow[ing] them to construct ideal sections wherever the terrain appears most promising” (Wood, 1991, page 118). The sections were studied using standard sedimentological techniques such as logging/sketching (at a scale of 1:20), sampling for grain-size analysis, and measuring particle orientation and shape (Figure 3.2). Detailed sediment descriptions were performed using a modified version of Krüger and Kjær (1999) and Evans and Benn (2004).

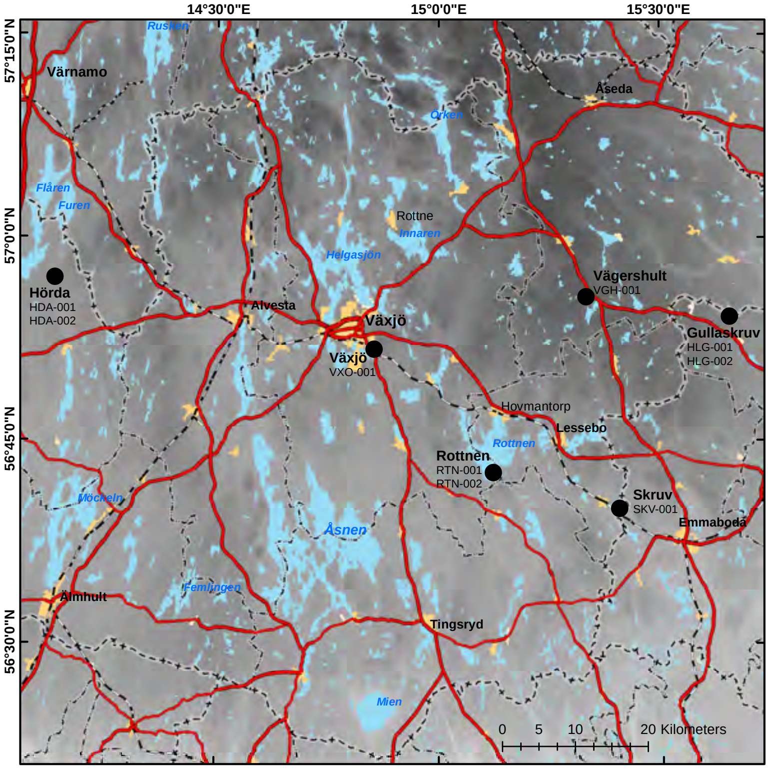

Figure 3.1: Excavations and outcrops from Paper III and IV.

Subglacial sediments are affected by the strain from the overlying ice sheet, and can be seen as fabric in the sediment. The particle's longest axis within a till have been shown to rapidly organize to be parallel to the direction of the shear stress, i.e., ice flow direction (Hooyer and Iverson, 2000). Measurement of clast fabrics was performed using a Brunton pocket transit compass. For each fabric measurement 25 clasts (2-6 cm) with a significantly longer long-axis were measured. The collected data was evaluated using the built-in functions of Stereonet 9.5.3 (Allmendinger, Cardozo and Fisher, 2011; Cardozo and Allmendinger, 2013). Additionally, there are structures that can be attributed to directional information, such as folds or faults (Derbyshire, McGown and Radwan, 1976; Benn and Evans, 2010).

Figure 3.2: Typical tools used for fabric measurements, a Brunton compass, notebook, and pencil. Photo: Gustaf Peterson Becher.

3.4 OSL Dating

Optically Stimulated Luminescence (OSL) dating is used to measure the elapsed time since sediment was last exposed to daylight. This can be done as defects in the crystals within the sediment grains trap ionized radiation, as electrons, in for example quartz or potassium feldspar. The radiation is derived from the sediment itself, as they contain trace amounts of radioactive isotopes such as uranium, thorium, and potassium (Huntley, Godfrey-Smith and Thewalt, 1985). As these elements decay their radiation get trapped in so called ‘electron traps’. The number of trapped electrons, the ‘paleodose’, is dependent on the radiation in the surrounding sediment, the ‘dose rate’ (Murray and Olley, 2002).

When the sediment is exposed to light, the traps are emptied of electrons, resetting the ‘OSL clock.’ By stimulating the sample with light in a laboratory and measuring the released electrons the amount of absorbed radiation dose trapped since burial can be estimated, the so called ‘equivalent dose’. Ages were determined at the Lund Luminescence Laboratory, Sweden, on quartz aliquots of 180–250 m grain size using a Single Aliquot Regeneration protocol (Murray and Wintle, 2003).

3.5 Thin-Section Analysis

Thin-section analysis, or micromorphology, is a method to study soils and sediments and has proven a successful tool when studying the often complex series of events connected to glacial sediments (e.g., Phillips, van der Meer and Ferguson, 2011) and has been used on subglacial till since the 1940s (Lundqvist, 1940). Samples were collected by cutting a metal box into the sediment without disturbing the sample and noting the direction of the sample. The samples were sent to and prepared at the British Geological Survey in Keyworth, Nottingham. The water within the sample was removed by adding acetone so that the sample does not have to be dried before impregnation. This is done to minimize the risk of fractures in the sample due to shrinking sediment volume during drying. Impregnation is then done by replacing the acetone with resin. The impregnated samples are then cut, polished, and placed on glass. Mapping and interpretation were performed using the methodology and terminology from (Phillips, van der Meer and Ferguson, 2011).

3.6 Multiple Working Hypotheses

The scientific method of geology is often seen as a version of the ideas and methods used in more classic branches of science, such as physics. Physics uses a defined, firm, precise, and predictive scientific method. However, some other fields of science cannot always reach up to some of these high standards, and classic geology is one of these. This is because there are some basic scientific techniques that are close to impossible to perform in geology but are standard procedure in for example physics (Frodeman, 1995). First, experiments are very hard to do in classic geology. Geologists are working on a spatial and temporal scale that is complicated for experimental set-ups. Second, geological data is often incomplete or has a poor resolution, making it problematic to study. Third, the concept of geological time, which spans billions of years, makes it hard to do direct observations of geological processes, such as the formation of mountains. The most dogmatic analytical philosophers would perhaps go so far as to call geology a pseudo-science based on that unfalsifiable claims might be the only way forward, as there are none of the scientific methods (in the sense of analytical philosophy) that can falsify it, or that there is a large risk of confirmation bias within geology. However, most geologists are aware of these problems and methods have been put forward for geology to be as true and scientific as possible.

Figure 3.3: Photo of Thomas Chrowder Chamberlin in the 1870s. Photo from the University of Wisconsin–Madison archive.

One approach to minimize the risk for confirmation bias is by using the 'Multiple working hypotheses', an idea put forward by the geologist Thomas C. Chamberlin (Chamberlin, 1890) (Figure 3.3). The idea of multiple working hypotheses offers an effective way of organizing geological research. By developing multiple hypotheses based on the data at hand early in the research process the idea is to not get a 'favorite hypotheses' that the geologist, unconsciously, tries to prove - not falsify. Some hypotheses that the researcher makes might be easy to falsify but some will perhaps stay valid until the final steps of the research project when they can be falsified and only the last standing hypotheses can be the 'ruling' hypotheses. This means that the questions chosen to ask, and the hypotheses that are set up, would not be directed to fit one context only making the methodology much more rigid, and with fewer risks of pitfalls. Moreover, it will also give the researcher a possibility to perhaps combine different ideas of thought, based on the different hypotheses.

4 Summary of Papers

4.1 Geomorphological Mapping

> 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), pp. 534–544.

The fundamental information, used as the base for Papers II, III, IV, and V is the map of the study area (Paper I). This map is the first comprehensive glacial geomorphology map of the south Swedish uplands. The map covers an area of 150 x 150 km and is presented at a 1:200k scale. In this summary, the landforms most important to frame this thesis are discussed.

Mapping of end moraines yield at least two interesting results. First, several new moraines and continuations of previously mapped moraines (i.e., Gothenburg moraine and Vimmerby moraine) were found (Figure 4.1). This suggests that the ice sheet was active to a larger extent during retreat than previously proposed (e.g., Möller, 1987). Second, several of the mapped moraines display a lobate pattern in the scale of 10s of km indicating an ice front with several independent lobes.

Eskers are common throughout the study area. The pattern shows a clear connection to the radial ice-flow pattern (Figure 4.1). The largest eskers follow the valley floors. Outside of these, the eskers are generally smaller.

Mapping of glacial lineations (drumlins and crag-n-tails) show an overall radial pattern, indicating that ice on the western side of the south Swedish uplands moved towards SW and ice on the eastern side towards the SE (Figure 4.1). However, what is more interesting is the variation on a smaller scale, also connected to the lobate moraines, indicating a more dynamic ice-flow history than previously suggested. Furthermore, it has been suggested that the length of glacial lineations could be connected to ice-flow velocity (Stokes and Clark, 2002) which would suggest that ice-flow rates varied over the area with the highest velocities in the central part. However, it should be noted that there are more factors than velocity that have the

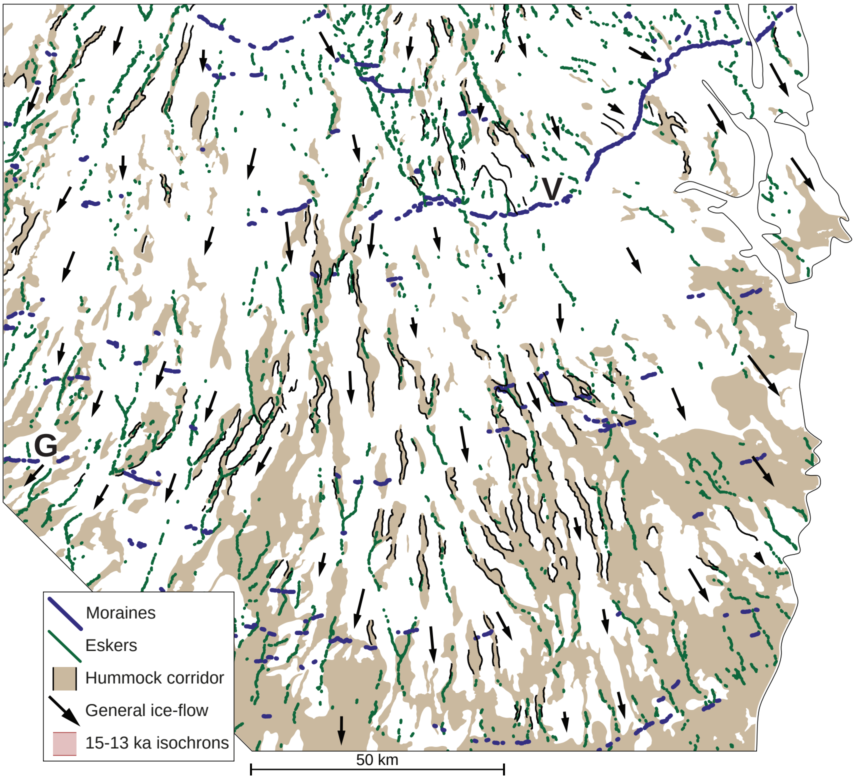

Figure 4.1: Simplified map of the study area. Light brown = Hummock tract, V = Vimmerby moraine, and G = Gothenburg moraine.

potential to affect the lineation form (e.g., time and erosional/deformational competence).

The landform, or landscape, that has been studied most within this thesis are discrete areas of hummocky topography that is referred to as 'hummock tracts.' The abundance of hummocks and hummock tracts has been known for more than 100 years within the study area (Gavelin and Munthe, 1907; Stolpe, 1911). A broad hummocky zone has been described as a lobate feature across much of southern Sweden, generally parallel to the former ice margin (Persson, 1972; Möller, 1987, 2010; Lundqvist and Wohlfarth, 2001) and this zone, as mentioned above, has been correlated with an ice-margin position along the west coast of Sweden called the Gothenburg moraine (Figure 4.1). Most of the hummocks in this zone and elsewhere in the south Swedish uplands have been interpreted to be the product of processes connected to the down wasting of stagnant ice (e.g., Andersson, 1998; Möller, 1987, 2010). During mapping, a more diverse picture of the hummock tracts emerged. First, individual hummock shapes differ markedly within the hummock tracts in the study area. The vast majority of the hummocks vary broadly in their shape, spacing and relief. They consist of disorganized irregular hills and depressions with a large variation in shape, size (10s to 100s of m) and relief (1 to 10s of m). However, within the hummock tracts, two distinct forms were identified that occur in various places in the south Swedish uplands. The first include semi-ordered systems of transverse ridges, which Möller (1987) called 'Åsnen-moraine', and can be referred to as 'ribbed moraine' because of their similarity with various forms of ribbed moraine (Dunlop and Clark, 2006). Well-developed ribbed moraine makes up only a small part of the large area of hummock tracts. It is predominantly found within the broad lobate hummocky zone in the southern part of the studied region. Second, V-shaped hummocks with apices pointing in the general ice-flow direction and gentle up-ice slopes were identified. Similar V-shaped hummocks were identified simultaneously in Finland (Mäkinen et al., 2017). Within the south Swedish uplands these landforms are found predominantly in the southern part of the study area. These landforms are studied in more detail in paper IV and V. Third, another important observation is that the hummock tracts of south Swedish uplands not only make up a broad lobate band through southern Sweden, but also as a distinct, radial pattern of linear hummock tracts that are referred to as corridors (Figure 4.1). The radial hummock tracts, or 'hummock corridors,' are distinct landforms with a width of about 1-2 km (Figure 4.1 and 4.2). The radial pattern of the hummock corridors shows a clear resemblance with the radial pattern of glacial lineations within the area, suggesting that they are formed in connection to the active ice sheet (Figure 4.1). In places, the corridors are incised into the surrounding upland producing a negative form (Figure 4.2A). Elsewhere, they are a positive feature (Figure 4.2BC). The corridors do not always follow valley bottoms but cross highlands, suggesting that they cannot be formed by glacier rivers in front of the ice sheet (Figure 4.2B). In a few places, hummocks within the corridors are superposed by eskers suggesting that they were formed subglacially. The hummock corridors of south Swedish uplands are geomorphometrically analyzed in Paper II and their internal structure in Paper III.

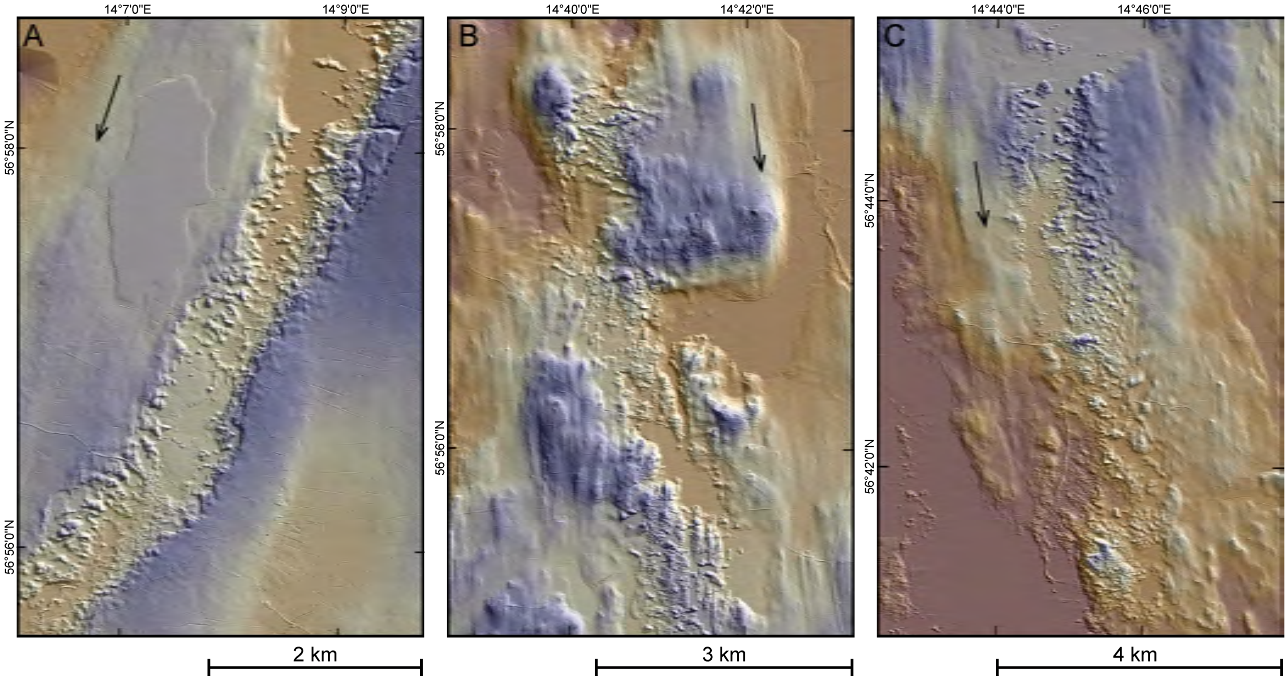

Figure 4.2: Three examples of hummock corridors. A, clearly incised. B, a positive morphological expression with clearly undulating long profile. C, a positive morphological expression.

4.2 Geomorphometry of Tunnel valleys and Glaciofluvial Meltwater Corridors

Peterson, G. and Johnson, M. D., 2017: Hummock corridors in the south-central sector of the Fennoscandian Ice Sheet, morphometry and pattern, *Earth Surface Processes and Landforms*, 43(4), pp. 919–929.

In Paper I the intriguing pattern of the radial hummock corridors on the south Swedish uplands were mapped. In Paper II, three of the main observations made in Paper I were further investigated in detail using detailed geomorphometric analysis.

First, the directions of the corridors were compared to the ice-sheet flow direction, based on the mapped glacial lineations, and show a positive linear correlation (Figure 4.3). This suggests that the formation of the hummock corridors could be connected to the subglacial environment.

Second, the floor of the hummock corridors longitudinal profiles are undulating (Paper I) (Figure 4.3). This was tested by retrieving elevation data along lines at the floor of each mapped hummock corridor (n=82) and searching for elevation increase from N-S. The analysis yielded that 32% of the hummock corridors displayed an increase of more than 20 m along their length. Subglacial meltwater can flow uphill as the hydraulic gradient is affected by the ice overburden. This suggests that the hummock corridors could have been formed by the action of subglacial meltwater.

Finally, another observation made was that some of the corridors are cut into sediment while some have a positive morphological expression. This was tested by retrieving elevation values for profiles (every 100 m) along each hummock corridors (n=738) and then calculating the cross-sectional area based on the elevation profile and a straight line from the profiles start and end. The result was that 74% of the hummock corridors were cut into the surrounding surface (Figure 4.3). Moreover, the corridors are narrower when sediment thickness is greater, a relationship noted for TVs in Canada (Sjogren et al., 2002).

Several other parameters were also analyzed, these include the width of corridors (mean width = 1.1 km) and the spacing between each corridor. The spacing is the length between each corridor and the mean value was calculated to 14.5 km. These values are comparable to values of spacing for eskers, suggesting a similar subglacial hydrological organization.

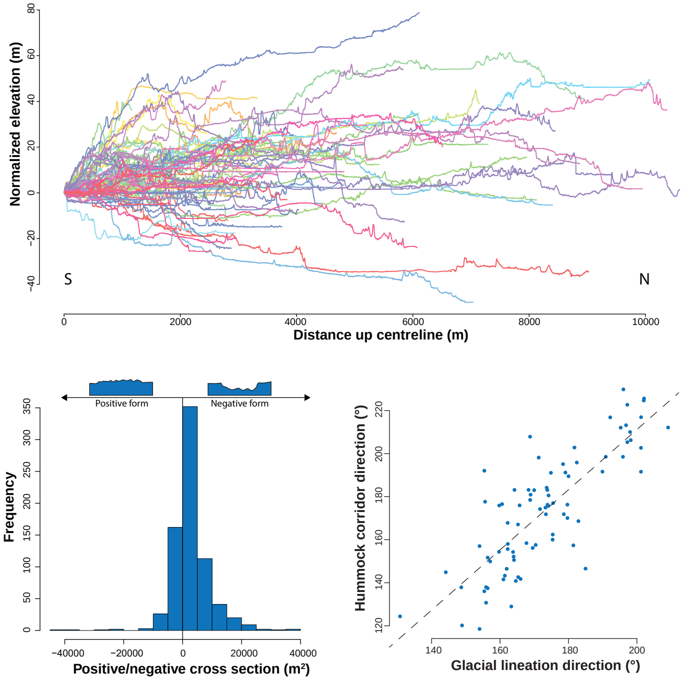

Figure 4.3: Above, elevation profiles along the hummock corridors normalized at their southern end. Interpreted subglacial water flow was from north to south, or right to left. Lower left, cross-sectional area of corridor cross profiles. Lower right, hummock corridor means orientation vs. orientation of nearby glacial lineations.

Furthermore, it was shown that about half of the corridors have eskers within. Taken together, several of the results from the geomorphometric analysis point to a formation by subglacial meltwater.

Another part of Paper II was a comparison of these landforms to other similar features observed elsewhere and it was clear that some of the hummock corridors (those with a negative form) had a resemblance to TVs. For the hummock corridors with a positive form it was noted that similar landforms are common in Canada, where they have been called GFCs. TVs are large over-deepened valleys (1-7 km wide) incised into sediment or bedrock (Ussing, 1903; Cofaigh, 1996; Clayton, Attig and Mickelson, 1999; Livingstone and Clark, 2016) spaced up to 30 km apart (van der Vegt, Janszen and Moscariello, 2012). TVs are formed by the erosion of meltwater below the ice sheet.

GFCs are elongate, linear features of similar dimensions as TVs mapped on the Canadian shield area (St-Onge, 1984; Brennand and Shaw, 1993; Rampton, 2000). They are often distinguishable as zones with thinner sediment cover, as the sediment (i.e., till) have been eroded by subglacial meltwater. Often they are described to have eskers within them as well as hummocks (Utting, Ward and Little, 2009).

The hummock corridors at south Swedish uplands show a large resemblance, both visually and statistically, to TVs and GFCs. Consequently, in Paper II it is suggested that the hummock corridors at south Swedish uplands are TVs, if incised in the surrounding surface, or GFCs, if they show a more positive morphological appearance. Moreover, GFCs are shown to be formed where sediment thickness is thinner, while TVs are formed where sediment thickness is greater. Furthermore, it is suggested that they were formed as a result of subglacial meltwater beneath the ice sheet. Supraglacial meltwater as a source for TV formation have been suggested beneath lobes of the Laurentide Ice Sheet (Mooers, 1989).

4.3 Sedimentology of Tunnel-Valley Hummocks

Peterson, G., Johnson, M. D., Dahlgren, S., Påsse, T. and Alexanderson, H., 2018: Genesis of hummocks found in tunnel valleys: an example from Hörda, southern Sweden, *GFF*, 140(2), pp. 189–201.

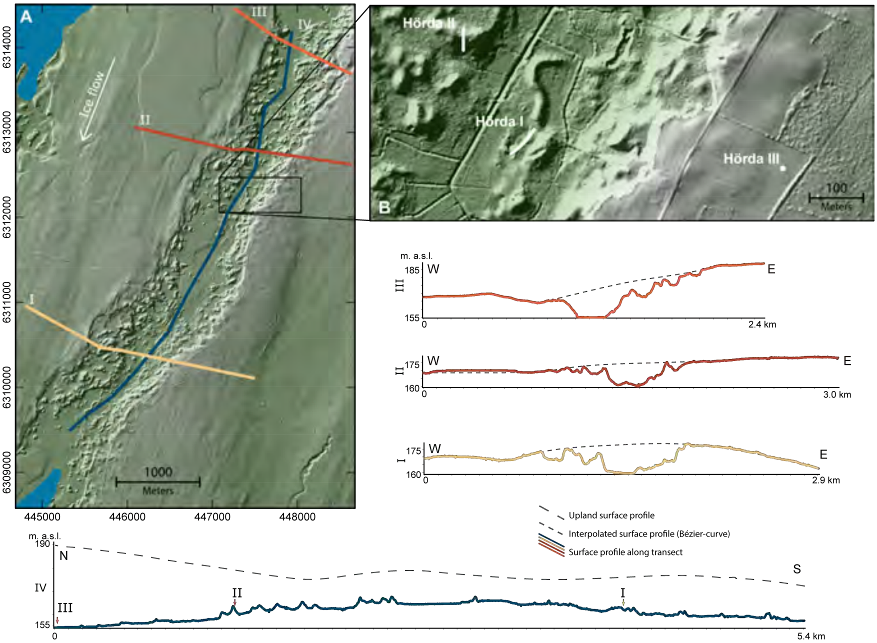

Figure 4.4: Hörda TV with excavations, cross sectional and long profiles.

Two hummocks within one hummock corridor, interpreted to be a TV in Paper II, were excavated and studied to learn more about their internal structure (Paper III). One of the excavations, Hörda I (Figure 4.4 and 3.1), shows two distinct units, a lower diamicton and overlying sorted sediments, mainly sand and gravel. The upper unit can be directly correlated to an esker ridge, superposed on the hummock, that can be followed as a sinuous ridge northward for about 700 m (Figure 4.4B). The diamicton is firm, compact, sandy to silty, and with moderate fabric orientations and strong fissility, indicative of subglacial till (Figure 4.5). Clast-shape analysis also suggests the diamict to be a subglacial till (Benn and Ballantyne, 1993). This

Figure 4.5: Example of sediment interpreted as subglacial traction till at Hörda. Observe the clear fissility. Photo: Gustaf Peterson Becher.

together with occurrence of striated boulders lead to the interpretation that this diamict is a subglacial traction till. The sandy-gravelly unit overlying the subglacial traction till include rounded, well-sorted clasts. This sediment is typical for glaciofluvially deposited material and together with the direct correlation with the superposed esker this sediment is interpreted as such.

The second hummock excavated, Hörda II (Figure 4.4), show three units. First, there is a lower silt to granule unite. Second, overlying the silt and granule, there is a diamict unit. Third, on the very top there is a sandy-gravelly unit. The lowermost unit consists of sorted sediment, silt to granules. Furthermore, this unit includes large parts of an amalgamated unit, hard to distinguish as either silt or granule. This amalgamated unit show signs of deformation, such as folding and thrust faults in a N-S direction. Both the overlying diamicton as wells as the sandy-gravelly unit at the very top show similar characteristics as in Hörda I, and is interpreted similarly, as a subglacial traction till with overlying glaciofluvial gravel. The lowermost sorted, amalgamated, and deformed units are, based on the overlying subglacial traction till, suggested to be pre-existing sediments deformed by an overriding ice advance. One of the sorted sand layers in the lower units was dated with OSL, clearly indicating pre-LGM ages (MIS 3). This suggests that the sediment was deposited in front of the ice sheet during an oscillation before the ice sheet reached the LGM, like the Ristinge advance (Figure 2.3).

Based on the sedimentology of these two hummocks and the chronology, it is suggested that they were formed by erosion of pre-existing material beneath the ice sheet during the final deglaciation during the same event as the TV formation. Finally, the compact fissile subglacial traction till and the overlying esker indicate that these hummock were not formed by dead-ice melt-out.

4.4 Geomorphometry of Murtoos

Ojala, A. E. K., Peterson, G., Mäkinen, J., Johnson, M. D., Kajuutti, K., Palmu, J.-P., Ahokangas, E. and Öhrling, C., 2019: Ice sheet scale distribution of unique triangular-shaped hummocks (murtoos) – a subglacial landform produced during rapid retreat of the Scandinavian Ice Sheet, *Annals of Glaciology*, 60(80), pp. 115–126.

During the mapping of glacial geomorphology in southern Sweden, a V-shaped type of hummock was described (Paper I). Simultaneously, similar forms were described in Finland (Mäkinen et al., 2017). These landforms are now called ‘murtoos’, the name is derived from one of the type localities in Finland, the village Murtoo. Moreover, the Finnish word ‘murtoo’ refer to fragmentary topography. In Paper IV their distribution was investigated on an ice-sheet scale, as well as their individual morphology. A total of 564 murtoo fields were mapped throughout Sweden and Finland, 56 of these fields were randomly selected for more detailed geomorphometric analysis on individual landforms (n=680).

Murtoos are about 30-200 m long and wide with a relief of typically less than 5 m (Figure 4.6). The landform is V-shaped in planar view, with the tip of the ‘V’ oriented in the former ice flow direction. In cross section murtoos have an asymmetric profile with a gentle proximal side and a steeper distal side. The tip of the murtoo, varies from 20 to 120 degrees. Moreover, murtoos occur in fields and exhibit a shingled appearance (Figure 4.6).

Murtoos are in places seen with eskers superposed, indicating a development prior to esker formation. Furthermore, murtoos are often observed in close relation to ribbed moraine, and in places they truncate the ribbed moraine, suggesting a formation after the ribbed moraine. In regions with Veiki-moraines, murtoos are absent. Veiki moraines, are a form of ice walled lake plain (Clayton et al., 2008), preserved by frozen bed conditions in northern Sweden (Lagerbäck, 1988). Consequently, this indicates that murtoos are confined to parts of the ice sheet that held warm bed conditions.

Murtoo fields, identified as groups with at least five individual murtoos, were mapped in Sweden and Finland (n=564) using LiDAR derived national DEMs. Their distribution at both local and regional scale suggest that they formed during periods of rapid ice-sheet melt, as they are most common in areas that were rapidly deglaciated. In southern Sweden the highest density of murtoos is in the region deglaciated during the Bølling-Allerød warm period. However, most striking on an ice-sheet scale is the frequency

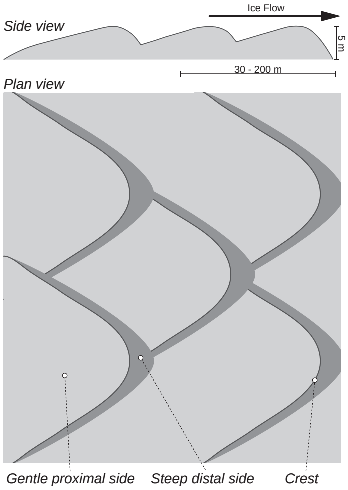

Figure 4.6: Generalized figure representing a cross section (above) and plan view (below) of a field of murtoos.

of observed murtoos north of the Younger Dryas moraines, both in Sweden and Finland. The landforms are absent up to 50 km north of the moraines but then increase significantly, between 50 and 100 km north. Assuming that the murtoos were formed when the ice margin was situated at its Younger Dryas position suggests that they were formed within a zone of the ice sheet generally suggested to be a part of the distributed hydrological system, prior to the development of a more efficient channelized system (Greenwood et al., 2016).

In places murtoos occur in routes parallel to regional ice flow. This is clear within the former ice lobes connected to the Younger Dryas moraines in Finland (i.e., Salpausselkäs), where these corridors end at the moraines. This phenomenon is also present in southern Sweden, where the corridors end at a continuation of the Gothenburg moraine (Paper V). Based on the work in Paper IV, some constraints are proposed for the formation of murtoos. First, they are formed subglacially during periods of rapid deglaciation. Second, murtoos form under warm-bed conditions. Third, they are formed in close association with subglacial meltwater flow and within the distributed zone.

4.5 Sedimentology of Murtoos

Peterson Becher, G. and Johnson, M. D., 2021: Sedimentology and internal structure of murtoos – V-shaped landforms indicative of a dynamic subglacial hydrological system, *Geomorphology*, 380(107644).

The geomorphological, geomorphometric, and geographical work on murtoos carried out in Paper IV generated an obvious next step; to describe and interpret the internal structure of murtoos.

Within the study area there are several occurrences of murtoos (Paper I and IV). Four of these locations were chosen based on morphological expression, road access, and landowner interest. A total of six outcrops were excavated at these locations (Figure 3.1). All outcrops display a complex internal structure with heterogeneous diamicton interbedded with sorted sediment. Structures show signs of ductile deformation. The four localities do not have completely similar characteristics. However, there are many similarities and observations that are present in several of the sections.

All sections include sorted sediment to some degree, although it varies from only a couple of percent to as much as 20%. The sorted sediment is interbedded with diamicton. Furthermore, the sorted sediments do not show typical characteristics of fluvially deposited sediments (i.e., bedding, lamination) but are instead mostly massive. Where bedding or lamination exist, it is either tilted or folded. This is interpreted to be connected to ductile deformation or liquefaction. Moreover, the boundaries between diamicton and sorted sediment are seldom sharp, which are interpreted to be connected to shearing of till on sorted sediments (Tylmann, Piotrowski and Wysota, 2013).

Crosscutting both the sorted sediment and diamicton described above are stringers of silt and very-fine sand with laminations conformal to their outer boundaries. This is particularly clear at the section in Växjö (Figure 3.1). These are interpreted to be clastic dikes based on their resemblance to clastic dikes described elsewhere and the clear cross-cutting relationships with other features in the section (Lowe, 1975; Rijsdijk et al., 1999; van der Meer, Kjaer and Krüger, 1999). Moreover, clastic dikes are also present in thin-section analysis as micro-scale features. These microscale clastic dikes clearly cross-cut other features, and it is possible to distinguish at least three events.

Figure 4.7: Example of murtoo sediment from the Växjö locality. Observe the crude bedding with silt and very-fine sand, and diamicton. Photo: Gustaf Peterson Becher.

In the outcrop in Växjö (Figure 3.1), the sediment has an accretional appearance with diamicton and interbedded silt and very-fine sand bed conformal to the overall shape of the murtoo (Figure 4.7).

The diamicton that makes up the majority of the sections has a loose and heterogenous character and does not have the compact appearance of a 'typical' subglacial till. Some of the fabric measurements are strong and ice-flow parallel, while others show moderate strength and are perpendicular to ice-flow, and in one section, Vägershult (Figure 3.1), striated boulders aligned with ice-flow were present. Collectively, the diamicton has characteristics of subglacial till, although the heterogeneity and weak fabrics are not in line with most observations of subglacial traction till (Benn and Evans, 2010). Furthermore, it is suggested that fabric and heterogeneity could have been altered by post-depositional deformation, which clearly can be seen in other parts of the sections. On the surface of murtoos there are frequent boulders, this is particularly clear on murtoo's distal sides and intervening hollows (Figure 4.8).

In all sections, there are silt caps on top of clast, even if present in sediment clearly deformed. Consequently, the silt caps are post-deformational,

Figure 4.8: Example of distal side of murtoo front, with bouldery surface. Photo: Gustaf Peterson Becher.

and these are suggested to be evidence of permafrost processes (Van Vliet-lanoë, Coutard and Pissart, 1984), in line with paleoclimatic reconstructions of southern Sweden at the time of de-glaciation (Björck and Möller, 1987).

Based on these observations murtoos are suggested to form by accumulation of diamicton and sorted sediments at the ice bed, and therefore are depositional landforms. The interbedded appearance, and evidence of periodic formation of clastic dikes leads us to a stepwise and cyclic formation. A formation invoking variations in subglacial water-pressure is suggested, including; till lodgment and deformation during periods of low water pressure, deposition of sand and gravel during periods of intermediate water-pressure, and development of clastic dikes during high water-pressure. Moreover, in Paper V a model is presented that is divided into 6 steps (A-F), primarily governed by variations in subglacial water pressure (Figure 4.9).

Step A: Till is deposited as a subglacial traction till. In several sections, there is a compact massive till at the base of the exposed sediment, and that the characteristics of this till show it not to have been later deformed and likely represents the initial character of the deformed diamicton occurring higher up in the murtoos.

Step B: At some point, large amounts of water are delivered to the bed. This results in high pore-water pressures within the bed material and previously deposited diamicton can be further deformed. Clastic dikes may form during this stage. If ice floatation pressure is reached, cavities will form, and sorted sediment can be transported and deposited by subglacial meltwater.

Step C: As ice-bed decoupling continues, a distributed system of subglacial cavities form. Within these cavities, sands and gravels continue to be deposited. These cavities can be inter-connected with orifices in a linked-cavity system. Ice-roof melting can provide a source for sediment, including outsized clasts. Where the bed is coupled to the till, shearing and perhaps liquefaction of the till causes the till to deform and creep in lobes forming a 'proto murtoo.'

Step D: As the friction of water on the ice roof, as well as in the bed, starts to produce more distinct and larger channels, primarily along orifices, the discharge becomes more efficient and the water pressure become lower than ice floatation pressure, leading to ice-bed coupling again, and an increase in effective pressure on the subglacial sediments and deformation of the till and sorted sediment.

Step E: As the channels continue to evolve, effective pressure increases on the murtoo surfaces whereas meltwater erosion becomes more prominent along the margins of the evolving murtoo. This is a step, especially at the later stages, responsible for the overall morphology of the murtoo fields.

Step F (a repeat of A): The higher effective pressure would again lead to till deposition, now on top of sorted sediments. Underlying sediments would exhibit strain by simple shear of the overriding ice and deforming till.

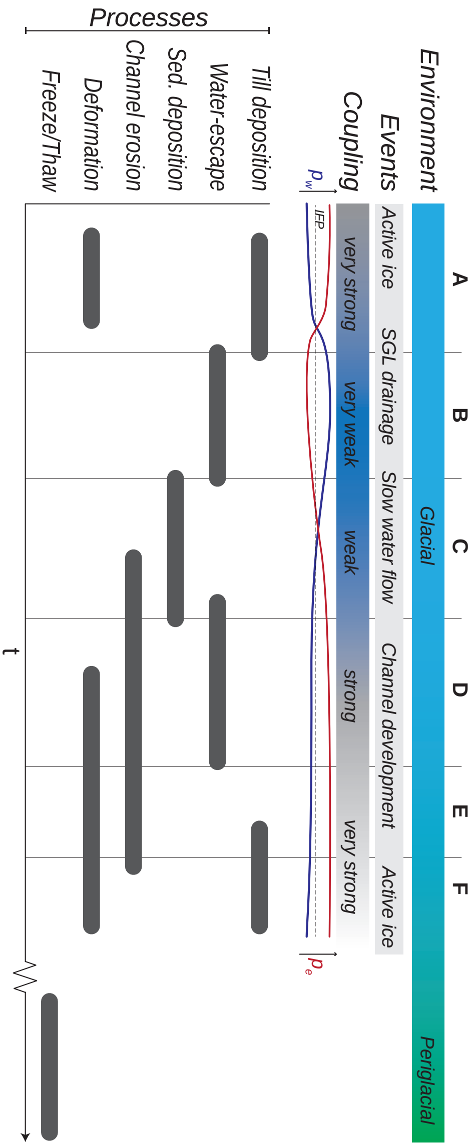

Figure 4.9: A schematic figure representing the model suggested for murtoo formation. SGL = Supraglacial Lake Drainage.

5 Synthesis

Studying the landscape in southern Sweden has led to three new landform discoveries; (1) the presence of TVs in the areas of south Swedish uplands with thicker drift cover (Paper II, III); (2) the widespread existence of GFCs, closely connected to the TVs, in a radial pattern covering the south Swedish uplands (Paper I, II, III); and (3) the distinct V-shaped landform called murtoo, was found, often associated with GFCs (Paper I, IV, V). Additionally, these landforms are suggested to be formed by an abundance of supraglacial meltwater supplied to the bed as expected with a rapidly decaying ice sheet, not unlike what is seen on southwestern Greenland today (Paper II, IV, V). In this synthesis, I will summarize what formational environment would be most plausible, elaborate how these landforms fit together in a landsystem, and how this landsystem corresponds to the paleoglaciolgical reconstruction.

5.1 Formational Environment and Timing

First, the timing and formational environment of TVs and GFCs will be discussed by connecting the time of formation to the climatic record, followed by a discussion on potential source of meltwater. Second, the formation of murtoos will be discussed together with some notes on how supraglacial lake drainages affect subglacial sediment deformation and deposition. Finally, a short discussion on where the sediment, suggested to have been eroded from beneath the ice sheet, was deposited.

5.1.1 Tunnel Valleys and Glaciofluvial Meltwater Corridors

The mapped hummock corridors (Paper I) are interpreted as GFCs and TVs, formed by the flow of subglacial meltwater. This interpretation is supported by the studies based on geomorphometry and internal structure (Papers II and III).

The study area was deglaciated during the warm Bølling-Allerød period, a period of intense melting of the ice sheets. This resulted in a rapid sea-level rise referred to as Meltwater Pulse 1A (Deschamps et al., 2012; Brendryen et al., 2020).

In paper II, the frequency of TVs and GFCs were compared with the oxygen-isotope record from Greenland ice-cores. The TVs and GFCs were assumed to have been formed subglacially relatively close (10-20 km) to the ice margin (Paper II), which is a reasonable assumption considering present models for TV and esker formation (Cofaigh, 1996; Clayton, Attig and Mickelson, 1999; Mäkinen, 2003; Livingstone and Clark, 2016; Creyts and Hewitt, 2017). The isochrones (Stroeven et al., 2016) were used to assign ages on the TVs and GFCs. To do so, the isochrones were interpolated to generate an ’enhanced’ set of isochrones for each hundred years. By calculating the frequency of TVs or GFCs intersecting the isochrones, it was possible to put an assumed age on each TV or GFC.

The frequency distribution of TVs and GFCs from 15.0 ka to 13.6 ka ago was compared to the δ^{18}O ratio (Rasmussen et al., 2014). It should be noted that the uncertainty of the isochrones could be as much as 500-2000 years pre-Younger Dryas (Stroeven et al., 2016). However, a correlation between the harmonized Greenland ice-core record and the end moraines on the Swedish west coast, that can be traced into the study area (Stroeven et al., 2016), strengthens the age assignments of the isochrones.

A visual comparison between a histogram of TV and GFC frequency per age interval and the Greenland record is noteworthy (Figure 5.1). This relationship shows that when climate was warmer, and more meltwater would have been produced, there is a greater frequency of TVs and GFCs. In other words, the landforms are interpreted to have been formed by abundant meltwater are more frequent when the climate record indicates more meltwater from the northern hemisphere ice sheets.

Because glacial hummocks have commonly been associated with stagnant ice (e.g., Johnson and Clayton, 2003), it is surprising that they are found associated with TVs and GFCs, which I interpret as formed by subglacial meltwater. In Paper III, one of the TVs were investigated by excavating two hummocks at its valley floor. This TV is clearly cut into the surrounding till plains and has an undulating long profile. By studying their internal structures, it was possible to conclude that the hummocks consist of pre-LGM subglacial till. Furthermore, one of the excavated hummocks was distinctly superposed by an esker ridge. Geomorphological, chronological, and sedimentological evidence taken together shows that the hummocks in the bottom of the TV were formed by erosion when the TV formed and not during stagnant-ice melting.

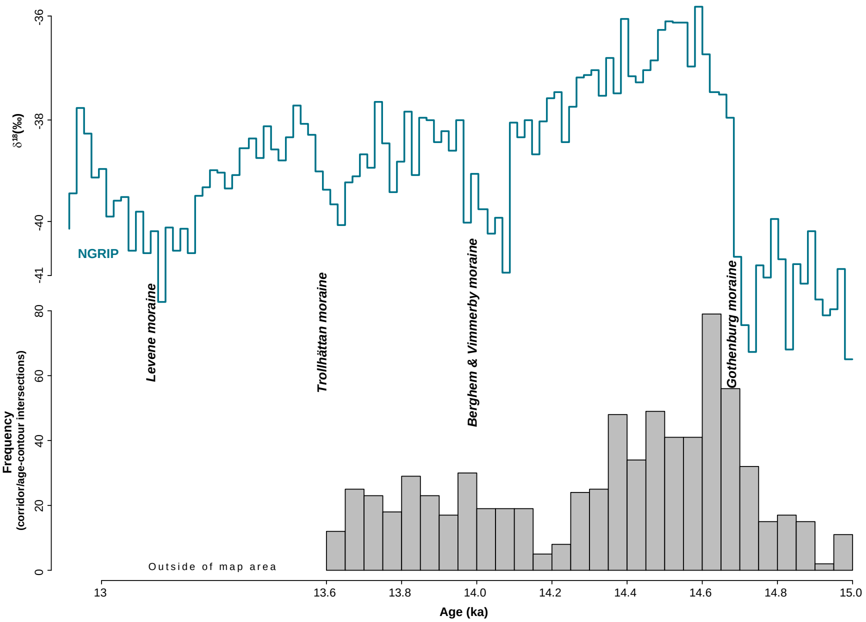

Figure 5.1: Comparison between TV and GFC frequency along deglacial isochrones and NGRIP data. Observe the visual similarities between the two curve and the histogram, indicating a positive correlation between TV and GFC formation and warmer periods.

The hummocks found in the GFCs are more difficult to explain because they are positive elements in the landscape and could not be formed by erosion. A process called the variable pressure axis hypothesis (Hubbard et al., 1995) has been applied as an explanatory model for GFC formation, as well as for their hummocks (Lewington et al., 2020). Generally, in a subglacial environment where the meltwater is efficiently channelized, water flow from the surrounding sediment and into the channel along the hydraulic gradient (i.e., towards lower pressure). However, during periodic large influx of meltwater into a channel the water could instead start to flow from the channel into the sediment, as the hydraulic gradient is reversed. This would create a zone at the ice bed interface surrounding the channel affected by these periodic influxes. Lewington et al. (2020) propose a model with an initial channel, hydraulically interacting with the surrounding bed. The zone affected by this interaction would develop a GFC. As the ice margin retreats and the hydraulic potential in the channel increases, the ice surface is steeper, a more consistent water pressure will maintain a tunnel, which may fill with sediment to form an esker, representing the final deposition in the GFC (Lewington et al., 2020). Although Lewington et al. (2020) suggest that this process most likely would act by eroding hummocks, it is reasonable to assume that flowage or deformation of the subglacial sediment would be an important process too, as the surrounding soft bed is drained towards the channel.

Although the geomorphological and sedimentological evidence suggest that the TVs and GFCs within the study were formed by the activity of subglacial meltwater during intense melting, the source of the subglacial meltwater is still unclear.

Subglacial meltwater can be derived from melting at the bed or from surface melting, where the meltwater is then moved to the bed englacially. However, results from Greenland suggest that subglacial melting (e.g., geothermal heat and frictional heat) is a minor component, 6-13 % (Bons et al., 2018), compared to meltwater reaching the bed from supraglacial sources, especially during the melt season (Nienow et al., 2017). Furthermore, an increase in subglacial melt is not directly expected to correlate to the regional climate, opposite to the initial results in Paper II. Based on this, I assume that subglacial melt is not responsible for the bulk of water responsible to the formation of the TVs and GFCs within the study area.

On the other hand, subglacial melt could recharge subglacial lakes, and the periodic drainage of such lakes might be responsible for the TVs and GFCs. Subglacial lakes could also receive meltwater from the surface, through moulins or hydrofracturing. The draining of subglacial lakes has been suggested as a source for increased meltwater discharge at the bed (Howat et al., 2015). However, indications from Antarctica, suggest that these drainages generally involve relatively small fluxes of water (e.g., Hodson et al., 2016; Alley, Cuffey and Zoet, 2019). Results from the Greenland ice sheet suggest that subglacial lakes are stable in the interior parts, but in the marginal regions could be hydrologically active, recharged by surface meltwater, and drain seasonally (Palmer, McMillan and Morlighem, 2015; Willis et al., 2015; Bowling et al., 2019). However, modelling of potential lake locations beneath the SIS show no occurrences during deglaciation of the study area and that subglacial lakes would have been uncommon and small (Shackleton et al., 2018) (Figure 5.2). In conclusion, although the drainage of subglacial lakes is a probable source of water, it is unlikely to have been the source of water to create the TVs and GFCs. Therefore, a more likely source is the drainage of supraglacial lakes.

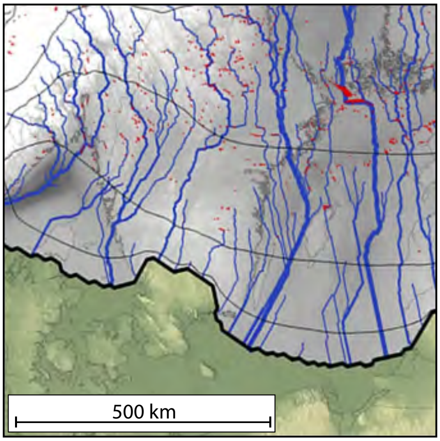

Figure 5.2: Predicted subglacial lakes at time of deglaciation. Blue = subglacial meltwater flow paths, Red = subglacial lake predictions. Modified from Shackleton et al. (2018).

Drainage of supraglacial lakes is possible through hydrofracturing, even on ice more than 1 km thick (Alley et al., 2005; Das et al., 2008). Supraglacial lakes are common in the ablation area of the western Greenland ice sheet (Chu, 2014) in a zone at least 100 km wide (van den Broeke et al., 2008). Supraglacial lake drainages occur annually and in places several times per year (McMillan et al., 2007; Selmes, Murray and James, 2011; Leeson et al., 2013; Chudley et al., 2019). Additionally, results from paleoglaciological work below the former Green Bay lobe, Wisconsin, yield that erosion of large channels eroded in a sediment bed was possible due to supraglacial lake drainage (Zoet et al., 2019). A similar process has also been suggested for channels in bedrock, formed at the ice margin during the final phase of deglaciation in northern Sweden (Jansen et al., 2014).

Even though supraglacial lakes can drain quickly (Selmes, Murray and James, 2011), it does not mean that the formation of the TVs and GFCs needs to be catastrophic or associated with a single lake-drainage event, but rather that it could be seasonal drainage of supraglacial lakes that reoccupied the same route multiple times. This idea is strengthened by the morphological properties of the TVs and GFCs. A catastrophic outburst flood is expected to generate a morphology with constant width along the length of the channel (Lamb and Fonstad, 2010). However, the TVs and GFCs instead show a large variation in width downstream, which could be connected to repeated drainages fed by multiple supraglacial drainages, which has been suggested for subglacial channels elsewhere (Livingstone and Clark, 2016). Moreover, it is in agreement with the proposed model invoking a variable pressure axis (Hubbard et al., 1995; Lewington et al., 2020). As the ice sheet retreats, this would imply headward erosion.

5.1.2 Murtoos

In Papers I, IV, and V, murtoos were mapped, analyzed based on morphology and distribution, and their internal structure was studied in outcrops. The murtoos have an ice-sheet scale distribution associated with times of rapid melt (i.e., early Holocene and Bølling-Allerød), and their formation is proposed to take place about 50-100 km inside the ice margin (Paper IV).

Based on murtoo internal structure, interpreted to include evidence of recurrent ice-bed decoupling, clastic dikes, and deformation, a formational model is proposed (Figure 4.9). The model is a cyclic model in that it repeats 6 steps (A-F); A) till deformation, B) decoupling and partial liquefaction by influx of meltwater, C) deposition of sediment in subglacial cavities and channels in a distributed system, D) evolution of a channelized system and coupling, E) channel formation and subsequent erosion, and F) stronger coupling and deformation by simple shear.

I suggest that this formation can be explained by repeated drainages of supraglacial meltwater into a distributed, subglacial hydrological system. The hydrologic shift between a distributed and channelized drainage system is envisaged to be a critical component in the suggested model, and I hypothesize that this is primarily connected to the sudden influx of supraglacial meltwater to the bed. Modeling and *in situ* observations of rapid supraglacial drainage suggest that the development of an efficient drainage system that effectively could remove excess water is not readily available, especially further in from the ice margin where the distributed system exists (Meierbachtol, Harper and Humphrey, 2013; Dow et al., 2015). Close to the ice margin, the effective pressure is high but decreases away from the margin (about 50 km, based on modeling at western Greenland), and sudden drainage from supraglacial lakes in these settings further from the ice margin can create an instability in the subglacial hydrological system and slow the development of an efficient channelized system (Das et al., 2008; Meierbachtol, Harper and Humphrey, 2013; Dow et al., 2015; Stevens et al., 2015).

Dow et al. (2015) suggest that during supraglacial-lake drainage into a distributed system (i.e., not in a marginal setting), the excess water, due to low effective pressure and based on limited hydraulic connectivity, will decouple the glacier from its bed, producing a subglacial water-blister at the ice-bed interface. The over-pressurized hydraulic system is capable of increasing effective pressure and decoupling at the ice bed interface (Chandler et al., 2013). Moreover, supraglacial drainages can last with concomitant elevated water pressures from hours to days (Box and Ski, 2007). Observations also show that eventually, a channelized system is established that causes the ice to decreases in velocity, which is interpreted to be a result of ice bed recoupling (Bartholomew et al., 2010).

I suggest that the sorted sediments within the murtoo outcrops were deposited by water flowing subglacially. Subglacial fluvial deposition beneath an ice sheet could be within large canals, this would suggest a channelized system (e.g., Röthlisberger, 1972; Nye and Frank, 1973; King, Woodward and Smith, 2004). But within the distributed system, other modes of water moving at the bed occur; in linked cavities, braided canals (Clark and Walder, 1994), as thin films (e.g., Kamb, 1987; Walder and Fowler, 1994; Ng, 2000; Creyts and Schoof, 2009), or within periods of decoupling during low effective pressure events (Benn and Evans, 2010).

Deposition in water-filled spaces at the ice bed interface during decoupling periods has been suggested for sorted beds beneath subglacial traction till (Lesemann, Alsop and Piotrowski, 2010). Therefore, I infer that the sorted sands and gravels are sorted and deposited by subglacial water, primarily within a distributed meltwater system, based on the arguments above.

Variations within this system produce shifts between high and low water pressures. I suggest that this would be a subglacial environment where sedimentation in low-velocity flows (water flow/ponding in the distributed system), development of water-escape structures (peaks of high water-pressure), ductile deformation (water-saturated sediments), and deposition of coarser sediment as well as erosion (development of channelized flow) could develop in a cyclic manner.

5.1.3 Where did the sediment go?

The processes described above, particularly the formation of TVs and GFCs, would indicate an abundance of sediment eroded subglacially by the subglacial meltwater, which would be delivered to the ice margin and to proglacial streams. An obvious issue to give some attention is where these sediments were deposited.

Within the study area, the deglaciation took place in a terrestrial setting. Distinct, ice-marginal outwash fans and plains, such as described in front of TVs at the Laurentide Ice Sheet's margin are not evident (Clayton, Attig and Mickelson, 1999; Cutler, Colgan and Mickelson, 2002). However, the distance from the ice margin (at around 15 ka ago) to the downstream

Baltic ice lake's coastline, during the period of most rapid melt, was from about 10 to 50 km. The highest coastline was formed immediately after deglaciation and ranges from 55 to 65 m asl (Persson, 2000; Hansson et al., 2019, Geological Survey of Sweden highest shoreline database), and several deltas are formed at these elevations (Persson, 2000).

Based on this, I hypothesize that some of the vast amounts of eroded sediment was deposited at or close to the highest shoreline as deltas. It is also reasonable that some of the river valleys, with flat valley fills of glaciofluvial material (Persson, 2000), could in fact be sandur deposits (e.g., Zielinski and Van Loon, 2003).

5.2 Landsystem of a Rapidly Decaying Terrestrial Ice Sheet

The deglaciation of south Swedish uplands was terrestrial and far from marine influence, such as tidewater glaciers, or substantial ice-streaming behavior. In Greenland for example, half of the mass loss is accounted for by ice streams (van den Broeke et al., 2009), the other half is melting. Consequently, in areas without ice-streaming, mass loss is to a large extent through melting, with subsequent meltwater activity at the bed. I hypothesize that murtoos, GFCs and TVs, and eskers are affected by this specific environment, and can be seen as a landform sequence. This sequence is governed by spatial and temporal variations in the glacial hydrological system. These landforms are developed time-transgressively, and although there is likely overlap in their formation, in general murtoos are thought to be formed first, followed by TVs or GFCs and last by eskers.

The streamlined till plains (e.g., drumlins and glacial lineations) within the study area are clearly cut by TVs and GFCs, and consequently the streamlined till plains formed first. This indicates warm-bed conditions at the onset of formation of both TVs and GFCs, as well as murtoos since they occur within these corridors.

Murtoos are suggested to form primarily within the distributed system. Closer to the margin, GFCs and TVs form further down-ice in the channelized system, but also affected by seasonal or periodic drainages from supraglacial sources, and perhaps also meltwater 'leaving' the murtoo formation process. Even closer to the ice margin, eskers will form as the water becomes confined in a more effective drainage system, controlled by the increased surface slope.

Esker-forming channels (*Röthlisberger*) are favored close to the margin where hydraulic potential is high, due to primarily the steeper ice surface (Shreve, 1972), while further from the ice margin shallow canals (*Nye*) should be present (Clark and Walder, 1994), before the distributed system with an instable high pressure system(Meierbachtol, Harper and Humphrey, 2013), where the murtoos are suggested to form.

It is reasonable to assume that the individual parts of this sequence can form independently, but this development is a times-transgressive process, making the landscape left after deglaciation considerably more complicated than the idealized description above. This idealized picture of the landscape could be conceptualized as a landsystem connected to rapid ice sheet decay in a terrestrial setting with little influence from ice streaming behavior on largely crystalline bedrock or with thin drift cover (Figure 5.3). A landsystem is a given set of landforms and subsurface materials that can be genetically related, based on geomorphology, sedimentology, and process (Evans, 2005).

5.2.1 Southern Sweden as an Analog to South Western Greenland

The landscape shaped by paleo ice-sheets can yield information on the long term view of subglacial process on an ice-sheet scale (Greenwood et al., 2016). In earlier parts of this thesis several connections between the study area and contemporary ice sheets have been made, and in particular to southwestern Greenland. The southwestern sector of Greenland has been used as an analog to the SIS and conditions related to the storage of nuclear waste (Liljedahl Claesson et al., 2016). For the south Swedish uplands these similarities are noticeable, and notably so for the theme of this thesis. The bedrock in the southwestern sector of Greenland is gneiss-dominated Precambrian bedrock (Henriksen et al., 2009), not unlike the study area (Wik et al., 2009). The proglacial landscape is affected by permafrost (Jørgensen and Andreasen, 2007), as is also suggested for the southern Swedish uplands (Björck and Möller, 1987). Furthermore, the southwestern sector of the Greenland ice sheet is land terminating and isolated from marine influences, suggesting most of mass loss is connected to surface-melt (Fitzpatrick et al., 2013; van den Broeke et al., 2009).

Production of meltwater in Greenland, as a consequence of a warming climate, is expected to increase (Tedesco et al., 2012). Large components of this melt is attributed to supraglacial melt, and some will end up in supraglacial lakes. Most supraglacial lakes drain into the channelized sys-

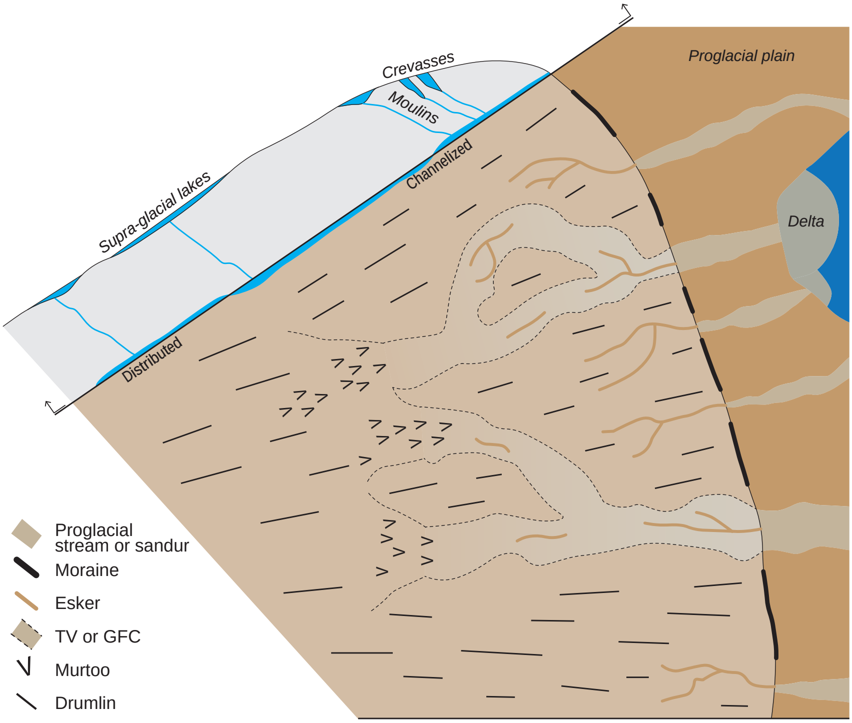

Figure 5.3: An idealized 'landsystem' for rapid ice sheet decay in a terrestrial setting with little influence from ice streaming behavior.

tem (Leeson et al., 2015). However, some lakes have been suggested to drain further inland, into the distributed system (e.g., Dow et al., 2015). Meltwater influx where no effective channels have evolved will speed up ice-sheet flow and this potentially works as a positive feedback to ice-sheet mass loss (Joughin et al., 2008). In a warming climate supraglacial lakes is suggested to form further from the ice margin, suggesting more drainages into the distributed system (Leeson et al., 2015).

This is in agreement with the models proposed in this thesis, with periodic drainages of primarily supraglacial lakes as a prerequisite for formation (Paper II and V). The variable morphology of TVs and GFCs in the region suggests periodic drainages, and it is plausible to imply headward erosion as the ice-margin retreats. Further in from the ice margin, within the ditributed system, the model proposed here suggests formation of murtoos (Paper V). The presence of murtoos up-ice from the TVs, GFCs, and eskers is in agreement with inland advance of supraglacial lakes in a warming climate (Leeson et al., 2015). Based on this, it seems reasonable that the inland advance of supraglacial lakes should be contemplated when modeling future ice-sheet behavior connected to a warming climate, especially, in the southwestern sector of Greenland.

5.3 Implications on Regional Deglaciation History

The landform record displayed within the study area reveals a deglaciation governed by an warm-based active and dynamic ice sheet (Paper I). This is evident based on the plentiful distribution of glacial lineations (i.e., drumlins and crag-n-tails), eskers, GFCs and TVs, as well as end moraines. Additionally, the end moraines and drumlins display lobate pattern in the scale of 1-20 km (Paper I), suggesting a dynamic ice front. Moreover, the landsystem introduced above fits for nearly the entire study area. However, there are two exceptions, and these indicate a change in the glacial dynamics and the associated land system; the Vimmerby moraine and the ribbed moraine.

5.3.1 Vimmerby Moraine

A correlation between Older Dryas and the Vimmerby moraine, in the northern part of the study area, has been suggested (Stroeven et al., 2016) based on recent chronological data (Johnsen et al., 2009).

The climate during Older Dryas was relatively cold compared to the otherwise warm Bølling-Allerød. The dynamic ice-sheet retreat during deglaciation of southern Sweden, indicate rapid responses to climate. Noteworthy, the Vimmerby moraine, especially in the eastern part around the town of Vimmerby, exhibit an ice margin with several lobes. These moraines clearly drape an older landscape (Paper I). Inside the Vimmerby moraine cross-cutting glacial lineations are clearly visible, with the younger direction clearly enveloped by a till sheet ending at the Vimmerby moraine (Figure 5.4). This relationship is also visible in the stratigraphy, with till covered sorted sediments north of the Vimmerby moraine, indicating an ice readvance (Persson, Persson and Lindén, 2007).

Although the Vimmerby moraine indicate a re-advance, no quantitative numbers on the magnitude of such an event has been suggested. Based on

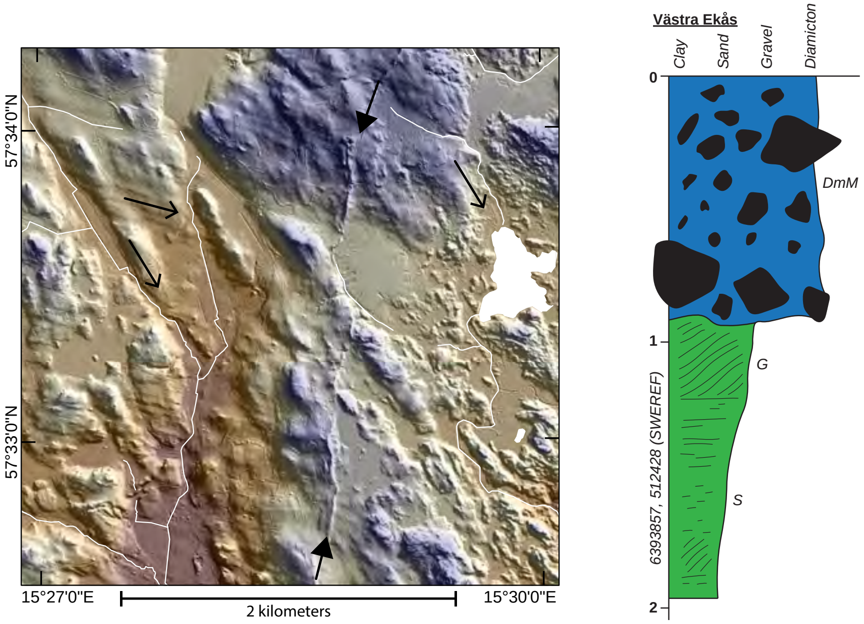

Figure 5.4: Example of the cross-cutting relationship at the Vimmerby moraine. Note the till ’blanket’ with finer lieations towards the end moraine, overlying the larger drumlins with NW-SE direvtion. To the right an example of till covered glaciofluvial sediment at Västra Ekås, north of the Vimmerby moraine.

the mapping, the distance behind the Vimmerby moraine including cross-cutting glacial lineations is up to 20 km (Figure 4.1). Furthermore, stratigraphy collected during a reconnaissance trip, indicate till covered glaciofluvial sediments, on a similar distance from the moraine (Figure 5.4). Based on the short discussion above it is reasonable to suggest an ice advance of at least 20 km.

5.3.2 Ribbed Moraine

The presence of ribbed moraine in the study area might indicate cold-bed conditions (e.g., Möller, 1987, 2010). It has been suggested that this diverse hummocky zone was formed by a combination of freeze-on, thrusting (ribbed moraine), and subglacial and supraglacial melt-out (Björck and Möller, 1987;

Möller, 1987, 2010). The ribbed moraine (Åsnen type) is suggested to form during frozen-bed conditions along the former ice margin, with a zone of freeze-on zone further up ice that causes the basal debris-rich zone to become thicker near the ice margin (Möller, 2010). This debris-rich zone, when it melts out at the glacier margin, will produce hummocks rich in melt-out till according to Möller (1987). However, where compression and thrusting has caused the debris-rich ice to form transversely elongated concentrations, ribbed moraine was formed.

Although the internal structure of these landforms are interpreted as stagnant-ice features based on a plethora of well-documented localities (Möller, 1987), ribbed moraines with glacial lineations on their tops have been mapped, indicating active ice flow (Paper I). The presence of superposed active glacial landforms does not suggest a formation during stagnant ice conditions. Albeit this slight disagreement, the mapping or stratigraphic studies during this work have not generated any results, and have not aimed to do so, that could be used to argue against the model proposed by Möller (1987).

However, it could also be worth, discussing the formation of the ribbed moraines by connecting them to another proposed model. Ribbed moraine formation have been suggested to form during extensional flow at the ice bed interface, by ripping apart the substrate, connected to a transition from interior frozen-bed conditions to distal warm-bed conditions (Hättestrand and Kleman, 1999; Kleman and Glasser, 2007). This transition is suggested to take place along a migrating frozen/thawed-bed boundary during deglaciation (Hättestrand and Kleman, 1999; Kleman and Hättestrand, 1999). Interestingly, on the south Swedish uplands there are occurrences of weathered bedrock (saprolites) in subaerial conditions preserved through the Quaternary (Lidmar-Bergström, Olsson and Olvmo, 1997), although the landform record suggest otherwise (Paper I). The existence of saprolites might suggest frozen-bed conditions during a full-sized ice sheet (i.e., the saprolites was preserved during frozen-bed conditions). As the ice retreated after LGM, the proposed migrating boundary would have passed the region of southern Sweden, forming ribbed moraines, later superposed by active ice sheet landforms. The two ideas presented above both envision frozen-bed conditions in the study area, and this contrasts with what the landform record implies (Paper I).

Although studied for over one hundred years (e.g., Fredholm, 1875; Hummel, 1877), there are still questions remaining to be answered in the field of glacial geology in southern Sweden.

6 Conclusion

The map produced is the first comprehensive inventory of glacial geomorphology produced for the south Swedish uplands. This mapping discovered several new features that are added to the plethora of already known landforms. Hummock tracts within the area demonstrate a heterogenous morphology with semi-organized landforms, such as ribbed moraine and murtoos, as well as disorganized forms. Age relationships between hummocks and glacial lineations indicate both hummocks overlying and underlying glacial lineations. The latter suggests that some hummocks formed subglacially or by overriding active ice. The hummocky tracts in southern Sweden display a lobate band, as previously suggested, and a radial pattern of hummock corridors associated with ice flow.

The radial pattern of hummock corridors are interpreted as GFCs and TVs, based on the overall pattern, overprinting eskers, adverse slopes, and morphometric relationships to subglaciofluvial landforms reported elsewhere. Incised corridors are interpreted as TVs, and positive forms, which are more common where till thickness is low, are interpreted as GFCs.

The internal structure of hummocks within one of these TVs indicates subglacial traction till superposed by esker gravel. Within and below the till, glaciotectonically deformed sorted sediments, dated by OSL to a late MIS 4 or early MIS 3, are suggested to be proglacial deposits in front of an older ice margin. The hummocks are interpreted to be erosional, formed by glaciofluvial erosion as the TV formed.

V-shaped landforms, called Murtoos, were discovered during the mapping in the area. The murtoo is suggested to be a distinct landform, with a morphology related to overall ice flow. Cross-cutting relationships indicate a subglacial genesis as well as warm-bed formation. Ice-sheet scale mapping of murtoos suggests a configuration that can be connected to ice-sheet dynamics and subglacial hydrology. The mapping displays a high frequency of landforms in a zone 50-100 km north of regions connected to intense melting during deglaciation. This suggests that murtoos form during rapid deglaciation, under warm-based ice, during periods of high subglacial meltwater influx, and within the distributed system.

The internal structure of murtoos exposes interbedded sorted sediments and subglacial till deformed by shearing and liquefaction. The interbeds are interpreted to connect to decoupling at the ice bed interface, the liquefaction to high water pressure events, and the deformation to recoupling at the ice bed interface. A cyclic model of formation is proposed, driven by variations in the subglacial hydrological system and connected to repeated influx from supraglacial lake drainages to the bed. Moreover, this model is in agreement with the glaciological and hydrological dynamics observed on contemporary ice sheets.

TVs and GFCs are tentatively connected to the deglacial chronology and the Greenland climate record. This relationship suggests formation during Bølling-Allerød, a period of intense melting from northern hemisphere ice sheets.

End moraines in the area are more common than previously known, but still few in numbers. Their pattern suggests a dynamic ice margin with multiple ice lobes. A variation in ice-flow indicators also strengthens this pattern. Cross-cutting relationships suggest that some of these moraines represent ice advances, particularly at the Vimmerby moraine, which is suggested to advance at least 20 km.

TVs, GFCs, and murtoos are all proposed to be parts of the subglacial hydrological system. The formation of these landforms indicates intense melting at the ice-sheet surface. This connection can be illustrated as a times-transgressive landform sequence, where murtoos are suggested to form first, followed by TVs, GFCs, and finally, eskers. Furthermore, it is put forward that this idealized landform sequence can be described as a landsystem. Such a landsystem could be formed during rapid ice sheet decay in a terrestrial setting, with little influence from ice streaming behavior on predominantly crystalline bedrock. Finally, this landsystem could potentially be applied to the southwestern sector of Greenland ice sheet.

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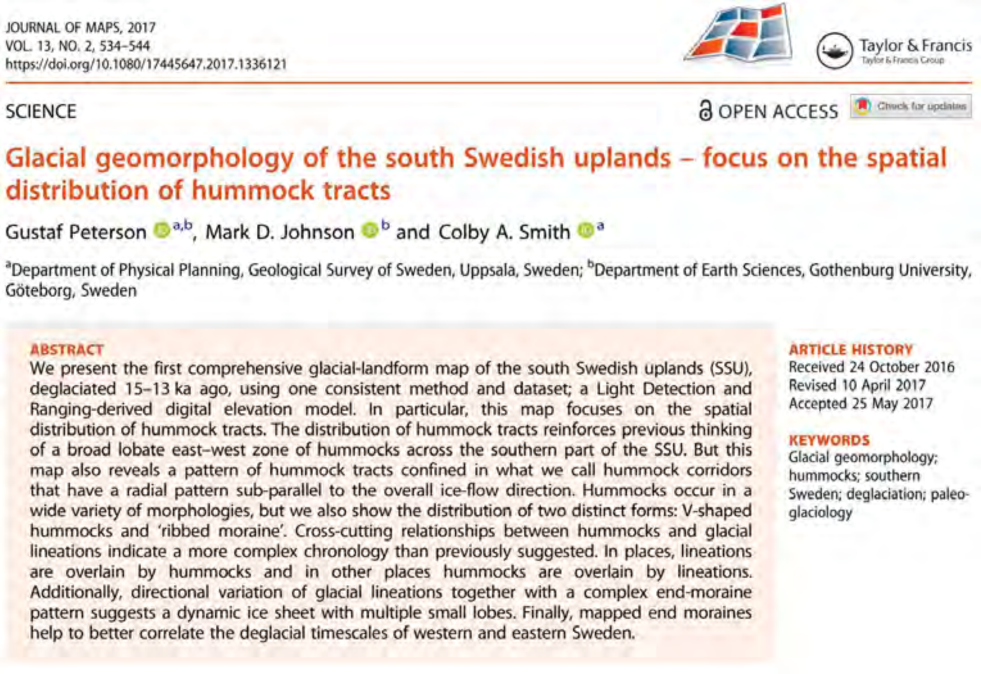
PAPER I



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SCIENCE

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Glacial geomorphology of the south Swedish uplands – focus on the spatial distribution of hummock tracts

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ABSTRACT
We present the first comprehensive glacial-landform map of the south Swedish uplands (SSU), deglaciated 15–13 ka ago, using one consistent method and dataset; a Light Detection and Ranging-derived digital elevation model. In particular, this map focuses on the spatial distribution of hummock tracts. The distribution of hummock tracts reinforces previous thinking of a broad lobate east–west zone of hummocks across the southern part of the SSU. But this map also reveals a pattern of hummock tracts confined in what we call hummock corridors that have a radial pattern sub-parallel to the overall ice-flow direction. Hummocks occur in a wide variety of morphologies, but we also show the distribution of two distinct forms: V-shaped hummocks and 'ribbed moraine'. Cross-cutting relationships between hummocks and glacial lineations indicate a more complex chronology than previously suggested. In places, lineations are overlain by hummocks and in other places hummocks are overlain by lineations. Additionally, directional variation of glacial lineations together with a complex end-moraine pattern suggests a dynamic ice sheet with multiple small lobes. Finally, mapped end moraines help to better correlate the deglacial timescales of western and eastern Sweden.

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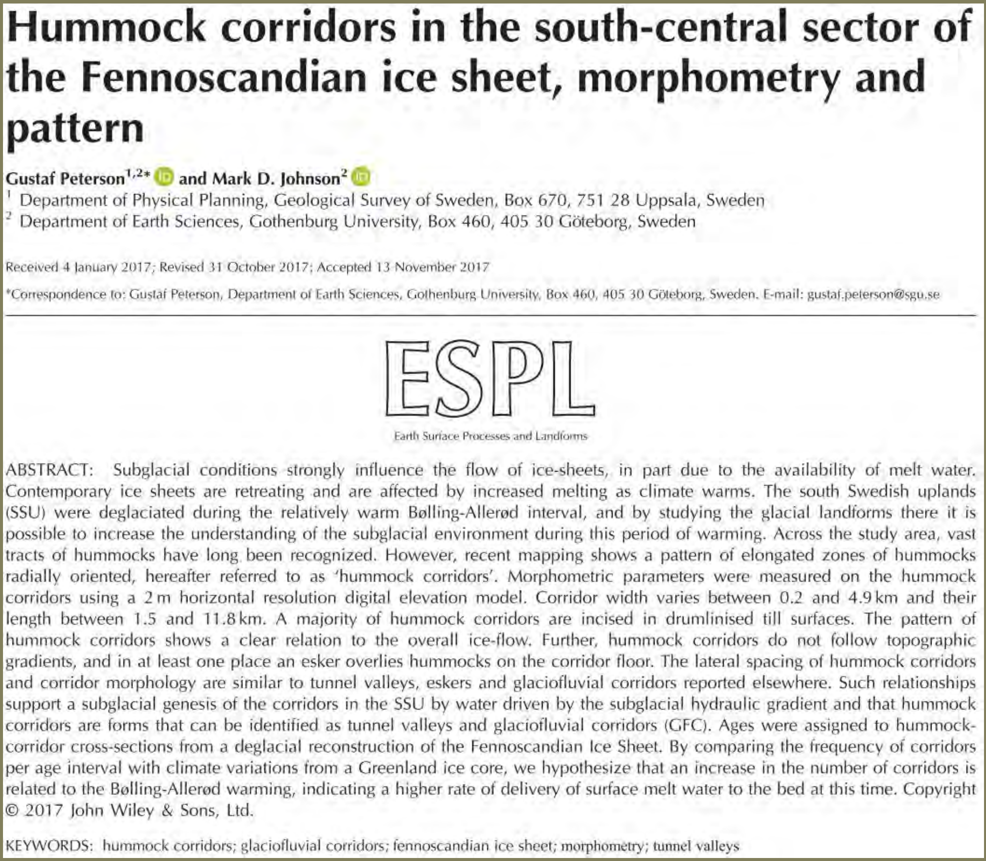
PAPER II



Hummock corridors in the south-central sector of the Fennoscandian ice sheet, morphometry and pattern

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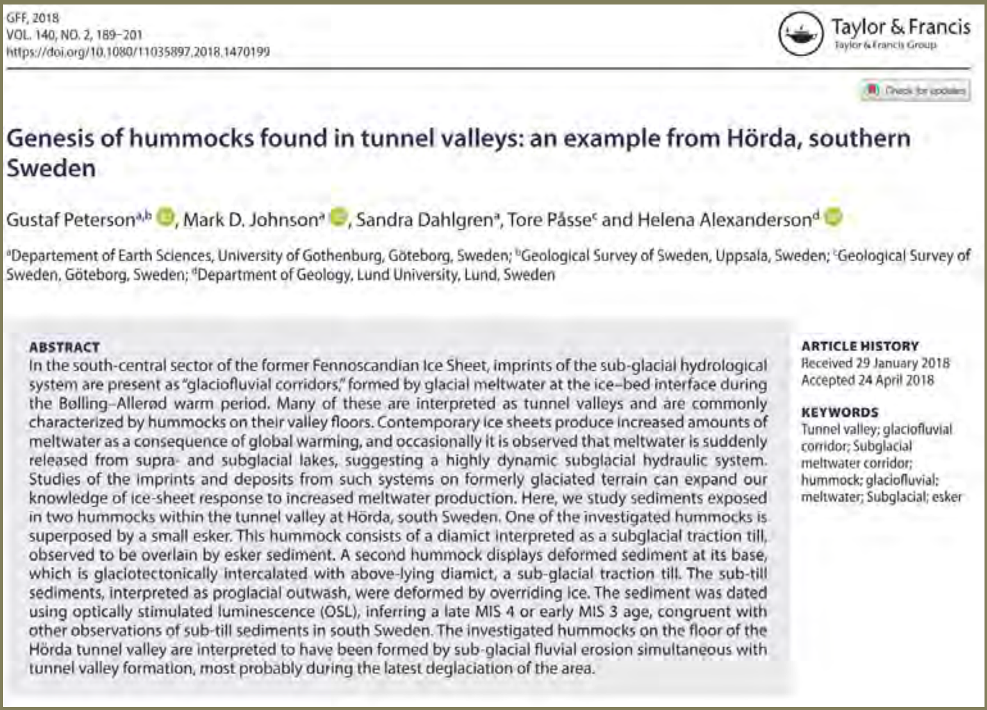
ESPL
Earth Surface Processes and Landforms

ABSTRACT: Subglacial conditions strongly influence the flow of ice-sheets, in part due to the availability of melt water. Contemporary ice sheets are retreating and are affected by increased melting as climate warms. The south Swedish uplands (SSU) were deglaciated during the relatively warm Bølling-Allerød interval, and by studying the glacial landforms there it is possible to increase the understanding of the subglacial environment during this period of warming. Across the study area, vast tracts of hummocks have long been recognized. However, recent mapping shows a pattern of elongated zones of hummocks radially oriented, hereafter referred to as 'hummock corridors'. Morphometric parameters were measured on the hummock corridors using a 2 m horizontal resolution digital elevation model. Corridor width varies between 0.2 and 4.9 km and their length between 1.5 and 11.8 km. A majority of hummock corridors are incised in drumlinised till surfaces. The pattern of hummock corridors shows a clear relation to the overall ice-flow. Further, hummock corridors do not follow topographic gradients, and in at least one place an esker overlies hummocks on the corridor floor. The lateral spacing of hummock corridors and corridor morphology are similar to tunnel valleys, eskers and glaciofluvial corridors reported elsewhere. Such relationships support a subglacial genesis of the corridors in the SSU by water driven by the subglacial hydraulic gradient and that hummock corridors are forms that can be identified as tunnel valleys and glaciofluvial corridors (GFC). Ages were assigned to hummock-corridor cross-sections from a deglacial reconstruction of the Fennoscandian Ice Sheet. By comparing the frequency of corridors per age interval with climate variations from a Greenland ice core, we hypothesize that an increase in the number of corridors is related to the Bølling-Allerød warming, indicating a higher rate of delivery of surface melt water to the bed at this time. Copyright © 2017 John Wiley & Sons, Ltd.

KEYWORDS: hummock corridors; glaciofluvial corridors; fennoscandian ice sheet; morphometry; tunnel valleys

PAPER III



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Genesis of hummocks found in tunnel valleys: an example from Hörda, southern Sweden

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ABSTRACT

In the south-central sector of the former Fennoscandian Ice Sheet, imprints of the sub-glacial hydrological system are present as "glaciofluvial corridors," formed by glacial meltwater at the ice–bed interface during the Bølling–Allerød warm period. Many of these are interpreted as tunnel valleys and are commonly characterized by hummocks on their valley floors. Contemporary ice sheets produce increased amounts of meltwater as a consequence of global warming, and occasionally it is observed that meltwater is suddenly released from supra- and subglacial lakes, suggesting a highly dynamic subglacial hydraulic system. Studies of the imprints and deposits from such systems on formerly glaciated terrain can expand our knowledge of ice-sheet response to increased meltwater production. Here, we study sediments exposed in two hummocks within the tunnel valley at Hörda, south Sweden. One of the investigated hummocks is superposed by a small esker. This hummock consists of a diamict interpreted as a subglacial traction till, observed to be overlain by esker sediment. A second hummock displays deformed sediment at its base, which is glaciotectonically intercalated with above-lying diamict, a sub-glacial traction till. The sub-till sediments, interpreted as proglacial outwash, were deformed by overriding ice. The sediment was dated using optically stimulated luminescence (OSL), inferring a late MIS 4 or early MIS 3 age, congruent with other observations of sub-till sediments in south Sweden. The investigated hummocks on the floor of the Hörda tunnel valley are interpreted to have been formed by sub-glacial fluvial erosion simultaneous with tunnel valley formation, most probably during the latest deglaciation of the area.

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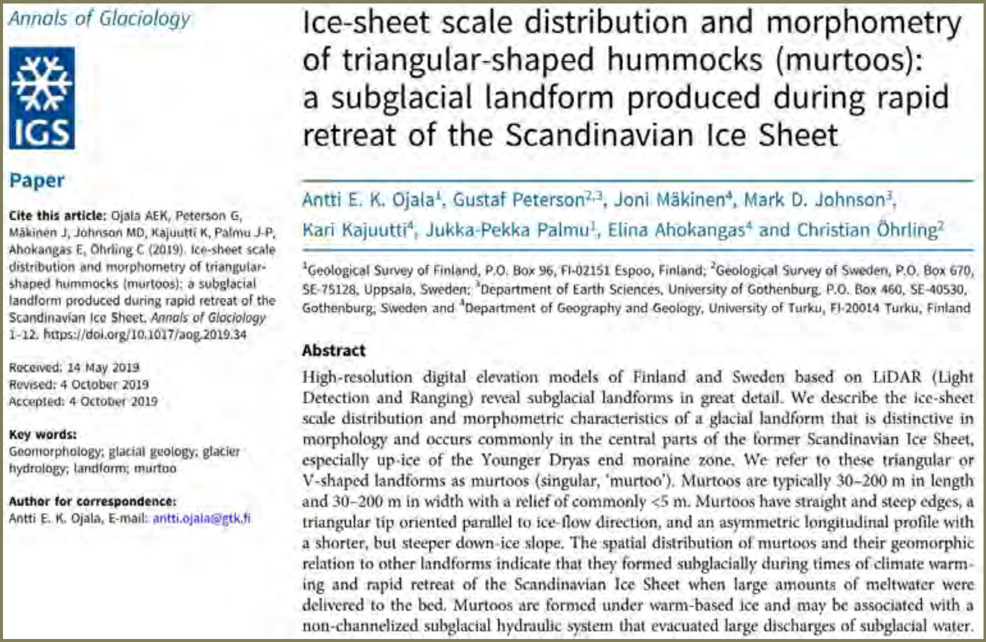
Tunnel valley; glaciofluvial corridor; Subglacial meltwater corridor; hummock; glaciofluvial; meltwater; Subglacial; esker

PAPER IV



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Paper

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Ice-sheet scale distribution and morphometry of triangular-shaped hummocks (murtoos): a subglacial landform produced during rapid retreat of the Scandinavian Ice Sheet

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Abstract

High-resolution digital elevation models of Finland and Sweden based on LiDAR (Light Detection and Ranging) reveal subglacial landforms in great detail. We describe the ice-sheet scale distribution and morphometric characteristics of a glacial landform that is distinctive in morphology and occurs commonly in the central parts of the former Scandinavian Ice Sheet, especially up-ice of the Younger Dryas end moraine zone. We refer to these triangular or V-shaped landforms as murtoos (singular, 'murtoo'). Murtoos are typically 30–200 m in length and 30–200 m in width with a relief of commonly <5 m. Murtoos have straight and steep edges, a triangular tip oriented parallel to ice-flow direction, and an asymmetric longitudinal profile with a shorter, but steeper down-ice slope. The spatial distribution of murtoos and their geomorphic relation to other landforms indicate that they formed subglacially during times of climate warming and rapid retreat of the Scandinavian Ice Sheet when large amounts of meltwater were delivered to the bed. Murtoos are formed under warm-based ice and may be associated with a non-channelized subglacial hydraulic system that evacuated large discharges of subglacial water.

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Sedimentology and internal structure of murtoos - V-shaped landforms indicative of a dynamic subglacial hydrological system

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ABSTRACT

Knowledge about processes beneath ice sheets, and in particular the processes connected to subglacial hydrology, is crucial for an understanding of ice sheets and how they react in a warming climate. Recently, v-shaped subglacial landforms (murtoos) have been found in those parts of the former Fennoscandian Ice Sheet where rapid ice-margin retreat occurred. Based on their geomorphology and distribution, murtoos have been suggested to form where the bed experienced high influxes of meltwater. Here, we investigate the sedimentology and internal structure of murtoos at four localities in southern Sweden to better understand murtoo genesis. The excavated murtoos consist of heterogenous diamict showing reasonably strong fabrics interbedded with sorted sediments. Sediments show signs of ductile deformation and lquefaction. We interpret these landforms as subglacial landforms created by till deposition and sedimentation from meltwater with subsequent deformation. Cross-cutting relationships and inter-bedding of sorted sediments suggest a stepwise formation including periodic deformation events. We propose a model that is based on a dynamic subglacial meltwater system. We suggest that the subglacial environment is within the distributed system where the bed receives meltwater from repeated influxes of supraglacially derived meltwater. The processes suggested in this model of formation are strikingly similar to the character of glaciological and hydrological dynamics observed on the Greenland ice sheet today.

Sedimentology and Geomorphology of Glacial Landforms in Southern Sweden

Studying the Landscape of a Melting Ice Sheet

Ice sheets are disintegrating due to global warming. One factor controlling ice-sheet behavior is the processes active beneath the ice sheet. These processes are complicated to study as they are covered by several km of ice. However, landforms and sediments formed by these processes, found in formerly glaciated regions, can be used as analogs to the present-day Greenland ice sheet. With high-resolution digital elevation models, it is possible to perform detailed geomorphological analysis of landforms and pinpoint locations for detailed sedimentological work. Increased knowledge of these processes helps us understand the ice sheet's reaction in a warming climate.

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The author is a glacial geologist interested in the processes active beneath paleo ice-sheets. Apart from pursuing this Ph.D. project, Gustaf works as a state geologist at the Geological Survey of Sweden with research and mapping of surficial deposits.

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