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Dynamics of a retreating ice sheet: a LiDAR study in Värmland, SW Sweden

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ABSTRACT

Värmland in south western Sweden lies across the established zone of marine-terrestrial transition of the Scandinavian Ice Sheet (SIS) margin. The region lies inside the Younger Dryas maximum limit reached at 12.7 cal ka BP and the area of rapid final SIS retreat from 11.5 cal ka BP. LiDAR data across Värmland allows more detailed observation and analysis of glacial landforms formed during this stage than previously possible. This study synthesises geomorphological mapping performed on highly detailed digital elevation models (DEMs) and field observations across the region around Torsby in northern Värmland to reconstruct the dynamics of the ice sheet as it retreated. Several landforms that developed during deglaciation are identified and clearly reflect the change from a marine to terrestrially terminating ice margin. Ice-marginal deltas suggest a slowing of retreat at the point of marine-terrestrial transition. Increased topographic control on ice-sheet flow, pattern of drainage and ice sheet decay is indicated by the distribution of streamlined terrain, eskers, and outwash material. Hummocky terrain across low ground and incised valleys suggest persistence of ice in topographic lows beyond the retreat of the main ice front. Combined analysis of identified landforms allows a model for the pattern of retreat to be produced that traces the retreating ice sheet margin in far greater detail than previously has been possible in this area. This provides important data for understanding the final retreat of the SIS and details processes likely occurring beneath the margin of the Greenland Ice Sheet today.

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Scandinavian Ice Sheet (SIS); deglaciation; DEM; glacial geomorphology; Holocene; ice-sheet dynamics; ice-sheet retreat; streamlined terrain; glacial geomorphology; De Geer moraines

Introduction

Dynamics

The complex dynamics of rapidly retreating ice margins reflect the interaction of variations in flow rate, morphology, hydrology, basal conditions, advance and retreat, and the reaction to topography along an ice margin. Understanding ice-margin dynamics is of increasing importance given the growing instability and retreat of the Greenland and Antarctic ice sheets in response to global warming. How these ice-sheets respond to increasing atmospheric and ocean temperatures and varying weather patterns is a source of much uncertainty (Vaughan & Arthern 2007).

The dynamics of ice margins over millennial to centennial scales are reasonably well established but the decadal to annual pattern of ice movement is less well understood. Monitoring of present day ice sheets shows annual variation in seasonal advance and retreat more rapid than previously thought possible (Truffer & Fahnestock 2007). There is a need to understand ice sheet margin dynamics on human scales from annual up to centennial due to the influence the retreating Greenland and Antarctic ice sheets will have on sea levels and climate in the immediate future. Ice-sheet modelling is a key tool to analyse dynamics on this scale, but this relies on input of reliable data both from present day observations across Greenland and Antarctica and from patterns of ice sheet retreat determined from the geological record. Thus, linking of current ice-sheet dynamics and annual to decadal observations to the larger scale pattern of retreat during the termination of the last glaciation is a key area of research. Attaining a more detailed model of retreat of former ice-sheets will allow better calibration of ice-sheet models focussed on Greenland and Antarctica.

Historically, the study of ice sheet dynamics has been based upon observations of existing ice sheets and glaciated areas and upon studies of landforms and glacial deposits in previously glaciated regions such as northern Europe and North America. In both cases reliable, consistent observations stretch back ~200 years and have relied on physical investigation and geological mapping of features often complemented by study of aerial photography and satellite imagery in later years. The Swedish varve chronology and the techniques developed to constrain it have been key tools in determining ice-sheet retreat rates in the area beneath the Scandinavian Ice Sheet (SIS) and also in other formerly glaciated regions (Zillén et al. 2003; DeJong et al. 2013; Stroeven et al. 2016; Brooks 2018). In many regions, the glacial landforms that are key to determining past ice-sheet behaviour are often masked or obscured by forest, later Quaternary deposits or by anthropological activities and features. Advances in remote sensing and observations within the last 20 years have produced a powerful new set of resources for the study of previously glaciated areas. Of particular importance is the advent of Light Detection and Ranging (LiDAR) surveying (Dowling et al. 2013) and the production of high resolution detailed land surface maps (Digital Elevation Models, DEMs). These maps are now key resources for the study of glacial features and geomorphology and have seen increasing use in recent years. A prominent

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example of this technique in use is the Swedish National height model, which has used LiDAR to reveal the glacial landscape of Sweden in detail never seen before (Johnson et al. 2015). It is now possible to define a greater range and higher concentration of relict glacial landforms. This allows detailed investigation of the dynamics of the retreating SIS.

This study aims to demonstrate the ability to use such new detailed remote sensing data, complemented by field investigation, to reconstruct ice margin dynamics in Värmland over a short, <200-year timescale. The focus is the review of geomorphology and distribution of glacial features in an area in which an ice margin experienced a change from marine to terrestrial conditions during retreat. The reconstruction allows direct comparisons with the rapidly retreating Greenland Ice Sheet (GIS) today.

Scandinavian Ice Sheet deglaciation

The areas that once lay beneath the SIS have been subject to particularly detailed study for the past century and have yielded much of the knowledge that comprises current understanding of ice sheet dynamics and Quaternary glaciations history (Rinterknecht et al. 2006; Francus et al. 2013). The SIS at its greatest extent was multi-domed and with multiple major ice-streams (Boulton et al. 2001). At the last glacial maximum (LGM) the ice sheet covered all of Scandinavia reaching into northern Germany in the south, the North Sea in the west and western Russia in the east (Stroeven et al. 2016). Not all areas of the ice-sheet reached their maximum extent at the same time and retreat was diachronous (Böse et al. 2012; Larsen et al. 2016). The Younger Dryas interval lasted from 12.7-11.6 calculated thousand years before present (cal ka BP) and saw a re-advance of the ice margin to the southern part of Lake Vänern (Fig. 1; Lundqvist 1995). This advance is also marked by the Salpausselkä moraines in Finland (Saarnisto & Saarinen 2001) and the Ra moraines in Norway (Andersen et al. 1995; Johansson et al. 2011). This Younger Dryas lasted until ~11.6 cal ka BP after which the margin began to rapidly retreat due to warming climate conditions (Baker et al. 2017).

Previous studies (Boulton et al. 2001; Saarnisto & Saarinen 2001; Stroeven et al. 2016) have interpreted retreat rates of 100 m to >250 m per year along the various sections of the margin. The ice margin around southern Norway and western Sweden, where this study is focussed, retreated increasingly rapidly following the end of the Younger Dryas, though with periods of standstill recognised by the deposition of end moraines and some marginal deltas (Solheim & Groenlie 1983; Lundqvist 1995). Outlet of ice via the Norwegian Channel Ice Stream through the Oslo fjord alongside initial marine

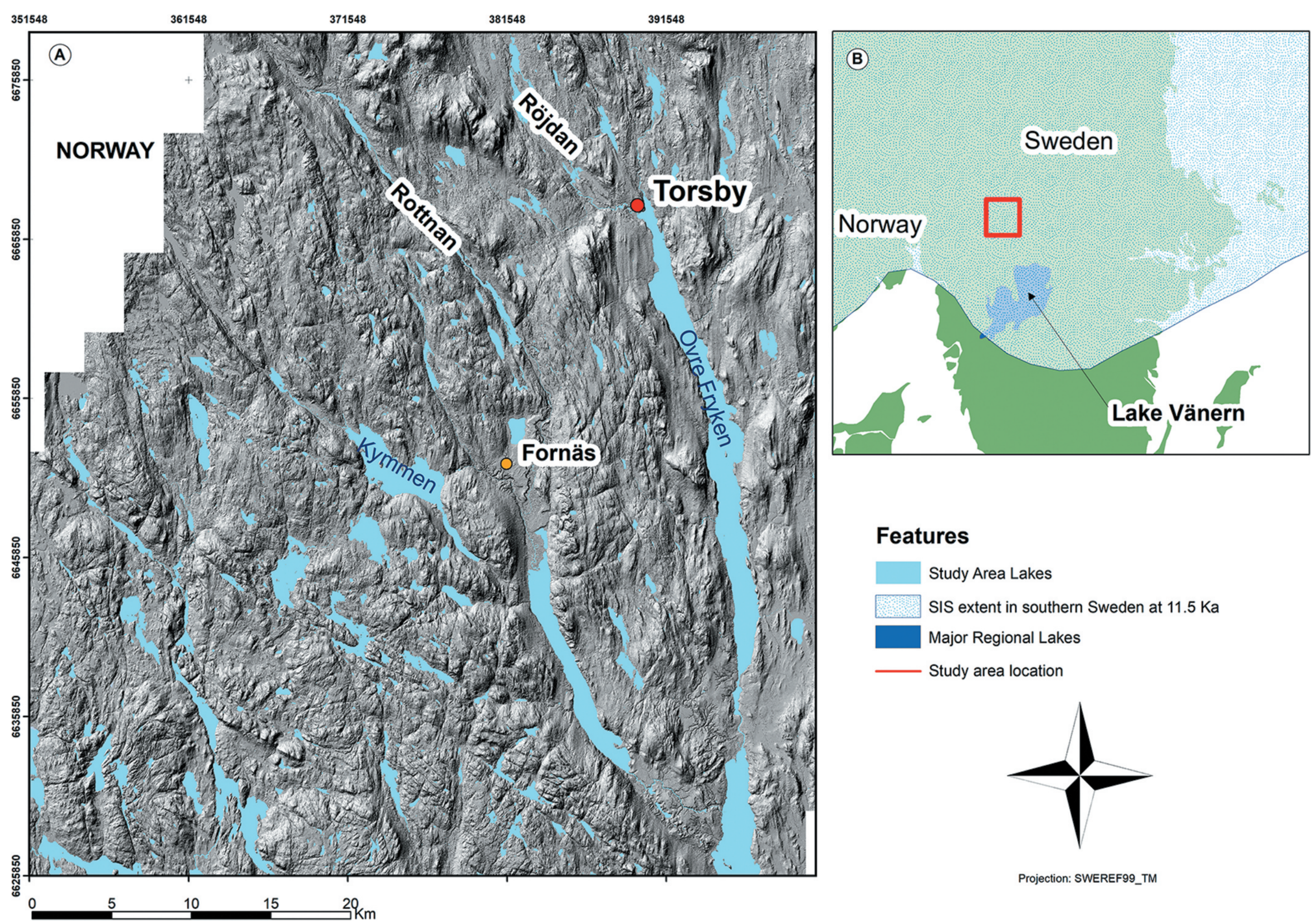

Figure 1. **A**. Overview of study area and location within Sweden along the Norwegian border. Note Lake Vänern, prominent rivers and NW-SE trend of valleys. Red square in **B** shows outline of study area. Trace of the general ice-sheet position at end of Younger Dryas is shown. Adapted from Stroeven et al. (2016). Hillshade generated from LiDAR scan data provided by Lantmäteriet, Sweden © Lantmäteriet, i2012/927.

termination of the margin allowed rapid drainage in this area. The rapid loss of ice led to thinning of the sheet and increasing topographical influence on flow patterns at the ice margin (Greenwood et al. 2015). Within just over 1500 years the entire SIS had disappeared altogether (Regnéll et al. 2019). This study is focused on this period of rapid final retreat, how it is reflected in the geomorphological and geological record and to what resolution the timescale for retreat of the ice-margin across the study area may be determined.

Study area

The study area lies in the county of Värmland in southwestern Sweden, around the town of Torsby (Fig 1). The area is 50 km by 50 km and lies in the transitional zone between marine and terrestrial ice marginal conditions for the SIS. It tapers to 38.5 km in width in the far north due to a data gap over the border with Norway to the west. The area is surrounded by the highlands and mountains of Sweden and Norway to the north and west and the low plains of central Sweden to the south and east. A thorough initial study and geological mapping of Värmland was carried out by Lundqvist (1958) and previous studies in Värmland have established a pattern of retreat for the areas south and east of the study area however, these predate the advent of the National Height Model. The work of Lundqvist (1988, 1992, 2003) has traced the retreat from southern Värmland past Lake Vänern and along the Klarälven valley system east of the study area. The region immediately surrounding Torsby has been less well studied. Quaternary mapping has been carried out by the Geological Survey of Sweden (Lundqvist 1958) and recent studies have investigated lakes in the south-east of the study area (Zillén et al. 2002; Stanton et al. 2010).

Exposed bedrock is common throughout the study area. Data from the Geological Survey of Sweden (SGU) online database (https://www.sgu.se/produkter/kartor/) shows surface till, glaciofluvial, fluvial and marine deposits of varying geographical extents overlie a bedrock of granite and gneiss with localised occurrences of dolerite, rhyolite and dacite. A large NW-SE to NNE-SSW trending fault zone runs through the west of Värmland and the study area (Lundegårdh et al. 1992; Larson et al. 1998). Most major valleys follow this trend. Two rivers, the Rottnan and the Röjdan, flow from NW to SE across the area (Fig. 1). The Rottnan flows through an incised valley to the NW before flowing south through the Lake Rottnen ending in Lake Mellan-Fryken. The Röjdan also flows southwards ending in Lake Övre Fryken to the south of Torsby. The highest coastline (HCL) is according to previous studies located around 190 m.a.s.l. though with increase towards 200 m.a.s.l towards the north (Lundqvist 1958), and formed approximately during the Yoldia Sea stage in the Vänern basin (Björck 1995).

Methods

LiDAR data analysis

LiDAR scans covering the study area were obtained from the Swedish national mapping agency Lantmäteriet (www.lantmateriet.se). These scans form the basis for the terrain model GSD-Höjddata, grid 2+ (Lantmateriet 2016-05-12 2015), which is part of the National Height Model for Sweden. The model has an average vertical accuracy of 0.1 m and pixel resolution of 2 m allowing detailed study of the landscape. Scans are pre-processed to present a "true" ground level without urban areas, wood cover and anomalous recordings (Möller & Dowling 2015).

ArcGIS 10.3™ was used to generate two main sets of hillshade models; one with an illumination azimuth at 135° and the other 225°, running parallel and normal to the general trend of glacial lineations in the study area, as described in the methods of Smith & Clark (2005). Both models have an illumination angle of 40° and vertical exaggeration of 5. Individual hillshades of varying illumination angles were generated where required to better define features identified from the 135° and 225° models. The DEM's were also reclassified and overlaid on to hillshade layers within ArcMap™ to plot a marine limit for 195 m within the study area allowing focused investigation both above and below this elevation for wave cut slopes and deltas. The SWEREF99_TM projection was used for all mapping analysis within ArcGIS.

Hillshade models were used for both initial landscape analysis of the area and subsequent review following field investigations. Geomorphological features were identified and marked using points, polylines, or polygons. Mapping and interpretations were carried out by one person (Goodship), thus limiting user bias.

Feature classification

The geomorphological features were assigned to five principal groups being 1. De Geer moraines, 2. streamlined terrain, 3. glaciofluvial features, 4. hummocky terrain, 5. shorelines and dunes. The five categories were chosen due to their unique landform features and associations, formation processes and specific use in determining past ice margin position, ice flow direction, ice-bed processes, and deglaciation pattern. Detailed categorisation is set out below.

De Geer moraines

De Geer moraines have been studied in detail on the National Height Model by Bouvier et al. (2015) and occur throughout the south of the study area.

De Geer moraines were defined from hillshade models as ridges perpendicular to ice flow direction and extending from several hundred metres to over 1 km in length and located in areas where other glacial landforms are present. Distances between ridges were measured from section lines applied across consecutive mapped moraines with intersection points created at the point where the section line and individual polylines representing ridges crossed. The ArcMap "Near" analysis tool was used to generate a table of distances from which mean, maximum and minimum values could be extracted.

Streamlined terrain

Streamlined features are a distinct set of subglacial landforms used for determining ice sheet and ice bed dynamics (McClenaghan et al. 2001; Benn & Evans 2010). They are representative of both erosional and depositional processes at the ice-bed interface and indicate the flow direction of a warm-based ice sheet (Möller & Dowling 2016). Individual landforms can range from a few metres to several 100 metres in length, and they can be found concentrated in zones ranging from 10's to 1000's of metres in length and width. LiDAR data is particularly useful for mapping these areas (Möller & Dowling 2015) because it allows for identification of intermediate to large scale individual features.

Glaciofluvial features

Four sub-categories were used for this group of features. All are key for tracing a retreating and decaying ice margin.

Eskers. Eskers are key identifiers of previous ice sheet presence and flow orientation during retreat. They often occur in association with distinct marginal and deglaciation features including hummocks, drainage channels and deltas. Eskers were identified according to widely accepted characteristics of sinuous or broken ridges standing above or distinct within surrounding terrain. Eskers may form subglacially, englacially or supraglacially and form parallel or sub-parallel to dominant ice flow direction. Typically, they are divided by cross-sectional shape into round-crested, sharp-crested, flat-crested and multi-crested morphologies with each representing formation at a different point within the glacial system and specific hydrological conditions (Hebrand & Åmark 1989; Lundqvist 1999; Brennand 2000; Boulton et al. 2009; Perkins et al. 2016).

Deltas. Deltas are important depositaries for sediment discharged from ice-sheets and glaciers, building out into standing water into which subaerial streams, or subglacial streams in the case of ice-contact deltas, discharge bedload (Benn & Evans 2010). Deltas in the study area were identified both via field work and analysis of hillshade models. Gravel pits provided access in the field to exposures of delta sequences allowing identification. Large sedimentary deposits in natural drainage points and basins at or below the HCL were identified in the hillshade models as deltas or possible delta deposits requiring further investigation. Key features to assist identification in hillshade models were the presence of braided and meandering streams and situation of deposits at natural drainage points for glacial meltwater.

Pitted outwash. Pitted outwash was identified by the presence of collapse pits within an outwash plain surface.

Material can also be deposited across delta topsets in shallow water or uplifted areas and form outwash plains.

Drainage channels. Channels are indicative of meltwater outflow from beneath and around ice margins and as such are common features within a deglaciated landscape. They may take the form of incisions into bedrock, shallow surficial channels or erosional features within underlying tills and sediments.

Hummocky terrain

Hummocky terrain represents both areas of sediment deposited from down wasting of stagnating ice, landforms formed via subglacial processes beneath active ice including glaciotectonic thrusting and proglacial processes such as groundwater blowouts. The varying theories for hummock-forming processes and associated landforms are well summarised by Johnson & Clayton (2003) and Benn & Evans (2010).

Areas of hummocky terrain were identified by typical morphology of conical, linear, and irregular shaped mounds readily identifiable within the hillshade models. Hummocks are largely composed of diamict material, though this cannot be revealed via LiDAR data. Reference was made to the study of Möller & Dowling (2015), which presented an area of hummocky terrain in southern Sweden studied via the same LiDAR dataset, and thus provided a basic analogue for initial landform analysis and classification.

Murtoos. The recently defined Murtoos (Ojala et al. 2019) are included in the analysis of hummocky terrain due to their occurrence in the same zones in the study area, often overlapping. Though their genesis is not clearly understood they are shown to form during times of rapid ice-margin retreat in areas where large volumes of meltwater are delivered to the bed (Ojala et al. 2019). Features clearly fitting the "v" form parallel to ice flow direction as described by Mäkinen et al. (2017); Peterson et al. (2017) and Ojala et al. (2019) are mapped. Limited murtoo occurrences were identified by the authors and the majority of the data and identified murtoos occurrences in the study area were supplied as a shapefile by Christian Ohrling.

Shoreline and dunes

This group includes features such as dunes and raised beaches that though not causally related to active glacial processes have a link to subsequent processes that occur following deglaciation. Dunes often form within glacial deposits shortly after glaciation, as for example, at Brattforsheden proximal to the study area (Alexanderson & Fabel 2015) and are thus evidence of landscape evolution immediately following ice retreat.

Dunes and shorelines were identified according to established morphologies and with reference to the summary of glacial features identified from the National Height Model data set by Peterson & Smith (2013) with a focus on dunes and highest coastline (HCL) appearance within hillshade models.

Determination of the HCL elevation within the study area was also carried out via DEM reclassification in ArcGIS. A baseline HCL of 195 m was interpolated according to the established general HCL elevation in the region (Lundqvist 1958). The 195 m was used as a guide and not taken as a definitive level for the study area. Further analysis and modelling were carried out upon completion of fieldwork. Elevation data was compared directly with the DEM's to check accuracy and agreement between the two data sets.

Quaternary-mapping analysis

Quaternary surficial deposit maps were for the study area obtained from the Geological Survey of Sweden (SGU) online database (https://www.sgu.se/produkter/kartor/). Specific maps for the study area were generated from the SGU Surficial Deposit Database. Following initial evaluation of field sites, ArcGIS layers of the Quaternary deposit data were obtained

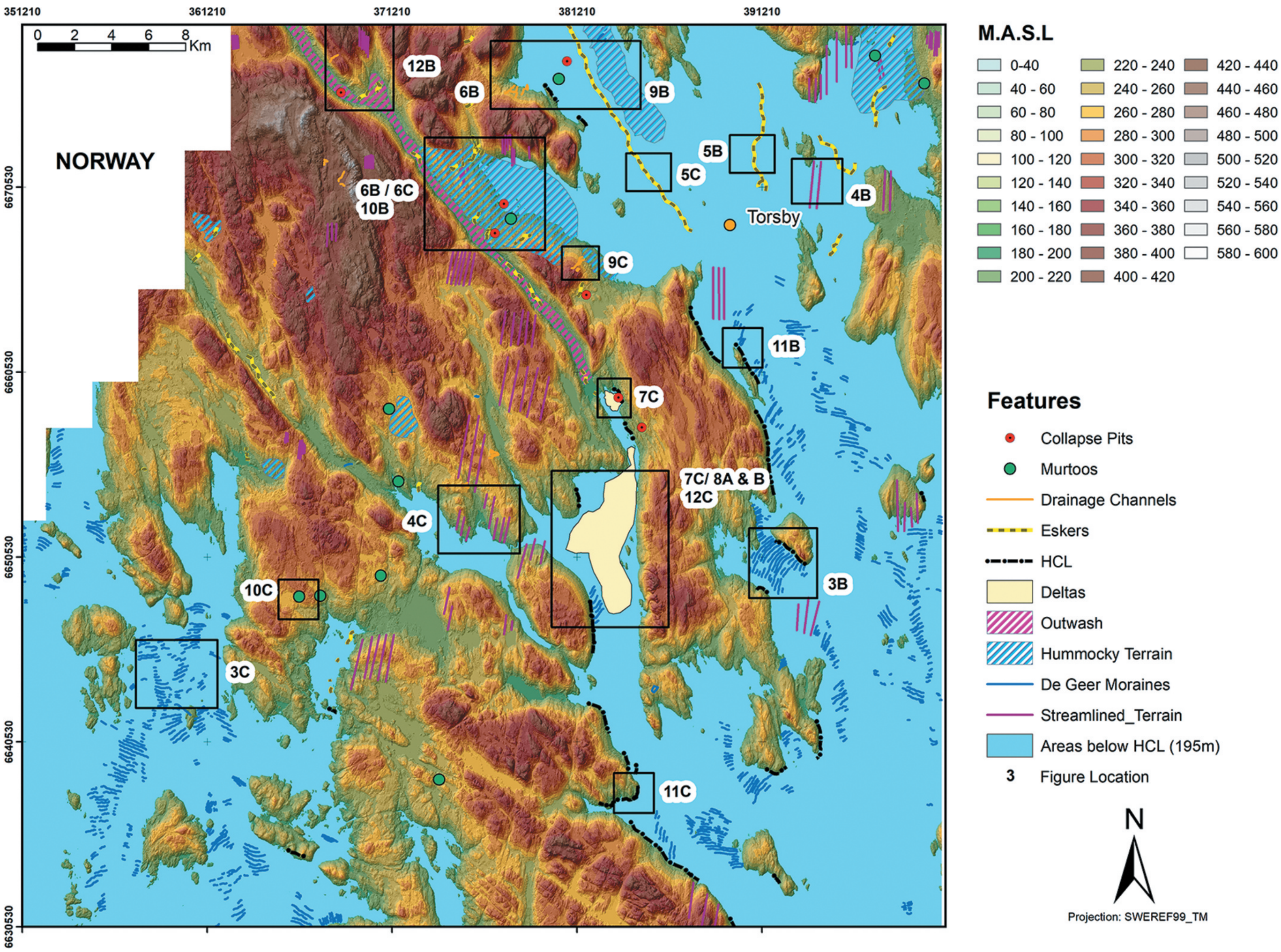

Figure 2. Overview of study area and field site investigation. Black outlines indicate areas shown in detail by following figures detailing results. Hillshade generated from LiDAR scan data provided by Lantmäteriet, Sweden © Lantmäteriet, i2012/927.

from the SGU Surficial Deposit Database. These maps predate the National Height Model and as such do not include all landforms visible in the LiDAR data set, where boundaries are clearer. Maps from the area are based on air photo interpretation and field controls with an estimated field error of 100 m to 200 m. As such there are large areas with limited or no previous field observations. Nonetheless the Surficial Deposit Database provides a valuable overview of Quaternary deposit distribution and aids in identification of key glacial and geomorphological features.

Following initial geomorphological analysis of the LiDAR data using DEM's, Quaternary-map layers were overlaid and compared to the features that had been identified. Correlating glacial features were marked and clear Quaternary deposit boundaries added to the LiDAR based map. Features that were present only on the Quaternary deposit map were compared alongside the relevant DEM and added to the working layer where correlating evidence could be identified.

Field mapping

Field work was carried out in September 2016. Features identified through LiDAR and Quaternary map data were ranked in order of priority for mapping and investigation. Accessibility was also considered to allow for most efficient use of time. The key field observations and data to be recorded for each feature and area were morphology of targeted feature and surrounding terrain, sedimentary composition of features, bedrock composition and structural features, vegetation cover and type where applicable. Field positions and elevation were recorded using a Garmin Map 62S handheld GPS unit with accuracy of ±3 m. Some sites were found to be inaccessible due to poor or no road access. Overview photos were taken of all sites visited and detailed photos taken where internal sedimentary structure of features was exposed and investigated.

Results

Combined LiDAR data analysis and field investigations within the study area reveals several glacial and post-glacial features with a clear variation in distribution around the highest coastline (HCL) and between topographic low and high points where regional scale bedrock faults strongly influenced meltwater drainage pattern and local ice flow direction. Twenty-one field sites have been investigated and that showed geomorphological, structural, and sedimentological characteristics that allowed the reconstruction of the pattern of deglaciation in the study area. An

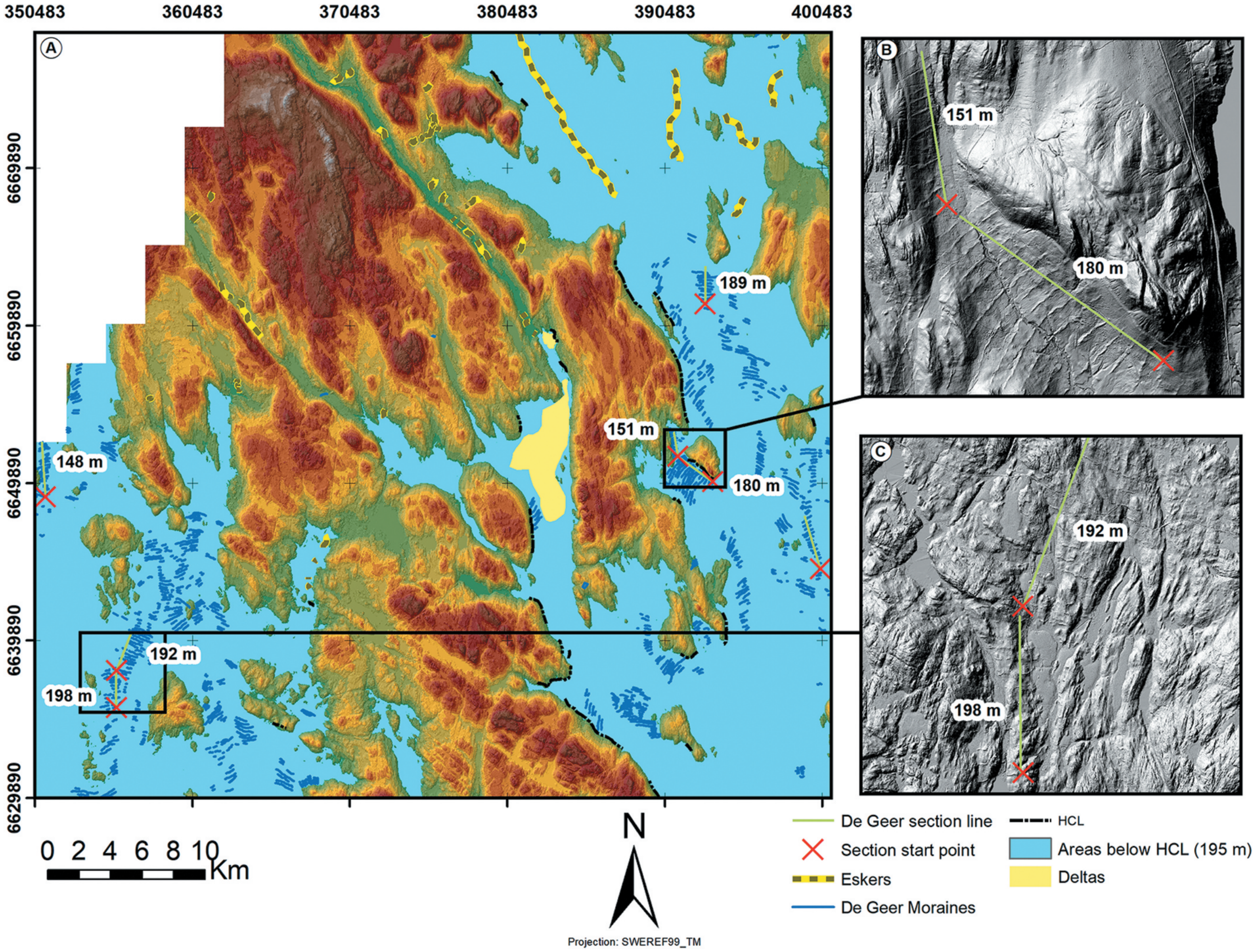

Figure 3. A. Prominent succession of De Geer moraines and appearance on DEM. Note increased concentration in valleys towards the north. Moraine orientation with sets of NE-SW and NW-SE trending ridges indicates the presence of calving bays within the ice front. Locations of section lines measuring distance between moraine ridges is shown in **A** with 4 sections shown in greater detail in **B** & **C**. Hillshade generated from LiDAR scan data provided by Lantmäteriet, Sweden © Lantmäteriet, i2012/927.

overview of identified features is given in Figure 2. Important features that are discussed later in this section are outlined with their associated figures shown. Results are presented in order of the environment in which the identified features are determined to have formed within the study area.

De Geer moraines

De Geer moraines are distributed across the southern half of the study area. These all lie below the HCL (Fig. 3) and within the formerly marine areas. They are clearly identifiable within hillshade models (Fig. 3(B, C)) as was also shown by Bouvier et al. (2015). The De Geer moraines are predominantly concentrated along narrow valleys in the south of the study area. Moraine ridges are on average 10–15 m wide and range from 200 m in length to over 3 km. Ridges show a NE-SW trend along western valley sides and NW-SE along eastern valley sides indicating the presence of embayed margins. The path of ice-margin retreat can be determined over several kilometres (Fig. 3). Seven cross sections perpendicular to moraine trends were plotted over the DEM with intersection points of moraines and section lines used to calculate distance between individual landforms; 106 features were measured in total in the study area. The maximum measured spacing between ridges is 280 m and minimum measured spacing is 67 m. Mean spacing is 176 m. A trend of decreasing distance between ridges is suggested towards the north-west with the two profiles at highest latitude showing spacing between ridges of 147 m and 151 m. Moraine ridges become increasingly concentrated in valleys towards the north with lateral extensions into neighbouring high ground not observed. The succession of De Geer moraines ceases ~4 km south of Torsby.

It is noticeable that the wide area below the HCL in the north east is lacking in De Geer moraines compared to other areas below the HCL. De Geer moraines may have formed in this area but have been subsequently buried beneath marine silt and sand or did not form at all. De Geer moraines are much more difficult to positively identify in the field though. Investigations of several sites including that shown in Figure 3B reveals a slightly undulating terrain with isolated 30–60 cm cobbles on small mounds. Despite this the clear definition of features shown within the hillshade models and their wide distribution in previously

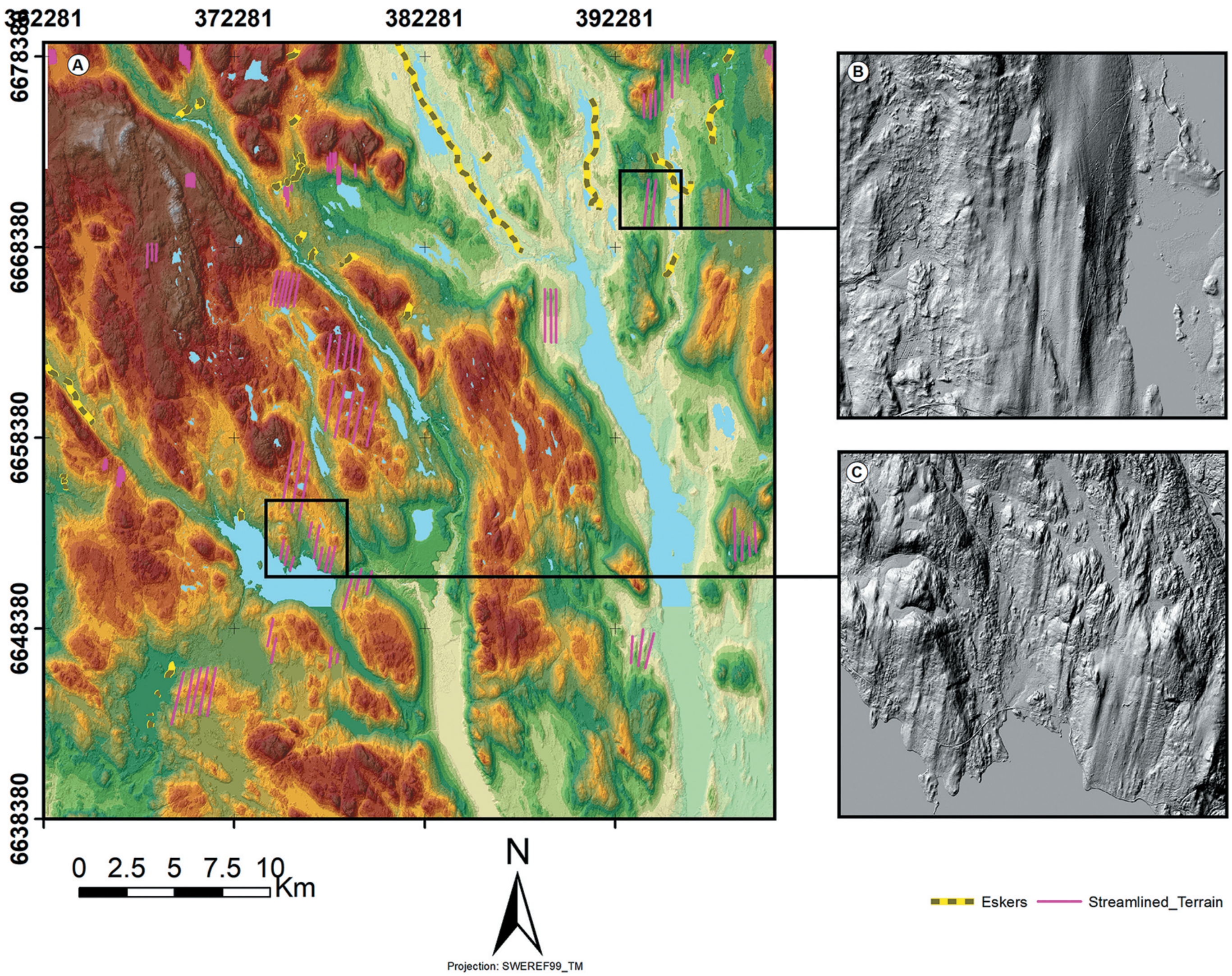

Figure 4. A. Streamlined terrain within study area. Prominent features including rock cored drumlins present over elevated ground but not visible in lower areas. Note shift from NNE-SSW to N-S orientation towards north of study area between **C** and **B**. Hillshade generated from LiDAR scan data provided by Lantmäteriet, Sweden © Lantmäteriet, i2012/927.

marine marginal areas allows a high level of confidence in their positive identification as De Geer type moraines.

Streamlined terrain

Streamlined features are present across the study area (Fig. 2). Features take the form of rock-cored drumlins, fluting and scoured terrain amongst general streamlining within cover till. Features fall in similar classes to those observed by Möller and Dowling (2015) but spatial distribution in the landscape differs in comparison to that study. At mid and low elevations there are no observable occurrences of streamlined features (Fig. 4); either they were never formed in these areas, were not preserved, or are buried.

Smoother surface texture in identified streamlined areas suggests a greater sediment and till thickness than neighbouring areas. The long axis of features trends NNE-SSW in the south but moves to a straight N-S orientation towards the north of the study area (Fig. 4). Most identified features exist well above the HCL and often on elevated ground of 250 + m.a.s.l (Fig. 2).

Glaciofluvial features

Major subglacial eskers

North of Torsby are several prominent long flat-crested ridges, identified here as major subglacial eskers, that can be traced for >10 km and range in widths from 20 m to ~200 m in some sections (Fig. 5). These eskers are oriented NW-SE, oblique to the N-S ice flow direction as shown from orientation of streamlined features (Fig. 5), but parallel to the valleys in which they lie, which trace the profile of the major NW-SE trending structural lineations within the crystalline bedrock in the region. The features are interpreted as subglacial tunnel-fill eskers deposited in sub-aquatic terminating R-channels as described by Brennand (2000).

Minor subglacial eskers

Small 100 m – 200 m long features are found across flat areas generally above the HCL in the north of the study area with orientation ranging between N-S and WSW-ENE and general orientation towards the centre of nearest valleys. The features likely represent subglacial tunnel-fill eskers beneath the main

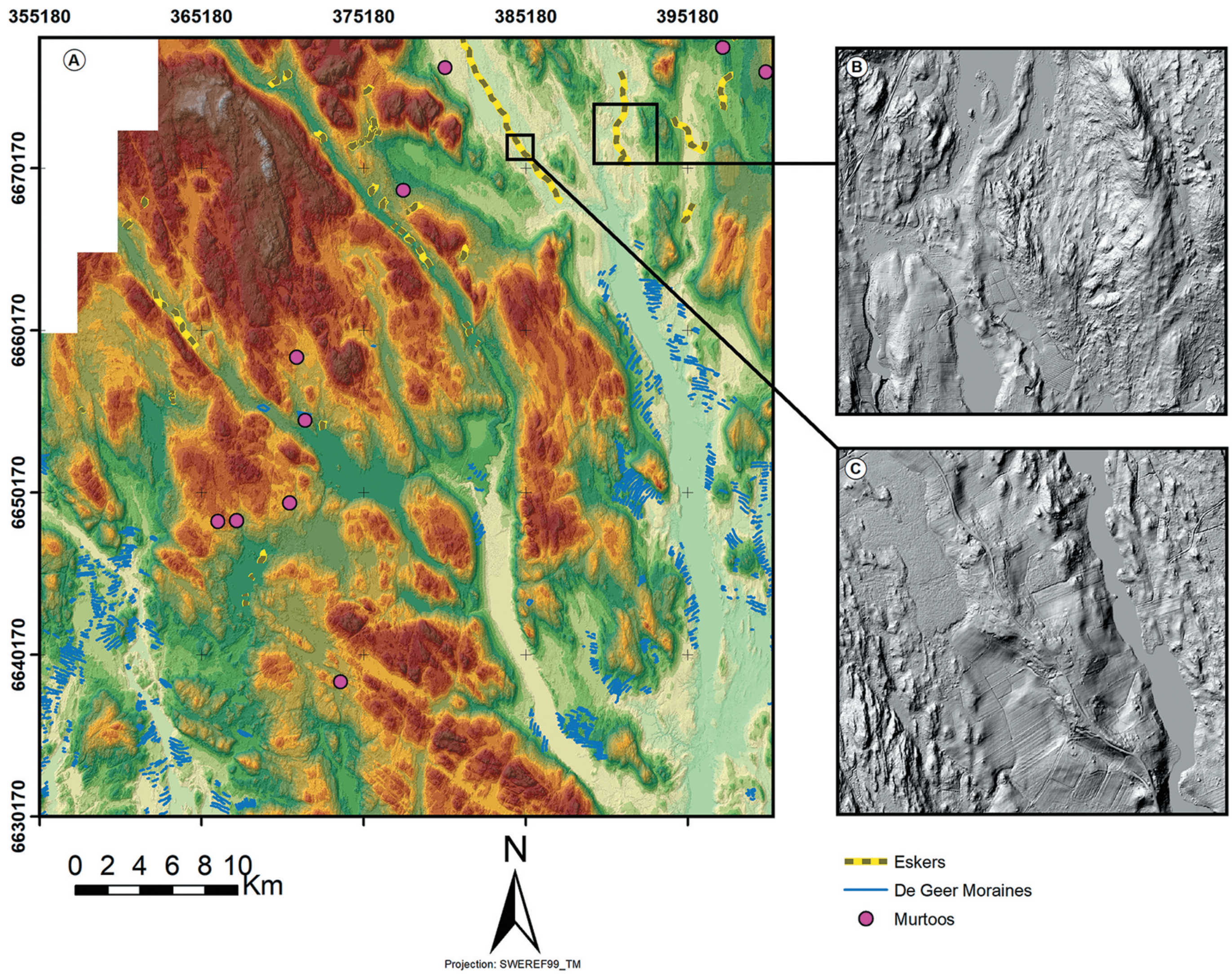

Figure 5. **A**. Major eskers located below the HCL in the north-east of the study area. Water depth in this area was shallower than to the south where De Geer moraines formed. Eskers follow the trend of the valleys they lie within. **B** & **C**. Hillshade generated from LiDAR scan data provided by Lantmäteriet, Sweden © Lantmäteriet, i2012/927.

ice-sheet in areas of lateral drainage towards the main valley or local bedrock depressions. The drainage perpendicular to rather than parallel to valleys of several minor eskers indicates a different drainage profile effecting these smaller features with local topography a strong influence. De Geer moraines distribution indicates the presence of calving bays in the margin and some of the smaller eskers likely drained towards these embayment's in the ice sheet margin, explaining their differing orientation to larger eskers.

Three prominent minor eskers are present to the east of the Rottnan River in low ground close to the HCL at 203 m (Fig. 6). The eskers are sinuous and sharp crested. They are unique within the study area and stand between 8 to 10 m higher than surrounding hummocky terrain and range from ~650 m to 1.8 km in length. Excavations into the sides of these eskers revealed successions of fine to medium grained sand. Cross bedding and ripples were observed in beds ranging from 5 cm to 60 cm thick. All three eskers are "capped" with a layer of sub-rounded, medium to coarse sandy gravel.

These eskers lie oblique to parallel to the assumed regional ENE-WSW trending ice margin suggesting the local margin was oriented towards an embayment in the ice sheet in the Rottnan valley immediately adjacent to the west or the eskers formed beneath an ice lobe that persisted in the valley after the main ice-sheet margin had retreated.

Deltas

Two ice-marginal delta deposits were identified in the hillshade models (Fig. 7A). The two delta areas are in the narrow area of the Rottnan Valley south-west of Torsby (Fig. 7B) and in a wider basin further south where the valley opens out (Fig. 7C).

The delta within the north of the Rottnan valley was visited during fieldwork (Fig. 7B). It consists of a succession of foreset beds of gravels and sand dipping at ~25 degrees to the west towards the valley. The GPS derived elevation of the present floor of the gravel pit places it at 189 m.a.s.l (±3 m). The delta sequence rising from the floor is ~10 m in height indicating the highest coastline was at ~200 m in this area. Measurements from the LiDAR data show a topset elevation of 203 m.

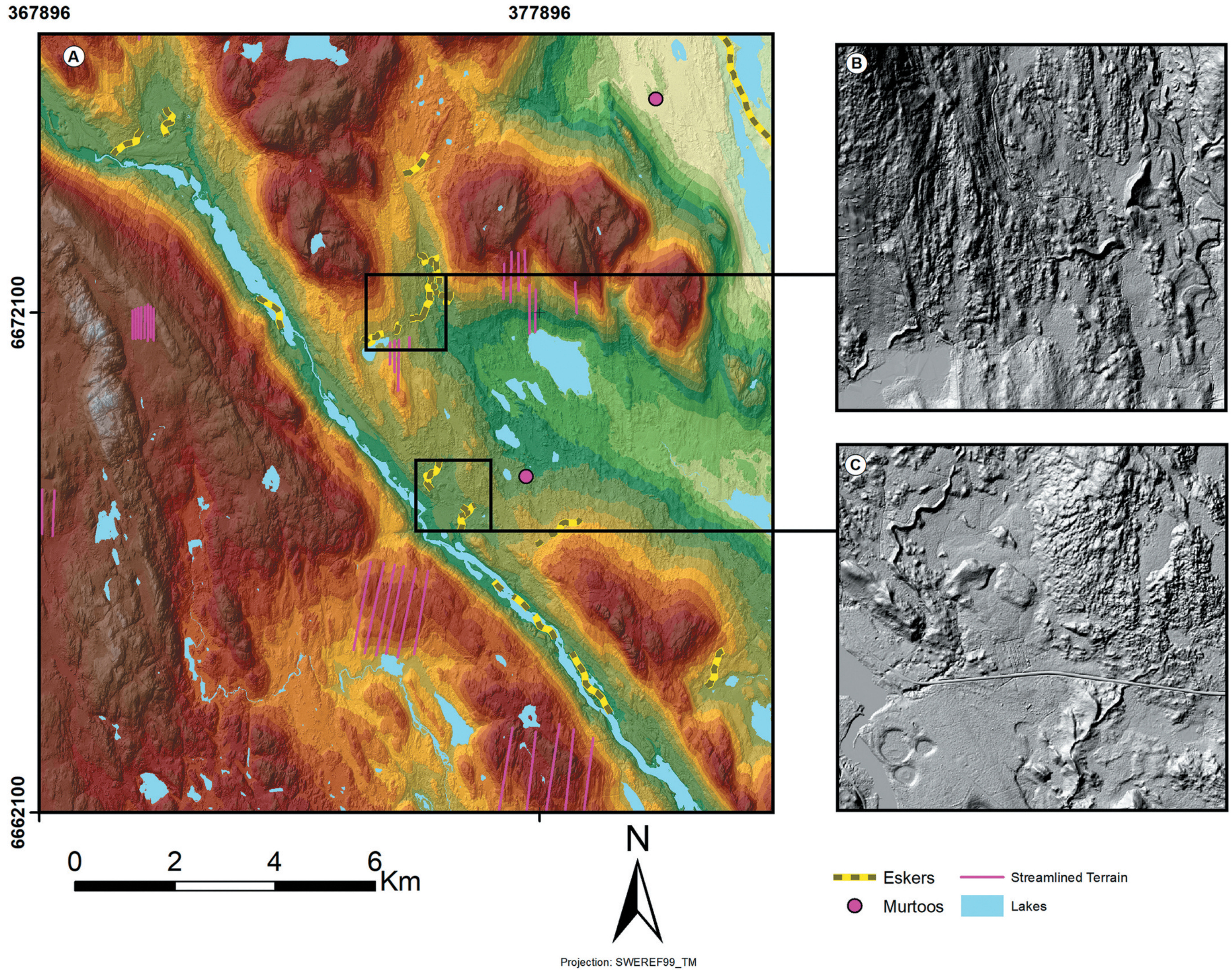

Figure 6. A. Minor eskers. Ridges run NE-SW sub-parallel towards topographic lows. **B & C**. Distinct sinuous sharp crested profile of eskers is clear with surrounding hummocky terrain and outwash material. Hillshade generated from LiDAR scan data provided by Lantmäteriet, Sweden © Lantmäteriet, i2012/927.

The delta succession in the basin at the end of the Rottnan Valley is shown in Figure 8 and covers an area of ~ 25 km^2. Spot heights on delta plains are shown in Figure 8 and boundaries between these surfaces are marked by dashed lines. A large regressive delta dominates the main basin and has 3 clear plains (Fig. 8B). The first, with a level of 193 to 195 m.a.s.l is found at the north of the basin and has a surface area of ~0.7 km^2 and extends 1.4 km from the mouth of the Rottnan valley. There is then a decrease of ~ 20 m in elevation over ~ 80 m horizontal distance to the next delta plain. The second level at 167 to 170 m.a.s.l adjoins the 195 m.a.s.l plain and has a surface area of 1.9 km^2 and extends a further ~1.8 km into the south of the basin. The third plain is found at 163 to 165 m.a.s.l, has a surface area of 1.15 km^2 and extends a further 1.3 km SSE from the edge of the second delta. A distinct feature of this third plain is the presence of dunes indicating the presence of fine to medium sand in the surface. The area in which dunes are found was investigated during fieldwork. Excavation into the delta surface and dune features revealed a layer of fine to medium grained, well sorted sand akin to that deposited by a waning water flow across delta topsets.

All levels of the delta have limited extension into the NW of the basin adjacent to Lake Grässjön. Erosional wave cut slopes at 200 m indicate that this area was ice-free at the time of the 195 m delta formation and no ice was therefore restricting flow into this area. A feature of note in this succession is an apparent 3 m deep, ~200 m wide flat-bottomed channel to the south west of the delta at 167 to 170 m.a.s.l, shown by arrows in Figure 8B. The channel runs SSE from Lake Grässjön in the north-west and along the western edge of the plain at 167 m.a.s.l. To the west of this channel the sedimentary deposits are also at 167 m.a.s.l suggesting that the delta built up to the edge of the basin and blocked Lake Grässjön. A later outflow of water from the lake when the HCL reduced to the 165 m.a.s.l would explain the presence of a channel. The flat base of the channel and lack of very sharp erosional contacts suggests a low energy flow. The channel may have acted as a focus for later water flow during HCL regression and eroded lower than the third delta to the 158 m.a.s.l shown in Figure 8.

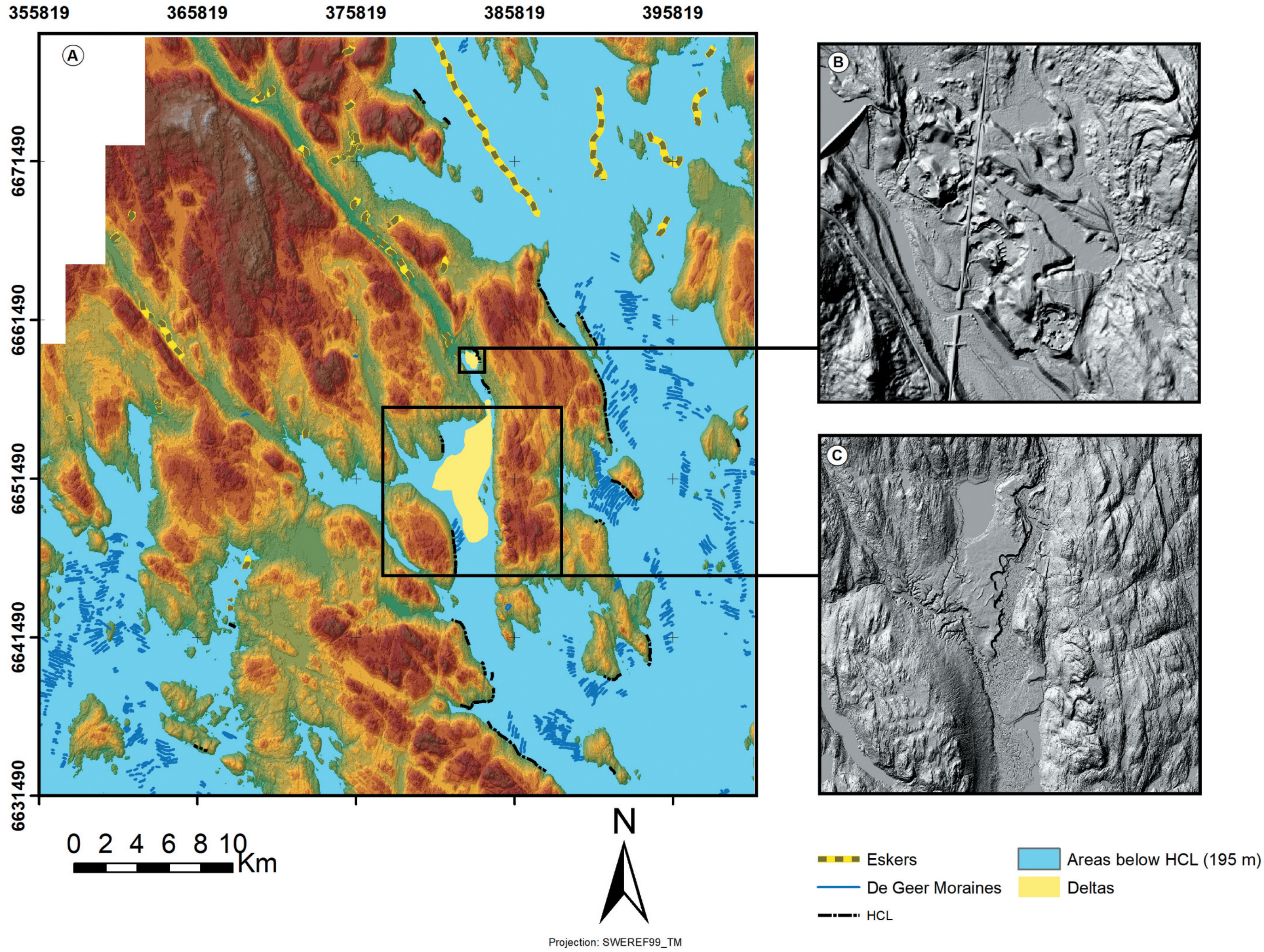

Figure 7. A. Overview of delta locations within the study area. **B**. Delta outline on eastern side of Rottnan river valley at 203 m **C**. Large delta sequence in basin to south of Rottnan valley. The two deltas indicate the position of the changing shoreline with isostatic rebound and eustatic changes during and following deglaciation in the study area and and represent a period of slowed ice margin retreat at the point of marine-terrestrial transition. Hillshade generated from LiDAR scan data provided by Lantmäteriet, Sweden © Lantmäteriet, i2012/927.

The three highest plains do not show braided channels on the surface indicating that transported material was dominantly sandy and channels shallow and wide. In the east of the basin the delta has been successively eroded into by the river and a series of terraces formed (Fig. 8A). Clear braided channels are visible in the hillshade model showing an increase in grain size in the lower deposited levels. In the south of the basin where the valley narrows once more are two deltas plains at 136 to 138 m.a.s.l and 115 to 120 m.a.s.l (Fig. 8A). These appear to be the limit of delta formation in the basin with an erosional meandering channel to the west and south that then flows into Lake Rottnen.

Pitted outwash

This topography is present within the Rottnan River valley within the study area (Fig. 2). Collapse pits with widths of 30 m to more than 300 m are present in the area around the murtoos shown in Figure 2. Pitted-outwash topography is evident by the gently sloping plateau surfaces in the valley interspersed with holes where dead ice has since melted to leave a depression or small lakes (Benn & Evans 2010). Varying levels of terraces are present within the valley with collapse pits concentrated in upper terraces. The upper terraces represent the immediate post-glacial surface within which dead-ice was prevalent. Post glacial erosion into this surface and underlying outwash material has produced the sequence of terraces now observable and left the pitted surface isolated above the present river level. The collapse pits present as clear depressions in the landscape, often forming isolated small ponds and lakes.

Drainage channels

Several drainage channels are identified in the study area (Figs. 2 & 9). Discerning an origin during deglaciation or within later Quaternary events directly from the hillshade models is difficult and field checks on identified sites were limited due to challenging access and available field time. The overall thinness of the sedimentary cover makes the former presence of drainage channels less apparent. Only channels that could be more confidently linked to glacial processes due to positioning in landscape and/or relationship to other glacial features were highlighted in the DEM. Channels that showed no clear link to current rivers and tributaries, were elevated above current

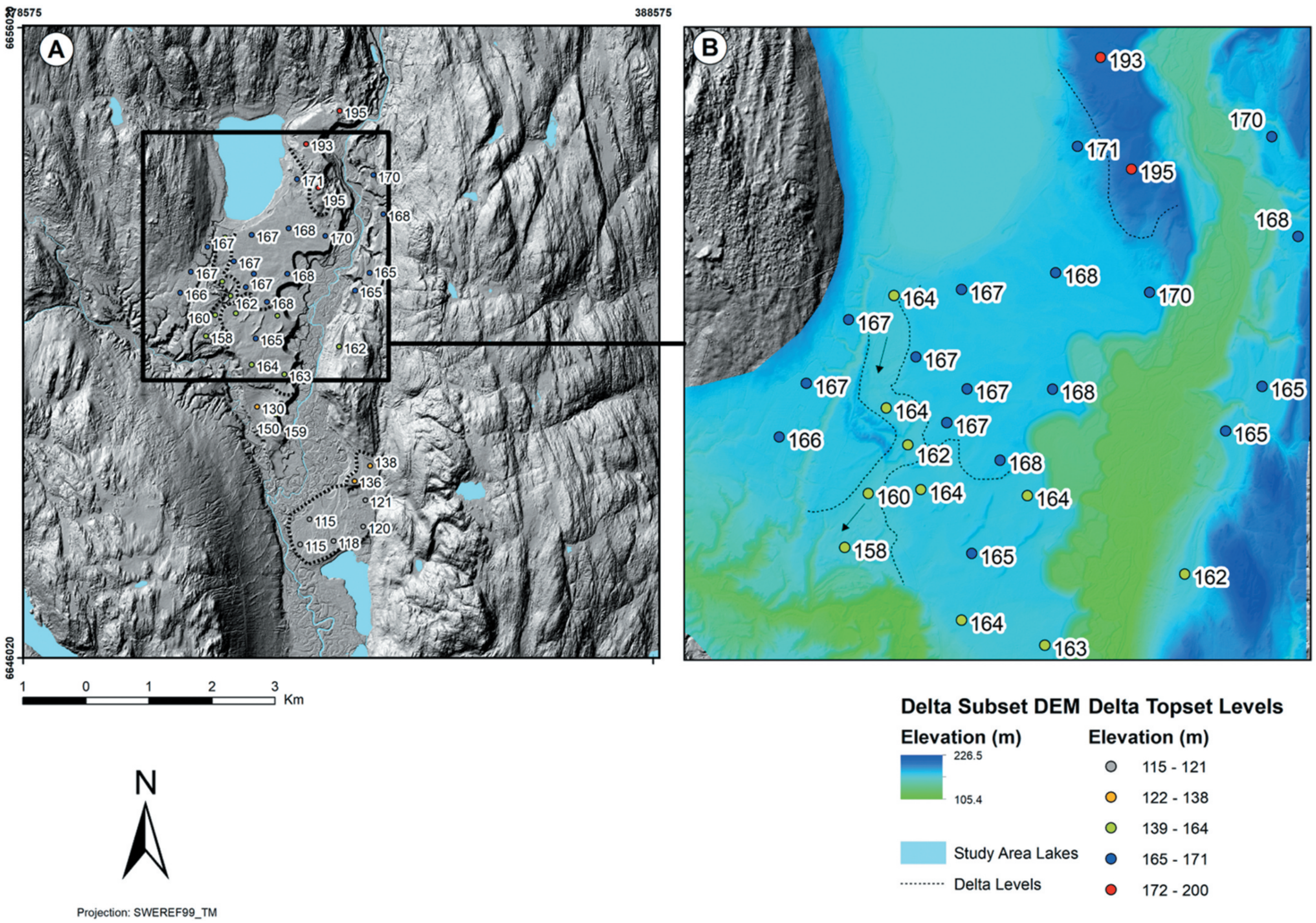

Figure 8. A. Overview of delta in basin at end of Rottnan valley (Fig 7A & B). Spot heights for different delta plains are shown. A large stepped delta with maximum elevation of 195 m is found in the NW of the basin. Younger delta deposits are present in the SE. **B** Detail of the larger delta sequence. Dashed line shows division between three levels. Arrows in the west show path of low energy channel from the lake in the north-west of the basin towards the present river channel and base level. Hillshade generated from LiDAR scan data provided by Lantmäteriet, Sweden © Lantmäteriet, i2012/927.

valleys, and sometimes appeared to flow across steeper terrain rather than directly down the path of least resistance were highlighted. However, a definitive classification as marginal related forms cannot be given.

Identified channels range in size from 30 m to 200 m+ in length and 10 to 30 m in width (Fig. 9 (B,C)) and are found to exist in positions isolated from present streams and to have incised into glacial till. The pattern of drainage suggested by the hillshade models is of flows from high elevations into valleys (Fig. 9A), where ice may have still been extant, lowland plains and lower lakes and depressions

Hummocky terrain

Hummocky areas are present in the northern section of the study area generally at wider, low elevations or flatter areas bounded by highland. Significant areas are shown in Figure 2 and Figure 10A. Conical mounds 10–50 m in diameter are interspersed with elongate ridges 30–150 m in length and stand 5–20 m above surrounding terrain (Fig. 10B). Distribution of mounds and ridges is irregular. Large zones of hummocky terrain are present in wide areas in the north east of the study area (Figs. 2 & 6).

Murtoos

Murtoos are present in the study area. One of the wider areas is shown in Figure 10B. Distribution is both around the HCL in areas of hummocky terrain with prominent eskers proximal and over high ground well above the HCL. The greatest concentrations are identified in wide, generally flatter areas in valleys in the north and far north-east (Fig. 2). Smaller concentrations such as those in Figure 10C are present in the west of the study area in high ground often around local depressions and topographic lows and drainage points.

Shorelines and dunes

Highest coastline (HCL)

Lundqvist (1958) found the HCL to be around 190–200 m.a.s.l in the field area. Our inspection of the LiDAR shows this to be true with a clear increase in HCL towards the north-west. Prominent shorelines are shown in Figure 11 and range from

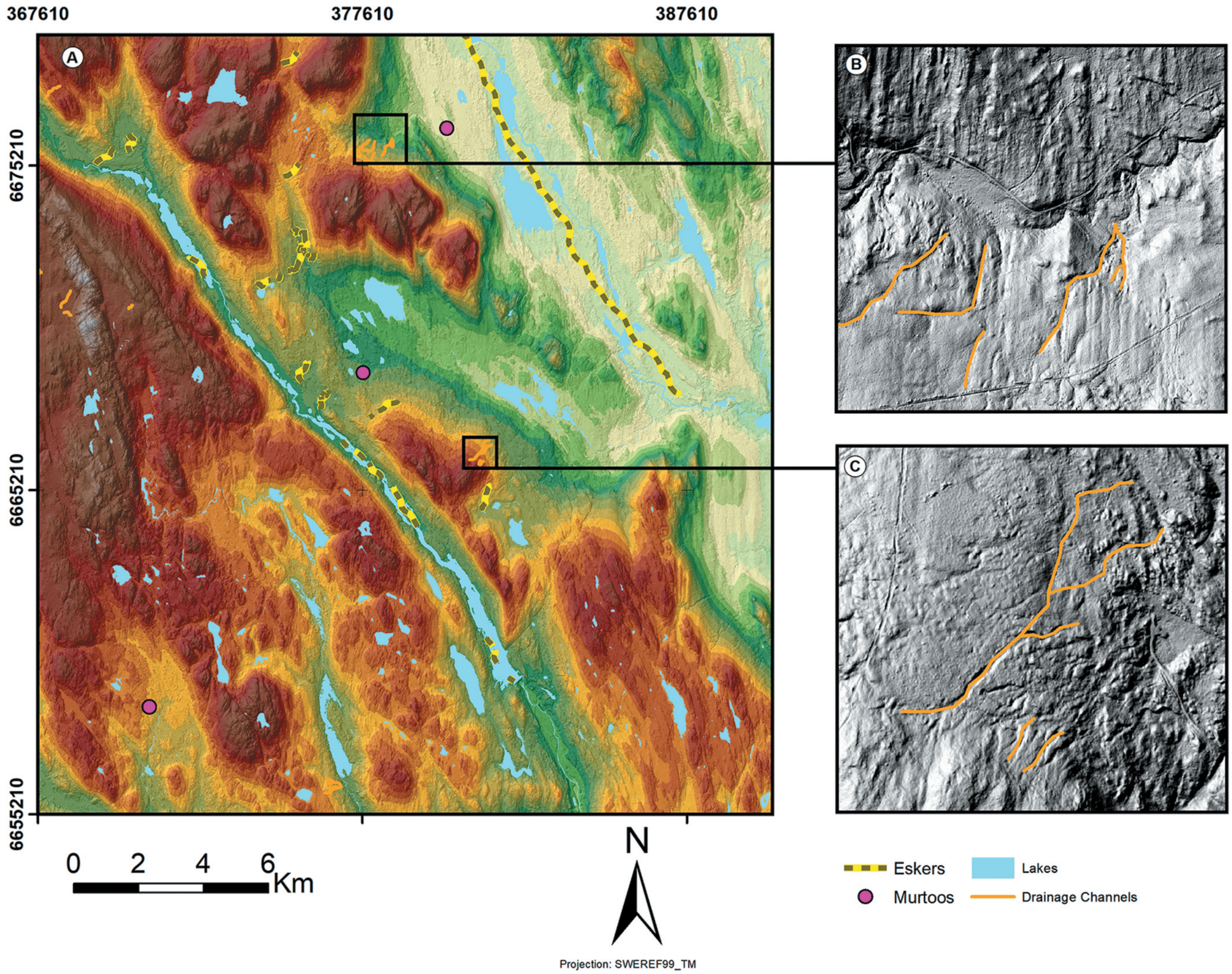

Figure 9. A Drainage channels identified within the study area. Channels highlighted here were observed to link to proglacial lakes and were often isolated from visible, active alluvial systems. **B** & **C**. Hillshade generated from LiDAR scan data provided by Lantmäteriet, Sweden © Lantmäteriet, i2012/927.

190 to 208 m.a.s.l with this change and increase in HCL towards the north shown through the labelled point features in Figure 11A. Though wave cut slopes are clear in the hillshade models they are difficult to observe in the field. The increase in HCL to the north of the study area reflects varying isostasy. Delta braid plains in the Rottnan valley in the centre of the study area have a highest elevation of 203 m.a.s.l (Fig. 7) and prominent breaks of slope at 195 m.a.s.l and 167 m.a.s.l (Fig. 8 (A,B)) suggesting a longer period during which the HCL remained at these levels.

Dunes

Two small dune sets were identified (Fig. 12). The set in Figure 12A to the north of the Rottnan Valley lies on top of sand rich outwash. The features identified in Figure 12C formed from a fine sand layer on the top of the third large delta in the basin delta around 165 m.a.s.l. The dunes are localised to this delta and a shallow channel to the west indicating that deposition of a sufficient volume of the fine to medium sand required for formation was limited to this delta level. Assuming that the dunes are transverse, they reflect a prevailing NW wind direction, likely the direction of katabatic winds from the ice-margin to the north and west.

Landform assemblages

The combination of LiDAR derived DEM and hillshade model analysis alongside field investigation of the study area has revealed a clear range of both terrestrial and marine glacial landforms. Features deposited within active and stagnant ice have been identified and linked to processes both sub-glacial and supra-glacial.

The study area lies through the zone across which the SIS margin retreated out of the Yoldia Sea, which occupied the greater Vänern basin, and became largely terrestrially based. This transition is reflected in the changing type of glacial landforms and deposits along a N-S line of glacial retreat.

The first part of this discussion focuses on the formation of the landforms identified within this study area and what they indicate about the position and dynamics of the ice-sheet

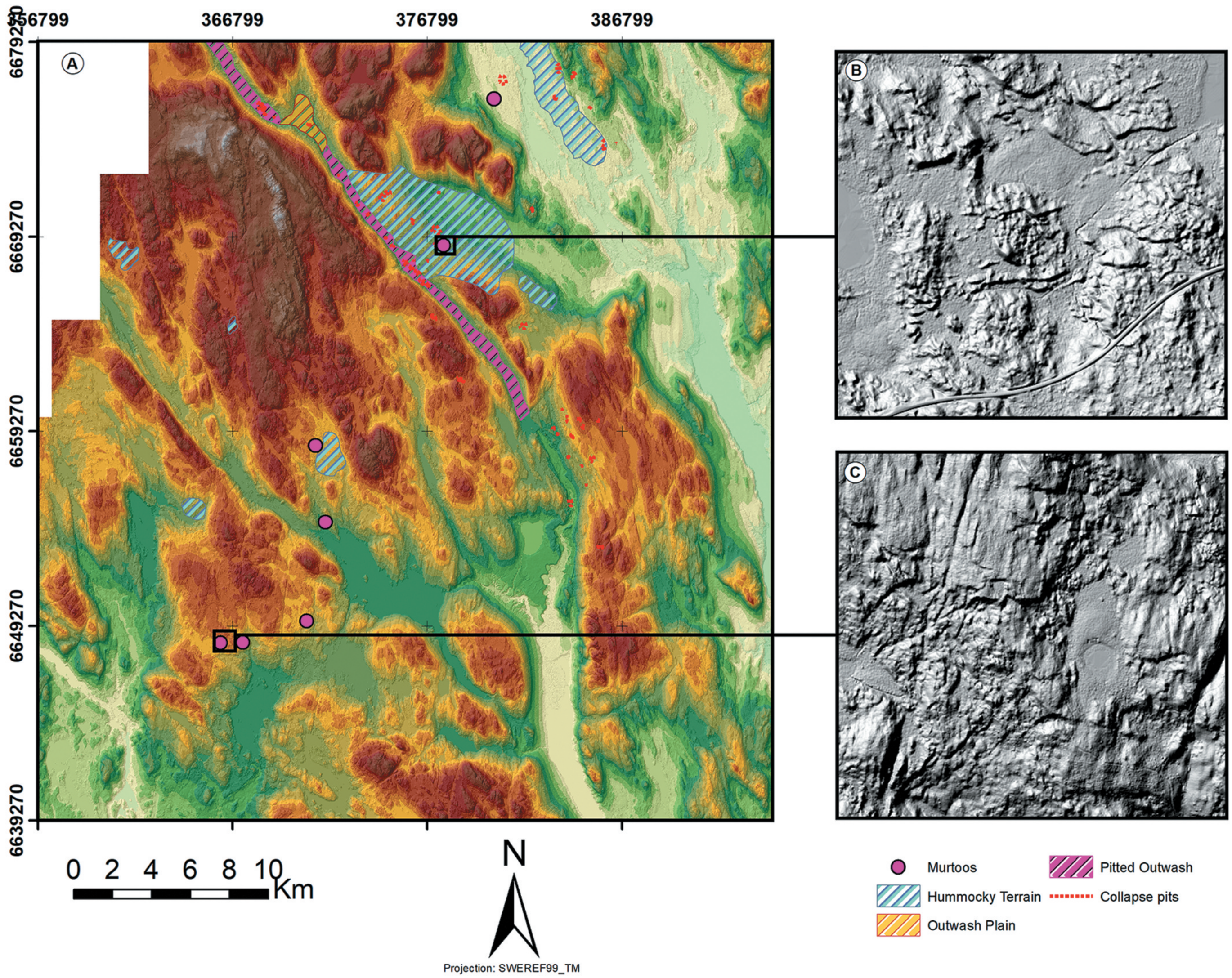

Figure 10. A. Hummocky terrain, pitted outwash and murtoos within and around Rottnan river valley. **B** Murtoos in lowland to east of valley with smaller hummocks in surrounding terrain. Triangular morphology of murtoos is clear in the north of highlighted area **C**. Murtoos in SW of study area on southerly facing slope. Features are less distinct than those in B. Hillshade generated from LiDAR scan data provided by Lantmäteriet, Sweden © Lantmäteriet, i2012/927.

margin in the study area. The features are discussed beginning with those below the HCL through those at the marine-terrestrial margin and finally those above the HCL, i.e. entirely terrestrial areas. The second part of discussion then presents an overall pattern of retreat for the study area linking the individual landform processes into a larger model.

Below the highest coastline

De Geer moraines

De Geer moraines reflect a general NE-SW ice-front trend within the wider study area. The orientation of the ridges indicates the location of pronounced calving bays within the ice margin. The far south of the study area was at time of deglaciation beneath up to 120 m of water in the west and east with a central highland ridge separating the two marine areas (Fig. 11). Water was 80–120 m deep across several kilometres of the ice margin, within the valleys seen in the study area today. The ice front in the west and east in these deep-water areas was likely steep and grounded given these are the prime conditions for allowing the formation of De Geer moraines (Lindén & Möller 2005). It is suggested by Bouvier et al. (2015) that where regularly spaced De Geer moraines occur their spacing likely represents local ice-margin retreat rate with ridges formed during annual winter advances. Measured distance between ridges in the study area suggests an average retreat rate of 176 m per year but with a faster retreat of up to 280 m per year recorded in the far south when more of the margin was marine terminating and lay in deeper water. A reduction in distance between moraine ridges with retreat into shallow water was also found by Ojala (2016) in a similar setting in Finland. Evidence of calving bay formation has been described from other areas across the SIS margin (Gillberg 1961; Strömberg 1981, 1989; Lindén & Möller 2005; Möller & Dowling 2016) and within Värmland (Lundqvist 1988). These bays act as major drainage outlets of ice and meltwater and can have the effect of thinning ice in surrounding areas and further back into the ice sheet itself (Benn et al. 2007).

The formation of De Geer moraines in the study area was limited to the south east and south west where water depths were

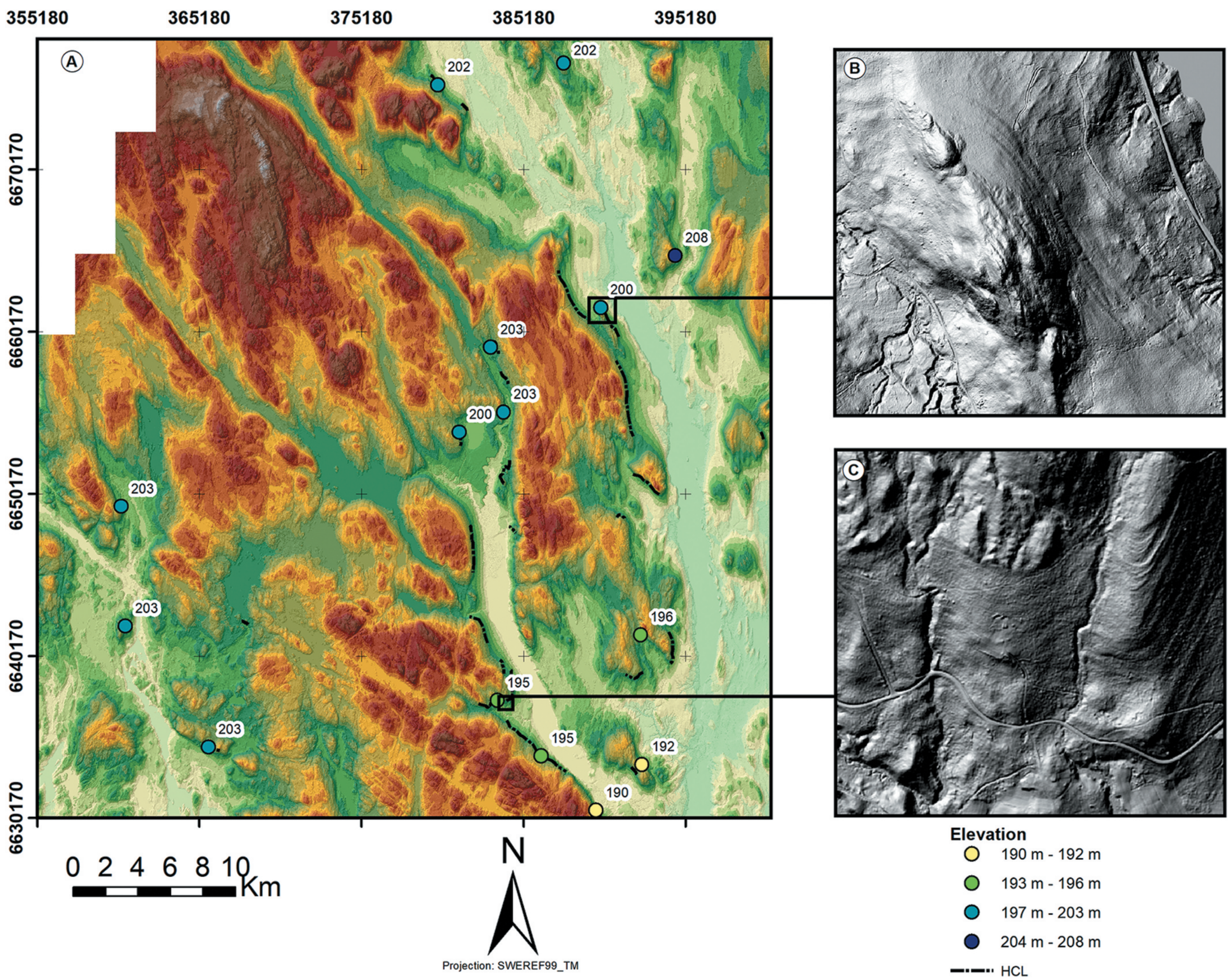

Figure 11. **A**. HCL measurements from wave cut slopes and delta plains across study area. North and west of study area shows HCL between 200 m and 203 m with a reduction to 190 m in the far SE **B & C** Wave cut slopes clearly visible in hillshade model. Hillshade generated from LiDAR scan data provided by Lantmäteriet, Sweden © Lantmäteriet, i2012/927.

80 m+ across several kilometres of the ice margin. Large, distinct ridges in the south of the study area likely represent the limit of winter advance of the ice sheet as described by Bouvier et al. (2015). To the north, where water depths were less, the ice margin was grounded in mostly shallow water. The buoyancy of the ice in the shallow water was not enough to lift large blocks and form De Geer moraines as in the model by Lindén and Möller (2005). This change in the deglaciation dynamics in this area, with the ice front sitting above a wide, shallow marine zone, is similar to variations noted to the east of the study area by Lundqvist (2003). The nature of ice-retreat and break-up changed with retreat into shallow water and calving bays became much smaller or absent.

Major subglacial eskers

The eskers present in the study area are in prominent valleys that follow major bedrock lineations indicating that ice flow at the margin, where the eskers formed, was topographically controlled. Deposition in the valley systems can be attributed to increasing topographical control on ice flow direction and sub-glacial drainage with thinning of the ice sheet. As such, the major valleys became principal conduits for drainage of melt water and entrained material from beneath the ice sheet. Sub-glacial tunnels formed within the valleys and channelled water to the ice front. These eskers are identified in areas both above and below the HCL suggesting the presence of R-channels in both sub-aquatic and sub-aerial ice marginal environments similar to the pattern documented by Brennand (2000). It is probable that NW-SE trending eskers were also deposited below the HCL in the base of the Rottnan and Röjdan river valleys and between De Geer moraines but were subsequently buried by fine silt and sands in deep water areas. The mode of deposition in tunnels in both marine and terrestrial settings is well established (Hebrand & Åmark 1989; Fyfe 1990; Warren & Ashley 1994; Benn & Evans 2010).

At the highest coastline

Deltas

The two delta zones within the study area (Fig. 7) occur along the HCL at the position where the ice margin was withdrawing from the marine environment and becoming terrestrially based

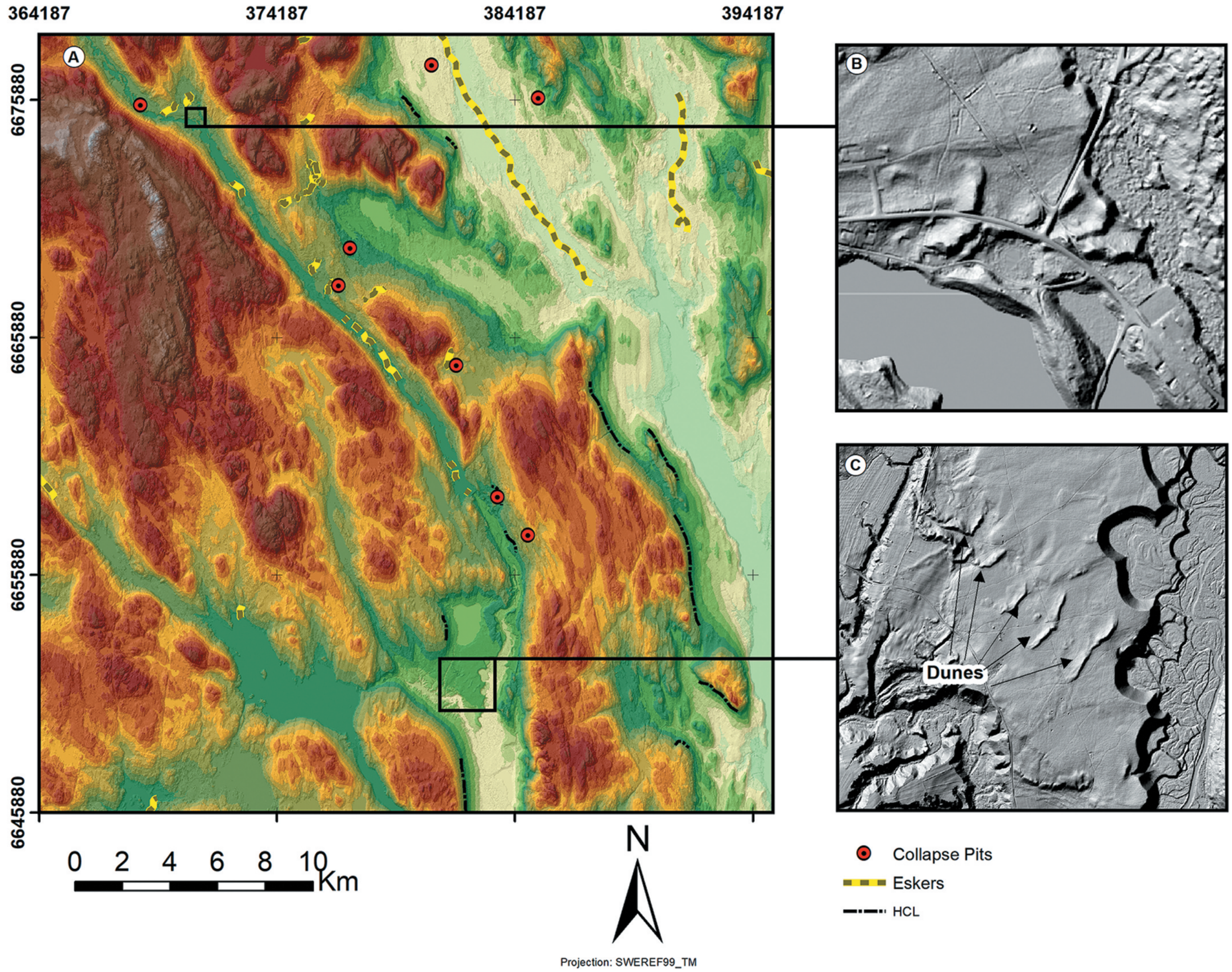

Figure 12. A. Dune sets identified in study area on outwash plains. Hillshade generated from LiDAR scan data provided by Lantmäteriet, Sweden © Lantmäteriet, i2012/927.

(Fig. 7A). The formation of deltas at this exact point indicates a period of slowed or stalled retreat of the ice margin as delta formation takes time, also noted by Lundqvist (2003) in the neighbouring Klarälven Valley. Both delta zones in the study area occur within the central highland area, which is dominantly above the HCL, and alongside or within steep valleys that acted as the focus of meltwater drainage. This positioning suggests that the rate of retreat of the terrestrially based margin slowed and became less regular compared to the stepwise retreat observed in the deep-water areas marked by the regular formation of De Geer moraines.

The size of the delta sequence in the basin to the south of the Rottnan valley, its distinctive terraces and relict braided channels on lower delta levels suggests a previous period of rapid deposition into the basin and delta progradation south into the basin during marine regression. Steep surrounding topography acted to focus drainage and resulted in outwash material being channelled down the Rottnan river valley until it entered deeper water and was deposited in deltaic sequences. The "stepped" morphology of the largest delta from 195 m.a.s.l through to 165 m.a.s.l suggests a threshold of conditions was reached on several occasions to initiate the "jump" from an established delta plain to the deposition of a new lower sequence in the manner of a forced regression similar to deltas described by Winsemann et al. (2018). The established shoreline displacement curve detailed in the SGU dataset for Sweden (http://www.sgu.se/produkter/kartor/kartgeneratorn/) for the area around the delta shows a regression of the HCL from >180 m.a.s.l at 11 ka BP to ~120 m.a.s.l at 10 ka BP indicating that all the identified delta levels formed whilst the basin remained marine. The basin became isolated once the HCL reduced below 110 m.a.s.l at ~ 9.5 ka BP

The noticeably steep change of elevation between the first and second delta levels in the basin over a short distance indicates that changes to the HCL in the basin during the earlier stages of ice-margin retreat was not gradual or that the supply of sediment to the basin was not constant. The levels at 168 m.a.s.l and 165 m.a.s.l represent a period in which sediment and meltwater supply was more constant and resulting in prograding of the delta further into the basin. With further regression of the shoreline delta formation moved south and erosional terraces were formed in older delta deposits before flow rate and sediment supply decreased,

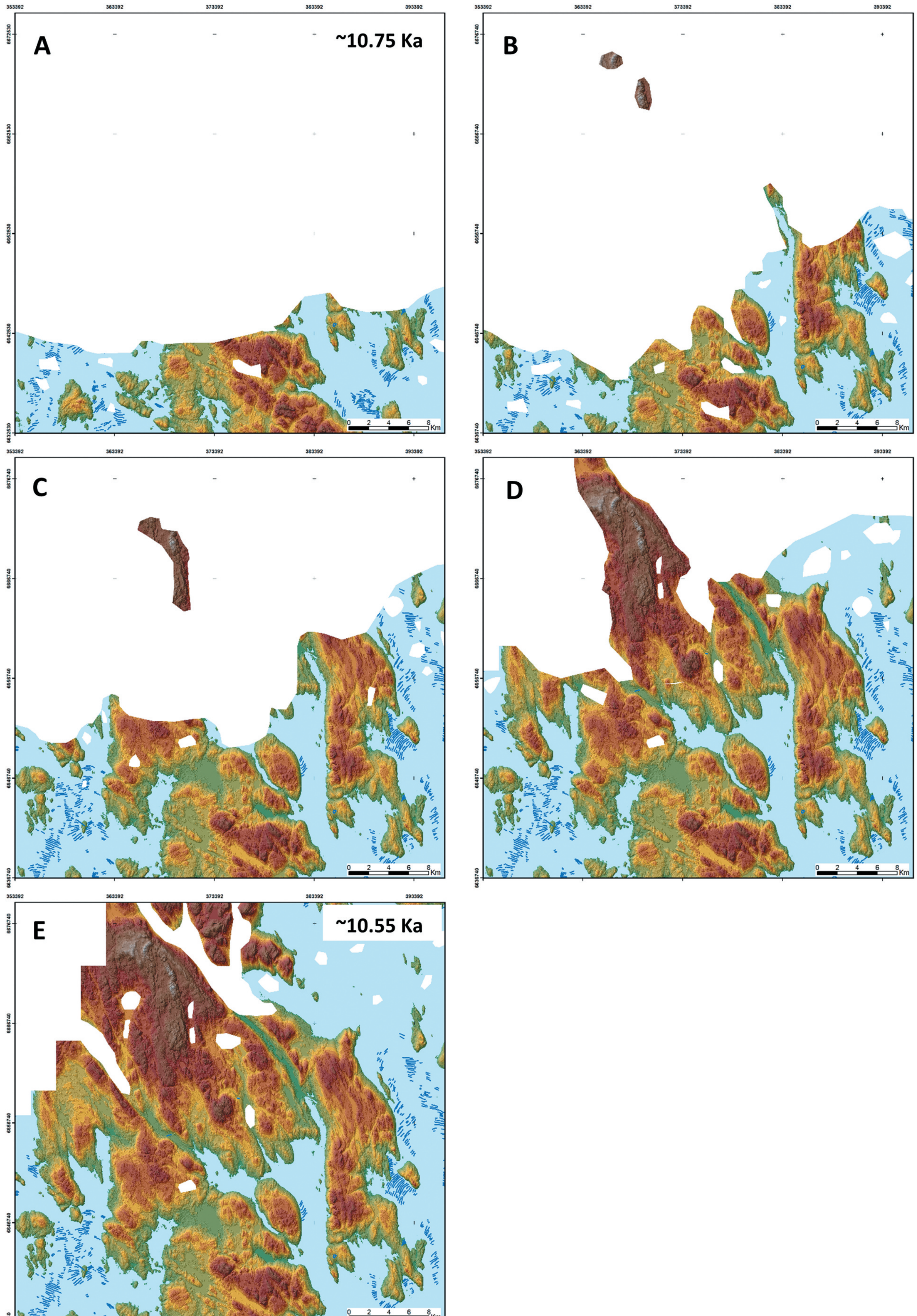

Figure 13. Pattern of retreat across study area.is separated into 5 main periods. Pattern of retreat shows changing dynamics of the ice front and increasing terrestrial control on ice flow. Hillshade generated from LiDAR scan data provided by Lantmäteriet, Sweden © Lantmäteriet, i2012/927.

formation of deltas stopped, and the river eroded down to the current base level.

Highest coastline

Wave cut slopes and deltas show a clear pattern of increasing HCL towards the north of the study area. Variation between ridge levels can be attributed to a combination of eustatic sea level changes and variable uplift of the area with isostatic rebound following ice sheet retreat (Risberg et al. 1996; Greve 2001). It is noticeable that the majority of wave cut slopes identified occur on the eastern side of high-ground areas. This may suggest a dominant easterly wind direction and reducing influence of katabatic winds during the period after ice-margin retreat studied herein and wave action being most consistent at points where fetch length moving from the east to the west was largest and produced greater wave sizes. This though is at odds with the NW wind direction indicated by dune orientation.

Pitted outwash

Outwash with collapse pits is identified in the Rottnan Valley. This valley lies in the centre of the high-ground ridge that runs through the study area. It is bounded to the east and west by elevated terrain up to 450 m in height and a wide bedrock plain lies to the west. The valley is incised ~200 m below the plain and acts as a prominent topographic low point and thus as a natural focus for drainage in the area. The pitted outwash is found in deposits above the HCL. Topography acted to channelize meltwater and entrained material into the valley where it was deposited rapidly and built up above the contemporary water level. Dead-ice blocks in levels above the HCL at 203 m, remaining from the ice-margin retreat, were buried by outwash. This process happened at the same time of delta formation in deeper water further down the valley. Once the transport of sediment began to reduce and isostatic and eustatic changes resulted in relative shoreline level drop, the river began to incise into its formerly deposited sediments, producing a series of erosional terraces and migrating channels that are evident in the hillshade models (Figs. 2 & 7), and in the field. Buried ice-blocks gradually melted and collapse pits formed.

Above the highest coastline

Streamlined terrain

The ice flow direction close to the ice margin, ice surface profile and basal conditions altered with retreat across the study area. Streamlined terrain suggests a shift from a dominantly NNE-SSW ice-sheet flow direction in the south of the study area (Fig. 4C) towards an N-S flow direction further north (Fig. 4B). The change in direction of streamlined features from NNE-SSW to N-S represents the start of a pivot of the ice front towards the higher elevations of central Sweden and the Scandes Mountains in Norway. Lundqvist (1992) noted the influence of two ice domes on ice flow and pattern of retreat. An ice dome over western Scandinavia was found to exert greater influence on western Värmland than the dome over the Gulf of Bothnia. The retreat around Torsby is moving towards the western Scandinavian dome and flow from the NE is of limited influence on the ice sheet in this area at this stage. Underlying bedrock topography began to exert a greater influence with the thinning and break-up of the ice sheet. The >200 m deep NW-SE trending fracture guided valleys began to exert greater control on ice-flow direction.

The flow direction indicated by the streamlined features is thus different to the NW-SE flow closer to the retreating margin, as indicated by the orientation of eskers and De Geer moraines identified in the study area (Fig. 2). This is probably due to that the streamlined features formed further from the margin in areas of thicker ice where topographic control on ice movement was less. A similar adjustment in ice flow direction with proximity to the margin was observed by Möller and Dowling (2016) on the Närke Plain in south-central Sweden.

Minor subglacial eskers

The sinuous eskers in the north of the study area (Fig. 2, 6A) are suggested to have formed in subglacial channels in a lobe that remained in low ground beyond main ice sheet retreat. The area in which the eskers formed is a flat plain surrounded on three sides by high relief and bisected by the HCL. This plain is now covered by hummocky terrain and murtoos indicating that deposition from meltwater was a prominent process in this area. The process of esker deposition in ice walled channels transverse to ice flow is described by Benn et al. (2007) and Johansson (1994). The eskers also lie right on the margin of the 203 m HCL limit indicated from the delta deposits further south in the Rottnan valley. These features likely formed during the final stages of deglaciation within the area. An ice lobe extended onto the plain and was fed by two outlets from the ice sheet, one within the Rottnan valley to the NW and another through a smaller valley directly north of the latter. Drainage of meltwater through the lobe was towards the low ground of the Rottnan valley to the west. The fine to medium sand dominated composition observed in the esker in Figure 6C suggests a medium to low energy flow towards the valley. This lobe probably became stagnant and detached, in a later stage, from active ice and final down wasting deposited the gravel cap observed on the top of the esker visited during field work. To cover the plain, the ice lobe would have had an area of at least 20 km^2.

The several other minor eskers identified in the high ground in the west of the study area represent local drainage patterns beneath the main ice sheet as is retreated with flow into bedrock hollows and towards major valleys.

Drainage channels

The drainage channels identified within the study area are generally found at higher elevations where thinning ice melted rapidly, and meltwater was channelled along the margins and then beneath remaining ice at lower elevations. In the case of drainage into valleys and lowland plains, the water and suspended material in the channels flowed into areas of both active and dead ice both sub-glacially and supra-glacially. This is evident by the presence of eskers, pitted outwash, and hummocky terrain in the study area.

Hummocky terrain

Hummocky terrain is most common in lowland areas in the north and north-east of the study area with largest areas found in zones near the HCL. Smaller areas are found across the highland to the north-west. Although hummocky topography can be created by several processes (Johnson & Clayton 2003), we consider most of the hummocks to have been made in association with stagnant ice. In these areas ice-melting was the source of englacial material being deposited into dead ice depressions or depressions over already deglaciated ground. Gradual melting of ice also produced lakes and drainage channels in which fine grained sands and silt were deposited. The elongated ridges of material identified may have been deposited by active ice squeezing material into crevasses or depositing ice-cored moraines then subsequently down wasted as ice melted (Benn & Evans 2010). Deposition of supraglacial material from ice in the north east into shallow water could have created a debris covered area below the HCL.

Murtoos

Murtoos identified in the study area indicate a period of rapid retreat with significant flow of meltwater to the bed, likely from the ice surface (Ojala et al. 2019). Given that channelized flow is not thought to be present during murtoo formation it is likely the landforms identified formed pre esker deposition in R-channels at the margin, with final retreat of the ice sheet and outlet glaciers in the valleys. The zone of formation for murtoos is thought to be ~50 km inside the margin (Öhrling, personal comms) and thus murtoo formation sits firmly within the interior of the main ice-sheet margin during the earlier stages of retreat.

Dunes

The two dune sets (Fig. 12(B,C)) are evidence of post-glacial aeolian processes. Formation likely started immediately following deglaciation (Alexanderson & Fabel 2015), cf. Hörner (1927). Fine sands and sediments not yet extensively vegetated in areas above the HCL were wind eroded, transported, and eventually deposited as dunes, predominantly transverse to prevailing katabatic wind direction. It is also possible that the dunes further developed during more recent periods of wind deflation e.g. as noted in the dune fields at Brattforsheden to the south east of the study area (Alexanderson & Fabel 2015; Alexanderson & Bernhardson 2019).

Reconstruction of ice margin retreat

The features identified in the study area present a pattern of transition from marine to terrestrial conditions as the margin retreated to the NW. They also highlight how the process of deglaciation and ice-loss alters with this change. Studies of the British Ice Sheet (Clark et al. 2012), the Barents Sea Ice Sheet (Winsborrow et al. 2010) and the Greenland Ice Sheet (Warren & Hulton 1990) have all suggested a clear reduction in retreat rates and increasing topographic control on ice sheet movement with transition from an marine to terrestrial margin. This change is attributed to ice-sheets adjustment to the loss of calving bays as an outlet and site of ice loss. The influence of underlying topography is clear in the study area with the differing orientation between streamlined terrain, which formed further inside the margin, and marginal glacial features that formed beneath thinner ice towards the ice margin or at the margin proper. An overview of the ice sheet retreat across the study area is presented below and summarised map-wise in five time-steps (Fig. 13(A, E)). The margin below the HCL was defined by following the orientation of De Geer moraines. Deltas determined points where the ice sheet slowed its retreat whilst eskers and drainage channels helped define position of ice within valleys. Collapse pits guided placement of pitted outwash. Inferred earlier exposure of the greatest elevations is drawn from drainage channels and sediment accumulations at the foot of exposed rocky ridges and outcrops and likely drawdown of ice over elevated areas as the ice sheet thinned close to the margin. An accurate chronology of retreat is not within the scope of this investigation and accurate dating of features and materials from the study area is lacking. Dates for ice-margin retreat over the area are suggested from comparisons with the work of Lundqvist (2003) and Stroeven et al. (2016).

Around 10.7 cal ka BP, most of the study area was covered by the SIS with the majority of the ice sheet in the area terminating in the Yoldia Sea/Vänern Basin as described by Björck (1995). The south of the study area lies along roughly the same latitude as Lake Grässjön in the Klarälven Valley, a different lake to the Lake Grässjön also present in the study area, where Lundqvist (2003) dated retreat at 10.75 cal ka BP. The central section of the ice sheet in the area terminated in a terrestrial margin along a central ridge rising above the HCL (Fig. 13A). Calving bays were present along a steep ice front to the west and east with the ice sheet grounded in the marine zone. The retreat in this manner is marked by the deposition of multiple De Geer moraines across the extent of the marine margin area (Fig. 3) with rates of margin retreat of up to 280 m per year indicated from distance between moraine ridges. Murtoos formed further up ice from eskers nearer the margin at this time as significant meltwater flowed to the bed (Ojala et al. 2019). The rapid outflow through calving bays caused a thinning of ice within the ice sheet, particularly over high-ground areas proximal to the margin. The terrestrially based ice along the central ridge thinned (Fig. 13(B,C)) and nunataks began to appear. As the ice receded over the ground above the HCL isolated blocks were left behind within bedrock hollows and along valleys where they became stagnant and decayed. Small eskers formed within valleys where larger ice volumes persisted and possibly remained active for a period beyond the main ice sheet retreat. The ice margin was oriented WSW-ENE with an ice flow direction at the margin perpendicular to this. The flow of ice further behind the margin, where the ice remained thicker, was from the NNE. With continued ice margin retreat towards the NNW, calving bays continued to funnel ice away from the ice-sheet margin but became less widespread as more of the ice sheet retreated into shallow water or became entirely terrestrially based. Ice flow became more influenced by and constrained within the major valleys, and between peninsulas that were now protruding into the sea (Fig. 13(B,C)). The steeper topography in the ~20 km long Rottnan and Röjdan valleys of the NW of the study area increasingly influenced ice flow direction (Payne & Sugden 1990; Stone et al. 2010). The ice sheet began a transition to terrestrial frontal conditions in the west and the marine extent of the margin was concentrated in the east (Fig. 13(C, D)). With the transition to dominantly terrestrial conditions the pattern of deglaciation began to alter. Thinning of ice over high ground areas continued and large volumes of meltwater were channelled to the ice front along the major NW-SE trending valleys. The ice sheet retreat slowed markedly at the area of marine-terrestrial transition and the deltas in the Rottnan valley could build as sediment carried within meltwater was deposited in deeper water at the ice-margin.

The ice-sheet had thinned significantly by the time the margin retreated to the north of the study area (Fig. 13E). Active ice was concentrated to flow within and directed by valleys in both the terrestrial and marine areas. Ice lobes formed across lowland areas at the heads and sides of valleys. The minor eskers identified in this study also formed at this time beneath active ice in valleys and lowland areas. These lobes eventually became stagnant and separated from active ice and began to decay. The decay of these lobes resulted in the formation of areas of hummocky terrain.

Finally, active ice retreated from the entire study area. However, dead-ice blocks remained along valleys and continuing fluvial action and deposition of outwash material from further north acted to form terraces and built deposits around dead ice blocks that would eventually form collapse pits. As earlier mentioned a similar pattern was found by Lundqvist (2003) in the Klarälven Valley adjacent to the study area to the east. The northern extension of the study area lies along the assumed margin from the confluence of the Hälgån River and the Klarälven with the margin placed at this point at 10.55 cal ka BP. (Lundqvist 2003). As the ice margin became increasingly distal to the study area, the volume of meltwater and entrained sediment decreased. Land uplift due to isostatic rebound and relative lowering of the base level with eustatic changes induced incision by rivers into earlier outwash and deltaic deposits. Dunes then began to form due to aeolian activity on delta plains as re-working by fluvial action ceased and water content decreased.

The style of retreat of the ice-margin in the study area as it transitioned from a marine to terrestrially terminating margin is analogous to the recent history of the Greenland ice-sheet (GrIS). Much of the GrIS margin has retreated and become terrestrially terminating during the Holocene (Long et al. 2006). Studies of recent GrIS margin dynamics have shown a rapid retreat rate in marine terminating areas but with variations along the margin and often slowed retreat once the margin was terrestrially terminating and a stronger topographic control developed (Long et al. 2006; Kelley et al. 2013; Håkansson et al. 2014; Khan et al. 2014; Winsor et al. 2015) . The varying retreat rate around the margin of the GrIS reflects the multiple factors that influence ice sheet mass balance and flow rate and highlights the need to understand ice-sheet behaviour in the marine-terrestrial transition zone.

Conclusions

Analysis of LiDAR data and field investigations have revealed a distinct pattern of retreat of the Scandinavian Ice Sheet across the study area in Värmland, south-central Sweden. A clear transitional zone exists with the ice sheet withdrawing from the Yoldia Sea/Vänern Basin into a terrestrial setting. This zone is recognised through the presence of characteristic marine, sub-glacial, ice-marginal, and pro-glacial features.

The ice sheet margin was initially marine terminating across the whole area except for a central ridge of elevated land. Calving bays drove rapid retreat and caused thinning of the ice sheet over the elevated areas, resulting in concentration of active ice within valleys and lowland. With retreat northwards, the western side of the margin withdrew on land and the marine terminating area of the eastern margin narrowed and withdrew into shallower water. The retreat slowed for a period when the margin reached the highest coastline and deltas formed. Thinning of ice over high ground continued, and active ice became further concentrated in valleys. Deltas established beyond the ice margin in the Rottnan valley and dead ice became isolated and buried. Topographic control on ice flow became more pronounced with retreat northwest-wards and active ice took the form of outlet tongues spurring off the main ice sheet. An ice lobe became isolated on the east of the Rottnan Valley and decayed, resulting in the formation of minor eskers and hummocky terrain in the surrounding area.

Rough dating of the retreat via correlation with previous studies places it at between 10.75 cal ka BP and 10.55 cal ka BP with an average retreat rate of ~176 m per year indicated by De Geer moraine spacing.

This study shows that combined analysis of detailed remote sensing data and targeted field investigations can quickly establish a pattern of ice-margin retreat at decadal to centennial scale. With the current requirement to better understand ice-sheet retreat on human timescales becoming ever more pressing, this combination of data allows more detail to be rapidly introduced to models of ice-sheet behaviour. The dynamics of present ice-sheets may still not be fully understood but they share many of the same conditions as experienced by now extinct sheets. Though we were not able to witness the decay of the SIS and its contemporaries they left their mark and with more detailed observations of formerly glaciated areas the shorter-term behaviour of these ice sheets is becoming clearer and applicable to the present day. The true test of geophysical models of ice-sheet retreat for the GrIS and Antarctic Ice Sheet are that they can produce results consistent with those recorded in the geological record (Young & Briner 2015). Studies such as this that track a margin in detail are thus a key part of this validation process.

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No potential conflict of interest was reported by the authors.

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