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Geomorphological characterisation, pattern, and distribution of ice-margin positions of the former Scandinavian Ice Sheet

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ABSTRACT

Retreating ice sheets leave behind rich landform records which can be used to understand glaciological processes and the responses of ice sheets to warming climates. Ice-marginal landforms are formed along glacier margins, and their distribution on the beds of palaeo-ice sheets can be used to reconstruct former ice-margin positions. Here we scrutinised high-resolution (1–2 m/pixel) digital terrain models across Norway, Sweden, and Finland, applying a consistent approach to observe ice-marginal landforms and then synthesising these to reconstruct former ice-margin positions of the Scandinavian Ice Sheet. We present a map of ~51,000 pieces of ice marginal evidence defined by assemblages of landforms. Each ice margin is categorised by the dominant landform type that defines it: moraines <250 m and > 250 m wide, De Geer moraines, hummocky moraines, ice-marginal meltwater channels, or glaciofluvial fans and deltas.

The distribution of the landform type that defines each ice margin is found to vary across the ice sheet. We investigate these spatial patterns and suggest; i) sediment cover controls the location of ice-margin positions interpreted from meltwater channels; ii) there is a climatic control on the formation of ice-margin positions interpreted from hummocky moraines; iii) moraine size is influenced by the presence or absence of a marine or lake environment at the ice margin. Our ice-margin positions are made available as maps and GIS data and complement the rich record of ice-marginal landforms previously reported in the literature. Importantly, our database provides seamless, internally-consistent maps and data for use with ice sheet modelling investigations.

1. Introduction

The Greenland and Antarctic ice sheets are diminishing in mass, and these losses are projected to accelerate in the future (Pattyn et al., 2018; Edwards et al., 2021; IPCC, 2023). Such forecasts are mostly made by numerical modelling (Goelzer et al., 2020; Pattyn and Morlighem, 2020; Choi et al., 2021) which are often initialised (spun up) or parameterised to explain the short time span (tens of years) of available observational records from present-day ice sheets. Such reliance on short timespans might bias model formulation and parametrisation such that projections insufficiently encompass the full range of possible ice sheet responses to climate change. Palaeo-ice sheets, left behind a rich landform record that can be used to reconstruct the evolution of ice sheets over timescales of many thousands of years (e.g. Kleman et al., 1997; Stroeven et al., 2016). It is being increasingly recognised that data-modelling investigations, including at these longer timescales, are required in order to trial or improve numerical modelling approaches (e.g. Aschwanden et al., 2021; Clark et al., 2022b; Ely et al., 2021, 2024; Leger et al., 2024). The glacial landform record can be used to understand how ice sheet margins and ice flow directions evolved in the past and be compared with numerical model simulations (e.g. Patton et al., 2016, 2017; Gandy et al., 2021; Ely et al., 2021, 2024; Archer et al., 2023). Such comparisons or data-modelling integration may improve understanding of ice sheet dynamics, which in turn, can help forecast the response of the existing ice sheets to projected climate change. A major limitation for investigations involving data-modelling integration is the

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lack of consistent and digitally available records of information such as ice-margin positions; something that we aim to help rectify in this paper for the former Scandinavian Ice Sheet across Norway, Sweden and Finland.

Glacial landforms hold a wealth of information about changes of extent and flow geometry of past ice sheets as they waxed and waned. Streamlined subglacial lineations, such as striae, drumlins and crag-and-tails retain information about past ice flow (Kleman et al., 1997; Clark, 1999). Subglacial meltwater routes, including eskers and tunnel valleys, contain information about ice sheet hydrology (Shreve, 1972; Brennand, 2000; Storrar et al., 2014; Dewald et al., 2022), and landforms eroded or deposited at ice margins, such as lateral and terminal moraines, De Geer moraines, ice-marginal deltas and ice-marginal meltwater channels, can be used to delineate former ice-marginal positions (Mannerfelt, 1949; Aario, 1977; Lundqvist, 1981; Kleman et al., 2006; Clark et al., 2012). Additionally, the distribution of ice-dammed lakes can be used to identify where outlet glaciers blocked natural drainage routes (Högbom, 1892; Lundqvist, 1972; Stroeven et al., 2016; Regnéll. et al., 2019, 2023b, 2025).

Esmark (1824) first hypothesised that Fennoscandia and northern Europe had been subjected to extensive glaciations based on field evidence observed in Norway, Denmark and northern Germany (Worsley, 2006; Hestmark, 2017). Through to the end of the 19th and into the early 20th centuries, glacial landforms were widely mapped in field-based studies and concepts of glacial landform genesis were developed (e.g. Hansen, 1886; De Geer, 1889, 1940; Ramsey, 1898; Frödin, 1916; Grønlie, 1938; Mannerfelt, 1945, 1949; Hoppe, 1959; Lavrova, 1960). In the second half of the 20th century the use of aerial photographs and satellite imagery for mapping glacial landforms to supplement continued field-based mapping became common practice (e.g. Punkari, 1982, 1985; Clark, 1997; Hättestrand, 1998) and detailed Quaternary Geology maps were compiled by the geological surveys of each country

Fig. 1. The physiography of Fennoscandia and northern Europe. The study area is shown by the red outline and includes all onshore areas of Norway, Sweden, and Finland. The white shading shows the asynchronous (time-transgressive) maximum achieved extent of the last Scandinavian Ice Sheet (SIS) based on Hughes et al. (2016). The locations of Figs. 3–10 and 17 are indicated. Basemap credit: GEBCO 2024 Grid (GEBCO Compilation Group, 2024).

(e.g. Raimo and Jouko, 1984; Svedlund, 1985; Klakegg et al., 1989; Rodhe, 1995). This facilitated empirical reconstructions at the ice-sheet scale (Lundqvist, 1986; Dongelmans, 1995; Kleman et al., 1997; Boulton et al., 2001; Stroeven et al., 2016). Additionally, international collaboration between the geological surveys and university-based researchers through research networks (e.g. the Nordic Union for Quaternary Research; Berthelsen and Königsson, 1975) and collaborative projects, such as the Nordkalott and Mid-Norden Projects (Nordkalott Project, 1986, 1987; Hirvas et al., 1988; Mid-Norden Project, 1999a, 1999b) advanced knowledge of ice sheet history and provide continued legacy data.

Since the 2010s, high-resolution, LiDAR-derived digital terrain models (DTMs) have become increasingly accessible, providing new opportunities to observe the former beds of Pleistocene ice sheets in high levels of detail and across large areas (Johnson et al., 2015; Stokes et al., 2015). In this investigation we focus on Norway, Sweden, and Finland (Fig. 1), where high-resolution (1 to 2 m/pixel) DTMs are available at national scales (Norwegian Mapping Authority, Kartverket, 2023; Swedish Ordnance Survey, Lantmäteriet, n.d; National Land Survey of Finland, n.d). Since their release, these DTMs have facilitated mapping at the regional (Smith and Peterson, 2014; Bouvier et al., 2015; Johnson et al., 2015; Möller and Dowling, 2015; Ojala et al., 2015; Peterson et al., 2017; Putkinen et al., 2017a; Öhrling et al., 2020) to national scale (e.g. Dewald et al., 2022; Butcher et al., 2026), with the Geological Survey of Finland paving the way by using LiDAR-derived DTMs to create a glacial features geodatabase of the entire country (Putkinen et al., 2017b; Geologian tutkimuskeskus, 2018).

Thus, a wealth of detailed information exists on ice-marginal landforms across Norway, Sweden and Finland. However, much of this information was produced before it was common, or even possible, to release and archive data in accessible and reusable digital formats. Often, is located on regional-to-national scale maps, or in figures in publications which can be difficult to combine and integrate due to differences in map scales, landform categories, mapping methods, and data formats. This means that such landform evidence and glaciological interpretations are often inaccessible.

In this study we aim to create a consistent and representative dataset of former ice-margin positions across the whole of Norway, Sweden and Finland that can be used to reconstruct the pattern and direction of ice margin retreat. We suppose that new mapping across the whole area by a small team with a single method is likely to achieve a more consistent dataset than by stitching together the numerous studies from the literature. The specific aims of this study are:

1) To use ice-marginal landforms observed on high-resolution DTMs across all three countries to produce a consistent and representative map of former margin positions.
2) To record the landform type used to define the ice-margin position (e.g. moraine or glaciofluvial fan) which then enables us to analyse and discuss the distribution and spatial relationships of different types of ice-marginal positions across the ice sheet.
3) To understand the extent to which margins of the ice sheet terminated in the sea or a lake during the last deglaciation.

Thus, we do not map the individual landforms, nor assimilate detailed mapping performed in numerous published local-to-regional-scale studies; instead, we interpret the observed landforms on DTMs to define what we call “ice-margin positions”. These are drawn as simple lines depicting where former ice-margin positions likely existed based on the observed assemblages of nearby landforms such as moraines, ice-marginal meltwater channels, and hummocky moraines. We note however that our aim is to build patterns of ice-marginal positions to aid ice sheet reconstructions and ice sheet modelling, and in no way replaces more detailed site-specific investigations, typical of geological surveys, and which tend to additionally include field and sedimentological work.

We release the data in a number of digital formats, making them accessible for numerical model-data comparison approaches (e.g. Patton et al., 2017; Ely et al., 2024). The interpreted ice-margin positions can be used with other palaeoglaciological lines of evidence, such as subglacial bedforms (e.g., Butcher et al., 2026) and subglacial meltwater routes (e.g., Dewald et al., 2022) to better understand the advance and retreat dynamics of the ice sheet.

2. Regional setting

The Scandinavian Ice Sheet (SIS) formed part of the Eurasian Ice Sheet Complex which repeatedly covered northern Europe through the Quaternary (Svendsen et al., 2004; Hughes et al., 2016; Batchelor et al., 2019). During the Last Glacial Maximum (LGM) the SIS covered Finland, Sweden and Norway, where it extended to the edge of the continental shelf. At its maximum extent, it coalesced with the British-Irish Ice Sheet to the southwest, Barents-Kara Ice Sheet to the north, extended across parts of Denmark, northern Germany and Poland to the south and reached several hundreds of kilometres into Russia to the east (Fig. 1; Hughes et al., 2016; Stroeven et al., 2016). During the LGM different sectors of the ice sheet reached their maximum areal extent asynchronously between approximately 27 and 18 ka (Hughes et al., 2016; Larsen et al., 2016).

Deglaciation of the ice sheet began along the southern margin as early as 21 ka (Hughes et al., 2016), with ice retreating from all directions towards the Scandinavian Mountains. This north-south trending mountain range located along the border of Norway and Sweden is a dominant topographic feature that reaches elevations over 2400 m a.s.l and played an important role in ice inception as well as the demise. This mountain range is composed of Caledonian orogenic rocks. The remainder of the study area, which is located to the east of the Scandinavian Mountains, is composed of Archean to Proterozoic igneous and metamorphic rocks known as the Fennoscandian Shield (Fig. 1; Lahtinen, 2012). The shield is low-lying with typical elevation values between 50 and 400 m a.s.l.

During retreat, the ice left extensive evidence of former ice-marginal positions across the landscape, including extensive moraines and glaciofluvial fans and deltas around Norway, Sweden and Finland during the Younger Dryas stadial, indicating that there was a substantial standstill or readvance of many sectors of the ice sheet at this time (e.g. Munthe, 1910; Andersen, 1979; Andersen et al., 1995a, 1995b; Berglund, 1979; Mangerud et al., 1979, 2023; Sollid and Sørbel, 1979; Björck and Digerfeldt, 1984; Punkari, 1985; Lundqvist, 1995; Rainio et al., 1995). Following the Younger Dryas, ice rapidly retreated towards the Scandinavian Mountains where it fragmented into smaller ice masses both in the mountains in Norway and immediately east of the mountain range in central and northern Sweden disappearing by 10 ka (Hughes et al., 2016; Stroeven et al., 2016; Regnéll. et al., 2019).

3. Overview of ice-marginal landforms reported in the literature

A variety of landforms can be formed by erosional and depositional processes along ice sheet margins (e.g. Mannerfelt, 1949; Aario, 1977; Lundqvist, 1981; Kleman et al., 2006), and these landforms can be used to reconstruct former ice-margin positions (e.g. Andersen, 1981; Lundqvist, 1986; Kleman and Borgström, 1996; Hättestrand and Clark, 2006; Kleman et al., 2006; Greenwood et al., 2007). Below we outline the depositional and erosional processes that form different ice-marginal landforms and summarise previous work on both landform mapping and the palaeo-glaciological interpretations of these landforms across the study area.

3.1. Moraines

A terminal or lateral moraine is a linear or arcuate ridge consisting of glaciogenic sediment deposited at an ice margin due to a pause in ice-margin retreat (stillstand) or by the deposition and deformation of sediment into a thrust or push moraine during a glacier readvance (Benn and Evans, 2010). Boulton et al. (2001) previously mapped ice-marginal moraines and other ice-marginal deposits across the SIS from decametre-scale satellite imagery (Fig. 2a), and Stroeven et al. (2016) presented a map of ice-marginal formations at the ice-sheet-scale (Fig. 2b) based on a summary of the available literature and new mapping in southern Sweden. Within our study area, both maps indicate that most of the ice-marginal evidence is located along the coast of Norway and in southern Sweden and Finland.

In southern Sweden, well-developed moraine ridges form a back-stepping series of ice-margin positions that can be traced over long distances (up to 150 km; Lundqvist and Wohlfarth, 2001). The outermost moraines are called the Halland Coastal Moraines (HCM; Caldenius, 1942; Hillefors, 1975; Fernlund, 1993) and consist of several short parallel moraines (up to 10 km long). The Göteborg (Wedel, 1971; Hillefors, 1975), Berghem (Caldenius, 1942; Mörner, 1969; Ronnert, 1989; Lundqvist and Wohlfarth, 2001), Trollhättan (Munthe, 1940; Johansson, 1976), and Levene (Strömberg, 1969; Johansson, 1982) moraines occur as a series of progressively younger ice-margin positions in southwest Sweden (Berglund, 1979; Lundqvist and Wohlfarth, 2001; Anjar et al., 2014; Stroeven et al., 2016). The Vimmerby moraine (Agrell et al., 1976; Malmberg Persson et al., 2007; Watts et al., 2024) is the only 'continuous' moraine (it can be traced for 90 km with irregular small gaps of less than 5 km) mapped on the southeastern side of Sweden, and has been correlated with the Berghem Moraine north of Gothenburg (Fig. 2; Anjar et al., 2014; Stroeven et al., 2016).

The Middle Swedish End Moraine Zone (MSEMZ) is a prominent moraine belt that runs across south central Sweden and consists of push moraines that are considered to have been deposited during the Younger Dryas stadial (Munthe, 1910; Berglund, 1979; Björck and Digerfeldt,

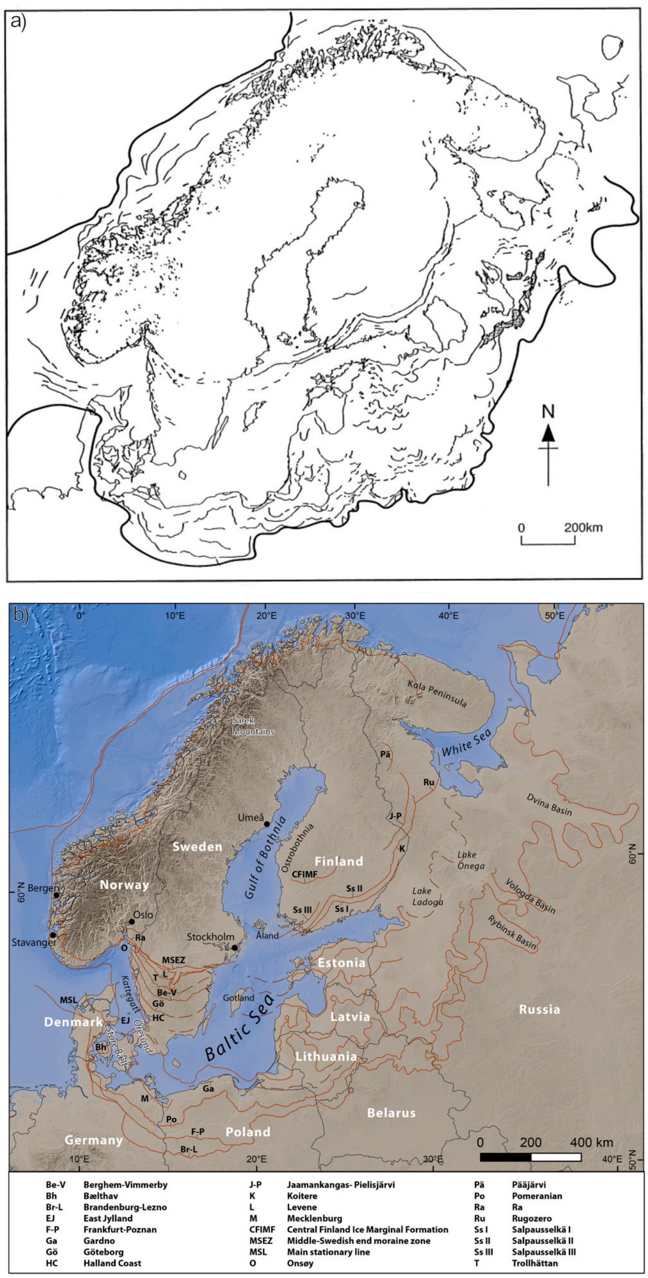


Fig. 2. Examples of published ice-marginal maps at the ice-sheet-scale. a) The principal zones of ice-marginal moraines and other ice-marginal deposits from Boulton et al. (2001). b) Ice-marginal formations from Stroeven et al. (2016).

1984; Lundqvist, 1995; Lundqvist and Wohlfarth, 2001; Johnson et al., 2019). Moraines deposited during the Younger Dryas have also been mapped in detail in Norway (Mangerud et al., 1979, 2016; Sollid et al., 1973; Sollid, 1975; Sollid and Sørbel, 1979; Andersen, 1979; Andersen et al., 1995a, 1995b; Vorren and Plassen, 2002; Høgaas et al., 2022) and Finland (Kurimo, 1982; Punkari, 1985; Rainio et al., 1995; Rainio, 1996).

3.2. De Geer moraines

De Geer moraines consist of narrow ridges of sediment (typically <50 m wide) that were first observed in Sweden and interpreted as annually emplaced moraines by De Geer (1889, 1940). They usually occur in swarms of ridges that have high parallel conformity at elevations below the highest-elevation palaeo-shorelines that represent sea or lake levels following ice retreat. De Geer moraines are therefore interpreted to have been deposited sub-aqueously along marine or lacustrine terminating ice margins (Hoppe, 1959; Borgström, 1979; Sollid, 1989; Larson et al., 1991; Blake, 2000; Lindén and Moller, 2005; Golledge and Phillips, 2008; Rivers et al., 2023). A number of different depositional theories have been proposed for De Geer moraines, however, the prevailing theory, first proposed by De Geer (1889, 1940), suggests they form by advection and push of basal till along the grounding-line during seasonal (possibly annual) re-advances (Larson et al., 1991; Blake, 2000; Lindén and Moller, 2005; Bouvier et al., 2015; Rivers et al., 2023). Swarms of De Geer moraines are common across the study area with clusters mapped below the highest palaeo-shoreline in Finland (Zilliacus, 1989; Ojala et al., 2015; Ojala, 2016; Rivers et al., 2023), Sweden (Bouvier et al., 2015; Öhrling et al., 2020), and northern Norway (Sollid et al., 1973; Sollid and Carlsson, 1984; Larson et al., 1991; Blake, 2000), as well as in the Scandinavian mountains (Høgaas and Longva, 2018; Regnéll. et al., 2019, 2023b).

3.3. Hummocky moraines

Hummocky moraines (also termed hummocky terrain and hummocky topography) consist of hummocks or mounds of sediment interspersed with hollows and linear ridges (Hoppe, 1952; Johnson et al., 1995; Möller and Dowling, 2015). Due to their complex and varied morphologies and chaotic appearances, interpretations of hummocky moraines are often more complex than for other glacial landforms, and it is possible that landforms grouped and mapped together as 'hummocky moraines' could be formed in more than one depositional mode. Hummocky moraines were initially thought to be deposited by the stagnation and down-wasting of ice close to the margin, and thus, they were often termed 'dead-ice moraines' (Tanner, 1914; Lundqvist, 1942; Mannerfelt, 1945). Distinctive ridges within the hummocky moraines in Sweden were noticed by Hoppe (1952) who suggested that they formed by the squeezing of till into crevasses within stagnant ice. Alternative hypotheses for their formation include sediment gravity flows and re-deposition from supra-glacial environments (Andersson, 1998) and subglacial sediment deformation under active ice (Aario, 1977). However, as remote sensing techniques improved, these models were challenged by the identification of repeated linear ridges transverse to ice flow contradicting notions of irregularity within hummocky moraines. These ridges were interpreted as push moraines within polythermal glacier snouts that are indicative of active retreat of the glacier (Bennett and Glasser, 1991; Bennett and Boulton, 1993; Hambrey et al., 1997; Benn and Lukas, 2006; Chandler et al., 2020) rather than ice stagnation and down-wasting. We therefore consider that hummocky moraines may provide useful information about former ice-marginal positions within our study area.

Hummocky moraines have been previously mapped in southern Sweden (Björck, 1987; Lidmar-Bergström et al., 1991; Andersson, 1998; Lundqvist and Wohlfarth, 2001; Möller and Dowling, 2015), southwest and northern Norway (Sollid et al., 1973; Knudsen et al., 2006), and Finland (Aartolahti, 1974; Aario, 1977). Care needs to be taken not to confuse hummocky moraines with 'hummock corridors', which are elongate tracks of hummocks and other landforms, such as eskers, channels and murtoos, formed by meltwater flow within subglacial meltwater routes. These are typically orientated traverse to the ice sheet margin (Rampton, 2000; Utting et al., 2009; Mäkinen et al., 2017; Peterson et al., 2017, 2018; Peterson and Johnson, 2018; Lewington et al., 2019; Dewald et al., 2022). Hummocky corridors have been mapped in southern Sweden and Finland (Peterson et al., 2017; Ahokangas et al., 2021; Dewald et al., 2022).

3.4. Ice-marginal channels

Ice-marginal channels (also termed lateral meltwater channels) are incised by water routed along an ice margin because the slope of flanking topography forces it to do so. Ice-marginal channels are therefore useful for delineating former ice-marginal positions (e.g. Mannerfelt, 1949; Greenwood et al., 2007, 2016; Margold et al., 2013; Boyes et al., 2023; Dulfer et al., 2022) and they often occur in flights of parallel channels on valley walls. These channels can be used to reconstruct ice surface lowering and ice-marginal retreat through time (Greenwood et al., 2007, 2016; Boyes et al., 2023; Dulfer et al., 2022). Numerous ice-marginal meltwater channels have been previously mapped within our study area and are particularly prevalent in the mountains of Norway and Sweden, where they have been used as evidence of large-scale down-wasting and stagnation of ice at the end of the last deglaciation (Mannerfelt, 1949; Kleman et al., 1992; Sollid and Sørbel, 1994; Borgström, 1999; Fredin and Hättestrand, 2002).

3.5. Glaciofluvial fans and deltas

Glaciofluvial fans and deltas consist of sorted sand and gravel deposited by glacial meltwater into aqueous environments, either lakes or the sea. They have a wide range of morphologies but often consist of accumulations of coarse-grained sediment with steeply dipping frontal beds (Lønne, 1995; Dietrich et al., 2017) and vary from a few hundred metres to several kilometres in width. They are often associated with eskers. Fans and deltas can form in ice-marginal settings where the margin terminates in water. In this setting, they are deposited when subglacial or englacial meltwater streams eject sediment directly into the sea or a lake. They can also be deposited in ice-distal locations, such as where a proglacial river enters a lake and it can be difficult to distinguish between such depositional environments (Krzyszkowski and Zieliński, 2002; Eilertsen et al., 2015). Nonetheless, there are two types of glaciofluvial deposits which can be confidently attributed to ice-marginal processes: (1) ice-contact fans and deltas; and (2) interlobate complexes (Punkari, 1980, 1997; Putkinen and Lunkka, 2008; Boyes and Pearce, 2023). Both types of deposit exist in Fennoscandia marking former ice-margin positions. For example, glaciofluvial fans and deltas form part of the widely studied Salpausselkä I, II and III ice-marginal zones in Finland (e.g. Punkari, 1982; Rainio et al., 1995; Glückert, 1995; Punkari, 1997; Lunkka et al., 2021; Boyes et al., 2024). Glaciofluvial fans and deltas also form short segments of prominent ice-marginal zones in southern Sweden, for example, along the Berghem Moraine (Berglund, 1979; Hillefors, 1979) and are often located within fjords along the Norwegian coast (e.g. Lønne, 1993; Nemec et al., 1999; Mangerud et al., 2019).

3.6. Ice-dammed lakes

Palaeo-shorelines and perched deltas have been used to reconstruct the extents of former ice-dammed lakes across Fennoscandia for over a century (e.g. Högbom, 1892; Gavelin and Högbom, 1910; Holmsen, 1915; Frödin, 1921; Lundqvist, 1972; Johansson, 2007; Stroeven et al., 2016; Regnéll. et al., 2019, 2023b, 2025) and these reconstructions have proved invaluable for understanding former ice-margin positions as the ice sheet retreated (Lundqvist, 1972; Stroeven et al., 2016; Regnéll. et al., 2019, 2023b, 2025). The largest was the Baltic Ice Lake, which formed along the southern margin of the SIS as it retreated into the Baltic Basin (Munthe, 1902; Björck, 1995; Jensen et al., 1997; Jakobsson et al., 2007; Rosentau et al., 2009). This lake reached its peak extent during the Younger Dryas, containing >29,000 km^3 of fresh water (Strömberg, 1992; Jakobsson et al., 2007).

Ice-dammed lakes also formed as ice retreated across northern Finland, including Lake Inari, Lake Somaslampi and the Sokli Ice Lake (Johansson, 1988, 1995, 2007; Kujansuu et al., 1998; Szeroczyńska et al., 2007; Shala et al., 2014). Glacial Lake Nedre Glomsjø is an example of a large ice-dammed lake that formed in mid-Norway during the early Holocene and is thought to have drained catastrophically as the ice sheet thinned and broke-up into smaller ice masses (Hansen, 1886; Holmsen, 1915; Høgaas and Longva, 2016, 2018). In fact, numerous ice-dammed lakes formed in the valleys of the Scandinavian Mountains as the ice retreated to its final location to the east of the mountain range (Lundqvist, 1972; Stroeven et al., 2016; Regnéll. et al., 2019, 2023b, 2025).

3.7. Evidence from older glaciations

Due to the erosive power of ice most, glacial landforms relate to the last deglaciation but we need to be aware of landforms formed during prior episodes of ice sheet retreat. Such landforms, including tors, blockfields and weathering mantles, have long been recognised in northern Sweden (Clarhäll and Kleman, 1999; Goodfellow et al., 2008; Hoppe, 1952, 1957; Lagerbäck, 1988; Hättestrand, 1998), Finland (Kaitanen, 1969; Kujansuu, 1975) and northern Norway (Fjellanger et al., 2006). Paired apparent cosmogenic exposure ages show that these areas survived under thick ice through multiple glaciations (Fabel et al., 2002; Stroeven et al., 2002; Harbor et al., 2006; Darmody et al., 2008). This suggests that some interior upland areas were covered by persistent, cold-based ice throughout the last glaciation, preserving such 'old' landscape features (Schytt, 1974; Kleman, 1994) in a similar manner to the present-day cold-based ice caps on Baffin Island, where tundra plants are preserved in their growth position beneath the ice (Falconer, 1966; Pendleton et al., 2019).

The Veiki Moraines in northern Sweden are one of the most discussed examples of 'older' glacial landforms that are considered to have survived through the last glacial (Fredholm, 1886; Lundqvist, 1981; Lagerbäck, 1988; Hättestrand, 1998). They have a hummocky morphology, contain distinctive circular plateaus and occur in NNE-SSW orientated bands (Hättestrand, 1998; Greenwood and Hughes, 2022). Morphologic and stratigraphic evidence indicates the Veiki Moraines were overrun by ice, such as the development of drumlins on the morainic sediments (Lagerbäck, 1988; Lagerbäck and Robertsson, 1988; Hättestrand, 1998; Alexanderson et al., 2022). While a number of hypotheses on their formation have been proposed, it is now generally accepted that they formed by the melting of debris-rich ice and their distinctive circular plateaus represent ice-walled lake plains that have been infilled with sediment (Lagerbäck, 1988; Alexanderson et al., 2022). Ridges within the hummocky Veiki Moraines have been interpreted as moraine ridges (Hättestrand, 1998), suggesting the moraines were deposited by active ice, and thus, they delineate former ice-marginal positions; albeit from a phase of ice sheet retreat that occurred before the last deglaciation.

4. Methods

4.1. Remotely sensed data and other mapping resources

Mapping of former ice-margin positions was undertaken in Esri ArcMap 10.7.1, Esri ArcPro 3.1 and QGIS 3.22 using high-resolution (2 m/pixel) LiDAR-based national DTMs of Norway (Norwegian Mapping Authority, Kartverket, 2023), Sweden (Swedish Ordnance Survey, Lantmäteriet, n.d) and Finland (National Land Survey of Finland, n.d). Elevation data from Norway with a 1 m resolution were downsampled to 2 m in order to reduce data volume and for consistency with Swedish and Finnish DTMs. For the purpose of mapping, the elevation data were visualised using shaded-relief maps artificially illuminated with a solar elevation of 45° from two different azimuths (45° and 315°) to avoid illumination bias on the identification of elongate landforms (Smith and Clark, 2005; Chandler et al., 2018). A vertical exaggeration factor of three was used. These DTMs and their solar-shaded products comprised over 1.4 terabytes (TB) of data.

To assist with the interpretations of the glacial landform record observed in the DTM data, an array of previously published geomorphological maps were consulted. However, due to the large volume of previous landform mapping across all three countries, produced at a range of scales and containing a variety of landform categories, we were not able to consult every individual surficial Quaternary or geomorphic map during this study because such a consultation would be too time-consuming. Such a task is made difficult because some cited sources are not easy to acquire, and the mapped data are often only available in inaccessible formats such as generalised figures in publications. Where possible, we used the following large scale (up to national-scale) glacial landform maps to assist with our own mapping interpretations: Sollid and Torp (1984); Norges Geologiske Undersøkelse (2023); Sveriges Geologiska Undersökning (2024); Hättestrand (1998); Geologian Tutkimuskeskus (2018); Punkari (1982); Nordkalott Project (1986, 1987); Mid-Norden Project (1999a, 1999b); Dewald et al. (2022).

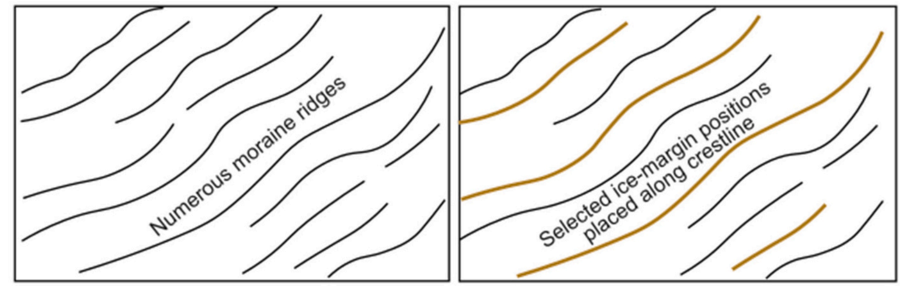
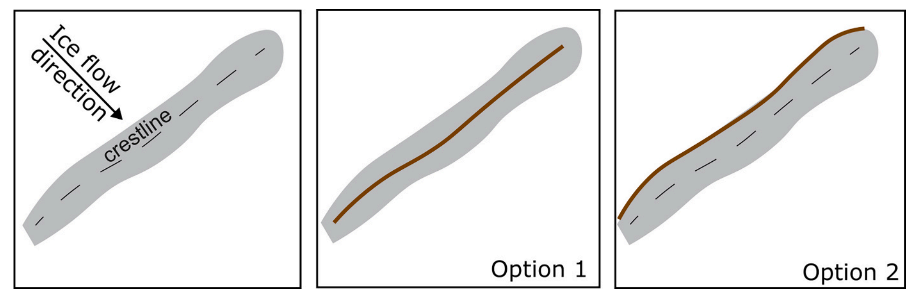
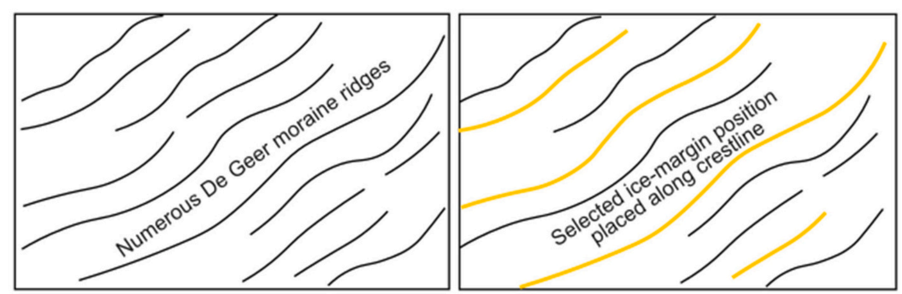
4.2. Method for mapping ice-margin positions

Due to practicalities arising from the large area and volume of elevation data, we devised a method of defining former ice-marginal positions that did not require individual mapping of component landforms, their categorisation, or their precise position and boundaries. This would have been prohibitively time-consuming and was not required by our aims. Instead, we visualised and interpreted the range of landform types in a given area (at a maximum scale of 1:12,500) on shaded-relief maps derived from the DTMs and drew ice-margin positions that locally satisfied or summarised the ice-marginal landform assemblages (see Table 1 and Figs. 3 to 8). Each mapped ice-margin position thus conveys the information that either a single ice-marginal landform, or assemblage of ice-marginal landforms, exist in that location, and the line indicates the orientation and lateral extent of the inferred ice-margin based on these landforms and contextual topography (Table 1). Taken together such ice-margin lines reveal the pattern and direction of ice-margin retreat.

Mapping was conducted at a variety of scales between 1:100,000 and 1:12,500. The study area was divided amongst three of the authors (HED, BMB, ND) who each independently mapped ice-margins inferred from all types of glacial landforms. To ensure consistency, a repeat-pass procedure was adopted whereby the entire study area was subsequently checked by the first two authors multiple times. Mapping interpretations were occasionally reviewed by all co-authors. A grid of 100 km^2 hexagons was used to ensure systematic scrutiny of the DTM data, ensuring no areas were accidentally missed. This hexagonal grid was originally deployed by Butcher et al. (2026) to reduce the tendency to bias mapping towards the centre of a square cell.

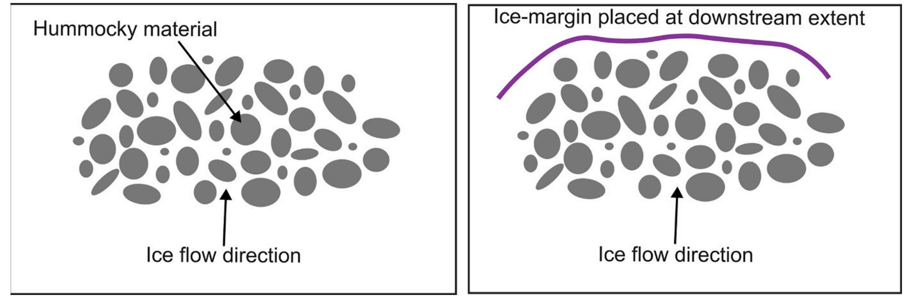
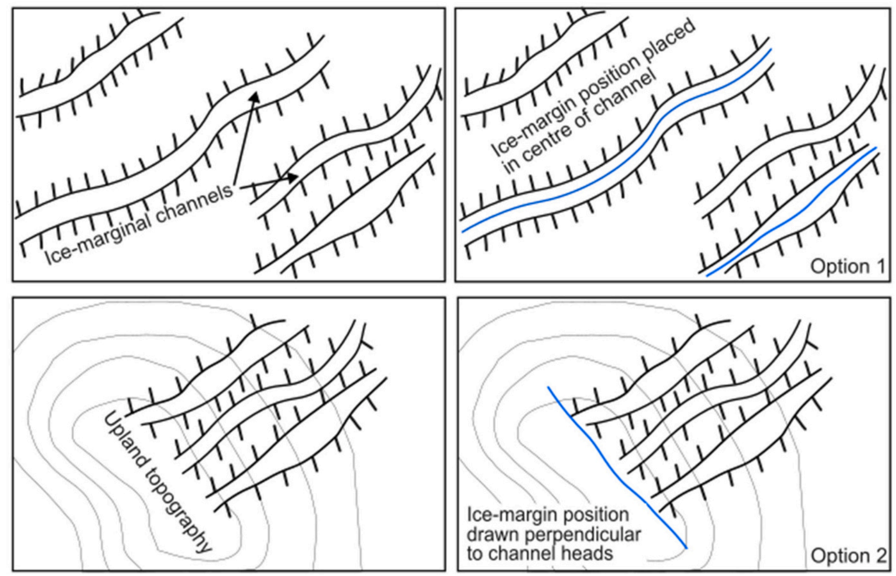
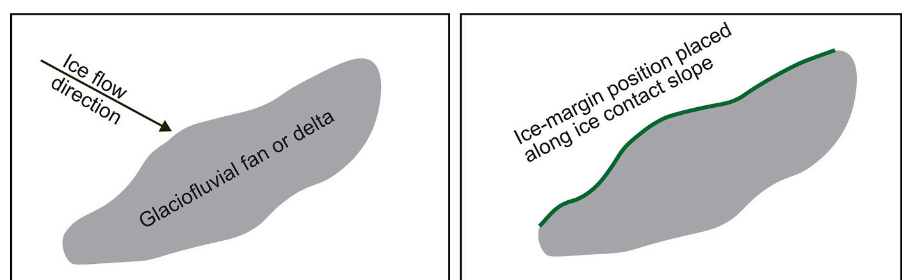
Mapping of every ice-margin position was beyond the scope of our investigation. Such mapping was not necessary, because our motivation was to capture the pattern and direction of retreat and thereby a representative distribution of ice margins across the study area. Therefore, where numerous ice-margins of the same type occurred in one hexagon (approximately 10 km across), we did not map every apparent ice-margin position, but mapped enough to capture the spatial distribution and pattern of the margins (up to 15 ice-margins per hexagon). Thus, we regard the resulting mapping to be a representative sample of the ice-margin positions, inscribed by landforms, distributed across the

Table 1
Criteria for the identification of ice-marginal landforms from remotely sensed data and description of where the ice-margin position was drawn based on the landform record.

Ice-marginal landform	Landform identification	Interpreted ice-margin position	Schematic example	Map example
Moraines <250 m wide	Sharp-crested straight or arcuate-shaped ridge.	Selected ice-margin position drawn along the landform crest. Individual ridges that likely represent the same ice-margin position can be connected along the features.		Fig. 3
Moraines >250 m wide	Sharp-crested straight or arcuate-shaped ridge. OR Broad straight or arcuate-shaped ridge.	Ice-margin position drawn along the landform crest. OR Ice-margin position drawn along the inferred ice-contact break in slope.		Fig. 3
De Geer moraines	Sharp-crested linear, concave or convex shaped ridges. Typically narrow (<50 m) and occur as swams of parallel ridges.	Selected ice-margin position drawn along the landform crest. Individual ridges that likely represent the same ice-margin position can be connected along the features.		Fig. 4
Hummocky moraines	Hummocky material (irregular surface containing mounds of sediment alternating with depressions) that forms a band broadly perpendicular to the inferred ice flow direction indicated by other glacial landforms such as eskers. OR The extent of hummocky material (irregular surface containing mounds of sediment alternating with depressions) that is controlled by topography.	Ice-margin position drawn along the outermost downstream extent of the hummocky moraines.		Fig. 5

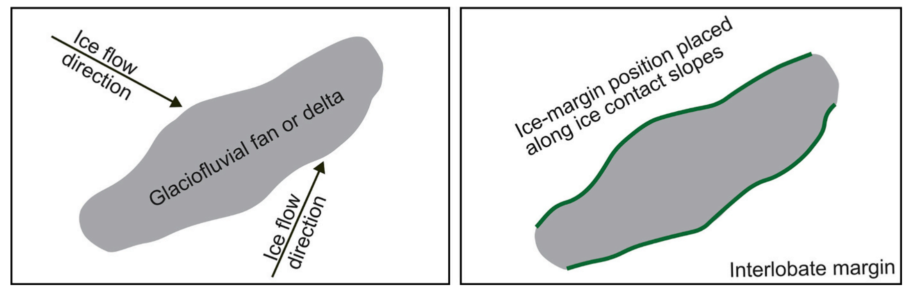
(*continued on next page*)

Table 1 (*continued*)

Ice-marginal landform	Landform identification	Interpreted ice-margin position	Schematic example	Map example
				
Ice-marginal meltwater channels	Meltwater channels that meet a number of the following criteria: (1) oriented parallel or sub-parallel to contours; (2) occur in a series of channels at different heights; (3) terminate in downslope chutes; (4) low to medium sinuosity. OR Meltwater channels that are incised into upland topography. These channels are characterised by an abrupt channel head on or near the upland summit, which transitions to a braided channel system downstream.	Selected ice-margin position is drawn along the centreline of the channel OR Ice-margin position is drawn perpendicular to the channel heads		Fig. 6
Glaciofluvial fans and deltas	Flat topped or fan-shaped accumulations of sediment with steeply dipping frontal beds. Ice-margin positions are only mapped where there is clear morphological evidence that the landforms were formed directly at the ice margin. E.g. eskers leading into the fan or delta or an association with other ice-marginal landforms.	Ice-margin position drawn along the inferred ice contact slope/s.		Figs. 7 and 8

(*continued on next page*)

Table 1 (*continued*)

Ice-marginal landform	Landform identification	Interpreted ice-margin position	Schematic example	Map example
				

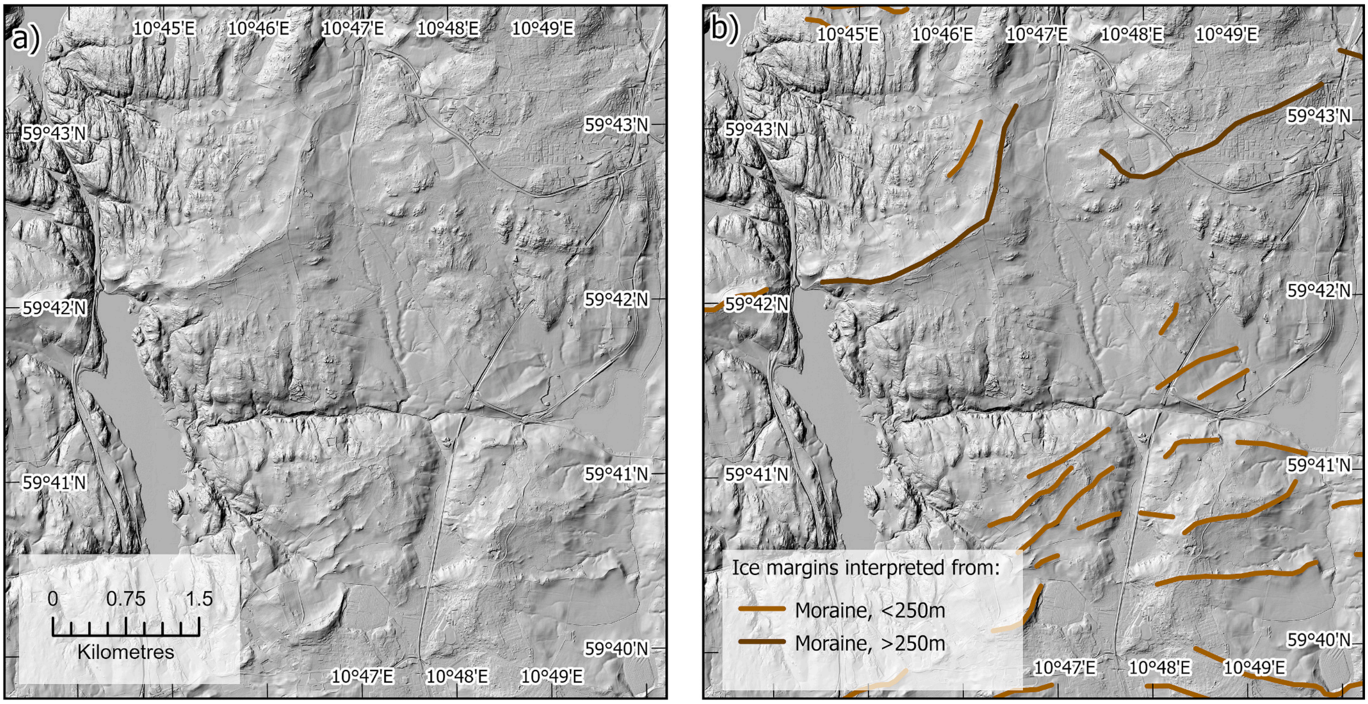


Fig. 3. Examples of ice-margin positions interpreted from moraines. a) DTM derived shaded-relief map (Norwegian Mapping Authority, Kartverket, 2023) and b) ice-margin positions interpreted from moraines >250 m and < 250 m wide. In both cases the ice-margin position has been drawn along the crest of the moraine. The location of this example is shown in Fig. 1.

entire study area.

Ice-margin positions were mapped into a single GIS polyline shapefile. We recorded the landform type that defines each ice-margin position within the attribute table of the shapefile. Six different landform-types were recorded: moraines >250 m (Fig. 3); moraines <250 m (Fig. 3); De Geer moraines (Fig. 4); hummocky moraines (Fig. 5); ice-marginal meltwater channels (Fig. 6); and glaciofluvial fans and deltas (Figs. 7 and 8; Table 1). We note that it is likely that some of the ice-margin positions are laterally time-equivalent, and therefore, deposited along the same ice-margin. However, as we don't have any absolute chorological information, we only interpolate the ice margin position across gaps in the ice-marginal landform record of less than 500 m.

4.3. Ice-margin positions formed prior to or after the last deglaciation

Upon completion of ice margin mapping, we separated out those that contained morphological evidence that they were likely formed prior to the last deglaciation (21–10 ka; Fig. 9a). Cross-cutting landform relationships provided key evidence that these landforms were overrun by ice, such as drumlins superimposed on the landform (Lagerbäck, 1988; Hättestrand, 1998; Alexanderson et al., 2022). This approach could also have identified readvance positions from the last deglaciation, and so to minimise this possibility, we cross-checked with previous studies on pre-LGM landforms that sometimes include numerical age constraints (e.g. Kleman et al., 1992; Hättestrand, 1998; Fabel et al., 2006; Heyman and Hättestrand, 2006).

During the mid-Holocene, it is believed that Norway, Sweden, and Finland were free of glacier ice, and present-day glaciers across Scandinavia formed during the Neoglaciation and advanced during the Little Ice Age (Karlén, 1988; Nesje and Kvamme, 1991; Nesje et al., 2008; Nesje, 2009). These Late Holocene advances left behind landform records including sharp-crested moraines and ice-marginal meltwater channels close to the present-day glaciers (e.g. Matthews and Shakesby, 1984; Karlén, 1988; Bickerton and Mathews, 1993; Nesje et al., 2008; Imhof et al., 2012; Weber et al., 2019; Leigh et al., 2020; Carrivick et al., 2022; Gjerde et al., 2023). Here we aim to capture only ice-margin positions from the last SIS and therefore, do not map the ice-margin positions that are clearly associated with these Late Holocene advances (Fig. 9b and c).

4.4. Identifying areas where ice sheet likely terminated in water

We identified zones of potential aqueous ice sheet termination during deglaciation using two methods: (1) we combined reconstructions of deglaciation stage ice-dammed lakes across Norway, Finland and Sweden; and (2) we derived the zone of potential aqueous ice sheet termination around the present-day coastline using isostatically-modelled palaeo-topographies for the Eurasian Ice Sheet Complex (Clark et al., 2022a; Bradley et al., 2023). In the first case, palaeo-shorelines and perched deltas observed on the DTMs provide evidence of either former ice-dammed lakes or higher relative sea levels during the last deglaciation. Here we aimed to capture the distribution of palaeo-shorelines formed by ice-dammed lakes by placing points at the highest and lowest elevation shorelines for a given set (Fig. 10a). This worked well for upland regions such as most of Norway. Around the present-day coastline of Sweden and Finland however, we could not easily differentiate between shorelines formed by ice-dammed lakes (e.g. the Baltic Ice Lake) from those formed by high relative sea levels. For such cases, we recorded shorelines without making the lake or marine distinction. With the exception of possible ice-dammed lakes formed below the highest shoreline in Sweden and Finland, we then reconstructed minimum extents of ice-dammed lakes using the mapped palaeo-shoreline point data and their relationship with the surrounding topography (Fig. 10b). Where multiple dam locations are required to satisfy all the palaeo-shoreline data, we merged the ice-dammed lake extents together to produce the zone of potential aqueous ice sheet termination in the inland regions.

Around the present-day coastline of Norway, Sweden, and Finland the zone of potential aqueous ice sheet termination was derived using isostatically-modelled palaeo-topographies for the Eurasian Ice Sheet Complex (Clark et al., 2022a; Bradley et al., 2023). Although these publications focussed on the United Kingdom and Ireland, palaeo-

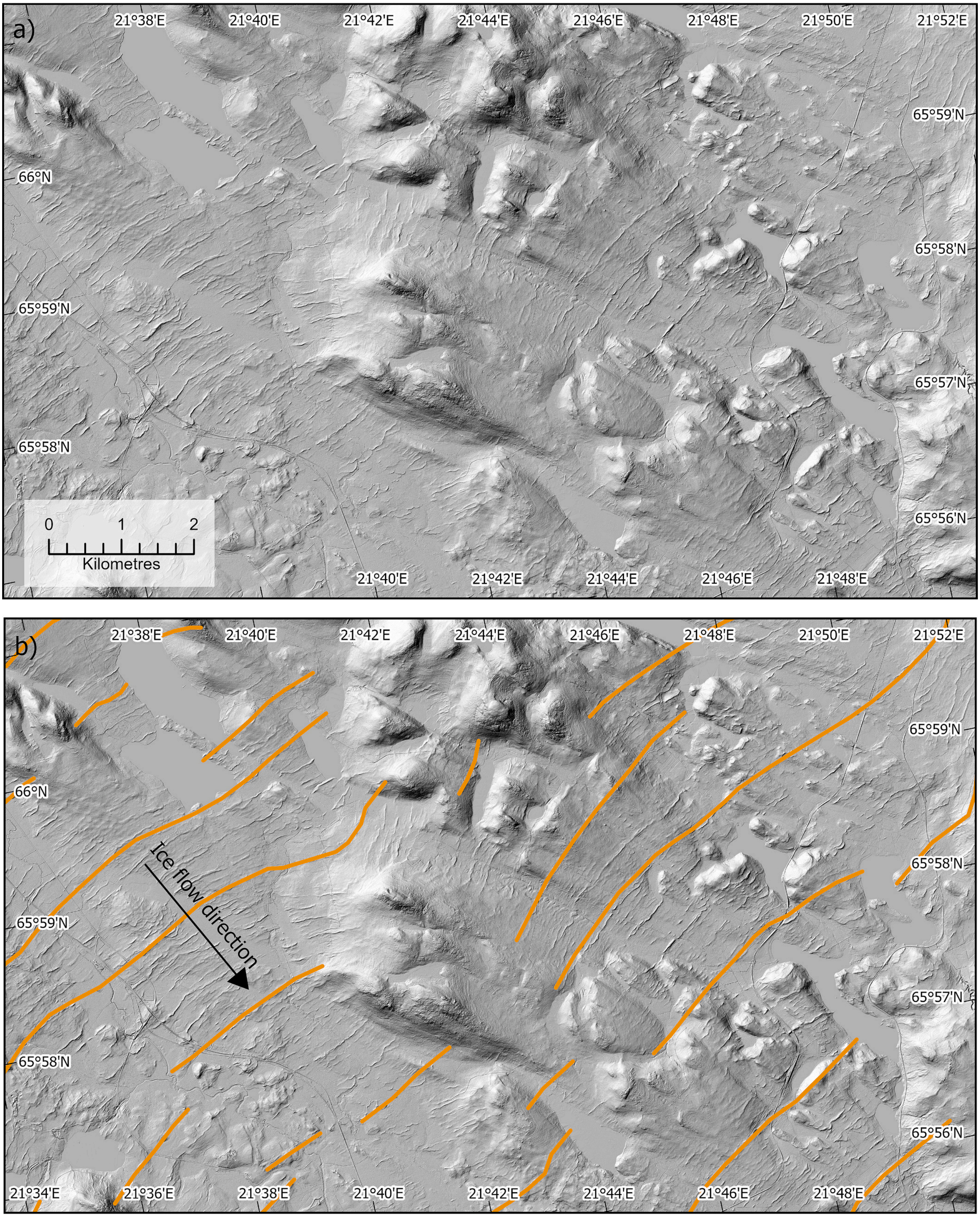


Fig. 4. Examples of ice-margin positions interpreted from De Geer moraines. a) DTM derived shaded relief map (Swedish Ordnance Survey, Lantmäteriet, n.d) and b) selected ice-margin positions interpreted from De Geer moraines (orange). As our main interest is in constraining the ice retreat pattern, we only map enough ice-margin positions to sufficiently capture the geometry and spatial extent of margins interpreted from De Geer moraines in the region. The location of this example is shown in Fig. 1.

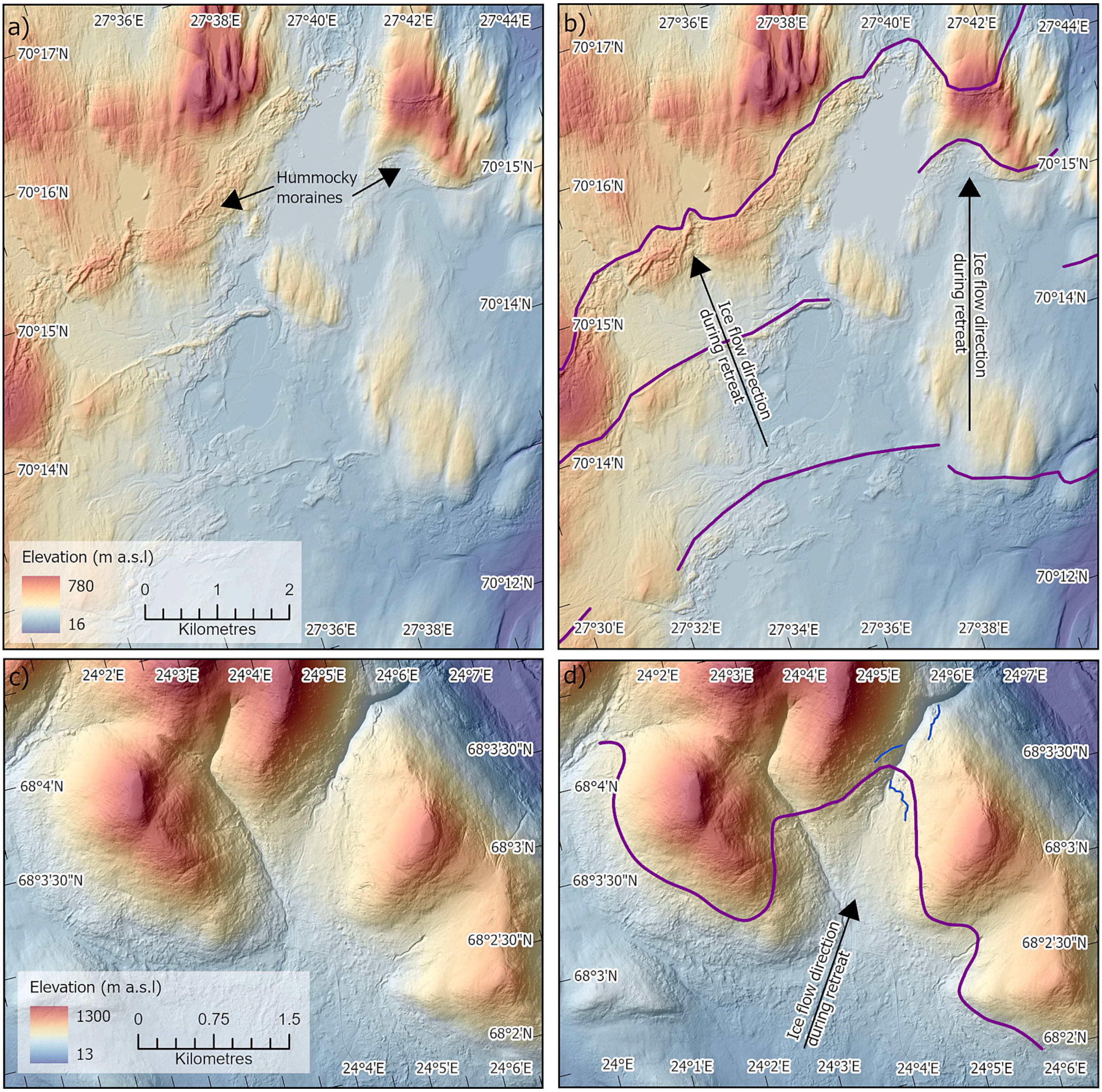


Fig. 5. Examples of ice-margin positions interpreted from hummocky moraines. a) DTM derived shaded relief map (Norwegian Mapping Authority, Kartverket, 2023) and b) ice-margin positions interpreted from hummocky moraines (purple). The ice-margin position is drawn along the downstream extent of the hummocky moraines. c) DTM derived shaded relief map (National Land Survey of Finland, n.d) and d) ice-margin positions interpreted from hummocky moraines (purple) and ice-marginal meltwater channels (blue). In this example there is a distinct boundary between an area of hummocky moraines that fills the valleys and the smooth upland areas. The locations of these examples are shown in Fig. 1.

topographies beneath the entire Eurasian Ice Sheet Complex were modelled. We used their DEMs of palaeo-topography at 1 ka timesteps to derive the sea level contours (0 m), i.e. the shoreline (Fig. 11a). Then, using the 12 ka timestep as an example, we used the DATED-1 most credible ice margins at 11 and 12 ka (Fig. 11b; Hughes et al., 2016) to derive the likely zone of potential aqueous ice sheet termination between these ice-margin positions (Fig. 11c). This is equal to the bed elevations that are below zero metres between these ice margins. This method is repeated for each palaeo-topography timestep between 15 and 10 ka and the results were merged into a single layer (Fig. 11d). The extent of this layer is limited to the maritime and terrestrial borders of Norway, Sweden, and Finland (i.e. we do not reconstruct the extent of marine or lake environments in Russia and along the southern margin of the ice sheet). The mapped palaeo-shoreline point data and distribution of ice-margins interpreted from De Geer moraines served as an independent check on these modelled aqueous-terminating extents in Sweden and Finland. The zone of potential aqueous ice sheet termination in the inland regions reconstructed from minimum ice-dammed lake extents and around the present-day coastline reconstructed from isostatically-modelled palaeo-topographies were then combined together to give the locations where the ice margin likely terminated in water rather than on land during the last deglaciation.

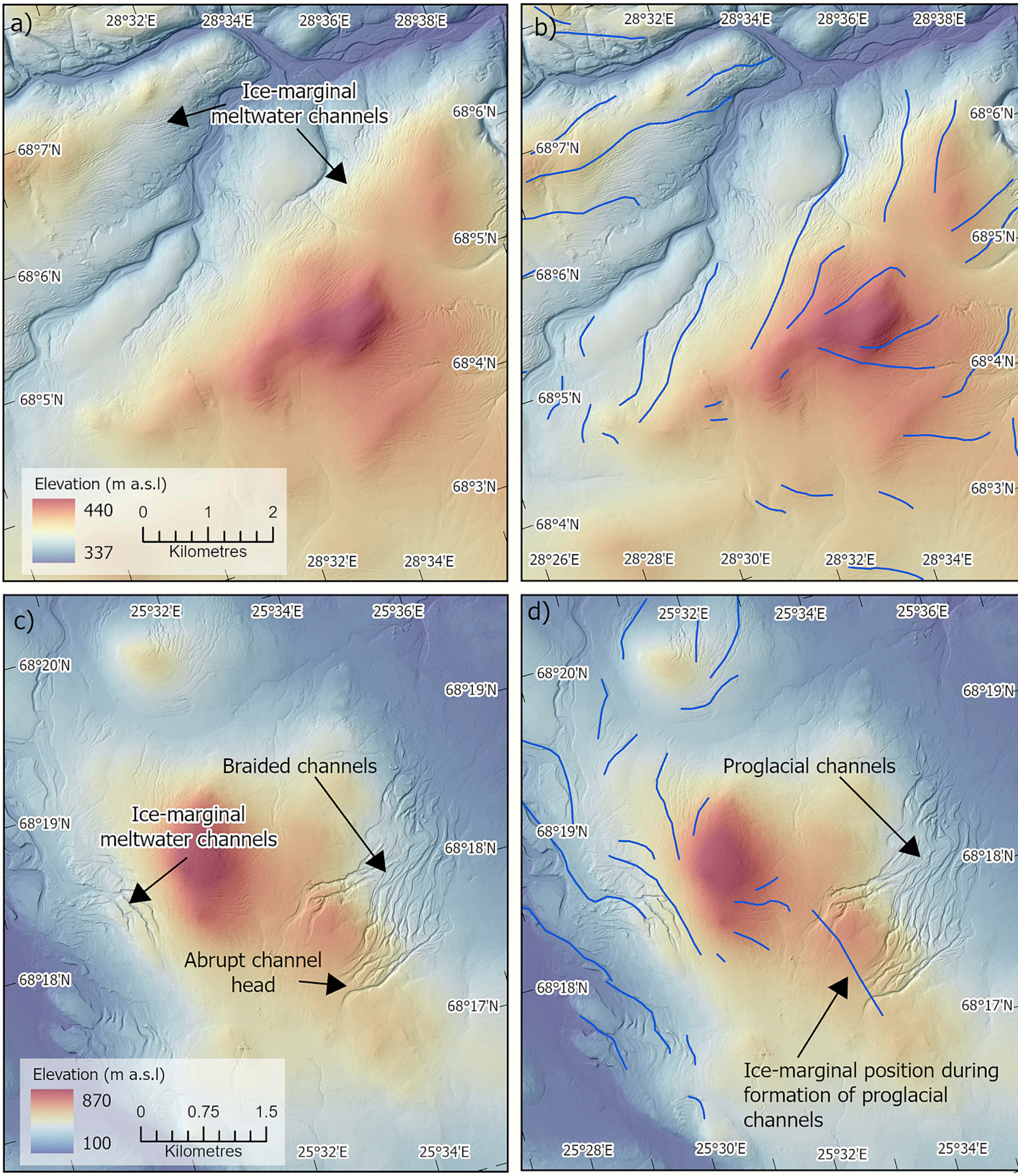


Fig. 6. Examples of ice-margin positions interpreted from ice-marginal channels a) DTM derived shaded relief map (National Land Survey of Finland, n.d) and b) ice-margin positions interpreted from ice-marginal meltwater channels (blue). c) DTM derived shaded relief map (National Land Survey of Finland, n.d) and d) ice-margin positions interpreted from ice-marginal meltwater channels (blue) with a rare example of an ice-margin position interpreted from proglacial channels cutting into upland topography. The locations of these examples are shown in Fig. 1.

4.5. Notes on the accuracy and completeness of the ice margin database

Many studies have demonstrated that remote-sensing approaches employing DTMs are extremely effective for identifying glacial landforms in large sample sizes and over broad spatial scales (e.g., Bouvier et al., 2015; Johnson et al., 2015; Putkinen et al., 2017b; Chandler et al., 2018; Geologian tutkimuskeskus, 2018; Boyes et al., 2021; Dulfer et al., 2023) and that simply wouldn't be practical or

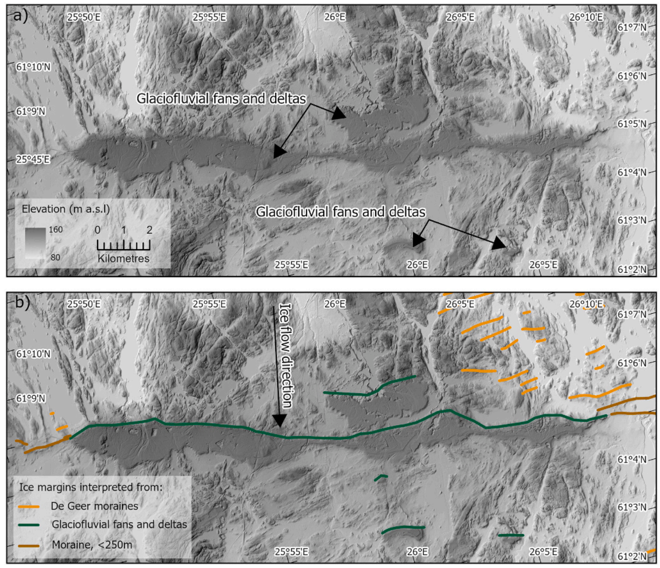


Fig. 7. Examples of ice-margin positions interpreted from glaciofluvial fans and deltas a) DTM derived shaded relief map (National Land Survey of Finland, n.d) of glaciofluvial fans and deltas and b) ice-margin positions interpreted from glaciofluvial fans and deltas (green), De Geer moraines (orange) and small moraines (brown). The location of this example is shown in Fig. 1.

possible with field-based observations alone. Indeed, some glacial landform types that are now fundamental to our understanding of glaciers and ice sheets were not identified until remote sensing datasets became available (e.g. megascale glacial lineations and murtoos; Clark, 1993; Spagnolo et al., 2014; Mäkinen et al., 2017; Peterson et al., 2017; Ojala et al., 2021). A major benefit of mapping from LiDAR-derived DTMs such as those used in our study (from which vegetation and cultural structures have been removed), is that they enable consideration of landforms at the landsystem-scale, regardless of landscape complexity and vegetation cover. We acknowledge, however, that a degree of unavoidable uncertainty exists in our interpretations because they are based solely on observations from remote-sensing. We attempted to reduce ice-margin misinterpretations and subjective errors by engaging multiple experienced and independent mappers (who have both remote and field mapping experience) in a repeat-pass mapping approach. Because of the scale of the study area we did not field-check our interpretations. We judge that ice-margin misidentifications are likely to constitute a small percentage of our mapping, and do not negate the overall value of our dataset. Our record of ice-margins interpreted from smaller glacial landforms, such as shorelines and some moraines, is likely to be incomplete as their size is often at or below the resolution of the mapping scale (1;12,500).

Because our intention was to create a map of ice-margin positions that is useful for palaeoglaciological investigations, such as whole ice sheet reconstructions, it should not be considered as a complete map of all ice marginal evidence that exists. We suggest that at local to regional scales, our map of ice-margin positions could be useful in conjunction with other more detailed mapping products, such as geomorphological

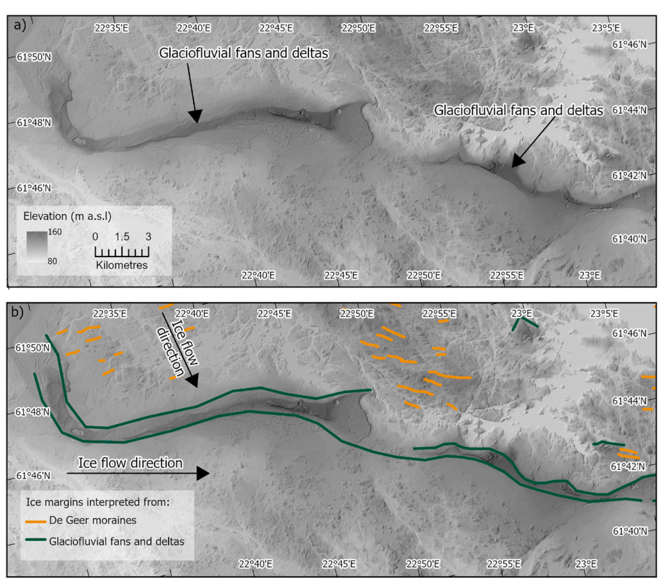


Fig. 8. Examples of ice-margin positions interpreted from glaciofluvial fans and deltas a) DTM derived shaded relief map (National Land Survey of Finland, n.d) of an interlobate complex with two ice-contact slopes. b) ice-margin positions interpreted from glaciofluvial fans and deltas (green) are drawn along both ice contact slopes. Here two different ice lobes were juxtaposed and glaciofluvial fans and deltas were deposited between the ice lobes. The location of this example is shown in Fig. 1.

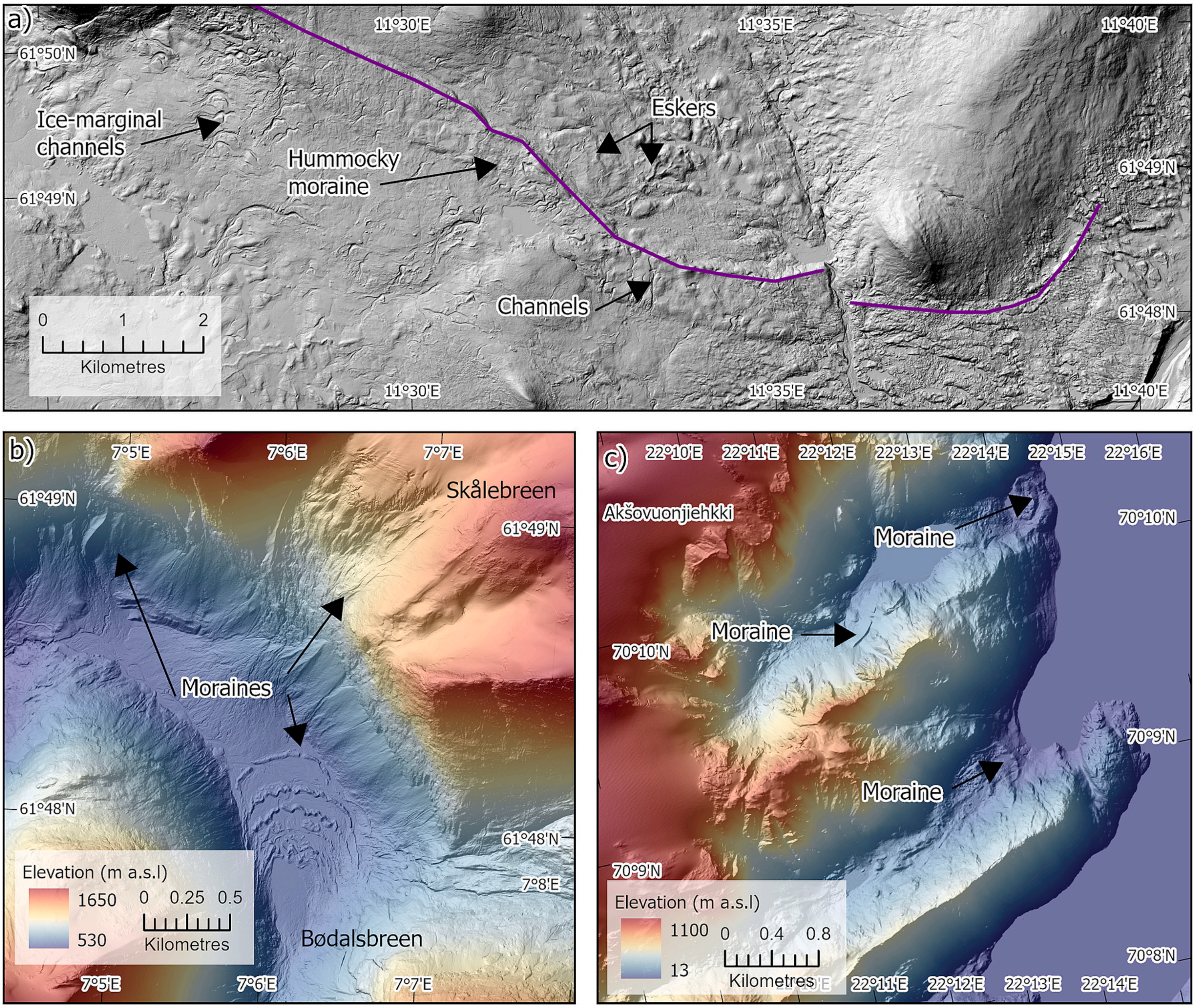


Fig. 9. a) An example of an ice-margin position interpreted from hummocky moraines (purple) that has been assigned to pre-LGM because they are cross-cut by other glacial landforms including ice-marginal channels and eskers. This cross-cutting indicates the hummocky moraine was formed prior to the final ice retreat. b) and c) Examples of ice-marginal landforms located close to present-day glaciers that were likely formed during Late Holocene ice advances, and therefore, these ice-margin positions have not been mapped. The locations of these examples are shown in Fig. 1.

maps.

5. Results

5.1. *Last deglaciation (21–10 ka)*

The distribution of the deglacial ice-margin positions derived from our landform analysis across Norway, Sweden, and Finland is shown in Fig. 12, totalling 50,811 pieces of ice-marginal evidence. We note that some of these margin positions are likely laterally equivalent, however, we're unable to connect them laterally without absolute chronological information. Fig. 13 demonstrates that spatial variability exists in which (dominant) landform types record margin positions. For example, across Norway, margins are mostly interpreted from moraines, whereas the interior region of the ice sheet margin positions are mostly interpreted from ice-marginal meltwater channels, and in the northern half of the study area, ice-margin positions interpreted from hummocky moraines are common. The spatial pattern of each ice-margin type is described below.

We identified 259 ice-margin positions interpreted from large moraines (>250 m wide; Fig. 13a). These vary in length from 350 m to 18 km. Ice-margin positions interpreted from large moraines occur across the study area, with clusters in southern Sweden and southern Norway and along the central western coast of Norway. There are 11,446 ice-margin positions interpreted from small moraines (< 250 m wide; Fig. 13b), which range in length between 40 m to 15 km. These occur relatively evenly throughout the study area but are more densely clustered along the coast of Norway and in southern Sweden.

Ice-margin positions interpreted from De Geer moraines ($n = 15{,}505$) vary in length from 40 m to 10 km. These occur in discrete clusters within our study area (Fig. 13c). Those in Sweden are clustered around the Middle Swedish End Moraine Zone in south-central Sweden, including on Åland Island, and along the present-day coastline of the Gulf of Bothnia in northeast Sweden, between the towns of Umeå and Luleå. Additionally, we identified several small clusters of ice-margin positions interpreted from De Geer moraines in the Swedish mountains. In Finland, clusters of ice-margin positions interpreted from De Geer moraines occur around the Salpausselkä I, II and III ice-marginal

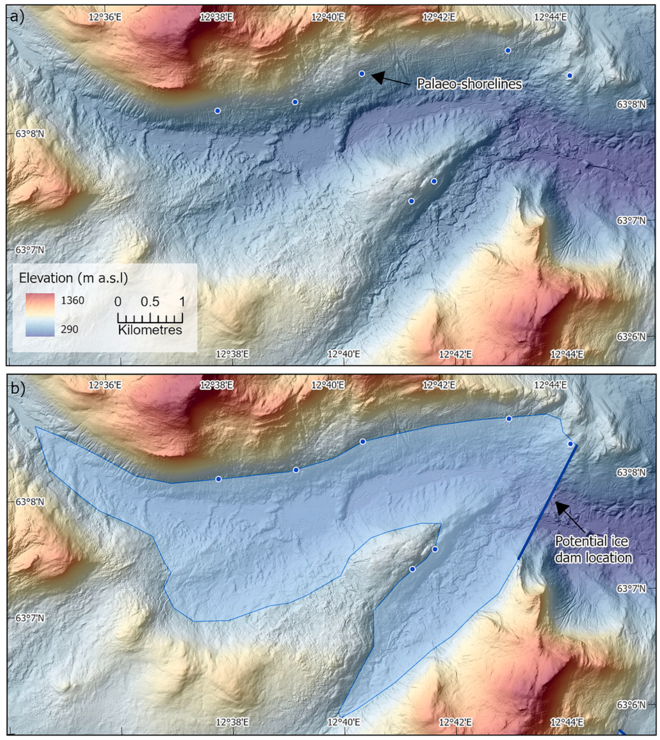


Fig. 10. a) An example from the Scandinavian Mountains where a palaeo-shoreline has been eroded into the valley walls at around 963 m asl. We placed points at regular intervals along this shoreline in order to capture its extent. b) The likely position of the ice-dam that would produce an ice-dammed lake which satisfies the palaeo-shoreline information (blue line) and the extent of the lake that was reconstructed (blue shading). Ice-dammed lakes can evolve over time as the ice margin retreats. Where multiple ice-dammed lakes overlap, they were merged together to form the zone of potential aqueous ice sheet termination. The location of this example is shown in Fig. 1.

zones and the Central Finland Ice Marginal Formation as well as near the town of Vaasa on the Gulf of Bothnia coast. Ice-margin positions interpreted from De Geer moraines are less frequent in Norway, with small swarms occurring along the central and northern present-day coastline, particularly between the towns of Bodø and Tromsø and near Kirkenes. They are also located in the Rondane Mountains of central southern Norway and in the mountains around Lierne in central Norway.

Ice-margin positions interpreted from hummocky moraines (n = 1028) range in length from 250 m to 62 km. This ice-margin type is predominantly located in the north of the study area, above a latitude of 65° North (Fig. 13d). In Finnmark, northern Norway, extensive ice-margin positions interpreted from hummocky moraines occur south of Porsanger, Lakse, and Tana fjords. In northern Sweden, these ice-margins are located to the east of the Swedish mountains. In Finland, ice-margin positions interpreted from hummocky moraines are located in the upland areas of northern Finland and they form short segments of the Salpausselkä I, and II ice-marginal zones as well as the Rugozero and Kalevala ice-marginal zones that extend into Russia. Finally, ice-margin positions interpreted from hummocky moraines are the dominant ice-margin type in southernmost Sweden (Skåne).

Ice-margin positions interpreted from meltwater channels (n = 20,724) range in length from 100 m to 15 km. This ice-margin type is abundant in the interior region of the ice sheet (Fig. 13e), including in the Rondane Mountains in Norway, throughout central and northern Sweden, northern Finland and in Finnmark, northern Norway.

Ice-margin positions interpreted from glaciofluvial fans and deltas (n = 1849) range in length from 200 m to 40 km. This ice-margin type occurs throughout the study area but is most abundant in Finland (Fig. 13f), where this ice-margin type dominates the Salpausselkä I, II and III ice-marginal zones. This ice-margin type also dominates the Central Finland Ice Marginal Formation. In southern Sweden, ice-margins interpreted from glaciofluvial fans and deltas often form short segments within prominent moraine complexes, such as the Göteborg, Berghem and Levene moraines.

5.2. Older glaciations (pre-LGM)

There are a total of 388 ice-margin positions that were identified to have formed prior to the last deglaciation based on cross-cutting relationships that imply more than one phase of advance and/or retreat (Fig. 14). The majority of these landforms are located in central and northern Sweden and are interpreted from hummocky moraines, but pre-LGM ice margins also include ice-margin positions within the study area interpreted from glaciofluvial fans and deltas, ice-marginal meltwater channels and moraines. We note that a number of studies have identified relict upland areas considered to represent older landscapes preserved under cold-based ice in the northern Swedish mountains (e.g. Fabel et al., 2002; Heyman and Hättestrand, 2006; Goodfellow, 2007; Goodfellow et al., 2008). However, we do not automatically assign the ice-margin positions throughout these relict upland areas to older glaciations. These ice-margin positions, which are dominated by ice-marginal meltwater channels that are commonly formed along the margins of cold based ice (Dyke, 1993; Kleman et al., 1992, 2006; Hättestrand, 1998; Atkins and Dickinson, 2008), may represent ice-marginal positions of the last deglaciation. For example, an ice-marginal meltwater channel that was eroded into a relict area in northeastern Sweden that was dated in Stroeven et al. (2002) returned a deglacial age.

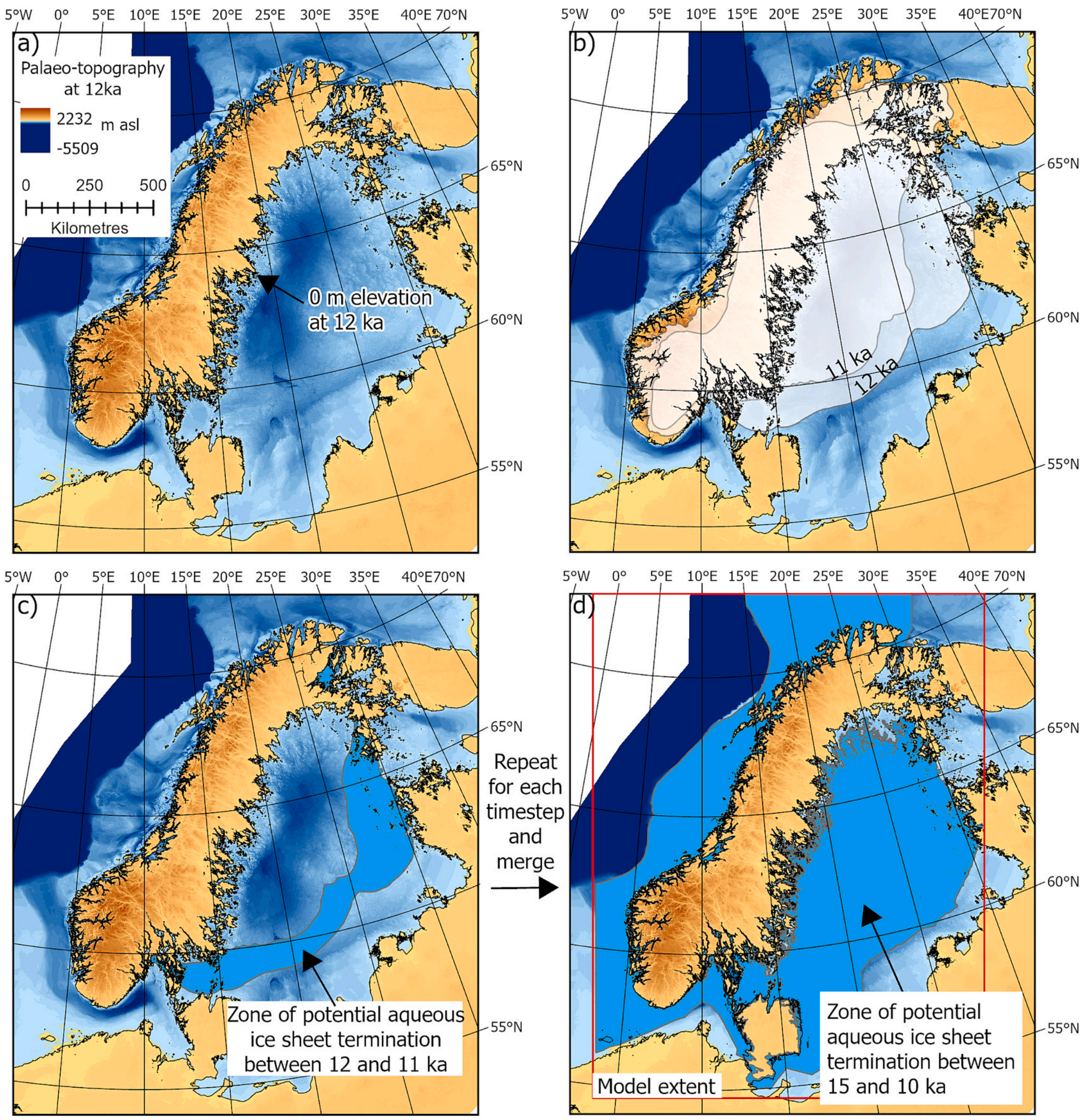


Fig. 11. Method for calculating the zone of potential aqueous ice sheet termination through the last deglaciation. a) Palaeo-topography at 12 ka (Clark et al., 2022a; Bradley et al., 2023) and zero metre elevation line (black). b) DATED-1 most credible ice-margin reconstruction for the SIS at 12 and 11 ka (Hughes et al., 2016). c) The zone of potential aqueous ice sheet termination between 12 and 11 ka (blue shading), which is defined by all elevations below zero m a.s.l. that occur in the region defined by the difference between the 12 and 11 ka DATED-1 margins. This method was repeated for each timestep between 15 and 10 ka and the results were merged into one layer shown in (d) giving the cumulative potential zone of aqueous terminating margins between 15 and 10 ka. This layer was then merged with the reconstructed ice-dammed lakes (see Fig. 10) to produce a total estimate of the zone of aqueous ice sheet termination during the last deglaciation.

5.3. Zone of potential aqueous ice sheet termination

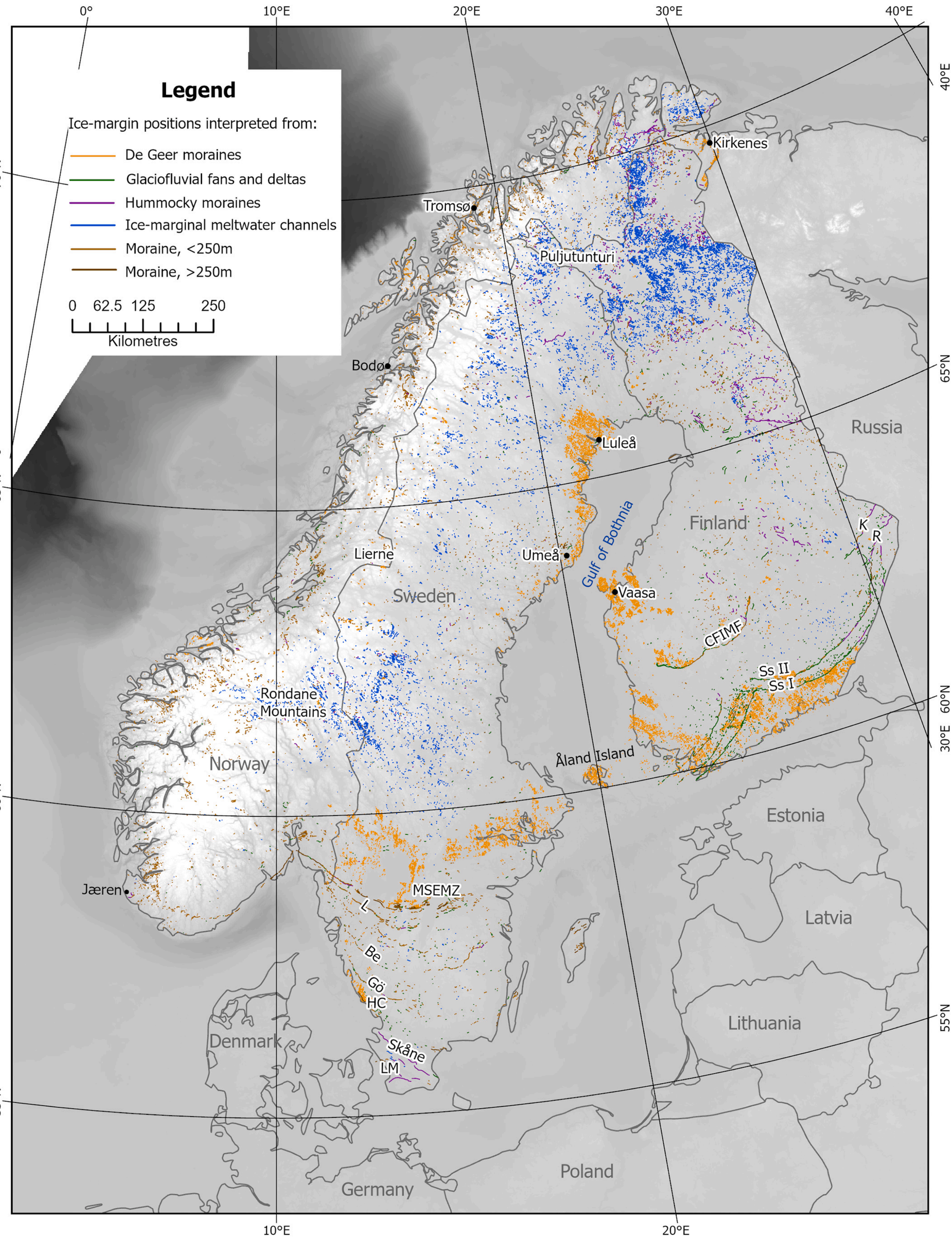
The zone of potential aqueous ice sheet termination across our study area is shown in Fig. 15. This zone is not a snapshot in time but is cumulative, showing locations where the ice sheet margin likely terminated in a lake or the sea at some point during the deglaciation of Norway, Sweden, and Finland (see method in Section 4.4). Fig. 15b compares the mapped deglacial ice-margin positions with the zone of potential aqueous ice sheet termination. We find that 44% of our ice-margin positions occur in this zone and were therefore likely to have been deposited into a lake or the sea (Fig. 15b). These ice-margin positions are predominately located along the coast of Sweden and through the majority of southern and central Finland. There is a spatial overlap with all types of ice-marginal positions and the zone of potential aqueous ice sheet termination, with ice-margin positions interpreted from De Geer moraines forming exclusively within this zone. Ice-margin positions interpreted form meltwater channels located in this zone in Finland formed on small islands located above the marine limit, however, these islands are not captured because they are below the resolution of the palaeo-topography data.

6. Discussion

6.1. Comparison with previous work

6.1.1. Deglacial ice-margin positions (21–10 ka)

We have produced a new spatially coherent and consistent map of ice-margin positions across all onshore areas of Norway, Sweden and Finland. This map locally satisfies the ice-marginal landform record observed in the DTMs. Our map of deglacial ice-margin positions captures those identified in the previous studies of Boulton et al. (2001) and Stroeven et al. (2016) (Fig. 2) but adds more detail in the central region of the ice sheet. The majority of our ice-margin positions that were previously reported in ice-sheet-wide maps are interpreted from large moraines (>250 m) or glaciofluvial fans and deltas, with many of them falling within the Younger Dryas ice-marginal zone (Munthe, 1910;



(caption on next page)

Fig. 12. Distribution of ice-margin positions from the last deglaciation identified across the study area coloured by the dominant ice-marginal landform used to interpret the ice-margin position. This map is available as a poster (A0 size) and GIS shapefile as part of the supplementary material. Abbreviations correspond to previously named ice-marginal zones referred to in the text: HC = Halland Coastal Moraine, MSEMZ = Middle-Swedish End Moraine Zone, VK = Veiki moraines, LM = Lund Moraine, Ss I = Salpausselkä I, Ss II = Salpausselkä II, Ss III = Salpausselkä III, R = Rugozero, K = Kalevala, CFIMF = Central Finland Ice Marginal Formation, Gö = Göteborg Moraine, Be = Berghem Moraine and L = Levene Moraine (Stroeven et al., 2016 and references therein; Boyes et al., 2024; Regnéll. et al., 2023a). Locations mentioned in the text are shown.

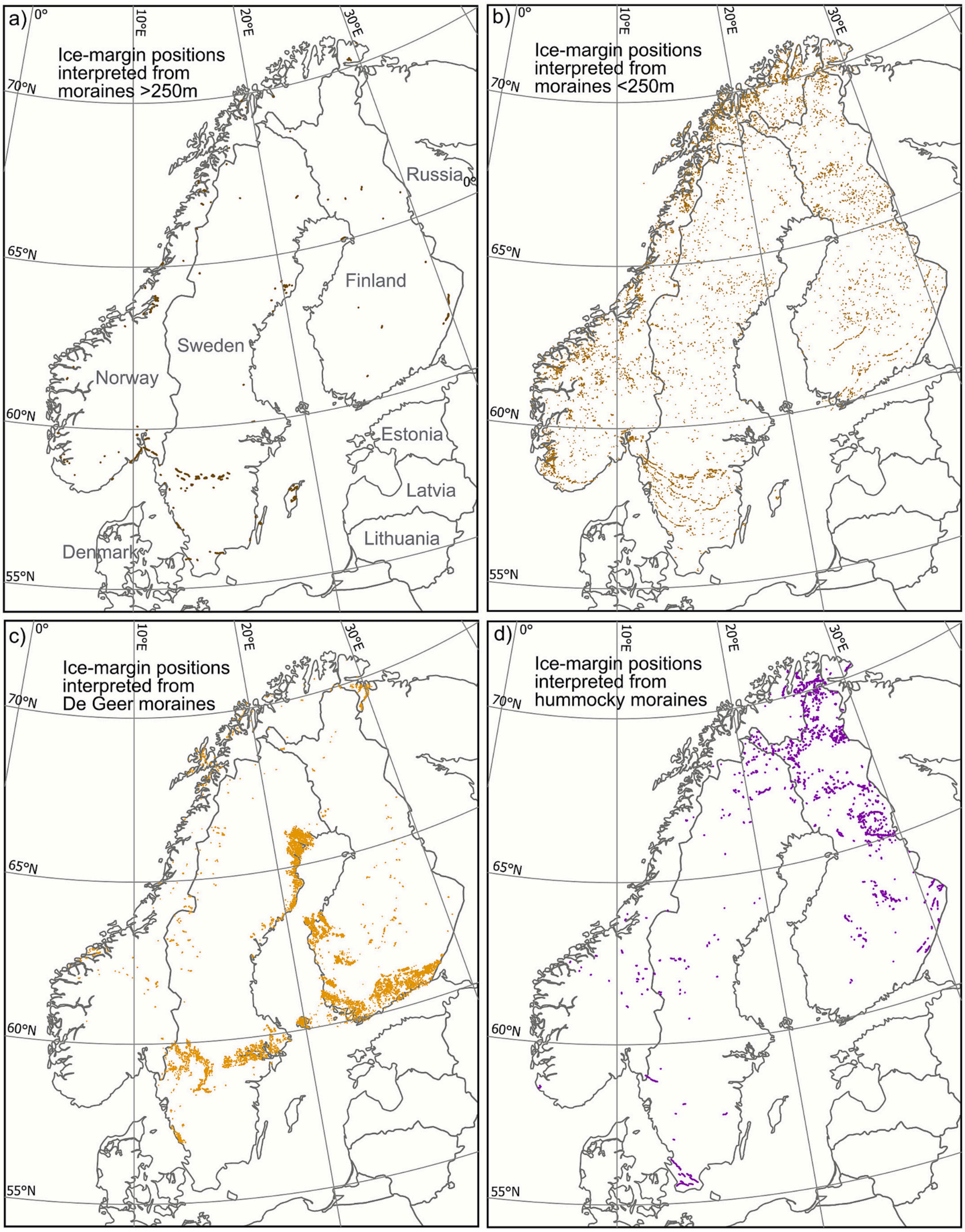


Fig. 13. Distribution of deglacial ice-margin positions interpreted from a) large moraines (>250 m), b) small moraines (<250 m), c) De Geer moraines and d) hummocky moraines. Distribution of deglacial ice-margin positions interpreted from e) ice-marginal meltwater channels and f) glaciofluvial fans and deltas.

Andersen, 1979; Andersen et al., 1995a, 1995b; Berglund, 1979; Mangerud et al., 1979, 2023; Sollid and Sørbel, 1979; Björck and Digerfeldt, 1984; Punkari, 1980, 1982, 1985, 1989, 1997; Glückert, 1995; Lundqvist, 1995; Rainio et al., 1995; Hughes et al., 2016; Stroeven et al., 2016; Johnson et al., 2019).

The main reason that we are able to interpret more ice-margin positions in the interior region of the ice sheet is that the high-resolution, bare-earth DTMs allow more landforms to be observed than in the

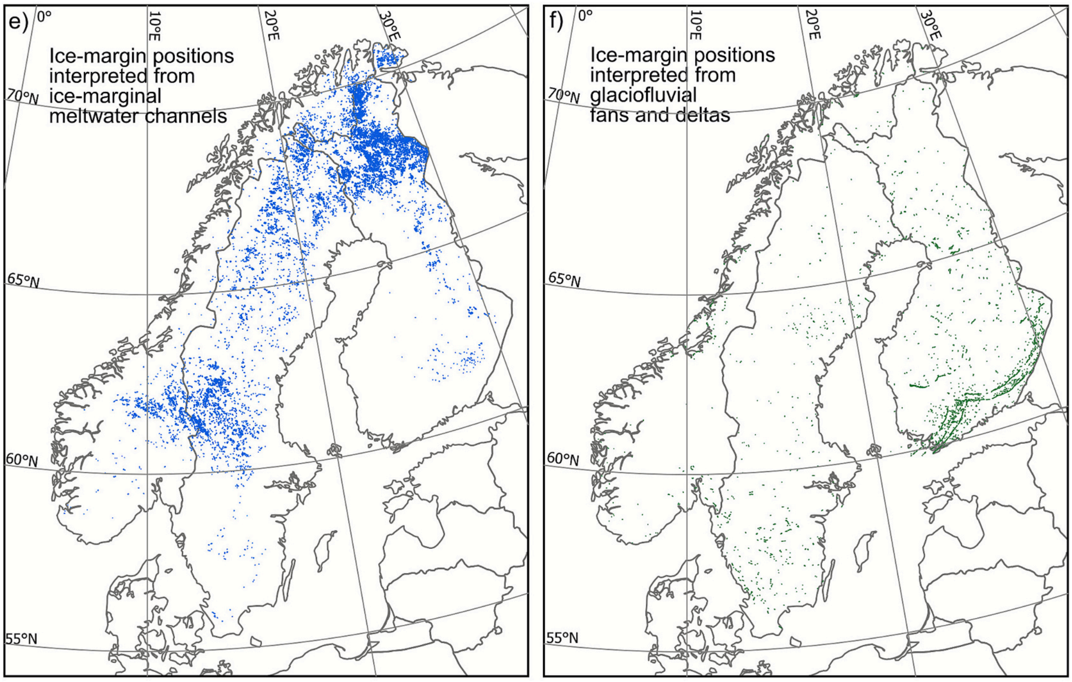


Fig. 13. (*continued*).

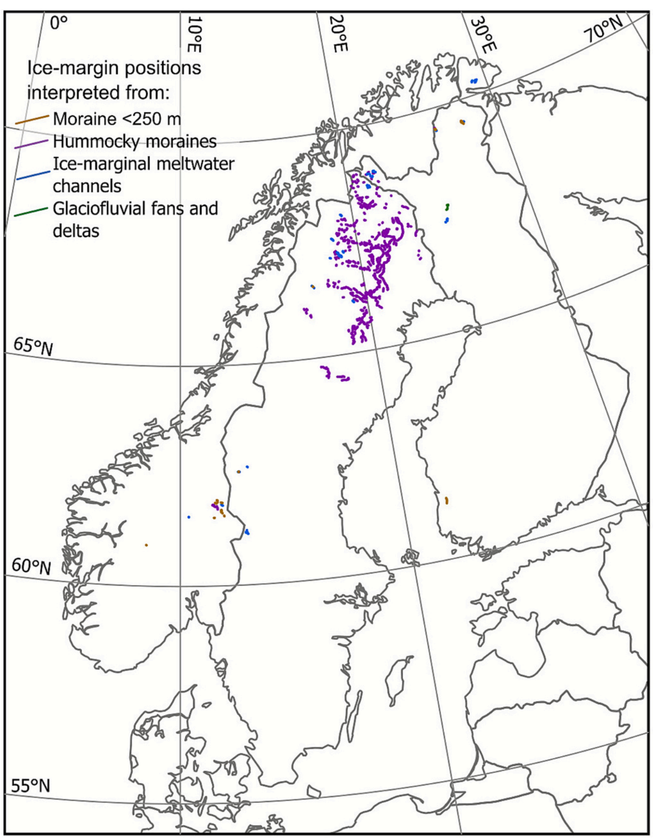


Fig. 14. The distribution of pre-LGM ice-margin positions coloured by the dominant ice-marginal landform used to interpret the margin position. Most of these ice-margin positions are located in northern Sweden and are interpreted from hummocky moraines.

satellite imagery used by Boulton et al. (2001). In the interior region of the ice sheet most margins are predominantly interpreted from De Geer moraines, meltwater channels, small moraines (<250 m wide), and hummocky moraines, and with the exception of hummocky moraines, these landforms all have small dimensions (generally <250 m wide and have low relief).

De Geer moraines have not previously been systematically mapped and explicitly used to build deglacial margin reconstructions across the ice sheet (e.g. Boulton et al., 2001; Stroeven et al., 2016). However, most are well known and have been mapped on a national to regional scale across Norway, Sweden and Finland (Sollid et al., 1973; Sollid and Carlsson, 1984; Larson et al., 1991; Blake, 2000; Bouvier et al., 2015; Ojala, 2016; Høgaas and Longva, 2018; Regnéll. et al., 2019, 2023b; Öhrling et al., 2020). Our ice-margin positions interpreted from De Geer moraines (Fig. 13c) replicate the known distribution of De Geer moraines across all three countries. This is likely because although De Geer moraines have small dimensions (typically <50 m) wide, the most recent studies have also used high resolution LiDAR-derived DTM data to map the landforms (e.g. Bouvier et al., 2015; Ojala, 2016; Høgaas and Longva, 2018; Regnéll. et al., 2019, 2023b; Öhrling et al., 2020).

Through the mountains of Norway, central and northern Sweden and northern Finland our ice-margin positions are mostly interpreted from ice-marginal meltwater channels (Fig. 13e). These have long been recognised in the mountains of Norway and Sweden (e.g. Mannerfelt, 1949; Kleman et al., 1992; Borgström, 1999) and have also been mapped in the upland areas of northern Finland (e.g. Geologian tutkimuskeskus, 2018). Thus, our ice-margin positions interpreted from meltwater channels replicates the known distribution of such channels.

Hummocky moraines have mostly already been identified in the literature, but have not been consistently mapped across the study area. Thus, our mapping (Fig. 13d) improves on our knowledge of this ice-margin type at the ice-sheet-scale. For example, on the southernmost tip of Sweden (Skåne), our ice-margin positions interpreted from hummocky moraines coincide with hummocky moraines with circular flat-topped features interpreted as ice-walled lake plains by Lidmar-Bergström et al. (1991). In Jæren, southwest Norway, we find that our

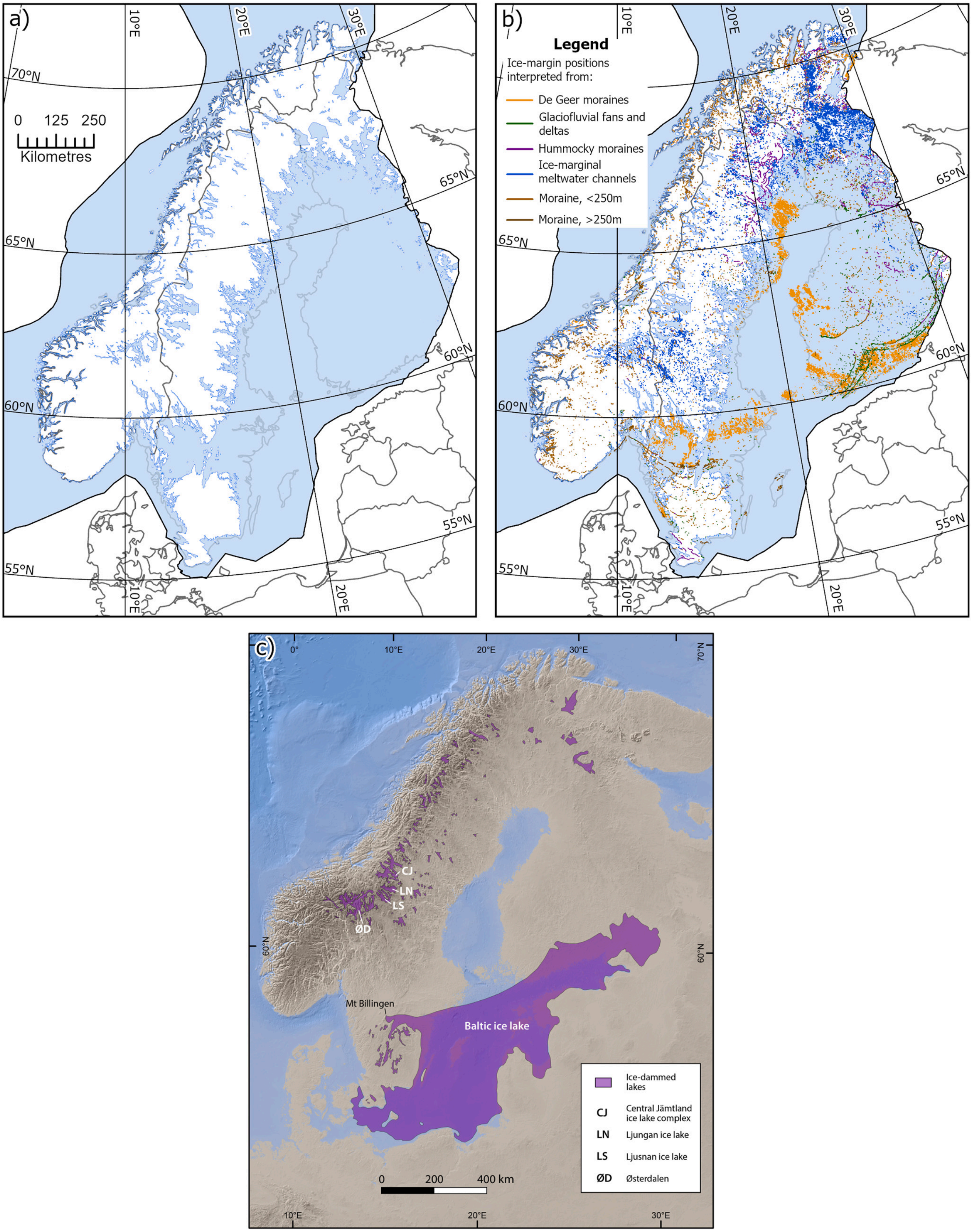


Fig. 15. a) Total estimate of the zone of potential aqueous ice sheet termination across our study during the last deglaciation (blue shading combines both marine and lacustrine environments). The black outline shows the reconstructed region (i.e. the extent in northern Europe has not been estimated). See Section 4.4 for a description of how this map was derived. b) Deglacial ice-margin positions coloured by their dominant ice-marginal landform, overlaid on the zone of potential aqueous ice sheet termination. This demonstrates that a large proportion (44%) of ice-margins were likely to have been deposited in a lake or the sea during deglaciation. c) Reconstructed ice-dammed lakes from Stroeven et al. (2016) used to constrain their ice-margin retreat pattern.

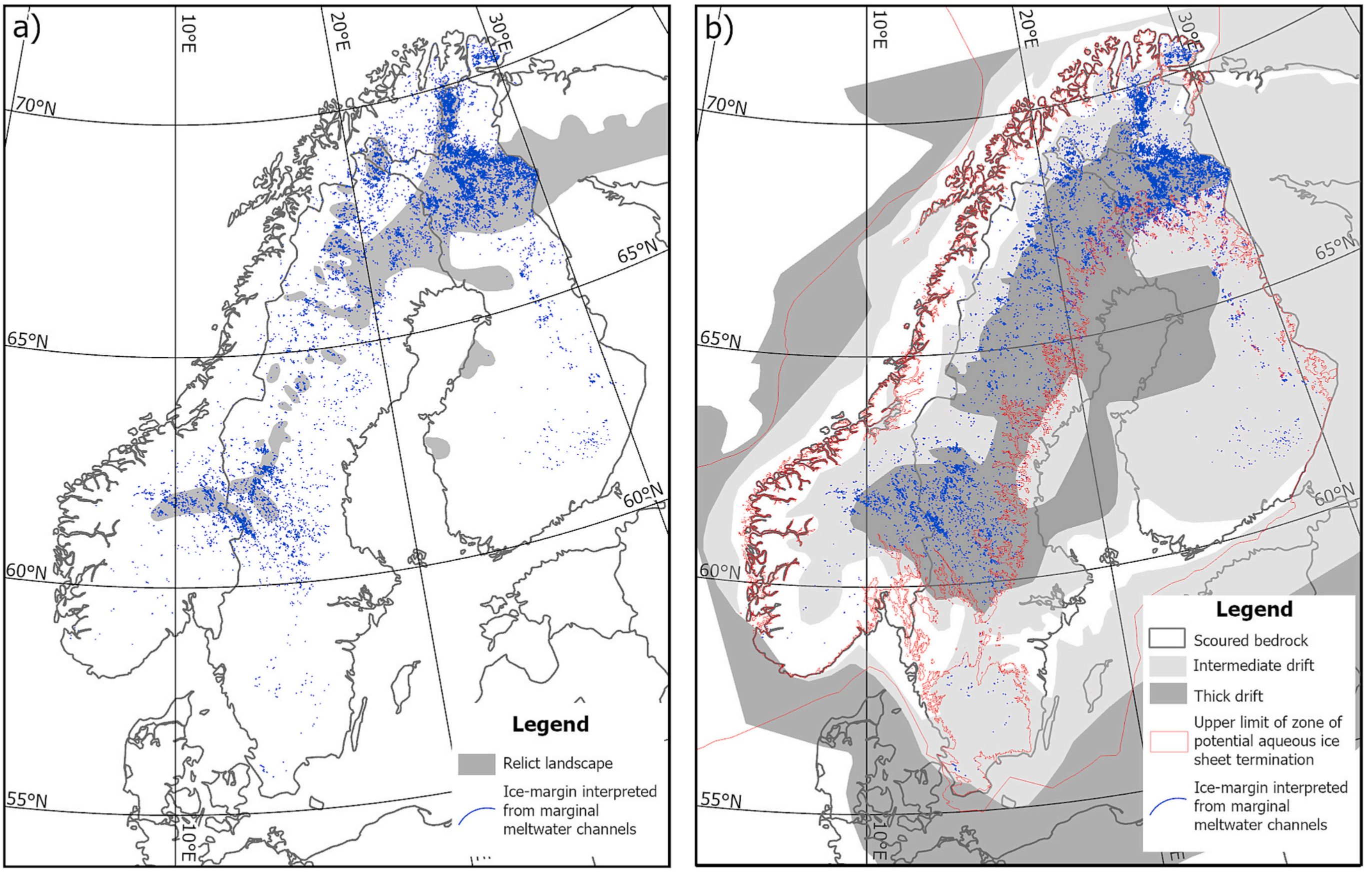


Fig. 16. a) Spatial overlap between ice-margin positions interpreted from ice-marginal meltwater channels and previously mapped areas of inferred cold-based ice (Kleman et al., 1997; Kleman and Hättestrand, 1999). This demonstrates some preferential occurrence in places but a mostly weak coincidence between the two. b) Spatial overlap between ice-margin positions interpreted from ice-marginal meltwater channels and areas of thick and intermediate "drift" cover (redrawn from Kleman et al., 2008). The red outline shows the upper limit of the marine or lake extent during deglaciation (see Section 5.3). Within terrestrial environments there is a strong overlap between ice-marginal meltwater channels and thick or intermediate drift.

mapped ice margins match well with the hummocky moraines and ice-margin positions reported in Knudsen et al. (2006). However, as understanding of the genesis of hummocky moraines has changed over time, this has led to some confusion as to what hummocky moraines actually is (see Section 3.3 Hummocky Moraines). There are some instances where our mapped margins do not correlate with the distributions of hummocky moraines in the literature. For example, hummocky moraines have been previously mapped over large areas of southeast Sweden (potentially correlating with the Göteborg moraine further west) and interpreted to be deposited by stagnating or down-wasting ice (Björck, 1987; Möller, 1987; Andersson, 1998; Lundqvist and Wohlfarth, 2001). We do not map ice-margin positions here because we find most of this hummocky material is located within flow-parallel meltwater corridors. This is supported by the recent interpretation that this hummocky material was deposited by subglacial meltwater rather than at the ice sheet margins (Peterson et al., 2018; Peterson and Johnson, 2018; Öhrling et al., 2020). Another example is the so-called Pulju moraines in the Puljutunturi area northern Finland (Kujansuu, 1967). They consist of mounds, ridges and circular flat-topped features, which show morphological similarities to the Veiki moraine in northern Sweden, and thus they have been hypothesised to be an extension of the Veiki moraine (Aartolahti, 1974; Lagerbäck, 1988). However, more recently, it has been hypothesised that Pulju moraines are a subglacial deformation landform associated with late-glacial earthquakes (Sutinen et al., 2014, 2018). We do not resolve this clash of interpretations. Based on the morphology of the hummocky material observed in the DTMs and owing to their similarity with known ice-marginal hummocky moraines elsewhere in Fennoscandia (Sollid and Sørbel, 1988; Boyes et al., 2021, 2024), we choose to map some features as deglacial ice-margin positions in the Puljutunturi area that are coincident with the Pulju moraines.

6.1.2. Pre-LGM ice-margin positions

Most ice-margin positions that we interpreted to have formed prior to the last deglaciation based on cross-cutting landform relationships (Fig. 14), have been previously identified as relict landforms. For example, all of the pre-LGM ice-margin positions interpreted from hummocky moraines in northern Sweden correlate with the Veiki moraine (Lagerbäck, 1988; Hättestrand, 1998). The Veiki moraines have long been considered to have survived through the last deglaciation (Fredholm, 1886; Lundqvist, 1981; Lagerbäck, 1988; Hättestrand, 1998) and optically stimulated luminescence ages suggest that they were deposited by an intermediate-sized ice sheet during MIS 3 (between 56 and 39 ka; Alexanderson et al., 2022). In northern Sweden, the pre-LGM ice-margin positions interpreted from moraines and ice-marginal meltwater channels align with those mapped by Kleman et al. (1992). However, we do not assign all the ice-margin positions that correspond to landforms mapped by Kleman et al. (1992) as pre-LGM because we make this assessment based on cross-cutting landform relationships alone, while Kleman et al. (1992) also used degraded landform morphology and landform orientation as criteria for interpreting these landforms. Similarly, we do not interpret the ice-margin positions that are coincident with the Pulju moraines, which are hypothesised to be an extension of the Veiki moraines (Aartolahti, 1974; Lagerbäck, 1988), to have formed prior to the last deglaciation because we do not observe any cross-cutting landform relationships along these ice margins. Further south, the pre-LGM ice-margin positions interpreted from ice-marginal meltwater channels in the Transtrand Mountains correlate with those recognised by Kleman et al. (1992) to have formed before the last deglaciation. Further, we interpret pre-LGM margins from hummocky moraines, moraines and ice-marginal meltwater channels in the neighbouring Norwegian mountains.

6.1.3. Zone of potential aqueous ice sheet termination

Around the present-day coastline of Norway, Sweden, and Finland, the upper altitudinal extent of the zone of potential aqueous ice sheet termination is similar to empirical measurements of the highest shoreline, or marine limit (Påsse and Andersson, 2005; Creel et al., 2022; Regnéll. et al., 2024), which supports the validity of our approach. In the inland regions, the zone is comparable to previous reconstructions of ice-dammed lakes in Finland (Johansson, 2007), Sweden (Regnéll. et al., 2019, 2023b) and Norway (Høgaas and Longva, 2018). They are also similar to the ice-dammed lakes reconstructed by Stroeven et al. (2016) that formed along the western side of the ice sheet as it retreated in the mountains of Norway and Sweden (Fig. 15c). However, our aqueous margin zone misses the ice-dammed lakes along the eastern side of the retreating ice sheet in central Sweden (e.g. Stroeven et al., 2016; Regnéll. et al., 2025) because we did not observe shorelines in the DTMs in these locations. This could indicate that either the shorelines are below the resolution of the DTM data or the lakes were short-lived and did not leave behind palaeo-shoreline evidence. Our zone of potential aqueous ice sheet termination also differs from the ice-dammed lake reconstructions of Stroeven et al. (2016) in northern Finland, where Stroeven et al. (2016) do not reconstruct the Muonio Ice Lake, and in southern Sweden, where we are unable to reconstruct ice-dammed lakes because they drain into the sea, which suggests the palaeotopographic data may not be accurate in this area.

6.2. Controls on the distribution of types of ice-margin positions

Ice-margin positions interpreted from small moraines (<250 m) occur relatively consistently across the study area, while the other ice-margin types tend to be concentrated in specific regions (Fig. 13). Below we discuss controls on the distribution of ice-margin positions interpreted from different types of ice-marginal landforms and investigate differences between terrestrial and aqueous ice sheet terminating environments.

6.2.1. Ice-margin positions interpreted from meltwater channels

Ice-margin positions interpreted from meltwater channels are abundant in the interior region of the ice sheet, in central and northern Sweden, central and northern Norway, and northern Finland (Fig. 13e). They are often thought to have formed exclusively where the ice sheet is frozen to the ground at cold-based ice margins. In such cases, meltwater cannot penetrate to the bed and therefore, runs off the ice surface, eroding ice-marginal channels along the confining valley slope (Kleman et al., 1992; Dyke, 1993; Sollid and Sørbel, 1994; Greenwood et al., 2007).

Areas of inferred cold basal ice have been previously reconstructed in the interior region of the ice sheet (Kleman et al., 1992, 1997; Kleman and Hättestrand, 1999; Goodfellow, 2007; Kleman and Glasser, 2007) and many of the ice-margin positions interpreted from ice-marginal meltwater channels are found to cluster around these areas (Fig. 16a). However, the connection between areas of reconstructed cold-based thermal regime and these ice-marginal meltwater channels landforms is not clear-cut. For example, eskers formed during the most recent deglaciation (Dewald et al., 2022), and which form under warm based conditions, occur adjacent to many of the ice-margin positions interpreted from ice-marginal meltwater channels within our dataset. This is consistent with ice-marginal meltwater channels that are being formed in Alaska today at the margins of glaciers with temperate basal ice conditions (Syverson and Mickelson, 2009), and suggests that ice-marginal meltwater channels are not a clear diagnostic indicator of the presence of cold basal ice.

Other factors that may control the distribution of ice-margin positions interpreted from ice-marginal meltwater channels include meltwater availability, ice retreat rates (regarding the time required to cut a channel), steepness of the ice surface profile in relation to adjacent slopes, height of the equilibrium line altitude and sediment thickness. When these landforms have been placed into a reconstruction of deglaciation within an absolute time framework it might permit assessment of controls relating to climate (on varying meltwater production; e.g. Storrar et al., 2014) or the amount of time available to erode or deposit landforms along the ice margins, but this is beyond the scope of this paper.

During deglaciation, the SIS was asymmetric in cross-profile, with steeper ice surface profiles on the western side compared to the east (Flint, 1947; Boulton et al., 2001; Larsen et al., 2016; Patton et al., 2017). As a greater number of ice-margin positions interpreted from ice-marginal meltwater channels were mapped on the eastern side of the ice sheet it follows that their distribution may be related to lower ice surface profiles. This is consistent with the long-held hypothesis that the ice-marginal meltwater channels in the mountains of Norway and Sweden were produced by ice sheet thinning which created low angled ice lobes (Mannerfelt, 1945; Garnes and Bergersen, 1980; Kleman et al., 1997; Hättestrand, 1998; Romundset et al., 2023). Therefore, the flights of ice-marginal channels record vertical lowering during deglaciation as well as back-stepping ice margin positions.

Fig. 16b shows that above the elevation of potential aqueous ice sheet termination, mapped ice-margin positions interpreted from ice-marginal meltwater channels have a good correspondence with the distribution of thick and intermediate drift cover and they are almost absent from areas of scoured bedrock (Kleman et al., 2008). Therefore, we propose that sediment cover is a dominant control on the distribution of ice-margin positions interpreted from ice-marginal meltwater channels. This is because much less energy is required to erode channels into sediment compared with bedrock (Whitbread et al., 2015), and this is especially relevant when margins are rapidly back-stepping, which limits the time available for erosion.

6.2.2. Ice-margin positions interpreted from hummocky moraines

Ice-margin positions interpreted from hummocky moraines are primarily located in the northern sector of the study area - 83% are located above 65°N (Fig. 13d) – and a similar latitudinal preference is observed in the Russian sector of the ice sheet (Korsakova et al., 2023; Boyes et al., 2024) as well as in North America (Prest et al., 1968; Fulton, 1995; Dyke and Savelle, 2000; Dyke and Evans, 2003; Evans et al., 2021; Dulfer et al., 2023; Stoker et al., 2025). This stark latitudinal contrast suggests a climatic control on their formation, as first hypothesised by Sollid and Sørbel (1988).

We find that ice-margin positions interpreted from hummocky moraine are located in three topographic settings. Firstly, these ice-margin positions present themselves on lowland landscapes as arcuate belts that can be many hundreds of metres wide, and in some places are bounded by ridges of sediment (e.g. Fig. 4). They are predominately located in the north, and include ice-margin positions that align with the Veiki and Pulju moraines, but there are isolated examples mapped in southern Finland and Sweden (Skåne). These landforms are widely thought to be representative of ice-margins that have undergone readvances followed by ice stagnation and downwasting of ice-cored sediment (Lagerbäck, 1988; Sollid and Sørbel, 1988; Ham and Attig, 1996; Evans, 2009; Boyes et al., 2024; Stoker et al., 2025; Vashkov and Nosova, 2024). In a subpolar climate with permafrost conditions (e.g. which occurs in Svalbard today) glaciers are more likely to have a polythermal regime with cold-based conditions around the periphery of the ice and temperate conditions up ice (Sollid and Sørbel, 1988). In this basal thermal regime, debris can freeze to the base of the ice at the transition between temperate and cold-based ice and be carried upwards in the ice by shearing, eventually being deposited on the ice surface

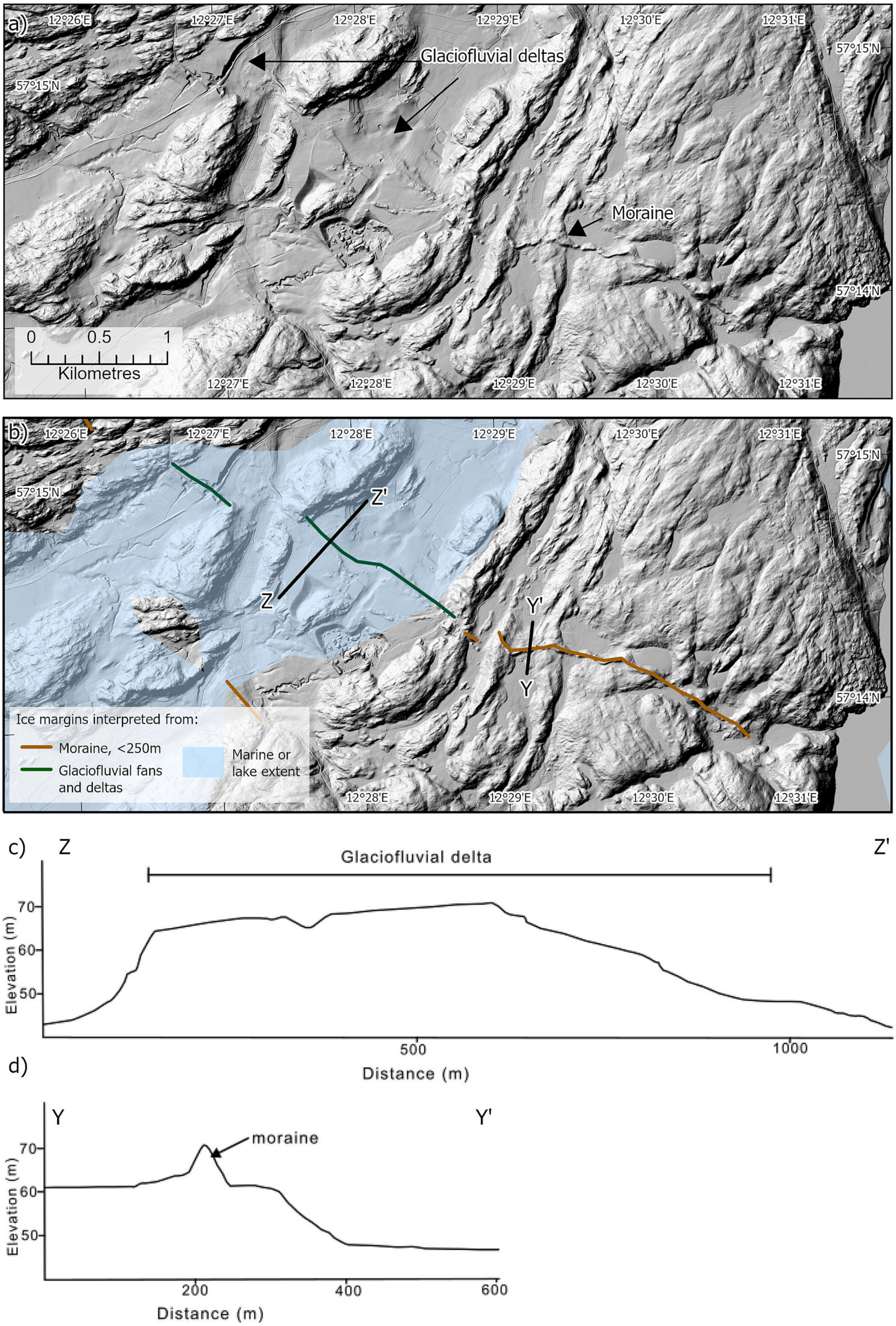


Fig. 17. a) DTM derived shaded relief map (Swedish Ordnance Survey, Lantmäteriet, n.d) and b) ice-margin positions interpreted from moraines <250 m wide (brown) and glaciofluvial fans and deltas (green). The zone of potential aqueous ice sheet termination is shown by the blue shading. Elevation profiles showing the difference in the size of adjacent ice-marginal landforms deposited into c) a lake or the sea (profile Z - Z') and d) on land (profile Y - Y′). As in this example, landforms deposited into the sea or a lake are larger than those deposited on land. The location of this figure is shown in Fig. 1.

forming a debris-rich tongue (Sollid and Sørbel, 1988; Hambrey et al., 1997; Dyke and Evans, 2003; Reinardy et al., 2019; Vashkov and Nosova, 2024). The debris-covered ice tongue and ice-cored sediment then detach from the retreating ice and down-waste, leading to the formation of the irregular surface of mounds and ridges that are interpreted as hummocky moraines (Lagerbäck, 1988; Sollid and Sørbel, 1988; Hättestrand, 1998; Dyke and Savelle, 2000; Lukas et al., 2005; Boyes et al., 2024; Vashkov and Nosova, 2024). Using this mechanism Sollid and Sørbel (1988) hypothesised that subpolar climate conditions were required in northern Fennoscandia and this explains this ice-margin type across our study area. For example, this hypothesis can also be used to explain the distribution of hummocky moraines in southern Sweden, which deglaciated shortly after the Last Glacial Maximum, when climate conditions were still cold (Buizert et al., 2014; Rasmussen et al., 2014; Denton et al., 2022).

The second topographic setting of our mapped ice-margin positions interpreted from hummocky moraines is upland locations at or near mountain summits. These are found primarily in northern Finland and there are some scattered examples in the southern Scandinavian mountains. We suggest that hummocky moraines arise in these isolated locations due to ice stagnation where sediment-rich ice near summits detaches and becomes separated from retreating ice in the valleys (Stoker et al., 2025). The spatial distribution of these upland hummocky moraines may be controlled by the retreat direction of the ice sheet. In central Sweden, margins are thought to have retreated away from the Scandinavian mountains towards the east during deglaciation, proceeding in a down-valley direction. This circumstance provided an opportunity for upland ice to detach from the ice sheet during deglaciation (Johansson, 1988; Regnéll. et al., 2019; Boyes et al., 2023, 2024). In contrast, in southern Norway the SIS retreated up valley into the Scandinavian mountains of southern Norway (Stroeven et al., 2016; Romundset et al., 2023). Thus, at least in Fennoscandia, upland ice-margin positions interpreted from hummocky moraines may be more likely where the ice-margin retreated down-valley during deglaciation rather than retreating into the mountains. The comparative paucity of mapped ice-margin positions interpreted from hummocky moraines in the upland areas of the southern Scandinavian mountains suggests that such ice detachment was less common here.

Finally, ice-margin positions interpreted from hummocky moraines are also found in Finland at the lateral margins of former ice lobes, such as the Finnish Lake District and Kuusamo lobes (Putkinen et al., 2017a). While these spreads of hummocky moraines may indicate ice-margin positions, alternatively they may signify interlobate deposits of the former ice lobes (Punkari, 1997; Gruszka et al., 2012), similar to the interlobate margins of the western Laurentide Ice Sheet (Norris et al., 2024; Stoker et al., 2025).

6.2.3. *Variation in size of ice-marginal landforms deposited on land versus in water*

In comparison of ice-marginal landforms deposited in the water versus those on land, there are notable differences in their size and sediment volume. In the zone of aqueous ice sheet termination (Fig. 15), moraines and glaciofluvial fans and deltas, are generally much larger in height and width, than landforms that were deposited at ice margins on land (Fig. 17). This is also highlighted by our finding that 84% of mapped ice-margin positions interpreted from large moraines (>250 m width) were deposited into the sea or a lake (Fig. 15b; 218 out of 259 ice-margin positions). The widely studied Salpausselkä ice-margin positions in Finland are prominent examples of this with high volumes of sediment accumulation. They comprise glaciofluvial sand and gravels deposited as subaqueous fans and deltas (Fig. 12; Fyfe, 1990; Palmu, 1999; Rainio et al., 1995; Lunkka et al., 2019) forming landforms of 20 to 70 m in relief. They were built during major readvances and/or standstills of the ice margin and their large size has been interpreted to be due to ice margin stability for a long period of time to enable the sedimentation (Rainio et al., 1995; Lunkka et al., 2019; Boyes et al., 2024). However, adjacent major ice-marginal landforms that were deposited on land have a much smaller size, such as those that extend into northwest Russia at a similar time (e.g. the Kalevala and Rugozero ice margins; Ekman and Iljin, 1991; Niemelä et al., 1993; Boyes and Pearce, 2023; Boyes et al., 2024).

We suggest that the difference in size of juxtaposed ice-marginal landforms deposited on land vs an aqueous environment (marine or lacustrine), is mostly controlled by differences in depositional processes. In terrestrial environments, a high proportion of the sediment is transported and redistributed away from the ice margin by proglacial rivers (Hammer and Smith, 1983; Marren, 2005; Carrivick and Tweed, 2021) acting against large sediment build-up. Moraines are then often formed by the bulldozing and deformation of pre-existing sediments directly in front of the ice margin, and thus the size is limited by the sediment availability in the terrestrial proglacial environment. However, when sediment is discharged from englacial or subglacial streams into a standing body of water, the coarse sediment is deposited directly at the ice margin while the finer material can be transported away in sediment plumes (Powell et al., 1990; Lønne, 1995; Ashley and Smith, 2000). Some of the sediment within the glaciofluvial fans and deltas may then be redistributed through sediment gravity flows or turbidity currents but most of the sediment deposited at the ice margin remains nearby, producing larger ice-marginal landforms than their terrestrial counterparts. It is thus likely that the depositional environment rather than sedimentation time is the main control of sediment volume and size of these ice-marginal landforms.

7. Summary and conclusions

We report a new method and workflow for systematically mapping former ice-marginal positions from high-resolution remotely sensed DTMs. This method permitted us to produce a consistent map of ~51,000 of ice-marginal indicators spread across all onshore areas of Norway, Sweden, and Finland, which has been made digitally available for further investigations and for use with ice sheet modelling.

We find differences in the densities and distributions of each ice-margin type across the study area. Ice-margin positions interpreted from moraines occur relatively evenly and are the main type mapped in Norway. Ice-margin positions interpreted from meltwater channels are abundant in the interior region of the ice sheet and we suggest that the presence of thick or intermediate sediment cover is a dominant control on their distribution because much less energy is required to erode channels in sediment compared with bedrock. This is especially so when the ice margin is withdrawing rapidly, limiting the time for erosion. Ice-margin positions interpreted from hummocky moraines are concentrated in the north of our study area, with 83% located above 65°N. In agreement with earlier ideas from the literature, we regard that the high concentration of hummocky moraines at high latitudes arises from a climatic control on their formation, where they are more likely to form under polythermal basal regimes.

Using glacio-isostatically modelled DEMs of palaeo-topographies, combined with mapping of shoreline positions and published deglacial isochrones we estimated the cumulative zone of potential ice sheet termination into marine and lake environments during deglaciation. It represents a surprisingly large area of the total footprint of the Scandinavian Ice Sheet, and would be larger if account was made of ice-dammed lakes across northern Europe and in Russia. A reassuring correspondence is found between this modelled area of aqueous ice sheet termination and landforms such as De Geer moraines and glaciofluvial fans and deltas that are regarded as being formed in water. Ice-marginal landforms created in the sea or a lake were typically found to be larger in width and height than those deposited on land, which deserves further investigation regarding sediment budgets.

We suggest that this Fennoscandian ice-marginal record of the core area of ice sheet will require comparison and reconciliation with the peripheral areas along the continental shelf and in northern Europe and

Russia. Together they could be used as landform-derived templates for building ice sheet wide patterns of retreat, and could be combined with geochronometric dates to aid understanding of the pace and timing of ice sheet recession.

CRediT authorship contribution statement

H.E. Dulfer: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **B.M. Boyes:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **C.D. Clark:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **N. Dewald:** Writing – review & editing, Visualization, Methodology, Investigation. **F.E.G. Butcher:** Writing – review & editing, Visualization, Methodology. **J.C. Ely:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **A.L.C. Hughes:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2026.110194.

Data availability

The ice-margin position shapefile and A0 map of the ice-margin positions are available as supplementary material. The DTM data can be downloaded from https://hoydedata.no/LaserInnsyn2/ for Norway, https://www.lantmateriet.se/en/geodata/our-products/product-list/elevation-model-download// for Sweden and https://www.maanmittauslaitos.fi/en/maps-and-spatial-data/datasets-and-interfaces/product-descriptions/elevation-model-2-m for Finland.

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