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Evaluation of the role of the Baltic depression during deglaciation of the last Scandinavian Ice Sheet; a landform-driven investigation

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Abstract. Landforms left behind by the last Scandinavian Ice Sheet (SIS) offer an opportunity to investigate controls governing ice sheet dynamics. Terrestrial sectors of the ice sheet have received considerable attention by landform and stratigraphic investigations, but much less so for marine areas such as in the Baltic Sea. In contrast, despite its geographical importance, the Baltic Sea remain poorly constrained due to limitations in bathymetric data. The Baltic depression hosted the extensive Baltic Ice Lake, which likely exerted a considerable control on ice dynamics, providing an aqueous calving front that might have resulted in rapid collapse of this ice sheet sector. Both ice sheet scale investigations and regional studies at the southern periphery of the SIS have considered the Baltic depression as a preferential conduit for ice flux towards the southern ice margin throughout the last glaciation. Here we test this hypothesis using newly available bathymetric data and peripheral topographic data. For the first time, these data reveal an extensive landform suite stretching from Denmark in the west to Estonia in the east and from the southern European coast to the Aland Sea, comprising an area of 0.3 million km^2. We use these landforms to reconstruct the ice dynamic history of the Baltic sector of the SIS. Landform evidence indicates a complex retreat pattern that changes from lobate ice margins with splaying lineations to parallel MSGL in the deeper depressions of the Baltic Basin. Ice margin still-stands on underlying geological structures indicate the likely importance of pinning points during deglaciation resulting in a stepped retreat signal. Over the length of the study area we identify broad changes in ice flow geometry, ranging from SE-NW to N-S and then to NW-SE. Mega-scale glacial lineations reveal distinct corridors of fast ice flow (ice streams) with widths of 30 up to 95 km, rather that the often-interpreted Baltic-wide (300 km) accelerated ice flow zone. These smaller ice streams are interpreted to have operated during late stages of deglaciation. Where previous ice sheet-scale investigations inferred a single ice source, our mapping identifies flow and ice marginal geometries from both Swedish and north Bothnian sources. We anticipate our landform mapping and interpretations may be used as a framework for more detailed empirical studies by identifying targets to acquire high resolution bathymetry and sediment cores and also for comparison with numerical ice sheet modelling.

1 Introduction

The Baltic depression (Fig. 1), currently occupied by the Baltic Sea, was a defining feature of the Scandinavian Ice Sheet (SIS) bed likely exerting considerable control on the direction of ice flow and position of ice margin during the last glaciation (Holmlund and Fastook, 1995; Patton et al., 2017; Patton et al., 2016; Stroeven et al., 2016). The depression has an amplitude of 200 to 300 m (Fig. 1D), and is positioned such that it may have acted as a conduit (very broad 'channel') facilitating ice evacuation from the main ice divide towards ice margins in the south. The topographic steering of ice flow may have been further enhanced by soft sediments, previously accumulated in the depression, reducing the basal shear stress and promoting faster ice flow velocities compared to surrounding bedrock shield areas (Amantov et al., 2011; Boulton and Jones, 1979; Boulton et al., 1985). Glacio-isostatic effects of ice loading increased the reverse-slope setting of the southern Baltic, impeding water evacuation from the ice margin (Larson et al., 2006; Uścinowicz, 2003). The ice margin retreating across the Baltic depression from its LGM position was thus water-terminating, impacting ice dynamics due to calving and sub-aqueous melting (e.g., Noormets and Flodén, 2002b, a; Uścinowicz, 1999).

Despite the factors, outlined above, that might have influenced the SIS geometry and ice dynamics, much of the glacial geomorphological record within the Baltic depression remains undocumented because it is obscured by the modern-day Baltic Sea. Here we have used a suite of newly available bathymetric and coastal datasets to map the glacial geomorphology across a ~310,000 km^2 region encompassing the current Baltic Sea floor and adjoining coastal areas (Fig. 1B). We present the first consistent sector-wide glacial landform map of the Baltic depression and use these data to reconstruct past ice flow geometries and major ice margin positions. Specifically, we use the mapped landform record to address the following questions:

1. Is there landform evidence that the Baltic depression played a prominent role in determining the maximum southern extent of the last Scandinavian Ice Sheet?
2. As has frequently been suggested from empirical and modelling investigations (Boulton et al., 1985; Patton et al., 2017; Patton et al., 2016; Punkari, 1997; Stephan, 2001), does the landform record support a depression-wide (300 km) Baltic Ice Stream during the LGM?
3. What was the character of ice margin retreat though the Baltic depression? Is there evidence of water-terminating calving ice fronts or lobate terrestrial-style margins?
4. To what extent did topographic pinning points arising from geological structures or lithological contrasts influence ice marginal retreat?

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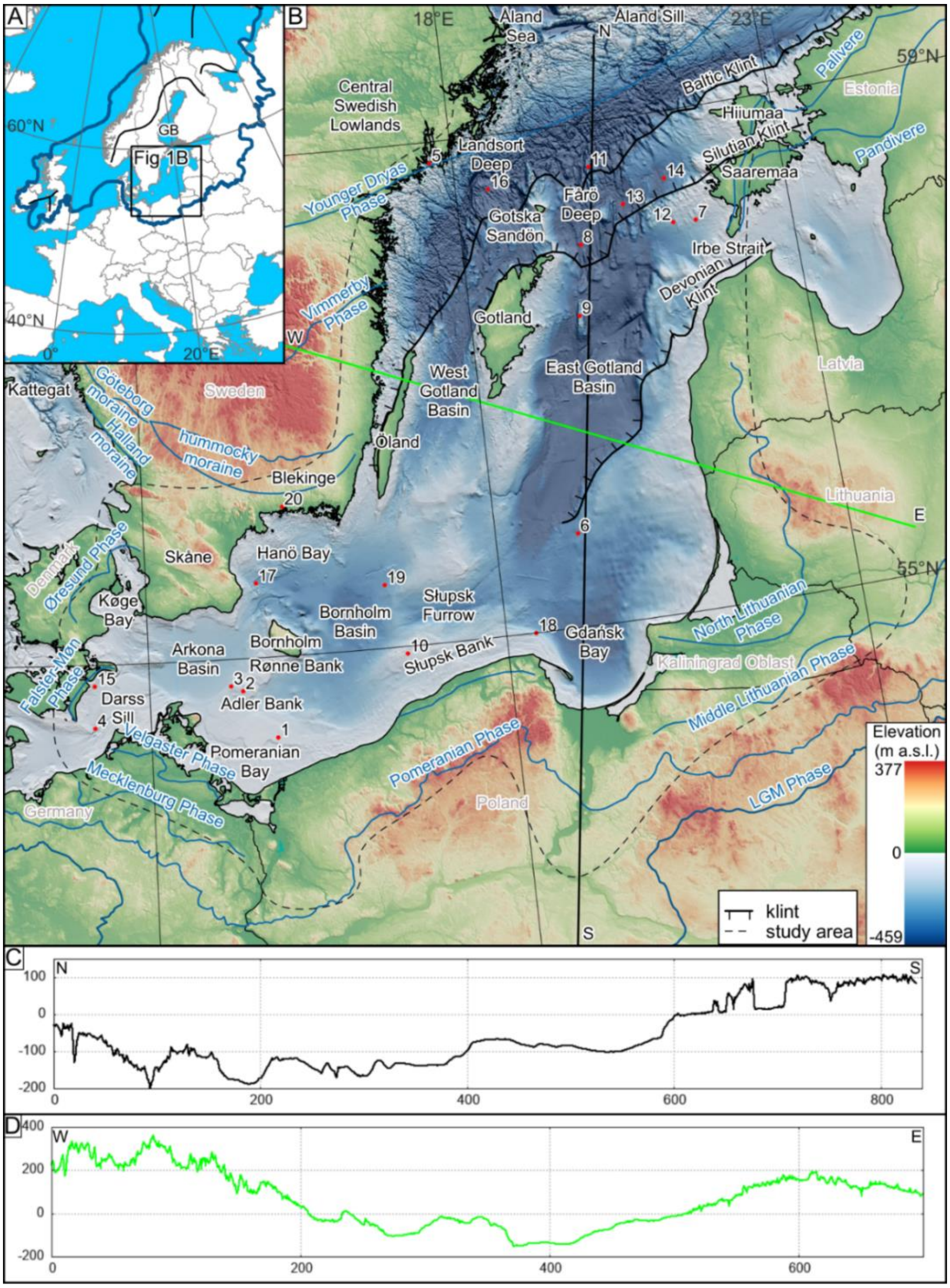


Figure 1: (A) Last Glacial Maximum extent over Europe (thick blue line; Svendsen et al. 2004). GB indicates Gulf of Bothnia, located north of study area. Black line indicates ice divides around LGM (after Kleman et al., 2008; Patton et al., 2016). The base map is from EuroGeographics and UN-FAO. (B) Study area, which covers the Baltic Sea and nearby coastal zone. Major terrestrial moraine systems are drawn in blue, with their names indicated. Red dots and associated numbers indicate key previous studies on offshore glacial landforms (see Table 1). The DEM is based on EU-DEM and EMODnet (see Table 2). (C) The N-S profile (see the black line in panel B) reveals a general upslope toward the south, which would have been even steeper during glaciation due to glacio-isostatic loading, and cuesta-like topography associated with geological steps at the Baltic Sea bottom. (D) The NW – SE profile (see the green line in panel B) depicts the ~ 400 km wide on-and-offshore depression divided by Gotland Island into two troughs: eastern and western along the East and West Gotland basins respectively.

Table 1: Key previous studies on offshore glacial landforms within the study area

Number in Fig. 1B	Localisation	Type of investigations	Referencess
1	Odra Bank	Stratigraphy based on sediment cores and radiocarbon dating	(Kramarska, 1998)
2	Adler Grund	Interpretation of glacial landforms based on hydroacoustic survey and seismic profiles	(Feldens et al., 2013)
3	SE Arkona Basin	Stratigraphy of glacial deposits inferred from seismic profiles and sediment cores	(Obst et al., 2017)
4	Darss Sill	Stratigraphy of sediments based on hydroacoustic survey and sediment cores	(Lemke and Kuijpers, 1995)
5	Stockholm Archipelago	Interpretation of landforms based on hydroacoustic and sub-bottom profiles	(Jakobsson et al., 2016)
6	Gdańsk-Gotland Sill	Analysis of iceberg and ice-keel ploughmarks based on hydroacoustic survey and sediment sampling	(Dorokhov et al., 2018)
7	W of Estonia	Interpretation of glacial deposits and landforms based on seismic profiles	(Noormets and Flodén, 2002a)
8	Around Fårö Deep	Interpretation of glacial deposits and landforms based on seismic profiles	(Noormets and Flodén, 2002b)
9	Klints Bank	Interpretation of seismic profiles	(Schäfer et al., 2021)
10	Southern Baltic	Interpretation of glacial landforms based on seismic profiles	(Uścinowicz, 1999)
11	The Baltic Klint	Interpretation of seismic profiles	(Tuuling and Flodén, 2016)
12	Silurian reefs, between Saaremaa and Gotland	Interpretation of seismic profiles	(Tuuling and Flodén, 2013)
13	between Gotland and Saarema	Interpretation of seismic profiles	(Tuuling and Flodén, 2001)
14	W of Estonia	Analysis of iceberg scours based on hydroacoustic survey	(Karpin et al., 2021)
15	Falster-Møn area	Interpretation of glacial deposits based on hydroacoustic survey and seismic profiles	(Jensen, 1993)
16	North of Gotland	Interpretation of seismic profiles	(All et al., 2006)
17	Hanö Bay	Stratigraphy of glacial deposits inferred from seismic profiles and sediment cores	(Björck et al., 1990)
18	Southern Baltic	Interpretation of glacial landforms based on seismic profiles	(Uścinowicz, 2003)
19	Arkona Basin, East Baltic	Analysis of glacial valleys (seismic profiles)	(Flodén et al., 1997)
20	Hanö Bay Stockholm Germany	Interpretation of hydroacustic survey	(Jakobsson et al., 2020)

1.1 Background: the role of the Baltic depression during the Last Glacial

75 The effects of the Baltic depression on the dynamics of the Last SIS have been discussed since the late 19th century (Madsen, 1898; Zeise, 1889; after Stephan, 2001). This includes evidence for a major, up to 130 degrees, switch in ice flow direction, from the south to west and north-westward in the region of the southern Baltic and Denmark. The north-westward and westward flow into Denmark, after the LGM, has subsequently been termed the Young Baltic Advances (Holmström, 1904; in Glückert, 1974; Stephan, 2001) (Fig. 2, arrow B1). Subsequently it was hypothesised that this change in ice flow direction

in the southern sector of the ice sheet was due to an eastward shift of the main ice divide (Ahlmann et al., 1942; Eissmann, 1967; Enquist, 1918; Ljunger, 1943; Woldstedt and Duphorn, 1974). An alternative explanation was that the uplands topography behind the German and Polish coasts caused ice to be redirected westward (e.g., Gripp, 1981 after Stephan 2001). Such a behaviour could be a consequence of increasing topographic dependence during deglaciation (Kjær et al., 2003). Lithostratigraphy and striae analysis by Ringberg (1988) indicated that reduced ice supply over Sweden caused the Baltic Ice Stream to turn westwards into Denmark when the ice sheet was retreating from its maximum extent (Fig. 2, B1). The westward ice flow redirection was also modelled by Boulton et al. (1985). North-westward flow into Skåne and Denmark has also been suggested for the period prior to the maximum ice sheet extent (termed the Old Baltic Advance, Ringberg, 1988), based on the lithostratigraphy of till deposited in Denmark and striae orientations.

Boulton et al. (2001) conducted one of the earliest satellite-driven mapping campaigns of glacial lineations at the ice sheet scale, resulting in possible ice stream configurations during ice sheet retreat (Fig. 2). Subsequent landform investigations using higher resolution data identified potential palaeo-ice streams in the marine and terrestrial record within- and surrounding the Baltic Sea, based on the identification of Mega-Scale Glacial Lineations (MSGLs) (Greenwood et al., 2016; Jögensen and Piotrowski, 2003; Kalm, 2012; Szuman et al., 2021). These ice streaming imprints commonly conform to local topographic depressions indicating that topography played a role on flow geometry, at least regionally, during ice retreat.

As our observational record of modern ice sheet dynamics expanded, so did the idea the Baltic depression facilitating an ice stream that operated throughout the last glacial (Holmlund and Fastook, 1995; Patton et al., 2017; Patton et al., 2016; Stroeven et al., 2016). Numerical ice sheet modelling efforts focused on the SIS generally input basal shear stress values based on substrate and the assumed existence of ice streams (Holmlund and Fastook, 1995; Patton et al., 2017; Patton et al., 2016), resulting in synchronous, Baltic-wide ice streaming in the low-shear-stress regions. It therefore remains difficult to determine whether the Baltic ice streams suggested by some of these earlier studies are realistic.

Sector-scale landform mapping has been carried out for the Bothnian Basin from high resolution bathymetry data (Greenwood et al., 2015; Greenwood et al., 2016). These data revealed early Holocene ice streaming, documented by cross cutting glacial lineations and an abundance of meltwater landforms and crevasses-squeeze ridges (e.g., Greenwood et al., 2016). In contrast, patchy bathymetric data has limited investigations in the Baltic depression to localized reconstruction and extrapolation from nearby terrestrial records (Boulton et al., 2001; Cuzzone et al., 2016; Kleman et al., 1997), mixed with inferences from glaciological intuitions and hunches (Fig. 1).

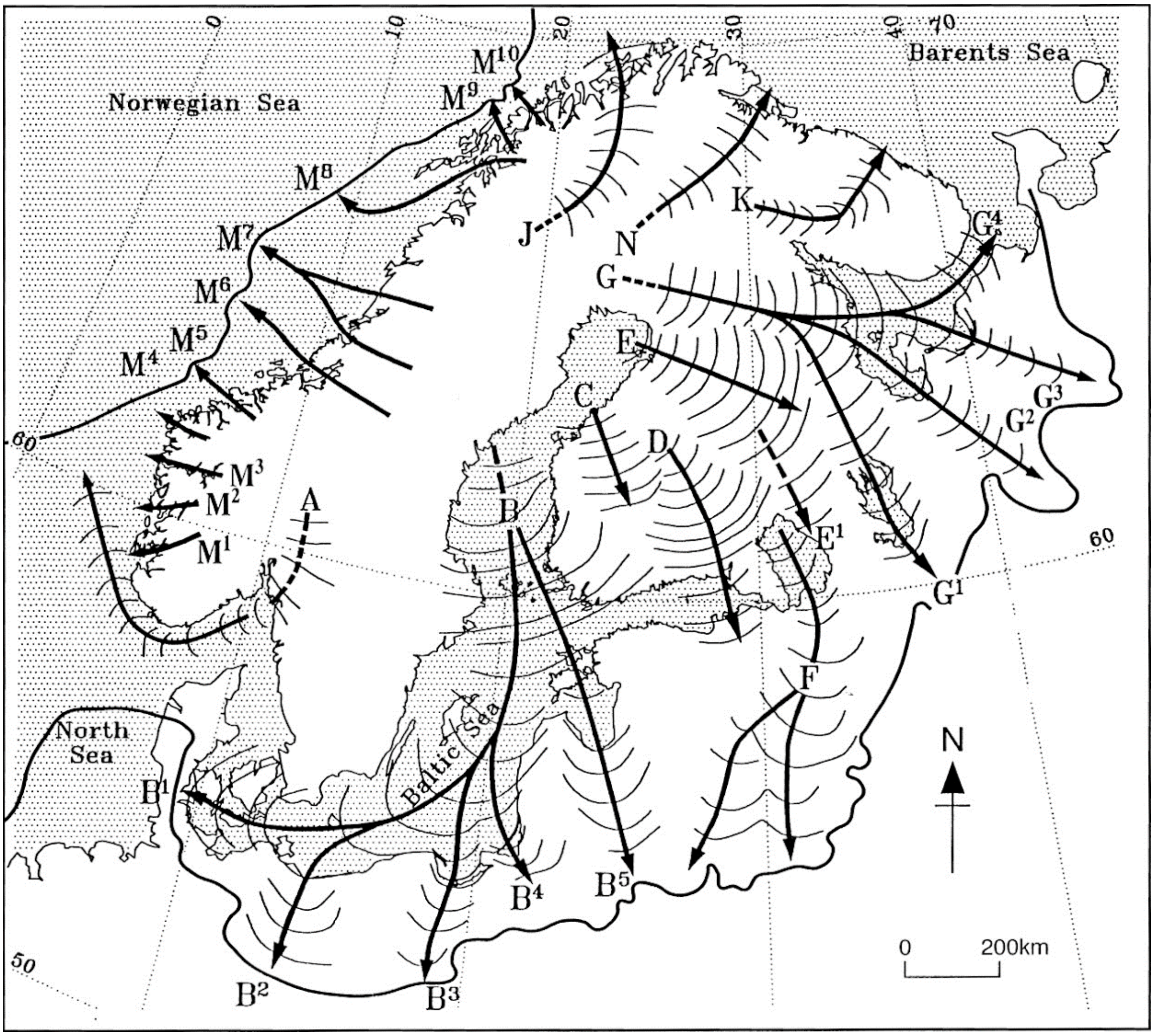


Figure 2. An early depiction of time-transgressive ice stream trajectories with associated back-stepping ice margins after Boulton et al. (2001; Reprinted from Quaternary Science Reviews, 20/9, Boulton, G.S., Dongelmans P., Punkari, M., Broadgate, M., Palaeoglaciology of an ice sheet through a glacial cycle: the European ice sheet through the Weichselian, 591-625, Copyright (2001), with permission from Elsevier). The Baltic Sea depression is inferred to control the ice stream location but note that this depiction does not imply a synchronous Baltic Ice Stream of this length (>1000 km) branching into B1 to B4. Instead, it depicts numerous short length (<300 km) ice streams on land (B1 to B4) that, once back-stepped into the Baltic depression, eventually merged into a single ice stream. No submarine evidence was available at the time Boulton et al. (2001) drew the figure and it is a purpose of this paper to seek information about the footprint of this ice stream and its likely width. The relative timing of the ice streams draining the Baltic depression has been established only partially, with Kjær et al. (2003) and Houmark-Nielsen and Kjær (2003) noting that B1 (called the Young Baltic Advances) came after the B2 lobe into Germany and Poland.

https://doi.org/10.5194/tc-2023-107
Preprint. Discussion started: 25 July 2023

2 Study Area

In this study, we map landforms in submarine and peripheral coastal regions (Fig. 1) of the present-day Baltic Sea. Our motivation for mapping the coastal periphery of the Baltic is twofold:

1. It eases integration with the much-studied onshore landform record,
2. To provide a high-resolution verification for ice-flow patterns and ice-marginal retreat patterns mapped from the lower quality and resolution bathymetric dataset.

The bathymetry of the Baltic Sea, with its prominent N-S and E-W trending depressions, has been attributed to the geological structures of the region and its differential erosion by Pleistocene ice sheets (Hall and Van Boeckel, 2020; Poprawa et al., 1999). The north-western Baltic has a crystalline Proterozoic substrate typical of the Scandinavian Shield and where sediment cover is limited, bedrock structure is clearly visible on bathymetric data (Fig. 1). Stratigraphic and seismic surveys have indicated that the sets of prominent NE-SW oriented ridges (‘Klints’) between Estonia and Sweden correspond to lithological transitions between Cambrian, Ordovician, and Silurian rocks, controlling erodibility and generating the stepped morphologies (Fig. 1C) (Tuuling and Flodén, 2016). The SE Baltic is dominated by more readily erodible lithologies with Paleogenic and Neogenic sandstones and mudstone sequences. Sediments thickness and composition varies through the Baltic with the north having patchier cover, between 20 and 30 m in thickness, while sediment cover further south is more extensive with thicknesses of up to 60 m (Björck et al., 1990; Noormets and Flodén, 2002b, a; Uścinowicz, 1999). The surficial deposits comprise glaciogenic sands and lacustrine sediments as well as marine strata (Sviridov and Emelyanov, 2000). Zones of soft sediment accumulation occur throughout the whole Baltic Sea. They form fan-shaped belts 50 to 70 km long and ca 50 km wide in the southern Baltic, up to 340 km long and 50 to 100 km wide in the central and northern sectors. Those, in the northern sector are composed of glaciofluvial material and were interpreted as subglacial outwash deposits and ice marginal grounding line deposits (Noormets and Flodén, 2002b). The accumulation of soft sediments has been found to correlate with the position of sills and banks (Kramarska, 1998; Lemke and Kuijpers, 1995; Obst et al., 2017; Uścinowicz, 1999).

3 Methods

Elevation data varied substantially in resolution and quality across offshore regions. We used the Digital Bathymetry Model of the European Marine Observation and Data Network (EMODnet Bathymetry Consortium, 2022). Its source data is a conglomerate of data sets with resolutions typically between 20 to 50 m but with some regions of 200 to 500 m resolution (Fig. 3) (Jakobsson et al., 2019). Identification of glacial landforms was not possible in the low-resolution regions. Artifacts are common in the dataset (see Fig. 3B) and where these occurred, cross-checking in the data from hydroacoustic surveys and seismic profiles were used to help identify glacigenic landforms (Dowdeswell et al., 2016). High resolution (1-5 m) Digital Elevation Models (DEM) were used to map the peripheral terrestrial regions (Table 2), with the exception of the Kaliningrad region, where a 25 m resolution DEM was used. Mapping was carried out manually using the open-source Quantum Geographic Information System (QGIS). Semi-transparent hillshades, with numerous azimuth angles to limit visualization bias (Smith and Clark, 2005) were superimposed on the DEM. Vertical exaggerations between 1 and 40 assisted in identification of low amplitude landforms, with cross-profiles proving a powerful tool for verifying landforms such as moraines, especially in regions of low resolution and quality of data.

Table 2. The elevation data sources used in this study.

Region	DEM spatial resolution [m]	Provider	Service
Baltic Sea	Dataset: 50 - 115 Source: 20 - 500	EMODnet	emodnet.ec.europa.eu
Kaliningrad	25 m	EU-DEM	eea.europa.eu
Sweden	1	Lantmäteriet	lantmateriet.se
Denmark	1	Styrelsen for dataforsyning og effektivisering	dataforsyningen.dk
Germany, Brandenburg	1	© GeoBasis-DE/LGB, dl-de/by-2-0	geobasis-bb.de
Germany, Mecklenburg-Vorpommern	1	© GeoBasis-DE/M-V 2020	laiv-mv.de
Poland	1	GUGiK	geoportal.gov.pl
Lithuania	5	© Nacionalinė žemės tarnyba prie Žemės ūkio ministerijos, GDR50LT, 22.07.2021	geoportal.lt
Latvia	1	Latvijas Ģeotelpiskās informācijas aģentūra	latvija.lv
Estonia	1	Estonian Land Board 2021	maaamet.ee

Glacial lineations were mapped along the crest-line using polylines and included bedrock and soft sediments features such as MSGLs, drumlins, crag-and-tails and grooves. Given their linear nature and the similarity to artifacts in low resolution data, lineations were subdivided into different confidence levels (‘glacial lineations’ and ‘uncertain glacial lineations’). Ribbed moraines, lacustrine wedges and regions of iceberg ploughmarks were mapped as polygons. Moraine ridges and eskers were mapped along the crest-line with the former grouped into two confidence levels. Meltwater channels were mapped by polylines along the margins and classified into tunnel valleys and marginal meltwater channels. Tunnel valleys were distinguished based on being parallel to the glacier flow. They are often associated with eskers, terminate near former ice margin, and have undulating long profiles (Kehew et al., 2012). In some offshore localities associated with the low-resolution DEM or unclear situation (e.g., lack of eskers) tunnel valleys were mapped as uncertain. Marginal meltwater channels often form a swarm of parallel channels that document the position of former glacier margins (Margold et al., 2013).

The mapped glacial lineations formed the basis for developing flowsets (Boulton and Clark, 1990; Clark, 1990; Greenwood and Clark, 2009). A flowset comprises a coherent set of morphologically and directionally associated lineations, interpreted to represent a discrete ice flow event. Low resolution data in regions such as the eastern part of East Gotland Basin and large parts of the southern Baltic (i.e., Arkona and Bornholm basins, Słupsk Furrow and Gdańsk Bay; Figs 1, 3) resulted in gaps between regions of higher density mapping. However, identifying larger features in these regions including moraines, ice marginal channels, and ice marginal deposits was often still possible and useful for reconstructing ice margin positions.

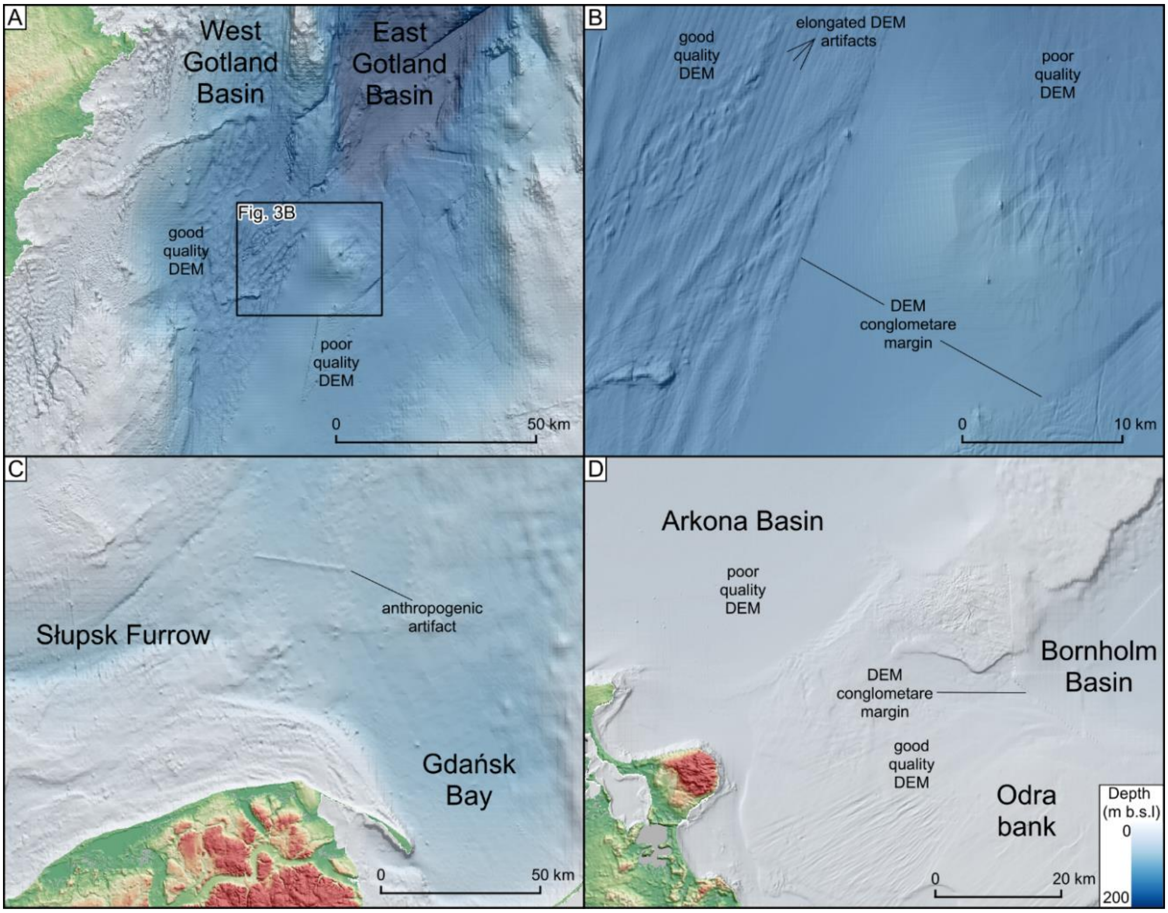


Figure 3: Examples of DEM artifacts and high- and low-resolution bathymetric data. The DEM is based on EMODnet (see Table 2). (A) Higher resolution bathymetric data for West Gotland Basin enabled landforms recognition, whereas the low-resolution data for East Gotland Basin made it difficult to identify glacial landforms. The onshore DEM is based on EU-DEM (see Table 2). (B) Examples of DEM artifacts in low- and high-resolution data, especially visible along the DEM conglomerate margin. Note the difficulty in identifying landforms in the low-quality data region. (C) Low resolution DEM for southern Baltic, with landforms not distinguishable in Gdańsk Bay but slightly more visible along the Słupsk Furrow. The onshore DEM was provided by GUGIK (see Table 2). (D) The contrasting data quality for the high resolution DEM of Odra Bank vs the low resolution DEM along the Arkona and Bornholm basins. The onshore DEM was provided by © GeoBasis-DE/M-V 2020 (see Table 2).

4 Results - Geomorphology and landforms of the Baltic Sea area

22,500 features were mapped within the study area (Fig. 4). Most of the regions with higher resolution data (both marine and terrestrial) display glacial landforms. The offshore features constitute 40% of the total object population. The highest density of landforms is found along the Swedish, German, Polish, and Lithuanian coast, and in vicinity of the area between Öland and Gotland islands. The lowest density of landforms is along the central and southern Baltic Sea, however, the few landforms found here are of considerable size. Glacial lineations comprise 14,600 of the mapped features with eskers numbering 4,200. The majority (in terms of percentage) of lineations and eskers were mapped in coastal regions. Burial of landforms in marine environments has been identified before (Flodén et al., 1997; Kirkham et al., 2022) and likely contributes to an incomplete morphological record in parts of the Baltic depression.

4.1 Streamlined bedforms

A variety of glacial streamlined bedforms including MSGLs, drumlins, crag-and-tails and grooves are mapped in the study region (Fig. 5). Streamlined bedforms are widely distributed and found in regions of soft sediments and imprinted on thin drift over predominantly bedrock exposed regions. Glacial lineations occur throughout the entire depth of the Baltic Sea, to a depth of at least 220 m b.s.l.. Almost 75% of the glacial lineations are shorter than 1200 m. They cluster in the terrestrial parts of the Baltic Shield and in the southern sector of the SIS in Poland (Dowling et al., 2015; Hermanowski et al., 2019). MSGLs are found in the deeper depressions and extend in length up to 80 km. Highly parallel MSGLs start abruptly at the geological transition between the crystalline shield and sedimentary rocks in the north Baltic (see also Tuuling and Flodén, 2001, 2016). A swarm of 138 grooves occurs between the Klints (Figs 5A, H). The grooves are inter-mixed with drumlins and exhibithigh parallel conformity with them. The grooves are straight, with an average length of ca 1300 m.

In the northern Baltic, the density and length of glacial lineations increase towards the central parts of the two troughs located either side of Gotland Island. In these, sets of highly parallel MSGLs are found, extending up to 80 km in length. Sparse eskers and meltwater channels with lengths up to 95 km also occur in the troughs. Glacial lineations, up to 5000 m long, in the terrestrial south form local fields typically restricted to drumlinised belts located close to arcuate moraines and marginal meltwater channels. However, these sets often comprise less than 30 lineations. Offshore glacial lineations in the southern Baltic occur in Pomeranian Bay and in the vicinity of Bornholm Island. The first area displays highly elongated lineations with an average length of 4450 m and width of 200 to 500 m. Cross-cutting of streamlined bedforms is common in the study area, especially in Skåne, Germany, Poland, Öland and Gotland, and offshore in the West and East Gotland basins and Pomeranian Bay. In contrast, no cross-cutting relationships are identified in the SE and E part of the study area. Typically, more delicate and shorter glacial lineations overprint more prominent ones.

https://doi.org/10.5194/tc-2023-107
Preprint. Discussion started: 25 July 2023

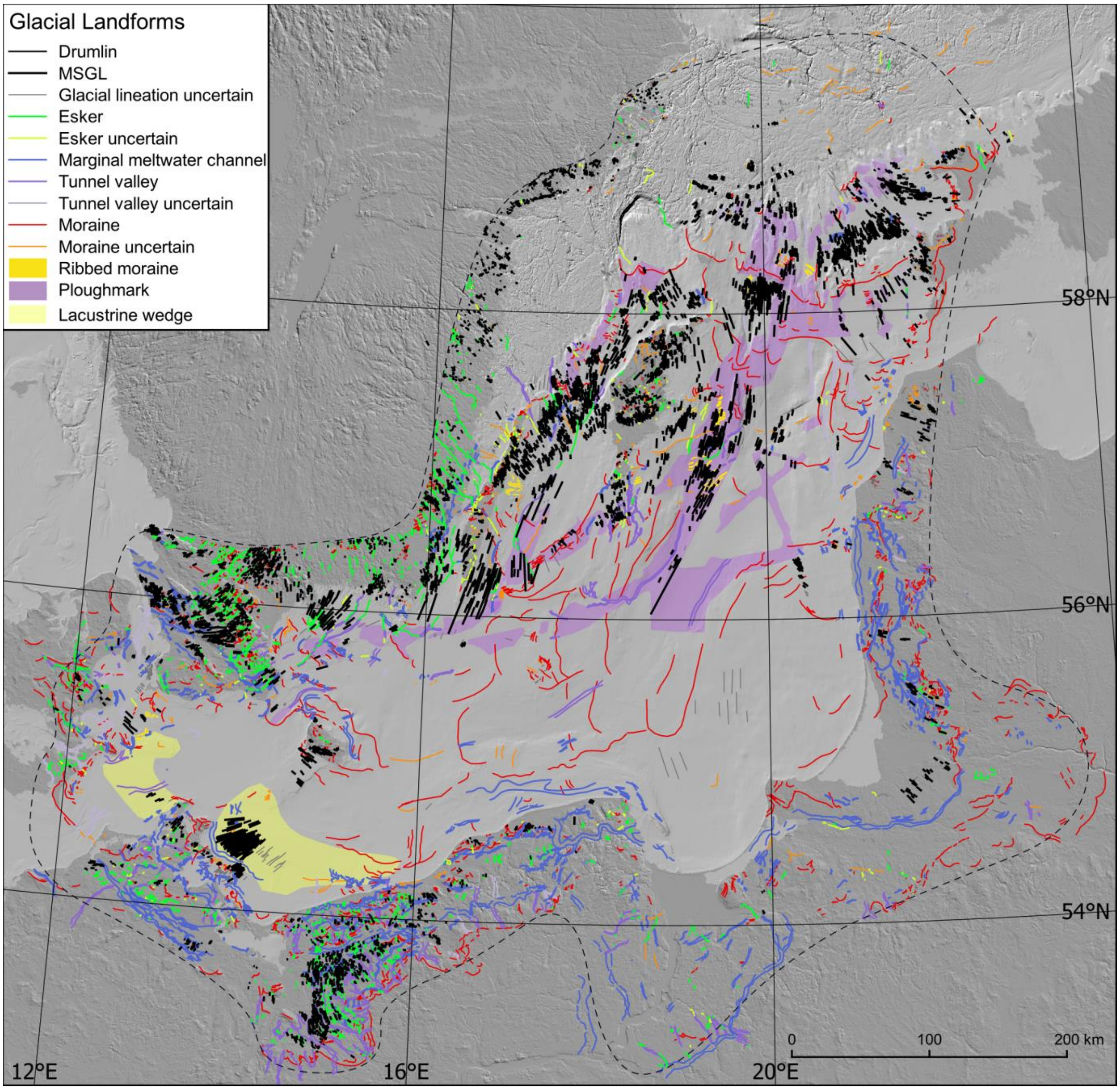


Figure 4. Landforms mapped in this study. A high resolution version can be downloaded from the Supplementary Material (Fig. S1). Study area is indicated with dashed line. Light and dark grey indicate onshore and offshore areas respectively. The DEM is based on EU-DEM and EMODnet (see Table 2)

4.2 Ribbed moraines

Ribbed moraines are identified along the study area in six offshore and three onshore localities (e.g., Fig. 5I), and typically exhibit a spatial transition downstream into glacial lineations. Ribs are often associated with-, and oriented perpendicularly to topographic highs and obstacles (Fig. 5B). In one locality, in the East Gotland Basin, glacial lineations are superimposed on ribbed moraines.

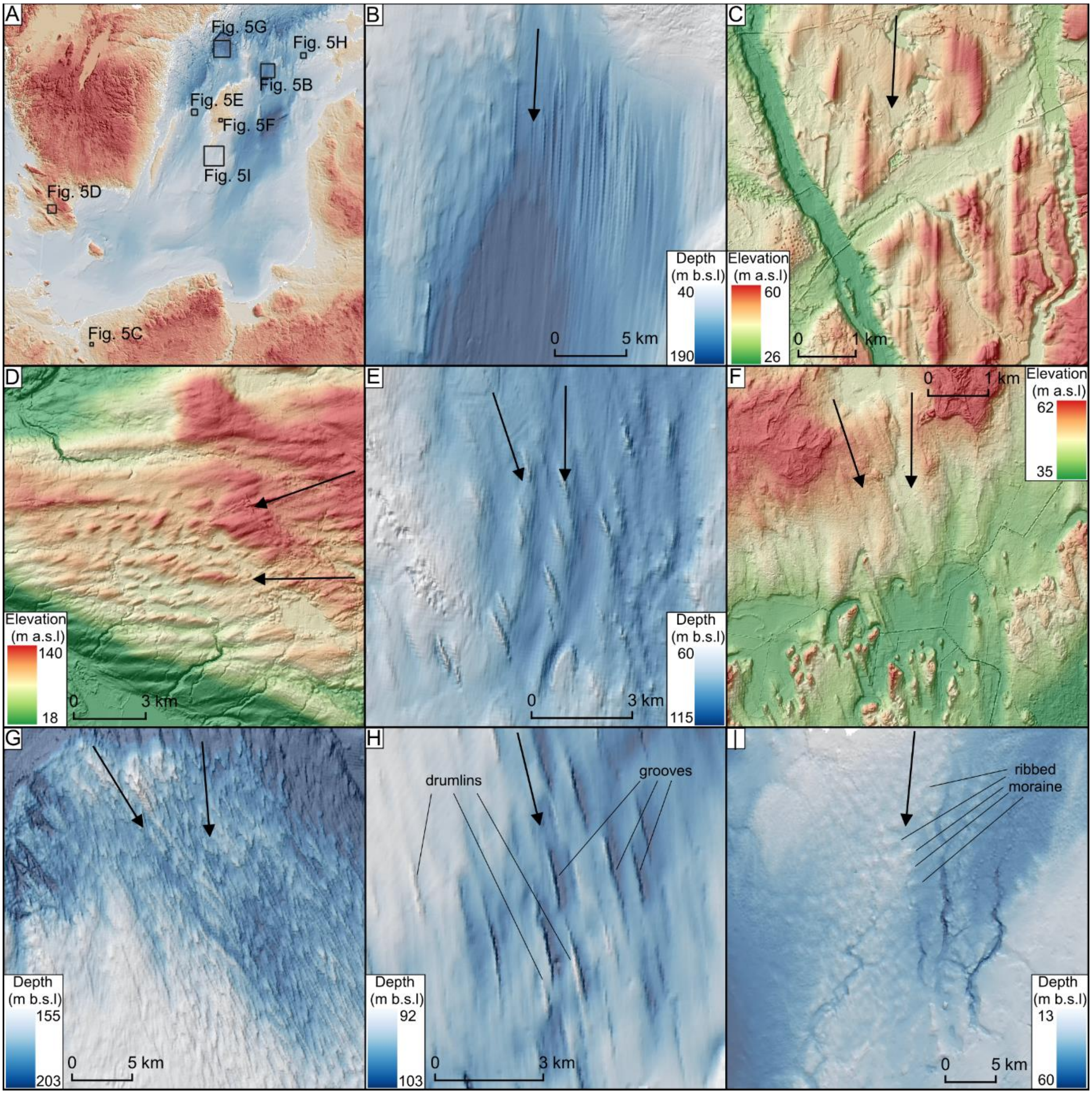


Figure 5: Examples of glacial lineations, grooves, and ribbed moraines found in the study area. Ice flow direction is indicated by black arrows. The DEMs are based on EU-DEM and EMODnet if not stated otherwise (see Table 2). (A) Locations of landform examples. (B) Mega-scale glacial lineations along Fårö Deep. (C) Drumlins on the Polish coast. The DEM is provided by GUGIK (see Table 2). (D) MSGLs in Skåne, Sweden oriented E-W and cross-cut by NE-SW oriented drumlins. The DEM is provided by © Lantmäteriet. (E) Cross-cutting glacial lineations in the West Gotland Basin. (F) Crag-and-tails in southern Gotland, overprinting larger N-S oriented MSGLs. Note the moats (scour-marks) around the stoss sides of the crag-and-tails. The DEM is provided by © Lantmäteriet. (G) Cross-cutting glacial lineations in the vicinity of Landsort Deep. Notice that the NW-SE trending lineations toward East Gotland Basin are more elongated and better developed than the N-S trending lineations toward West Gotland Basin. This overlapping arrangement, seen here, is not common across the study area. (H) Glacial grooves identified in an area of basal till overlain by lacustrine and marine deposits (see Noormets and Flodén, 2002a) on the Silurian basement, between Klints. (I) Ridges south of Gotland Island oriented perpendicularly to inferred ice flow direction and interpreted as ribbed moraine.

https://doi.org/10.5194/tc-2023-107
Preprint. Discussion started: 25 July 2023

4.3 Flowsets and their relative age relationship

Figure 6 shows the 75flowsets that were identified. The flowsets display a range of geometries with parallel lineation sets in deeper sections of the Baltic, and splaying geometries found across much of the study area from the terrestrial southern margin to the regions further north in the vicinity of the Klints. Flowset orientations vary substantially in the study region documenting ice flow directions to the E in the Eastern Baltic and to the NW in the western part of the study area. Overprinting (e.g., Figs 6B, C), on Gotland Island records 10 flowsets with orientations switching from N-S to NNE-SSW oriented, through NE-SW, ENE-WSW, and NW-SE (Fig. 6C). Flowset relative timing was distinguishable in several parts of the study area by superposition, cross cutting and smudging of landforms (Fig. 6). We suppose that such complex shifts in ice flow direction were likely common through much of the study area, but are not always visible due to low resolution data. Individual flowsets with no overprinting relationships (Fig. 6A) dominate in the eastern and the northernmost part of the study area.

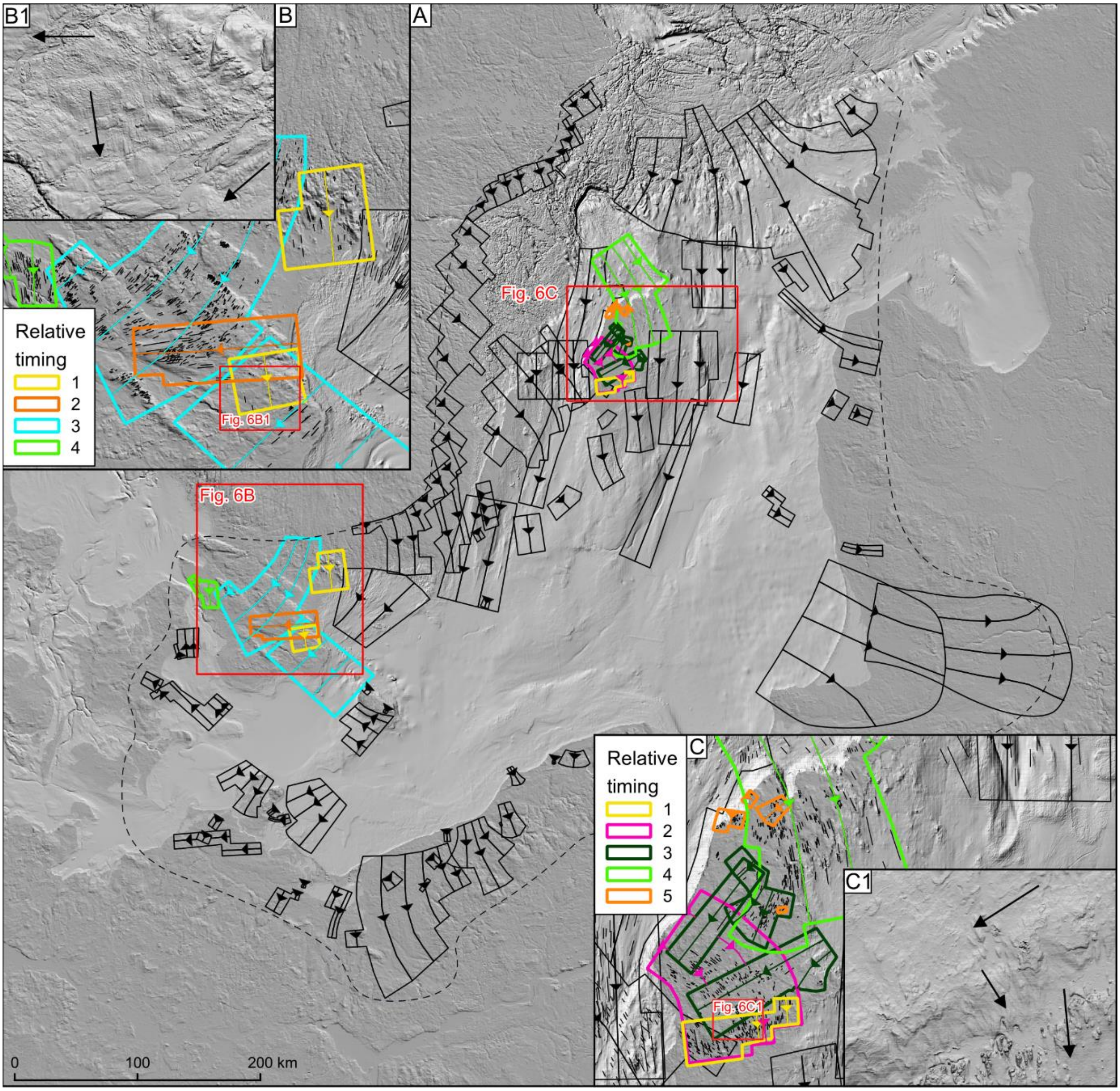
4.4 Ice marginal and meltwater landforms

A range of ice marginal sediment accumulations are mapped (Fig. 7) including moraine ridges (Fig. 7B) and low-angled wedge-like fans (Fig. 7D). Prominent end moraines are found throughout the study region including the central Baltic where they are up to 30 m high and 45 km wide (Fig. 7E).The highest elevated moraines, east of Öland Island, and just north the Słupsk Furrow, are only 13.5 - 16 m b.s.l. Series of closely spaced recessional moraines are identified locally (e.g., in Irbe Strait; Fig. 7C) with 3 –4 m amplitude and 300–400 width. These moraines are only distinguished in areas with high-quality DEM. The only information on the sedimentological composition of the moraines in the study area comes from the southern Baltic where seismoacoustic profiles indicate that moraine ridges are composed of till and glaciofluvial sediments (Uścinowicz, 1999). Cross-cutting and overprinting of moraines occurs in the vicinity of the Danish islands, eastern Germany, and Słupsk Bank (Fig. 7D) in the central Baltic. Cross-cutting moraines such as those in the central Baltic record changes in ice flow geometry during retreat. Here a distinct N to NW, NE to N and E-W flow geometry can inferred (Fig. 7E), with moraines associated with the NE-N ice flow direction being the youngest. In addition to moraine ridges, two wedge-like fans (10 m high and ca 20 km wide) are found in the southernmost part of the study area. They have a steep distal slope and wider and lower-angled proximal slopes (Fig. 7D).

Single- or multiple-crested eskers are common (n> 3000) in the west and southwest of the study area (e.g., 7G) but almost completely absent in the east (East Gotland Basin and eastern Baltic coast). Most of the eskers identified in this study occur onshore with only 2% of the total population located offshore. The longest and most complex eskers occur in southern Sweden, where they form dendritic networks(Dewald et al., 2022; Stroeven et al., 2016), and offshore from here, where eskers are up to ca 45 km long. The offshore eskers located in the vicinity of the Swedish coast conform to the splaying pattern of the inland esker networks. Another group of SSW-orientated single-ridged offshore eskers, up to 45 km long, align with the streamlined bedforms in the deepest parts of the Baltic Sea. The two esker groups of opposing orientations are divided by the island of Gotland. Eskers are not present in offshore regions of the southern Baltic, and are common but short (< 10 km in length) in

https://doi.org/10.5194/tc-2023-107
Preprint. Discussion started: 25 July 2023

280 the adjoining coastal areas of northern Germany and Poland (Frydrych, 2022). We speculate that such small landforms might not be distinguishable in the poor-quality DEM available for the offshore areas or that eskers could be buried by postglacial deposits (Uścinowicz, 1999).



285 **Figure 6: (A) The flowsets defined for the study area (dashed line). Close-ups of flowsets in the area of (B) Skåne and (C) Gotland islands. Colours indicate their relative age based on overprinting relationships. Higher numbers in (B) and (C) are younger. The DEM is based on EU-DEM and EMODnet (see Table 2).**

However, the general distribution of better-developed esker networks on the shield compared to the regions of sedimentary lithologies is consistent with observations from the former Laurentide Ice Sheet in North America (Clark and Walder, 1994).
Ice-marginal meltwater channels in the study are often associated with the lobate shape of the moraines located in their vicinity. They vary in size, from long (exceeding 100 km sections), wide (up to 5 km), and well-preserved channels (in, e.g., Germany, Poland, Kaliningrad) to short and fragmented (10-100 m wide) channel segments (Fig. 7H). The ice-marginal meltwater channels along the Kaliningrad, Poland, and German coasts form semi-continuous drainage systems almost 400 km long. Offshore meltwater channels are generally restricted to the southern part of the study area; the widest examples here are up to 7 km in cross section (along the Polish coast).

Tunnel valleys are identified both onshore (Fig. 7E) and offshore, some up to 20 km in length. A minority (n=23) of tunnel valleys are identified in regions of poor- quality DEM from their regular pattern and spacing of 5-12 km. Tunnel valleys do not exceed 2 km in width, consistent with other examples from Scandinavia(cf. Jørgensen and Sandersen, 2006). Tunnel valleys occupy geological structures along the Swedish coast and the Klints, whereas in the southern sector they occur in soft sediments. Terrestrial examples are often associated with eskers, but only nine such associations are identified offshore possibly due to the coarser DEM resolution making eskers difficult to identify.

Moraines and much of the sea bottom in the central and northern sector of the Baltic Sea are covered with iceberg ploughmarks (Fig. 7I). They have an identifiable U- to V-shaped cross-profile with thalwegs that are typically curvilinear to straight. The ploughmarks rarely exceed a depth of two meters and their length varies between 45 m and 20 km, consistent with other studies on ploughmarks in the region (Karpin et al., 2021). Orientations vary from perpendicular to the inferred ice margins to chaotic with ploughmarks cross-cutting each other. Iceberg pits are identified in one locality, with MSGLs up-ice of them (Fig. 7D). No ploughmarks are identified in the southern part of the study area (Fig. 4).

4.5 Ice margin positions

To reconstruct the character of ice margins and the pattern of deglaciation we used the suite of mapped landforms and our glaciological understanding of how they formed to infer major ice margin retreat geometries (Fig. 8).

The margin configuration along the terrestrial southern sector spanning Denmark, Germany, Poland, Kaliningrad region and Lithuania comprised a series of lobesas evidenced by meltwater channels, eskers and moraines. The spacing between the identified ice margin positions varies, with the southern sector generally having a closer spacing of about 10 to 40 km. Ice retreat down a reverse slope is reflected in the presence of long (almost 400 km) ice marginal channel systems that are well-preserved along the German, Polish, and Kaliningrad coasts. Offshore, ice margin positions are mainly identified from moraines. Along the eastern Baltic ice margin positions are typically 40 – 80 km spacing, with 180 km between the central Baltic moraines and the Devonian Klint (Fig. 1), and 120 km between the Silurian Klint and Åland Sill. In the western Baltic the spacing is similar, up to ca 80 km, with a larger gap of ca 100 km east of Öland Island. It is probable that uniform and better quality data for the whole Baltic area would permit the detection of closer spacing.

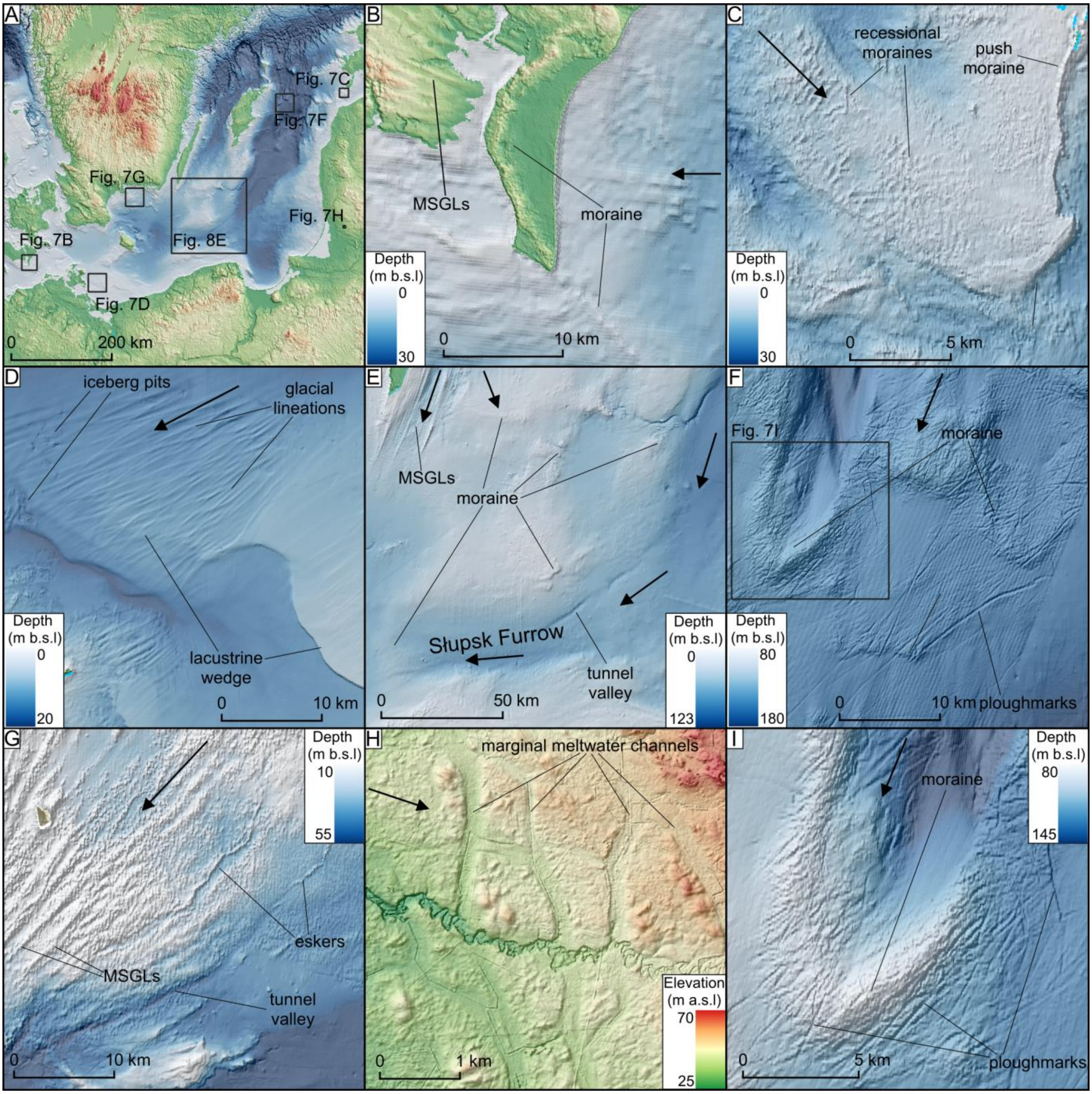


Figure 7: Examples of ice marginal landforms. Ice flow direction is indicated by black arrows. The DEMs are based on EU-DEM and EMODnet if not stated otherwise (see Table 2). (A) Location of landform examples. (B) Example of W-oriented moraine, onshore

and offshore, in Denmark. The onshore DEM is provided by Styrelsen for dataforsyning og effektivisering (see Table 2). (C) Sequence of small, closely spaced moraines at Irbe Strait. (D) Lacustrine wedge overprinted by glacial lineations in shallow waters of Pomeranian Bay. Note that even the distal slope of the wedge is overprinted by glacial lineations. In the shallow water there are no ploughmarks, but iceberg pits do occur. The sharp banks truncating glacial lineations were thought to form due to drainage of a local ice-dammed lake (see Uścinowicz, 1999). (E) The central Baltic, near the Słupsk Furrow, is occupied by the largest moraines in the study area. Tunnel valleys are oriented towards the westernmost moraine. (F) Glaciofluvial deposits down-ice from a pinning point (Noormets and Flodén, 2002b, a), with smaller push moraines covered by ploughmarks. (G) Eskers and an associated tunnel valley system in Hanö Bay, parallel to MSGLs. (H) Examples of marginal meltwater channels in Latvia. The DEM is provided by Latvijas Ģeotelpiskās informācijas aģentūra (see Table 2). (I) Plough marks in the vicinity of the push moraine in 7F. Note that many of the ploughmarks indicate NE-SW iceberg movement.

In Hanö Bay and east of Öland Island, the ice margin forms two 70-100 km wide lobes, each with eskers oriented perpendicular to the arcuate moraines, with an interlobate zone in-between eskers towards separate arcuate moraines (Fig. 8). In the central part of the study area, separate arcuate ice margin positions are reconstructed east and west of the SW-NE oriented ridge of Gotland Island and its offshore southern continuation. In this region, the ice margin positions are defined by the broad-scale topography, indicating that separate ice lobes formed in the basins either side of Gotland. The marginal pattern becomes more lobate in the north of the study area with a clear interlobate zone along Gotska Sandön (GS in Fig. 8)

5 Discussion

Our landform mapping of the previously mostly unexplored Baltic Basin (0.3 million km^2) provides new information on the dynamics of the southern margin of the SIS during the last deglaciation. This helps to fill the gap in reconstructions of the SIS over the Baltic Sea (e.g., Boulton et al., 2001; Stroeven et al., 2016; Tylmann and Uścinowicz, 2022) that previously had to rely on inferences and extrapolations from the adjacent terrestrial evidence. We then use the reconstructed flowsets and ice margin positions to address the research questions raised in the introduction.

5.1 Was there a Baltic-wide ice stream?

The existence of a large Baltic-wide (300 km) ice stream at the local LGM, feeding ice to the southern margin and westwards to Denmark (e.g., Holmlund and Fastook, 1995; see Fig. 2; Stephan, 2001) is largely based on glaciological inferences stemming from the broad-scale morphology of the ice sheet bed and its lithological properties, rather than on a landform-defined footprint of the ice stream. We do not identify a landform 'footprint' of simultaneous fast ice flow spanning the Baltic depression; the landforms in the central Baltic appear to record more fragmented corridors of fast ice flow consistent with later stages of deglaciation and with much smaller ice stream widths (typically 30 to 60 km, up to 95 km; Figs 6, 9C). Such widths are more typical of ice streams found elsewhere (e.g., Gandy et al., 2019; Livingstone et al., 2012; Margold et al., 2015; Stokes, 2018). This is indicated by presence of distinct flowsets located in vicinity of Gotland Island (Fig. 6) and multiple lobes indicated by the marginal retreat geometry in the central Baltic (Fig. 8). Some ice sheet modelling experiments (e.g., Patton et al., 2017; Patton et al., 2016) reproduce a Baltic-wide area of fast flow (an ice stream) through much of the growth and decay of the ice sheet. We suggest that this fast flow zone is a response to the prescription of a soft substrate in the Baltic in contrast to the hard-bedded surroundings (Patton et al., 2017; Patton et al., 2016).

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Preprint. Discussion started: 25 July 2023

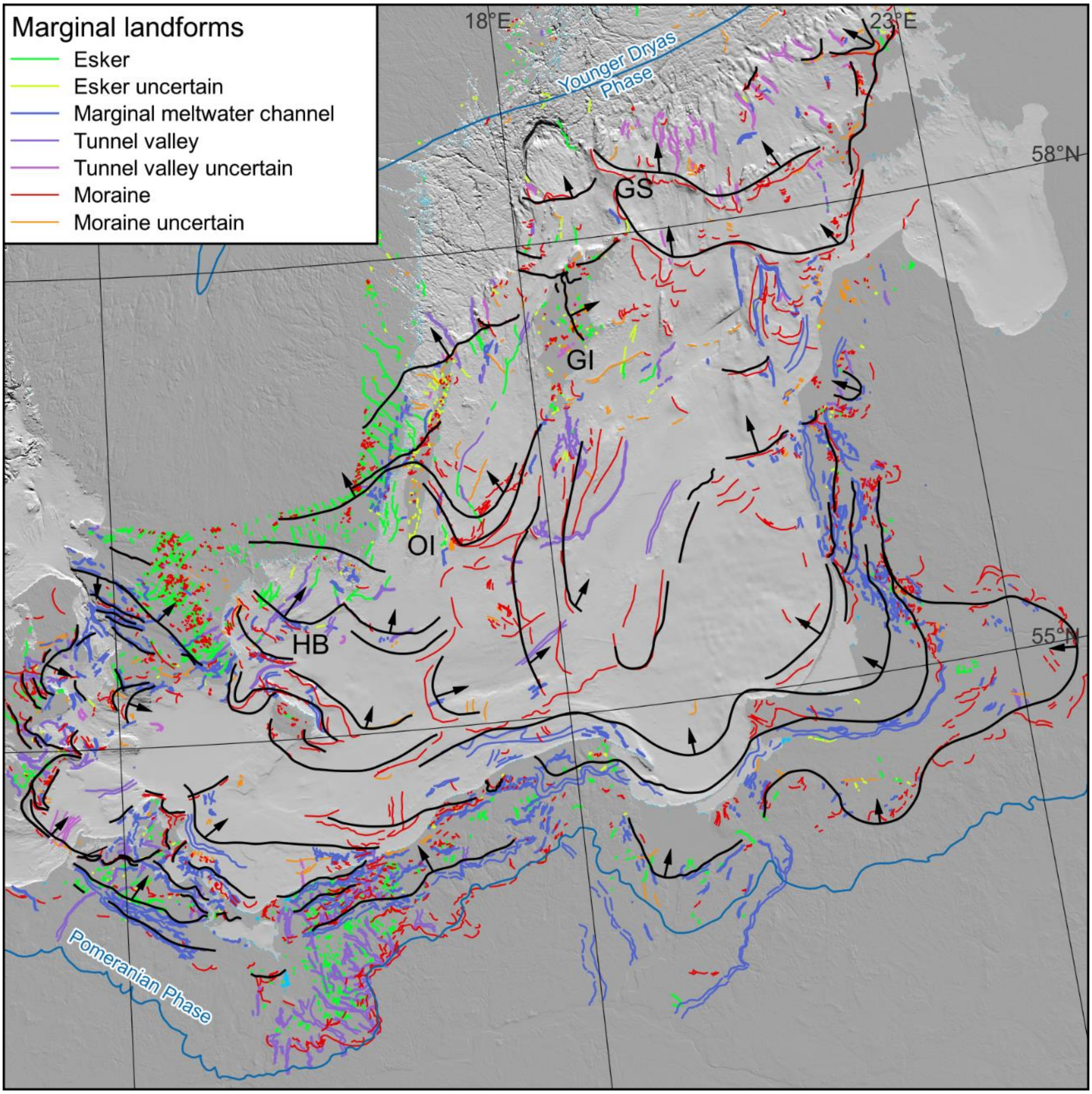

Figure 8: Broad overview of possible ice marginal retreat geometries (black lines with arrows showing the direction of retreat) inferred from the new mapping of landforms. Gaps in the bathymetric data and the known complexity of flowsets and the flow-switching through time mean that the ice sheet retreat was likely more complex than illustrated here. Notice, highly lobate nature of ice margin to the south west and south east and some offshore examples of interlobate zones where ice margin separates into two lobes: at Hanö Bay (HB) and over Öland Island (OI); along Gotland Island (GI) and Gotska Sandön (GS). The DEM is based on EU-DEM and EMODnet (see Table 2).

However, modern observations of, for example, the Siple Coast ice streams in Antarctica (Catania et al., 2012), and numerical modelling experiments (Fowler and Johnson, 1996; Hindmarsh, 2009; Payne, 1998), suggest that narrow corridors of fast ice flow can exist even in soft-bedded regions of little relief; this is, in fact, what Bennett (2003) defined as 'pure ice streams'. We therefore suggest that some width-limiting processes on ice stream formation have yet to be sufficiently added into numerical ice sheet models. Gandy et al. (2019) have made progress with such work for the British-Irish Ice Sheet where they explored the ingredients required in their modelling experiments to simulate ice streams in the correct places and with appropriate spacing and widths. They used the BISICLES higher order model, which as well as having variable cell-size resolution, which helps with apportioning ice steaming, also incorporates approximations of membrane stresses which are necessary for yielding accurate ice streams.

We interpret the flowsets confined to the depressions and flanking slopes either side of Gotland (Figs 6, 9C), consisting of highly parallel MSGLs, with locally splayed termini, as the trunks of a number of narrow (30 - 60 km) palaeo-ice streams that operated during deglaciation behind a back-stepping ice margin. Whilst ice must have traversed the Baltic to reach the maximum southern extent of the last SIS, as evidenced by the provenance of glacigenic sediments in the southern study area (e.g., Kjær et al., 2003; Woźniak and Czubla, 2015) we do not find any landform evidence in the Baltic depression that we could interpret as originating from this stage. Landforms from the maximum phase of glaciation may have been erased or have yet to be found.

5.2 What was the character of ice margin retreat though the Baltic depression?

Rather than congruent Baltic-wide ice streaming, flowsets can generally be incorporated into a time-transgressive deglacial retreat sequence that in some cases conforms with the pattern of reconstructed ice margins (Fig. 8). We find that the ice margin geometry changes significantly during the retreat through the Baltic (Figs 9B, C). In the southeast and southwest, lobate moraines with splaying geometries, flanked by marginal meltwater channels (Figs 7B, 8), are common, resembling lobate land terminating margins documented elsewhere on the soft-bedded southern and eastern margins of the SIS (e.g., Kalm, 2012; Szuman et al., 2021) and Laurentide Ice Sheet (Margold et al., 2015). Ice marginal signatures in the southern sector often comprise overprinted lobes arising from oscillations and readvances of ice margins along with switching of flow orientations and changing lobe positions during overall retreat (Kjær et al., 2003).

The presence of ice marginal meltwater channels in Denmark, Germany, Poland, Kaliningrad and Lithuania, and in the present-day coastal zone indicates that the marginal environment in this phase of retreat was terrestrial (Fig. 4) (cf. Uścinowicz, 1999). However, flat-topped and low-angled wedge-like fans interpreted here as glaciolacustrine wedges (Figs 7D, 9B) similar to ice-contact subaqueous fans described in literature (Benn and Evans, 2010; Gruszka and Zieliński, 2021) indicate a shallow glaciolacustrine environment once the ice margin stepped back north of the present-day coast. An example of this is in Pomeranian Bay where a glaciolacustrine fan is overprinted by long cross-cutting MSGLs, indicating a subaquatic origin. While these lacustrine wedges resemble the shape of grounding zone wedges (cf. Batchelor and Dowdeswell, 2015), the water depth, only up to 30 m along the coast (Figs 3D, 7D), is considered too shallow for ice shelf development. However, we note here the strong resemblance of the features we map to the Pas Moraine in Manitoba, which has recently been re-interpreted as a grounding zone wedge (Gauthier et al., 2022), formed in glacial Lake Agassiz.

In the southern part of study area, numerous ice dammed lakes have been reconstructed in and adjacent to the Baltic Depression from sedimentological investigations (Houmark-Nielsen and Kjær, 2003; Larsen et al., 2009) and the identification of palaeo-shorelines (Uścinowicz, 1999). The largest of these is the Baltic Ice Lake (Uścinowicz, 2006). During the retreat of the SIS margin through the Baltic Depression, the ice margin may have terminated on land, or been grounded in an ice dammed lake, and we suggest that the varying geomorphologies noted above likely reflect these terminal environments.

The prominent moraines in the central Baltic (up to 30 m high and 4500 m wide, Fig. 7E) mark the ice-sheet margin position during still-stands during overall retreat. Further north, parallel MSGLs are found aligned within the deeper depressions (Fig. 9C). Here specific MSGL sets cannot be conclusively linked to specific ice marginal landforms. Given their highly parallel nature, alignment with the orientation of depressions that are up to 200 m deep and overprinting by iceberg ploughmarks, we suggest these landforms are indicative of a water-terminating ice margin with icebergs calving either directly at the ice front or from an ice shelf that might have existed over the deeper sections of the Baltic Ice Lake. The change from the ploughmark-free southern sector (Fig. 4) to numerous ploughmarks in the deeper (up to 220 m b.s.l.) northern sector likely reflects a transition from land-terminating or shallow lacustrine margin to an aqueous calving margin. Similar parallel corridors of MSGLs (i.e., not splaying) have been found at former marine-terminating margins of the contemporary Antarctic Ice Sheet (Livingstone et al., 2012). This is consistent with Noormets and Flodén (2002b), who suggested an ice thickness of 180 m at the grounding line, with a floating ice shelf over Fårö Deep (see Fig. 1 for location). The distal slopes of elevated structures at pinning points especially along the Klints are covered with ploughmarks (Figs 8F, I; see also Karpin et al., 2021), indicating either a long still-stand or that the calving processes were intensive, and the icebergs were smaller than the full depth of ice and could passed topographic barriers.

5.3 What was the role of bedrock structures in controlling stepped retreat?

Though the Baltic depression is mostly floored with thick glaciolacustrine sediment (Boulton and Jones, 1979; Boulton et al., 1985; Noormets and Flodén, 2002b, a; Uścinowicz, 1999), there are locations where bedrock is found to outcrop at the seafloor including at the Island of Bornholm and the Klints in the northern Baltic (Fig. 1; Tuuling and Flodén, 2016). These outcrops are generally the results of more resistant geological units resulting in topographic protrusions. The topographic relief associated with the Klints is associated with ice marginal landforms (Fig. 8) like outwash fans (Noormets and Flodén, 2002b), moraines (Figs 7F, 7I) and tunnel valleys (Fig. 4). Lineations further north splay according to the Klints' position (Fig. 9D) and can be incorporated into a stepped pattern of retreat.

The quasi-regular pattern of ice margin positions (Fig. 8) gives an impression of stepped recession. In our interpretation, stepped retreat could be related to the presence of pinning points formed by the Klints and other topographic/bathymetric features (cf. Boyce et al., 2017; Noormets and Flodén, 2002b). In the study area, the presence of lacustrine wedges (Fig. 4), outwash fans (Noormets and Flodén, 2002b), and large moraines in the central Baltic is consistently associated with these

https://doi.org/10.5194/tc-2023-107
Preprint. Discussion started: 25 July 2023

geological structures. This indicates the importance of pinning points in ice stabilisation (e.g., Favier et al., 2016; Still and Hulbe, 2021). The only prominent high on the Baltic bed where we do not map accumulations of glacigenic sediments is Åland Sill, possibly because of patchier sediment availability over the crystalline bedrock.

5.4 Was there an interaction between northern (ice flowing from Bothnian Basin) and north western (ice flowing from Sweden) ice sources?

Past ice-sheet-scale investigations have inferred an ice lobe with a gently arcuate ice front spanning the width of the Baltic depression during northwards retreat, implying that ice was steered through the Gulf of Bothnia (Boulton et al., 2001). We confirm this Bothnian ice source from the north, but also identify a Swedish ice source with a ~NW-SE orientation based on our ice marginal and flowset geometries (Figs 6, 8, 9C). The landform record records the interplay between these two ice sources, with high resolution DEM from the islands of Gotland and northern Öland assisting in the identification of five independent ice flow directions (Figs 6C, 9C). Our mapping indicates the predominance of a western ice lobe over the West Gotland Basin in the earlier stages of deglaciation and a later switch to dominance of the eastern lobe. The suture between the two lobes was located along Gotland Island (Fig. 9C) and extended towards the north and south. We also identify more localised ice flow splitting north of the island of Gotland, indicated by diverging streamlined bedforms (N-S and more NW-SE) in Landsort Deep (Figs 6A, 9F).

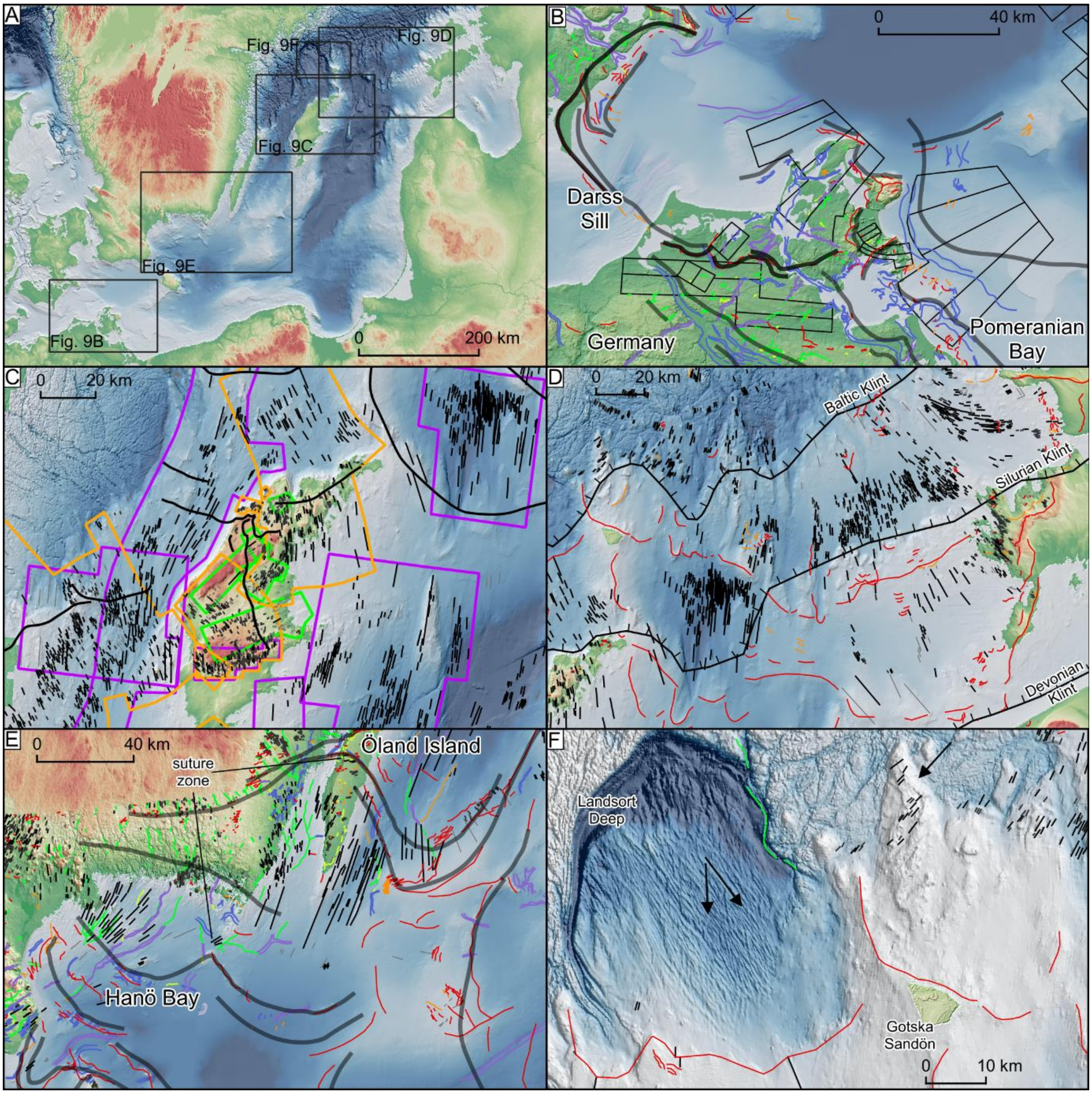

Figure 9: (A) Location of panels B-F. The DEMs (A-F) are based on EU-DEM and EMODnet if not stated otherwise (see Table 2). (B) Lobate ice margin positions along the German coast, with splaying pattern of lineations in Pomeranian Bay and a lobate onshore-offshore moraine near Darss Sill (the legend is indicated in Fig. 4), (C) highly parallel MSGLs in the bathymetric depressions (purple polygons). The parallel MSGLs indicate ice stream widths of roughly 30-60 km, with a maximum up to 95 km. Notice that splaying lineation patterns are rare in this location. The orientation of ice flow within the classified flowsets is indicated by colours: violet for N-S to NNE-SSW oriented (possibly the oldest), orange for NW-SE (younger), green for NE-SW to ENE-WSW (the youngest). The flowset pattern underlines the interplay between ice margins with Swedish-oriented and Bothnian-oriented ice sources. The onshore DEM is provided by © Lantmäteriet (see Table 2). (D) ice-margins associated with topographic highs formed by the Klints (black lines). Notice the highly lobate shape of moraines that fits to the position of the Klints. Glacial lineations have splaying patterns, especially down-ice from the Baltic Klint. The onshore DEM was provided by Estonian Land Board 2021 (see Table 2). (E) Suture zones in Hanö Bay and Öland Island. Note ice splitting into two lobes, indicated by the pattern of eskers (green) and tunnel valleys (purple), and by the positions of moraines (red). The onshore DEM is provided by © Lantmäteriet (see Table 2). (F) Glacial lineations in vicinity of Landsort Deep and Gotska Sandön indicate ice flow divergence towards the SE and SW.

6 Conclusion

The first Baltic wide glacial landform-based map is presented, filling in a geographical gap in the record that has been speculated about by palaeoglaciologists for over a century. The glacial landforms we map are interpreted as primarily recording phases of ice retreat through the Baltic, rather than an extensive landform record related to the maximum ice extent phase. Instead of an often interpreted or modelled accelerated ice flow zone spanning the Baltic depression (300 km), we provide landform evidence for narrower corridors of fast ice flow that we interpret as distinct and smaller ice streams (widths of 30 to 60 km, up to 95 km), consistent with later stages of deglaciation rather than the maximum stage. In the central Baltic, assemblages of landforms resemble lobate ice margins typical of terrestrial-style landsystems, whereas locally within the deeper bathymetric depressions landform assemblages more typical of water-terminating ice margins are found. In these latter cases ploughmarks suggest significant ice evacuation by calving. Episodic rather than steady ice retreat is inferred based on ice margin positions associated with exposed bedrock structures (Klints) that acted as pinning points. Where previous ice sheet-scale investigations inferred a single ice source, our mapping identifies flow and ice marginal geometries from both Swedish and north Bothnian sources. We anticipate our landform mapping and interpretations may be used as a framework for more detailed empirical studies by identifying targets to acquire high resolution bathymetry and sediment cores and also for comparison with numerical ice sheet modelling.

References

Ahlmann, H. W., Laurell, E., and Mannerfelt, C.: Det norrländska landskapet, Ymer, 62, 1-50, 1942.

All, T., Flodén, T., and Puura, V.: A complex model of Mesoproteozoic sedimentary and igneous suites in a graben setting north of Gotland, Baltic Sea, GFF, 128, 53-63, doi: 10.1080/11035890601281053, 2006.

Amantov, A., Fjeldskaar, W., and Cathles, L.: Glacial Erosion/Sedimentation of the Baltic Region and the Effect on the Postglacial Uplift, in: The Baltic Sea Basin, edited by: Harff, J., Björck, S., and Hoth, P., Springer Berlin Heidelberg, Berlin, Heidelberg, 53-71, doi:10.1007/978-3-642-17220-5_3, 2011.

Batchelor, C. L. and Dowdeswell, J. A.: Ice-sheet grounding-zone wedges (GZWs) on high-latitude continental margins, Marine Geology, 363, 65-92, doi:10.1016/j.margeo.2015.02.001, 2015.

Benn, D. I. and Evans, D. J. A.: Glaciers and glaciation, Hodder Education, London 2010.

Bennett, M. R.: Ice streams as the arteries of an ice sheet: their mechanics, stability and significance, Earth-Science Reviews, 61, 309-339, doi:10.1016/S0012-8252(02)00130-7, 2003.

Björck, S., Dennegård, B., and Sandgren, P.: The marine stratigraphy of the Hanö Bay, SE Sweden, based on different sediment stratigraphic methods, Geologiska Föreningen i Stockholm Förhandlingar, 112, 265-280, doi:10.1080/11035899009454774, 1990.

Boulton, G. S. and Clark, C. D.: A highly mobile Laurentide ice sheet revealed by satellite images of glacial lineations, Nature, 346, 813-817, doi:10.1038/346813a0, 1990.

Boulton, G. S. and Jones, A. S.: Stability of Temperate Ice Caps and Ice Sheets Resting on Beds of Deformable Sediment, Journal of Glaciology, 24, 29-43, doi:10.3189/S0022143000014623, 1979.

Boulton, G. S., Dongelmans, P., Punkari, M., and Broadgate, M.: Palaeoglaciology of an ice sheet through a glacial cycle:: the European ice sheet through the Weichselian, Quaternary Science Reviews, 20, 591-625, doi:10.1016/S0277-3791(00)00160-8, 2001.

Boulton, G. S., Smith, G. D., Jones, A. S., and Newsome, J.: Glacial geology and glaciology of the last mid-latitude ice sheets, Journal of the Geological Society, 142, 447-474, doi:10.1144/gsjgs.142.3.0447, 1985.

Boyce, E. S., Motyka, R. J., and Truffer, M.: Flotation and retreat of a lake-calving terminus, Mendenhall Glacier, southeast Alaska, USA, Journal of Glaciology, 53, 211-224, doi:10.3189/172756507782202928, 2017.

Catania, G., Hulbe, C., Conway, H., Scambos, T. A., and Raymond, C. F.: Variability in the mass flux of the Ross ice streams, West Antarctica, over the last millennium, Journal of Glaciology, 58, 741-752, 10.3189/2012JoG11J219, 2012.

Clark, C. D.: Remote Sensing Scales Related To The Frequency Of Natural Variation: An Example From Paleo-ice Flow In Canada, IEEE Transactions on Geoscience and Remote Sensing, 28, 503-508, doi:10.1109/TGRS.1990.572932, 1990.

Clark, P. U. and Walder, J. S.: Subglacial drainage, eskers, and deforming beds beneath the Laurentide and Eurasian ice sheets, GSA Bulletin, 106, 304-314, doi:10.1130/0016-7606(1994)106<0304:SDEADB>2.3.CO;2, 1994.

Cuzzone, J. K., Clark, P. U., Carlson, A. E., Ullman, D. J., Rinterknecht, V. R., Milne, G. A., Lunkka, J.-P., Wohlfarth, B., Marcott, S. A., and Caffee, M.: Final deglaciation of the Scandinavian Ice Sheet and implications for the Holocene global sea-level budget, Earth and Planetary Science Letters, 448, 34-41, doi:10.1016/j.epsl.2016.05.019, 2016.

Dewald, N., Livingstone, S. J., and Clark, C. D.: Subglacial meltwater routes of the Fennoscandian Ice Sheet, Journal of Maps, 18, 382-396, doi:10.1080/17445647.2022.2071648, 2022.

Dorokhov, D. V., Dorokhova, E. V., and Sivkov, V. V.: Iceberg and ice-keel ploughmarks on the Gdansk-Gotland Sill (south-eastern Baltic Sea), Geo-Marine Letters, 38, 83-94, doi:10.1007/s00367-017-0517-3, 2018.

Dowdeswell, J. A., Canals, M., Jakobsson, M., Todd, B. J., Dowdeswell, E. K., and Hogan, K. A.: The variety and distribution of submarine glacial landforms and implications for ice-sheet reconstruction, Geological Society, London, Memoirs, 46, 519-552, doi:10.1144/M46.183, 2016.

Dowling, T. P. F., Spagnolo, M., and Möller, P.: Morphometry and core type of streamlined bedforms in southern Sweden from high resolution LiDAR, Geomorphology, 236, 54-63, doi:10.1016/j.geomorph.2015.02.018, 2015.

Eissmann, L.: Rhombenporphyrgeschiebe in Elster und Saalemoränen des Leipziger Raumes, Abh. Ber. Naturkund. Mus. Mauritianum Altenbg., 5, 37-46, 1967.

EMODnet Bathymetry Consortium: EMODnet Digital Bathymetry [dataset], 2022.

Enquist, F.: Die glaziale Entwicklungsgeschichte Nordwestskandinaviens, Sveriges Geologiska Undersökning Serie C 285, 1918.

Favier, L., Pattyn, F., Berger, S., and Drews, R.: Dynamic influence of pinning points on marine ice-sheet stability: a numerical study in Dronning Maud Land, East Antarctica, The Cryosphere, 10, 2623-2635, doi:10.5194/tc-10-2623-2016, 2016.

Feldens, P., Diesing, M., Wilken, D., and Schwarzer, K.: Submarine eskers preserved on Adler Grund, south-western Baltic Sea, Baltica: The International Journal on Geosciences, 26, 137-144, doi:10.5200/baltica.2013.26.14 2013.

Flodén, T., Bjerkéus, M., Sturkell, E., Gelumbauskaitė, Ž., Grigelis, A., Endler, R., and Lemke, W.: Distribution and seismic stratigraphy of glacially incised valleys in the southern part of the Baltic, Proceedings of the Fourth Marine Geological Conference–the Baltic, Sveriges Geologiska Undersökning, Ser. Ca, 86, 43-49, 1997.

Fowler, A. C. and Johnson, C.: Ice-sheet surging and ice-stream formation, Annals of Glaciology, 23, 68-73, doi:10.3189/S0260305500013276, 1996.

Frydrych, M.: Morphology of eskers in Poland, southward of the Last Glacial Maximum, Geomorphology, 415, 108418, doi:10.1016/j.geomorph.2022.108418, 2022.

Gandy, N., Gregoire, L. J., Ely, J. C., Cornford, S. L., Clark, C. D., and Hodgson, D. M.: Exploring the ingredients required to successfully model the placement, generation, and evolution of ice streams in the British-Irish Ice Sheet, Quaternary Science Reviews, 223, 105915, doi:10.1016/j.quascirev.2019.105915, 2019.

Gauthier, M. S., Breckenridge, A., and Hodder, T. J.: Patterns of ice recession and ice stream activity for the MIS 2 Laurentide Ice Sheet in Manitoba, Canada, Boreas, 51, 274-298, doi:10.1111/bor.12571, 2022.

Glückert, G.: Map of glacial striation of the Scandinavian ice sheet during the last (Weichsel) glaciation in northern Europe, Bulletin Geological Society of Finland, 46, 1-8, doi:10.17741/bgsf/46.1.001, 1974.

Greenwood, S. L. and Clark, C. D.: Reconstructing the last Irish Ice Sheet 2: a geomorphologically-driven model of ice sheet growth, retreat and dynamics, Quaternary Science Reviews, 28, 3101-3123, doi:10.1016/j.quascirev.2009.09.014, 2009.

Greenwood, S. L., Clason, C. C., Nyberg, J., Jakobsson, M., and Holmlund, P.: The Bothnian Sea ice stream: early Holocene retreat dynamics of the south-central Fennoscandian Ice Sheet, Boreas, 46, 346-362, doi:10.1111/bor.12217, 2016.

Greenwood, S. L., Clason, C. C., Mikko, H., Nyberg, J., Peterson, G., and Smith, C. A.: Integrated use of LiDAR and multibeam bathymetry reveals onset of ice streaming in the northern Bothnian Sea, GFF, 137, 284-292, doi:10.1080/11035897.2015.1055513, 2015.

Gripp, K.: Der Ablauf der Würm-Vereisung in der Senkungszone am Südrand Skandinaviens, Meyniana, 33, 9-22, 1981.

Gruszka, B. and Zieliński, T.: Lacustrine deltas and subaqueous fans: almost the same, but different – a review, Geologos, 27, 43-55, doi:10.2478/logos-2021-0004, 2021.

Hall, A. and van Boeckel, M.: Origin of the Baltic Sea basin by Pleistocene glacial erosion, GFF, 142, 237-252, doi:10.1080/11035897.2020.1781246, 2020.

Hermanowski, P., Piotrowski, J. A., and Szuman, I.: An erosional origin for drumlins of NW Poland, Earth Surface Processes and Landforms, 0, doi:10.1002/esp.4630, 2019.

Hindmarsh, R. C. A.: Consistent generation of ice-streams via thermo-viscous instabilities modulated by membrane stresses, Geophysical Research Letters, 36, doi:10.1029/2008GL036877, 2009.

Holmlund, P. and Fastook, J.: A time dependent glaciological model of the Weichselian Ice Sheet, Quaternary International, 27, 53-58, doi:10.1016/1040-6182(94)00060-I, 1995.

Holmström, L.: Öfversikt af den glaciala afslipningen i Sydskandinavien, Geologiska Föreningen i Stockholm Förhandlingar, 26, 241-316, doi:10.1080/11035890409445487, 1904.

Houmark-Nielsen, M. and Kjær, K. H.: Southwest Scandinavia, 40–15 kyr BP: palaeogeography and environmental change, Journal of Quaternary Science, 18, 769-786, doi:10.1002/jqs.802, 2003.

Jakobsson, M., O'Regan, M., Gyllencreutz, R., and Flodén, T.: Seafloor terraces and semi-circular depressions related to fluid discharge in Stockholm Archipelago, Baltic Sea, Geological Society, London, Memoirs, 46, 305-306, doi:10.1144/M46.162, 2016.

Jakobsson, M., Stranne, C., O'Regan, M., Greenwood, S. L., Gustafsson, B., Humborg, C., and Weidner, E.: Bathymetric properties of the Baltic Sea, Ocean Sci., 15, 905-924, doi:10.5194/os-15-905-2019, 2019.

Jakobsson, M., O'Regan, M., Mörth, C. M., Stranne, C., Weidner, E., Hansson, J., Gyllencreutz, R., Humborg, C., Elfwing, T., Norkko, A., Norkko, J., Nilsson, B., and Sjöström, A.: Potential links between Baltic Sea submarine terraces and groundwater seeping, Earth Surf. Dynam., 8, doi:1-15, 10.5194/esurf-8-1-2020, 2020.

Jensen, J. B.: Late Weichselian deglaciation pattern in the southwestern Baltic: Evidence from glacial deposits off the island of Møn, Denmark Bulletin of the Geological Society of Denmark, 40, 314-331, 1993.

Jögensen, F. and Piotrowski, J. A.: Signature of the Baltic Ice Stream on Funen Island, Denmark during the Weichselian glaciation, Boreas, 32, 242-255, doi:10.1111/j.1502-3885.2003.tb01440.x, 2003.

Jørgensen, F. and Sandersen, P. B. E.: Buried and open tunnel valleys in Denmark—erosion beneath multiple ice sheets, Quaternary Science Reviews, 25, 1339-1363, doi:10.1016/j.quascirev.2005.11.006, 2006.

Kalm, V.: Ice-flow pattern and extent of the last Scandinavian Ice Sheet southeast of the Baltic Sea, Quaternary Science Reviews, 44, 51-59, doi:10.1016/j.quascirev.2010.01.019, 2012.

Karpin, V., Heinsalu, A., and Virtasalo, J. J.: Late Pleistocene iceberg scouring in the north-eastern Baltic Sea, west of Estonia, Marine Geology, 438, 106537, doi:10.1016/j.margeo.2021.106537, 2021.

Kehew, A. E., Piotrowski, J. A., and Jørgensen, F.: Tunnel valleys: Concepts and controversies — A review, Earth-Science Reviews, 113, 33-58, doi:10.1016/j.earscirev.2012.02.002, 2012.

Kirkham, J. D., Hogan, K. A., Larter, R. D., Arnold, N. S., Ely, J. C., Clark, C. D., Self, E., Games, K., Huuse, M., Stewart, M. A., Ottesen, D., and Dowdeswell, J. A.: Tunnel valley formation beneath deglaciating mid-latitude ice sheets: Observations and modelling, Quaternary Science Reviews, 107680, doi:10.1016/j.quascirev.2022.107680, 2022.

Kjær, K. H., Houmark-Nielsen, M., and Richardt, N.: Ice-flow patterns and dispersal of erratics at the southwestern margin of the last Scandinavian Ice Sheet: signature of palaeo-ice streams, Boreas, 32, 130-148, doi:10.1111/j.1502-3885.2003.tb01434.x, 2003.

Kleman, J., Stroeven, A. P., and Lundqvist, J.: Patterns of Quaternary ice sheet erosion and deposition in Fennoscandia and a theoretical framework for explanation, Geomorphology, 97, 73-90, doi:10.1016/j.geomorph.2007.02.049, 2008.

Kleman, J., Hättestrand, C., Borgström, I., and Stroeven, A.: Fennoscandian palaeoglaciology reconstructed using a glacial geological inversion model, Journal of Glaciology, 43, 283-299, doi:10.3189/S0022143000003233, 1997.

Kramarska, R.: Origin and development of the Odra Bank in the light of the geologic structure and radiocarbon dating, Geo log ica l Quarterl y, 42, 277-288, 1998.

Larsen, N. K., Knudsen, K. L., Krohn, C. F., Kronborg, C., Murray, A. S., and Nielsen, O. L. E. B.: Late Quaternary ice sheet, lake and sea history of southwest Scandinavia – a synthesis, Boreas, 38, 732-761, doi:10.1111/j.1502-3885.2009.00101.x, 2009.

Larson, G. J., Lawson, D. E., Evenson, E. B., Alley, R. B., Knudsen, Ó., Lachniet, M. S., and Goetz, S. L.: Glaciohydraulic supercooling in former ice sheets?, Geomorphology, 75, 20-32, doi:10.1016/j.geomorph.2004.12.009, 2006.

Lemke, W. and Kuijpers, A.: Late Pleistocene and early Holocene paleogeography of the Darss Sill area, southwestern Baltic, Quaternary International, 27, 73-81, doi:10.1016/1040-6182(94)00063-B, 1995.

Livingstone, S. J., Ó Cofaigh, C., Stokes, C. R., Hillenbrand, C.-D., Vieli, A., and Jamieson, S. S. R.: Antarctic palaeo-ice streams, Earth-Science Reviews, 111, 90-128, doi:10.1016/j.earscirev.2011.10.003, 2012.

Ljunger, E.: Isdelarstudier vid polcirkeln, Geol. Fören. Stockholm Förhand., 65, 198-210, 1943.

Madsen, V.: Om indelingen af de danske kvartærdannelser., Fören, 5, 1-22, 1898.

Margold, M., Stokes, C. R., and Clark, C. D.: Ice streams in the Laurentide Ice Sheet: Identification, characteristics and comparison to modern ice sheets, Earth-Science Reviews, 143, 117-146, doi:10.1016/j.earscirev.2015.01.011, 2015.

Margold, M., Jansson, K. N., Kleman, J., Stroeven, A. P., and Clague, J. J.: Retreat pattern of the Cordilleran Ice Sheet in central British Columbia at the end of the last glaciation reconstructed from glacial meltwater landforms, Boreas, 42, 830-847, doi:10.1111/bor.12007, 2013.

Noormets, R. and Flodén, T.: Glacial deposits and Late Weichselian ice-sheet dynamics in the northeastern Baltic Sea, Boreas, 31, 36-56, doi:10.1111/j.1502-3885.2002.tb01054.x, 2002a.

Noormets, R. and Flodén, T.: Glacial deposits and ice-sheet dynamics in the north-central Baltic Sea during the last deglaciation, Boreas, 31, 362-377, doi:10.1111/j.1502-3885.2002.tb01080.x, 2002b.

Obst, K., Nachtweide, C., and Müller, U.: Late Saalian and Weichselian glaciations in the German Baltic Sea documented by Pleistocene successions at the southeastern margin of the Arkona Basin, Boreas, 46, 18-33, doi:10.1111/bor.12212, 2017.

Patton, H., Hubbard, A., Andreassen, K., Winsborrow, M., and Stroeven, A. P.: The build-up, configuration, and dynamical sensitivity of the Eurasian ice-sheet complex to Late Weichselian climatic and oceanic forcing, Quaternary Science Reviews, 153, 97-121, doi:10.1016/j.quascirev.2016.10.009, 2016.

Patton, H., Hubbard, A., Andreassen, K., Auriac, A., Whitehouse, P. L., Stroeven, A. P., Shackleton, C., Winsborrow, M., Heyman, J., and Hall, A. M.: Deglaciation of the Eurasian ice sheet complex, Quaternary Science Reviews, 169, 148-172, doi:10.1016/j.quascirev.2017.05.019, 2017.

Payne, A. J.: Dynamics of the Siple Coast ice streams, west Antarctica: Results from a thermomechanical ice sheet model, Geophysical Research Letters, 25, 3173-3176, doi:10.1029/98GL52327, 1998.

Poprawa, P., Šliaupa, S., Stephenson, R., and Lazauskienė, J.: Late Vendian–Early Palæozoic tectonic evolution of the Baltic Basin: regional tectonic implications from subsidence analysis, Tectonophysics, 314, 219-239, doi:10.1016/S0040-1951(99)00245-0, 1999.

Punkari, M.: Glacial and glaciofluvial deposits in the interlobate areas of the Scandinavian ice sheet, Quaternary Science Reviews, 16, 741-753, doi:10.1016/S0277-3791(97)00020-6, 1997.

Ringberg, B.: Late Weichselian geology of southernmost Sweden, Boreas, 17, 243-263, doi:10.1111/j.1502-3885.1988.tb00554.x, 1988.

Schäfer, W., Hübscher, C., and Sopher, D.: Seismic stratigraphy of the Klints Bank east of Gotland (Baltic Sea): a giant drumlin sealing thermogenic hydrocarbons, Geo-Marine Letters, 41, 9, doi:10.1007/s00367-020-00683-3, 2021.

Smith, M. J. and Clark, C. D.: Methods for the visualization of digital elevation models for landform mapping, Earth Surface Processes and Landforms, 30, 885-900, doi:10.1002/esp.1210, 2005.

Stephan, H.-J.: The Young Baltic advance in the western Baltic depression, Geological Quarterly, 45, 5, 2001.

Still, H. and Hulbe, C.: Mechanics and dynamics of pinning points on the Shirase Coast, West Antarctica, The Cryosphere, 15, 2647-2665, doi:10.5194/tc-15-2647-2021, 2021.

Stokes, C. R.: Geomorphology under ice streams: Moving from form to process, Earth Surface Processes and Landforms, 43, 85-123, doi:10.1002/esp.4259, 2018.

Stroeven, A. P., Hättestrand, C., Kleman, J., Heyman, J., Fabel, D., Fredin, O., Goodfellow, B. W., Harbor, J. M., Jansen, J. D., Olsen, L., Caffee, M. W., Fink, D., Lundqvist, J., Rosqvist, G. C., Strömberg, B., and Jansson, K. N.: Deglaciation of Fennoscandia, Quaternary Science Reviews, 147, 91-121, doi:10.1016/j.quascirev.2015.09.016, 2016.

Sviridov, N. I. and Emelyanov, E. M.: Lithofacial complexes of quaternary deposits in the central and southeastern baltic sea, Lithology and Mineral Resources, 35, 211-231, doi:10.1007/BF02821956, 2000.

Szuman, I., Kalita, J. Z., Ewertowski, M. W., Clark, C. D., and Livingstone, S. J.: Dynamics of the last Scandinavian Ice Sheet's southernmost sector revealed by the pattern of ice streams, Boreas, 50, 764-780, doi:10.1111/bor.12512, 2021.

Tuuling, I. and Flodén, T.: The structure and relief of the bedrock sequence in the Gotland-Hiiumaa area, northern Baltic Sea, GFF, 123, 35-49, doi:10.1080/11035890101231035, 2001.

Tuuling, I. and Flodén, T.: The Baltic Klint beneath the central Baltic Sea and its comparison with the North Estonian Klint, Geomorphology, 263, 1-18, doi:10.1016/j.geomorph.2016.03.030, 2016.

Tuuling, I. and Flodén, T. O. M.: Silurian reefs off Saaremaa and their extension towards Gotland, central Baltic Sea, Geological Magazine, 150, 923-936, doi:10.1017/S0016756813000101, 2013.

Tylmann, K. and Uścinowicz, S.: Timing of the last deglaciation phases in the southern Baltic area inferred from Bayesian age modeling, Quaternary Science Reviews, 287, 107563, doi:10.1016/j.quascirev.2022.107563, 2022.

Uścinowicz, S.: Southern Baltic area during the last deglaciation Geological Quarterly, 43, 137-148, 1999.

Uścinowicz, S.: Relative sea level changes, glacio-isostatic rebound and shoreline displacement in the Southern Baltic, Polish Geological Institute Special Papers, 10, 1-79, 2003.

Uścinowicz, S.: A relative sea-level curve for the Polish Southern Baltic Sea, Quaternary International, 145-146, 86-105, doi:10.1016/j.quaint.2005.07.007, 2006.

Woldstedt, P. and Duphorn, K.: Norddeutschland und angrenzende Gebiete im Eiszeitalter, Stuttgart1974.

Woźniak, P. P. and Czubla, P.: The Late Weichselian glacial record in northern Poland: A new look at debris transport routes by the Fennoscandian Ice Sheet, Quaternary International, 386, 3-17, doi:10.1016/j.quaint.2015.01.014, 2015.

Zeise, O.: Beitrag zur Kenntnis der Ausbreitung, sowie besonders der Bewegungsrichtung des nordeuropäischen Inlandeises in diluvialer Zeit, Inaugural-Dissertation, Albertus-Universität, Königsberg. Preußen.1889.