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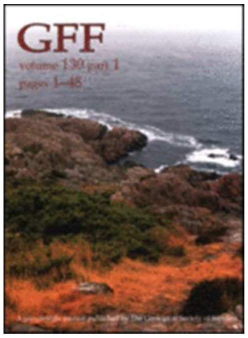

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Integrated use of LiDAR and multibeam bathymetry reveals onset of ice streaming in the northern Bothnian Sea.

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Abstract

~~From G~~Geomorphological mapping from the new LiDAR-derived digital elevation model for Sweden and a high resolution multibeam bathymetry dataset for the Gulf of Bothnia, reveals a continuous system of glacial landforms ~~is reconstructed~~ crossing the transition between the ~~present day~~modern terrestrial and marine ~~and terrestrial~~ environments. A palaeo-ice stream in the northern Bothnian Sea is reconstructed, with an onset tributary over the present-day Ångermanland-Västerbotten coastline. ~~A fast-flowing, likely late stage ice stream is identified based upon c~~Systematic contrasts in landform morphology and lineation length ~~from crestline mapping,~~ indicate that this ice stream comprised~~ing~~ a relatively narrow (~40 km) corridor of fast flow, flowing first SW then S, and likely fed by converging flow around the upper Bothnian Sea. ~~in a south/south-westward direction. Mapping also infers that south/south-eastward trending lineations onshore are the product of an onset tributary flowing from the present day south Västerbotten/north Ångermanland coastline. Lineations interpreted from sidescan sonar data in the nearshore zone confirm that onshore and offshore lineations form part of a continuous system, linking the LiDAR and mutlibeam datasets. These mapped landform assemblages are thus representative of a single palaeo-ice flowline, and imply that ice flow originating from this sector of the northern Swedish coastline did not directly feed an ice sheet lobe terminating over southeast Finland during the stage represented in these data~~The geometry and landform associations of this system imply that ice, at the time period represented here, did not flow across the Gulf of Bothnia: SSE-ward ice flow indicators on the northern Swedish coast do not correspond directly with landform assemblages of the large SE-oriented Finnish deglacial lobes. Instead, we suggest they may contribute to a late-stage fast-flow event to the S/SW. ~~The~~ M~~m~~ultibeam bathymetry data offer entirely new access into the rich, landform-scale geomorphological record on the seafloor of the Gulf of Bothnia. The c~~C~~ombination~~ed~~ of

offshore multibeam with the new terrestrial LiDAR data~~, this~~ provides unprecedented insight into and renewed understanding of the glacial dynamics of the Bothnian Sea sector of the Fennoscandian Ice Sheet, hitherto interpreted over large areas of unmapped ice sheet bed.

Keywords

Glacial geomorphology; Fennoscandian Ice Sheet; ice stream; lineations; Gulf of Bothnia

1. Introduction

The Gulf of Bothnia sits in the heart of the palaeo-Fennoscandian Ice Sheet (FIS). It is considered to have played host to a variety of ice dynamic environments during the last glacial period: at times under or close to the main ice divide (e.g. Kleman et al 1997) the head of an extensive fast-flowing ice stream (e.g. Holmlund & Fastook 1995; Boulton et al 2001), the source of deglacial ice lobes splaying across southern Finland (Punkari 1980, 1995), the location of a deglacial calving embayment and rapid post-Younger Dryas retreat (e.g. De Geer 1940; Hoppe 1961; Strömberg 1981) and the corridor of a postulated late-stage readvance or surge (e.g. Sandegren 1929; Lundqvist 2007). Given such a variety of proposed glacial environments, it is to be expected that the Gulf should present a complex, time-transgressive geological and geomorphological record. Similarly, it is not surprising that many details of the glacial history are still matters of debate.

Approximately 120,000 km^2 and oriented ~NNE-SSW, the Gulf of Bothnia separates Sweden and Finland by 100-250 km (Fig. 1). Almost 90% of its area is shallower than 100 m water depth. The latest phase of ice flow and the trajectory during retreat is generally considered to have been directed east and southwards across the Gulf (Lunkka 2004; Johansson et al 2011). Late-glacial ice directional indicators along the eastern Swedish coast are oriented broadly southeast-wards into the Gulf (Kautsky 1986; Lundqvist 1987; Kleman et al 1997) and,~~.~~ a~~A~~lthough flow is known to have shifted some degrees during ice sheet configuration changes of the last glacial phase, the Swedish ice-flow indicators are widely assumed to correspond to the large, well-known deglacial Finnish lobes (Punkari 1980, 1995; Boulton et al 2001). The most southerly of these, the Baltic Sea lobe~~ (cf Punkari 1980, 1995; Boulton et al 2001)~~, has a stronger SSE component than the lobes farther north. It is depicted as originating from the Swedish High Coast and Västerbotten, and ultimately encroaching onto southwestern Finland where it is associated with the Salpausselkä suite of moraines, formed during episodes of the Younger Dryas (Lunkka 2004). The pattern of subsequent retreat, widely charted by De Geer moraines, glaciofluvial landforms and the Swedish and Finnish varve chronologies, is generally considered to be NW, turning WNW across the Bothnian Bay and Finnish Lappland (Ignatius et al 1980;

Punkari 1980; Lunkka 2004; Sarala 2005). There are scant traces of ice flow directed through the Gulf, along its main N-S (NNE-SSW) axis. T~~, but t~~here exists, however, a lasting debate over a late-stage, post Younger Dryas readvance or surge through the basin: the so-called Gävle oscillation, or readvance (e.g. Sandegren 1929; Hoppe 1961; Lundqvist 2007), argued by some to have encroached from the Bothnian Sea onto the central Swedish coast.~~ In all of these cases,~~ ~~a~~Almost all of our understanding in all of these cases, and the basis for debate over glacial history and dynamics in the Gulf of Bothnia, is inferred indirectly from peripheral terrestrial evidence. Records from the Gulf itself are extremely limited. Large scale models of Fennoscandian Ice Sheet dynamics have been based almost entirely on assumed correlations between terrestrial data from either side of this large tract of the ice sheet bed.

Here we exploit two complementary datasets: the new LiDAR-derived, 2 m grid cell digital elevation model for Sweden, and a high-resolution (5 m grid cell) multibeam bathymetry dataset from the Gulf of Bothnia (Fig. 1). Each of these datasets has the potential to revolutionise our understanding of sectors of the Fennoscandian Ice Sheet, and of Scandinavian geomorphology. The resolution and the coverage of the LiDAR model present a powerful new view of the terrestrial record, whilst extensive multibeam surveys in the Gulf access the rich offshore geomorphological record for the very first time. Together, their integrated use allows us to reconstruct continuous geomorphological systems as they cross the terrestrial/marine boundary and, for the first time, to reliably link palaeo-glacial information from different sectors of the ice sheet based on direct evidence.

2. LiDAR and multibeam: complementary methods for glacial geomorphology

Whilst mapping of glacial landforms and landscapes from remotely sensed data has long been a part of palaeo-glaciology (e.g. Prest et al 1968; Punkari 1980, 1982; Boulton & Clark 1990; Kleman 1992; Hättestrand 1998), the development of techniques and technologies for gathering high resolution and high accuracy digital elevation data has arguably revolutionised the field. Recent years have witnessed the widespread and systematic collection, often under national survey schemes, of airborne radar and LiDAR data for the production of extremely high resolution (decimetre-scale) terrestrial digital surface models. The form of the land surface is being captured over large areas with unprecedented clarity, granting new perspectives over hitherto 'known' glacial landscapes and permitting highly detailed, systematic and large area assessments of glacial geomorphological records and their palaeo-glaciodynamic environments (e.g. Hughes et al 2010, 2014; Livingstone et al 2012; Dowling et al 2013). In parallel, developments in multibeam echo-sounding of the ocean floor have revolutionised palaeo-glaciology as a whole discipline, by providing a view of the large marine sectors of ice sheets hitherto only blank gaps on maps and in ice sheet histories known predominantly from their modern terrestrial domains (e.g. Shipp et al 1999; Lowe & Anderson 2002; Ottesen et al 2005; Graham et al 2009; Todd & Shaw 2012). The latest generation of multibeam sonars yield bathymetric surfaces with a resolution better than 25 m in water depths up to 1000 m, and up to cm-m scale in shallow waters. Importantly, surveying of glacial geomorphic systems proximal to contemporary ice sheets has allowed process links between geomorphic forms and assemblages and their formative glaciodynamic environments to be more securely established (e.g. Canals et al 2000; Wellner et al 2006; Graham et al 2013; Rebesco et al 2014). Furthermore, comparison between marine and terrestrial geomorphic assemblages, which are both contrasting and complementary, has the potential to yield a greater understanding of the dynamics and controls upon ice sheet systems in these two domains, an approach thus far under-utilised.

Use of high resolution LiDAR digital terrain models in the terrestrial domain and multibeam bathymetry models in the marine are now, independently, at the forefront of palaeo-glaciological research in their respective sectors of the ice sheet. Whilst research is often still divided by traditional working groups, the principles of the technologies for building digital terrain models either above or below the sea level are very similar, and resulting datasets highly complementary. Both techniques emit a pulse of energy (in light or sound frequencies) and 'listen' for its echo, reflected off the target surface. The two-way travel time for the pulse and its echo is a function of distance, trajectory and wave velocity through the medium of travel (e.g. sound velocity through water). ~~. LiDAR is based on the emission of light energy (ultraviolet to near infrared) through a laser, spread across a swath using a rotating mirror. Multibeam echo-sounding uses a much lower frequency pulse in the sonar range of the spectrum (10s-100s kHz). An array of transducers generate a swath of beams emitted in a single 'ping' of sound. For both techniques, the two-way travel time between an emitted pulse and its echo is a function of its trajectory to/from the target surface, and is converted to elevation (depth) based on the velocity of the pulse wave (e.g. sound velocity through water). A point cloud of returned measurements is~~ Depth (distance) conversions for each individual measurement are gridded to represent the target surface. Using these two complementary techniques, a single geomorphic system which crosses the present-day coastline can be investigated with directly comparable results (e.g. Stoker et al 2009; Howe et al 2012). Optimally, via coordinated research efforts, the techniques can yield fully integrated, seamless datasets (e.g. Persson et al 2014).

Deglacial shorelines along the Swedish High Coast are up to ~280 m above the current sea level, a consequence of~~and~~ isostatic uplift which continues today at a rate of nearly 1 cm/year (Berglund 2004). Geologically the present coastline is insignificant, but logistically it marks a distinct boundary that has inhibited correlation of distant data sets. In this paper, we combine onshore investigation of the glaciated terrestrial landscape from LiDAR on the Swedish High Coast & Västerbotten, with directly comparable offshore study of a large multibeam dataset in the northern Bothnian Sea (Fig. 1B). Each dataset independently reveals a snapshot of fast flowing ice attributed to the last glaciation. In combination, we identify a continuous ice stream system funnelled SW and S-wards through the Bothnian Sea with an onset tributary on the Swedish Ångermanland/Västerbotten Coast.

3. Northern Bothnian Sea: datasets and methods

The new LiDAR-based Swedish national elevation dataset forms the basis of our terrestrial work, from Örnsköldsvik to Umeå on the Swedish Bothnian coast (Fig. 1). The data presently cover about 90% of Sweden, and are gridded at 2 m with a stated accuracy of 40 cm in the horizontal plane and a vertical accuracy of 10 cm (Lantmäteriet, 2014). In the Gulf of Bothnia, a large multibeam dataset (~20% of the Gulf covered) has been collected in recent years for the Swedish Maritime Administration.~~, , a portion of which is held at the Geological Survey of Sweden.~~ While analysis of the full dataset is the subject of ongoing work, we report here on a~~A~~ 4500 km^2 sector ~~of this dataset~~ which lies in close proximity to the coast, immediately offshore~~,~~ and to the south and east of our terrestrial area of interest on the Västerbotten/Ångermanland coast (Fig. 1). The data in this area were collected with a Reson 7125 SV multibeam from May to November 2013 and a Kongsberg ~~EM2050~~ EM2040 multibeam during November 2013, and these data are gridded at 5 m. These datasets represent the first view of the landform-scale geomorphology of the seafloor of the Gulf of Bothnia, and provide an entirely unprecedented insight into ~~offshore~~ palaeo-glacial dynamics in this offshore region.

From the gridded elevation surfaces, the LiDAR and multibeam datasets are treated in exactly the same way for geomorphological interpretation: the approach becomes entirely independent of their position above or below the present-day sea level (Fig. 2). A quasi-systematic combination of relief shading and slope maps, together with the raw elevation surfaces, are the basis for geomorphological mapping. Peterson & Smith (2013) describe a set of protocols which have been employed for terrestrial mapping and classification of glacial geomorphology; these are largely similar to those adopted offshore. Landforms identified and mapped in our study areas include glacial lineations (drumlins, crag and tails, mega-scale glacial lineations), ribbed moraine, meltwater channels, eskers, moraines and crevasse squeeze ridges. Mapping of morphological crestlines rather than break-of-slope was the dominant strategy to time-efficiently yield adequate palaeo-glaciological information from (quasi-)linear features; ribbed moraine and larger moraines were mapped by break-of-slope. A~~a~~ll discernible glacial landforms have been mapped within a defined area onshore and the full extent of the shown datasets offshore.

Landform mapping was initially, and principally, performed on these two topographic datasets. However, multibeam bathymetry was not available in a zone closest to shore, leaving a gap in data coverage. Here, sidescan sonar datasets collected by the Geological Survey of Sweden (Nyberg & Thelander 2012) were employed to investigate the continuity of landform assemblages between the LiDAR and multibeam coverage. Sidescan sonars are sideways (oblique) looking instruments, which record a swath of data but do not measure seafloor depth (e.g. pulse travel time), rather the strength of the return signal is recorded. Compositional differences in seafloor targets are highlighted, which may relate to geomorphic forms. All glacial lineations interpreted from the available coverage of sidescan imagery were recorded.

4. Landform analysis and interpretations

Whilst all glacial landforms from subglacial, meltwater and ice-marginal domains were mapped from our topographic datasets, we focus here on the extensive assemblages of glacial lineations recorded throughout ~~our datasets~~. Figure 3 presents the distribution of glacial lineations in our northern Bothnia survey areas. A coherent set of lineations is evident in both areas. On the Ångermanland/Västerbotten coast, the LiDAR data reveal a converging group of lineations, oriented to the S and SSE, and including both crag & tail and drumlin forms (Fig. 2A,B). Analysis of lineation lengths within this flowset indicates some internal arrangement of morphology: a central corridor ~~of~~ with an abundance of longer lineations ~~are~~ is clearly bounded laterally by an abrupt transition to shorter, smaller features (Fig. 3).

The multibeam datasets reveal a suite of highly elongate and parallel lineations, forming a sweeping assemblage oriented SW (in the northern sector) to S (in the southern sector), following the trajectory of the Gulf of Bothnia at this location (Fig. 2C,D; Fig. 3). There is a clear downstream extension of lineations, from relatively short drumlins (300-1200 m) in the north of the group, to forms better described as mega-scale glacial lineations up to 14 km long in the southern reaches of the area. The landforms also display an across-set gradation of lengths, with shorter forms on the lateral eastern flank of the group. The texture of the multibeam surface and the thickness of the sediment column in this area (of the 8000+ depth to bedrock estimates in this area, 62% are greater than 20 m and >94% greater than 10 m) suggest these are predominantly sediment forms, though we cannot rule out that some lineations have bedrock cores. Crag and tail forms occur in the northwest of the multibeam sector, closer to the shore and overlying crystalline bedrock (Ahlberg, 1986; Nyberg & Thelander 2012).

Both the terrestrial and the marine lineation assemblages are interpreted as representing a fast flowing corridor of ice, based on the lineation form (length) and the distribution of this parameter across each respective set (cf Stokes & Clark 2002). We hypothesise that these are two stretches of the same ice stream system, and that the onshore corridor identified in the LiDAR-based mapping is a tributary to an offshore ice stream in the northern Bothnian Sea which flows south and south-westward through the Gulf. The two sets are thus linked in a continuous palaeo-ice flowline. This hypothesis requires that the onshore tributary bends towards the south and southwest when it is captured in the offshore corridor; the alternative possibility would be that the terrestrial and marine flowsets belong to two separate flow events of contrasting orientation. We are missing adequate elevation data from a nearshore zone to provide a seamless link in comparable data, but instead refer to sidescan sonar datasets ~~collected by the Geological Survey of Sweden~~ to test our hypothesis. Lineations mapped from sidescan images are shown in Fig. 4, and display a progressive shift in landform orientations between the two mapping zones. Although the sidescan images do not provide complete spatial coverage, we argue that these data~~Sidescan sonar images~~ ~~which lie~~lying between our LiDAR and multibeam datasets clearly reveal a continuous suite of glacial lineations which link our two earlier mapped sets (Fig. 4). We are therefore confident in reconstructing a continuous palaeo-flowline, representing the capture of an onshore ice stream tributary by the main stream corridor funnelled south/southwestward through the northern Bothnian Sea.

5. Discussion ~~and Conclusions~~

An upper Bothnian palaeo-ice stream

We reconstruct a fast-flowing ice stream in the upper Bothnian Sea, sourced by at least one tributary ~~on land~~ on the present-day Västerbotten coast of northern Sweden (Fig. 5). It has long been anticipated that ice along the southern and eastern margins of the FIS was characterised by fast-flowing corridors (e.g. Punkari 1980; Holmlund & Fastook 1995; Boulton et al 2001; Kjær et al 2003), based on an extended flow trajectory with far-travelled erratics, terrestrial landform-based delineation of discrete flow corridors, and the occupation of shallow marine basins floored with soft sediments. The flow feature presented here represents the first palaeo-ice stream of the southern/eastern FIS margin to be definitively identified based on a diagnostic subglacial record of ice streaming.

The sharp contrasts in lineation length and morphology that we witness in both the terrestrial and marine sectors enable us to delimit the lateral boundaries of a ~~fast-flowing~~ central ice stream corridor. ~~These~~ The lateral transition from longer to shorter forms indicates that this stream was rather narrow: about 40 km. It likely did not occupy the full breadth of the present-day basin, but rather flowed along the western coast of the Gulf of Bothnia, feeding into the depression of Härnösandsdjupet. We may infer from this that the large-scale topography of the basins had some role in directing the path of ice flow, although it was likely not an overriding control as the ice stream is directed south from Härnösandsdjupet, and is apparently not captured by the eastern trough which follows the axis of the Bothnian Sea. At the time our identified ice stream was operating, significant flow across Kvarken (the shallows between the Bothnian Bay and Sea) would be required to steer the ice flow coming off the Ångermanland/Västerbotten coast from its terrestrial SSE trajectory abruptly towards the SW.

Relative timing and (un)conformity with the Finnish deglacial lobes

~~Though the onshore glacial lineations indicate a SSE flow path, t~~The ice stream we have identified offshore follows first a SW ~~or~~ then S~~W~~ trajectory in the northern Bothnian Sea, with a S/SSE tributary from present-day terrestrial Västerbotten. This configuration~~. This direction~~ contrasts~~s~~ with that invoked by many late-stage models of flow in northern Sweden, western Finland and around the Gulf of Bothnia (e.g. Ignatius et al 1980; Punkari 1995; Kleman et al 1997; Boulton et al 2001; Lunkka 2004; Johansson et al 2011), which depict ~SE flow across the Gulf, and retreat back along a NW or WNW trajectory from the Younger Dryas onwards. We consider three possible explanations for this contrast. First, it is possible our identified ice stream corresponds to an earlier, pre-Younger Dryas stage in the last glacial. The S/SW ice stream flow trajectory would demand an ice divide or source flow positioned over the Bothnian Bay or Finnish Lappland, with significant flow across or convergence around Kvarken. ~~We also suggest that at the time our identified ice stream was operating, significant flow across Kvarken (the shallows between the Bothnian Bay and Sea) would be required to steer the ice flow coming off the Ångermanland/Västerbotten coast from its terrestrial SSE trajectory towards the SW.~~ Secondly, the narrow flow corridor interpreted here could correspond to a sector of a broader Baltic Sea lobe (Punkari, 1980, 1995). This would imply that the broad lobes which splayed across south-west Finland possessed internally spatially variable dynamics: they did not behave uniformly across their span. Third and f~~F~~inally, our data raise the possibility of a newly found component of late-stage deglaciation, which has not hitherto been widely recognised.

An ice sheet configuration with a source over the northern Bothnian Bay, outflow across Kvarken and subsequent passage SW through the Bothnian Sea may indeed have operated at an earlier stage than the traditional deglacial W-E models depict. This would be consistent with where the main ice divide of the Fennoscandian Ice Sheet at its maximum stages has been suggested to lie (Kleman et al 1997). We consider it unlikely, however, that an LGM flow geometry was responsible for the geomorphological imprints we have recorded here. Onshore and offshore assemblages exhibit no significant overprinting by a later ice flow path. Given a wealthy late-stage deglacial landform record across Finland, comprising subglacial ice flow indicators and abundant glaciofluvial and ice-marginal traces (e.g. Ignatius et al 1980; Punkari 1980; Zilliacus 1989; Mäkinen 2003; Ahokangas & Mäkinen 2013), it would be rather surprising to find no strong trace of this configuration in the offshore sectors, if they were the latest event to affect the Gulf. Furthermore, flow recorded by our lineation sets appears to terminate in, or is at least overprinted at its distal end by crevasse squeeze ridges (Fig. 6A), which have a criss-crossing form broadly orthogonal to the underlying lineations. These low amplitude and rather subtle landforms are widely taken to indicate the cessation of a rapid advance, followed by stagnation and/or collapse of the extended ice toe (Solheim & Pfirmann 1985; Evans & Rea 1999; Ottesen & Dowdeswell 2006; Bjarnadóttir et al 2014). We may, therefore, expect their presence to indicate large-scale loss of ice shortly thereafter. Here, their orientation is ~perpendicular to the lineations, indicating conformity ~~of marginal and~~with the subglacial landform assemblage~~s~~ and likely correspondence to the same event. On this basis, it would seem unlikely that the main sets of lineations represent an early, pre-deglacial stage.

A number of workers have postulated the late-stage development of a short-lived S/SW flow configuration in the Gulf of Bothnia (e.g. Sandegren 1929; De Geer 1940; Strömberg 1981; Lundqvist 2007), described variably as a product of flow reconfiguration, development of a calving embayment, a readvance, margin oscillation or short-lived surge. These interpretations have been based on localised terrestrial evidence from the southern and western Bothnian Sea, beyond our study area, and from around Kvarken. Lundqvist (2007) reports ~~There is some consistency between the offshore lineation assemblage we report here and~~ striae on the Finnish coast,~~;~~ south of Vaasa, oriented ~~which are oriented~~ towards the SW and recording an episode of SW-ward flow ~~(Lundqvist 2007). According to Lundqvist (2007) the SW-wards event represented by these striae was~~ bracketed by ~~more dominant and widespread~~ SE flow both earlier and later. He interprets a short-lived SW-ward surge event which postdates widespread SE-ward flow across the Gulf and across Finland. ~~Together with our interpreted flow system, these SW-trending striae would indicate convergence of ice around the head of the Bothnian Sea into the main basin. Lundqvist interprets the SW trending striae as the product of a short-lived surge event which postdates widespread SE-ward flow across the Gulf and across Finland; this is consistent with our interpretations above.~~ This model was postulated earlier by Winterhalter (1972) who,~~:~~ based on early echo-sounding in the Bothnian Sea, reported drumlinised/lineated terrain NE of Härnösandsdjupet ~~was reported. He interpreted a 'glacial drift' composition, based on acoustic profiles, but had difficulty to explain their great length (several km) and~~

~~orientation~~Oriented ~~–~~perpendicular to the~~a~~ presumed NNW-SSE flow, these elongate~~. T~~ landforms ~~he landforms~~ were initially interpreted as primarily of ice-marginal origin, with subsequent overriding from the NE to drumlinise ~~the then~~supposed pre-existing moraine deposits (Winterhalter~~,~~ 1972). Here, with high resolution data and a greater understanding of the scales of subglacial bedforms (e.g. Clark 1993; Ottesen et al 2005;~~,~~ Spagnolo et al 2014) we can demonstrate that these landforms (Fig. 2D) are subglacial lineations of extremely high elongation, corresponding primarily to a palaeo-ice flow trajectory from the NE.

These earlier observations and those presented herein collectively indicate convergence of ice around the head of the Bothnian Sea into the main basin. The absence of widespread cross-cutting, overprinted assemblages, and the association of the fast-flow lineations with landforms suggestive of rapid advance and collapse are consistent with a model of a late-stage, short-lived ice streaming event. It is difficult to assess whether this relatively narrow ice stream path could represent a corridor within a broader Baltic Sea lobe, and that our newly reported assemblages could in fact adhere to the classical cross-Gulf lobe configuration at a broader, regional scale. Much more extensive onshore and offshore high resolution landform assemblage analysis will be required to address this question more rigorously, and it remains a possibility. However, we tentatively speculate that the ice stream we have identified on the northern Swedish coast and Bothnian Sea is a late-stage feature, characterised by rapid collapse and retreat. Given the considerable isostatic depression in this region (De Geer 1940; Berglund 2004), this ice stream would have been marine- (or lake-) terminating with a calving margin. A small, localised patch of small scale ~~We also note very small scale~~ drumlins/flutes, oriented SE and confined to the far west of our study area, cross-cut~~ting~~ the offshore mega-scale glacial lineations (Fig. 6B). ~~. These smaller features, oriented SE, overprint the latter but have only a limited extent across our survey area, confined to the far west. Their small size and superimposed position suggest they are the most recent landform imprints. Whilst we cannot address the question of whether our ice stream path represents a narrow corridor within a broader Baltic Sea lobe without much more extensive onshore and offshore high resolution landform assemblage analysis, we tentatively speculate that the ice stream we have identified on the northern Swedish coast and Bothnian Sea is a late-stage feature, characterised by rapid collapse and retreat.~~ We find no evidence of SE-ward overprinting elsewhere in our datasets, and we interpret a~~A~~ highly localised final ESE oscillation of ice off the present-day coast, which followed the S/SW ice stream event. We may further speculate this was a response to the loss of buttressing ice in the Bothnian Sea and drawdown into the open calving bay.

~~It requires further investigation of both the onshore and offshore sectors of the Bothnian Basin to assess these scenarios more rigorously, and to link our new found evidence to existing frameworks and understanding of the regional glacial history.~~ ~~There is some consistency between the offshore lineation assemblage we report here and striae on the Finnish coast, south of Vaasa, which are oriented towards the SW (Lundqvist 2007). According to Lundqvist (2007) the SW-wards event represented by these striae was bracketed by more dominant and widespread SE flow both earlier and later. Together with our interpreted flow system, these SW-trending striae would indicate convergence of ice around the head of the Bothnian Sea into the main basin. Lundqvist interprets the SW trending striae as the product of a short-lived surge event which postdates widespread SE-ward flow across the Gulf and across Finland; this is consistent with our interpretations above. This model was postulated earlier by Winterhalter (1972): based on early echo-sounding in the Bothnian Sea, drumlinised/lineated terrain NE of Härnösandsdjupet was reported. He interpreted a 'glacial drift' composition, based on acoustic profiles, but had difficulty to explain their great length (several km) and orientation perpendicular to a presumed NNW-SSE flow. The landforms were interpreted as primarily of ice-marginal origin, with subsequent overriding from the NE to drumlinise the then pre-existing moraine deposits (Winterhalter, 1972). Here, with high resolution data and a greater understanding of the scales of subglacial bedforms (e.g. Clark 1993; Ottesen et al 2005, Spagnolo et al 2014) we can demonstrate that these landforms (Fig. 2D) are subglacial lineations of extremely high elongation, corresponding primarily to a palaeo-ice flow trajectory from the NE.~~

~~6.~~ Conclusions

6.

High resolution digital elevation data from both present-day terrestrial and marine domains reveal a glacial landform assemblage indicative of a palaeo-ice stream in the northern Bothnian Sea. Detailed, complementary LiDAR- and multibeam-based mapping~~SSE-ward glacial lineations and other ice directional indicators on the northern Bothnian coast in Sweden have long been known (see Lundqvist 1987). Here, with individual landform crestline mapping from high resolution digital elevation data, their distribution and morphometry~~ defines a corridor of glacial lineations on the Västerbotten coast, which we interpret as an ice stream tributary feeding ~~. Their connection to~~ a large ~~S/~~SW- then S-ward offshore palaeo-ice stream trunk. This represents an important dynamic component of the retreating ice sheet, and suggests that onshore palaeo-ice flow indicators of SSE ice flow do not directly correspond to~~landform assemblage revealed by multibeam echo-sounding data indicates that the Ångermanland/Västerbotten landforms do not directly feed~~ (a) wide deglacial ice sheet lobe(s) terminating over southern Finland, as has often been held. ~~SSE-ward glacial lineations and other ice directional indicators on the northern Bothnian coast in Sweden have long been known (see~~

~~Lundqvist 1987).~~Whilst the new LiDAR models of Scandinavia will undoubtedly permit highly detailed assessments of the terrestrial glacial geomorphological record and its palaeo-glaciodynamic environments, high resolution multibeam bathymetry data from the Gulf of Bothnia will be invaluable to refining the palaeo-glacial dynamics of the region, hitherto built on assumed correlations over wide tracts of unmapped and uninvestigated ice sheet bed. The two datasets in combination are an extremely powerful tool for palaeo-glacial reconstruction in an area that, whether present-day land or sea, was largely all submerged below sea level during the last deglaciation. New discoveries in the offshore realm promise to be exciting and challenging; how they fit with or challenge terrestrial-based frameworks for Fennoscandian ice sheet history is key.

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Figure Captions

Figure 1: Location and regional topography-bathymetry of the study area, in Ångermanland (the High Coast) & Västerbotten, and the northern Bothnian Sea. LiDAR and multibeam datasets highlighted in (B). (A) based on GEBCO data; background topography in (B) from GEBCO and bathymetry from Baltic Sea Bathymetry Database. Panels in Figure 2 marked by red squares in (B). White star marks the >200 m deep Härnösandsdjupet.

Figure 2: Example glacial lineations identified in LiDAR (A,B) and multibeam (C,D) datasets. Lineations display a range of scales and forms. Drumlin-like forms (e.g. A,C) occur predominantly on the lateral flanks of the LiDAR study area and the lateral and upstream reaches of the multibeam area. Extended lineations (B,D) occur in the central and downstream portions of our study areas. Panel (A)

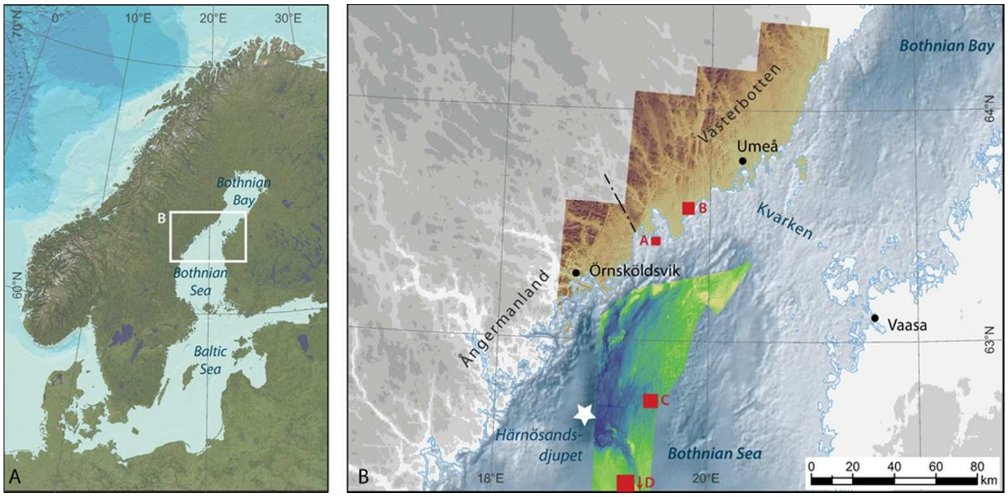
illustrates an abrupt division between shorter and more elongate forms. Locations marked in Fig. 1B. Note that the fine, sinuous lines in the upper part of panel B and N-to-SE in panel A are roads.

Figure 3: ~~l~~Lineation lengths (coloured red-green by quantiles) reveal shorter (red) forms lateral to each dataset; there is a central corridor of longer (green) lineations, up to >14 km in length. Location of Figs. 6A & 6B marked.

Figure 4: ~~i~~Inspection of sidescan sonar data ~~(inset panels)~~ shows ~~continuity~~ a progression of lineation form and orientation between the areas in which we have LiDAR and multibeam coverage, and we~~.~~ ~~Note that not all lineations visible in the sidescan data have been mapped, but a representative distribution to examine the hypothesis that the terrestrial and marine assemblages mark a~~ interpret a continuous palaeo-ice flowline~~ with consistent lineation orientations~~. The dashed blue lines mark the bounds of the sidescan sonar data, inset panels give examples of the imagery.

Figure 5: ~~p~~Proposed path of a palaeo-ice stream sourced on the Västerbotten coast, and directed SW and S through the western sectors of the northern Bothnian Sea. Its downstream continuation is unknown, limited by the extent of multibeam coverage; lateral margins are delineated according to transitions or boundaries in lineation morphology. A possible later flow event (grey dotted lines) encroaches over the ice stream path in the west, but has limited extent.

Figure 6: ~~l~~Landform assemblages which suggest that the palaeo-ice stream assemblage represents a late-stage ice flow configuration. A) crevasse squeeze ridges overprint N-S lineations in the far south of the multibeam survey area. B) subtle, low amplitude streamlining from NW-SE overprints earlier ice stream mega-scale glacial lineations, but confined to ~~in~~ the west of the multibeam sector. Their limited extent suggests a final, minor oscillation of ~~Ångermanland~~ Ångermanland / Västerbotten ice after the retreat of the ice stream.



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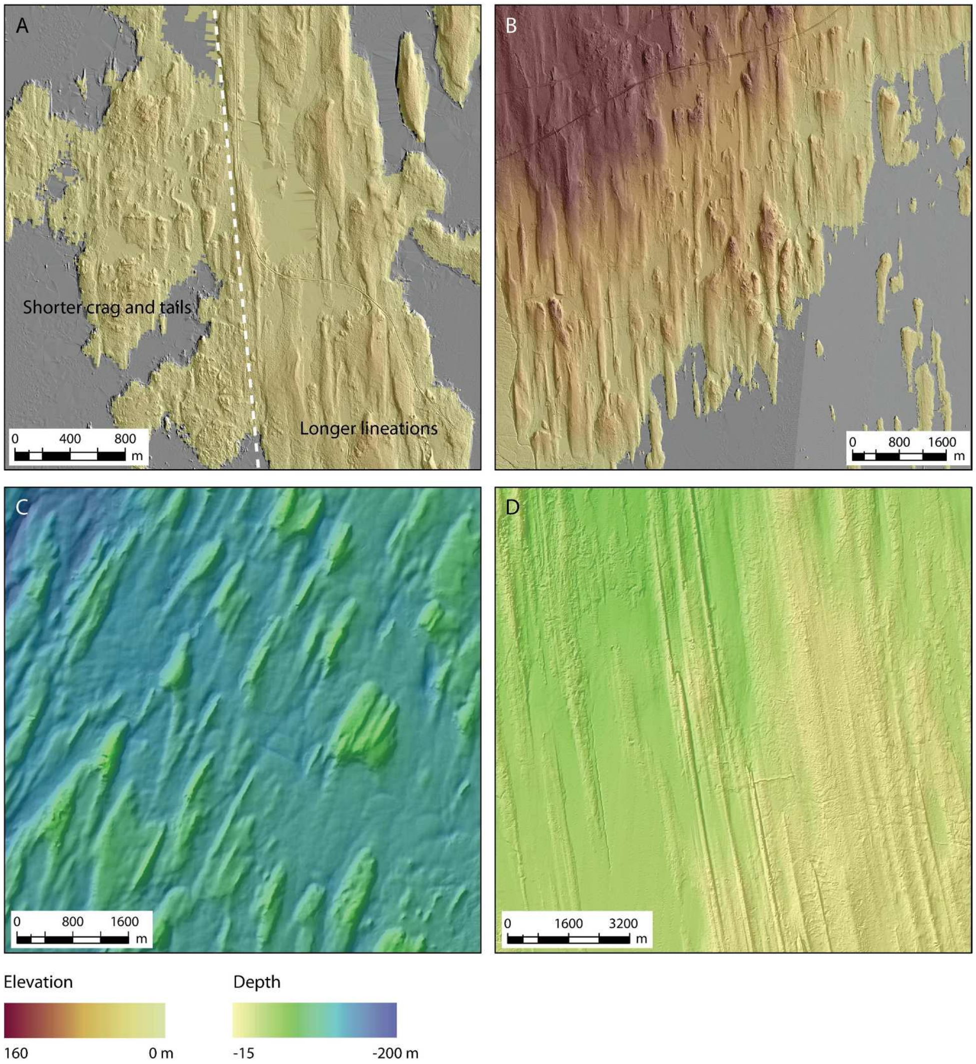
81x39mm (300 x 300 DPI)



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210x260mm (300 x 300 DPI)

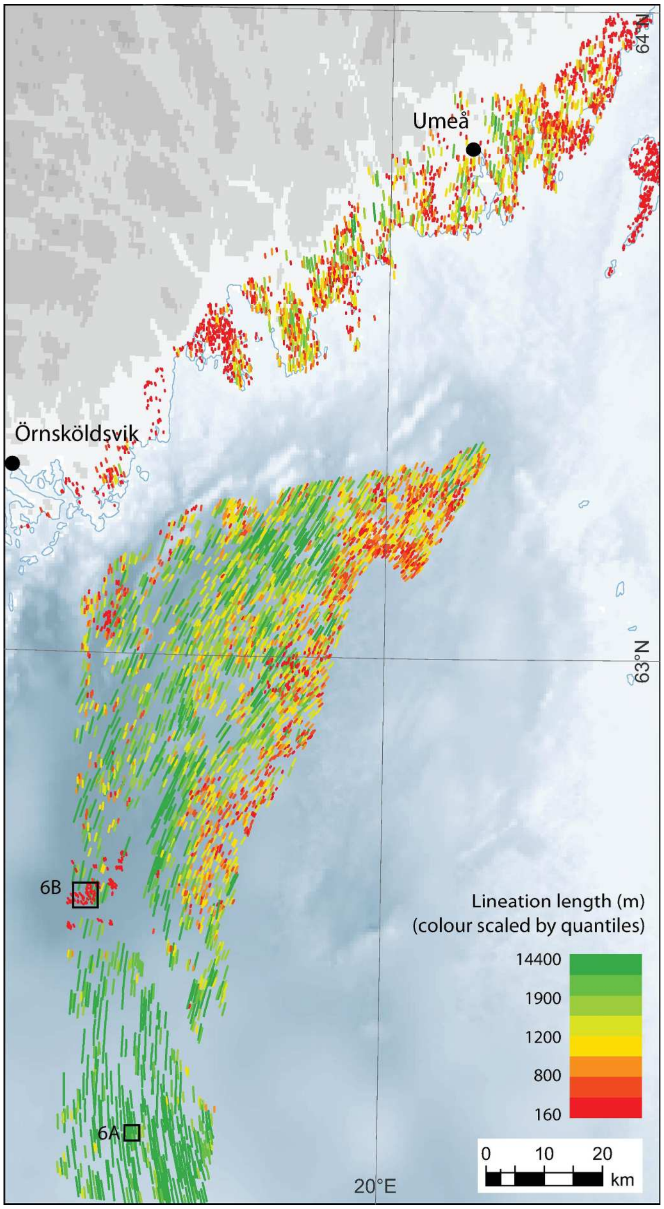

Figure 3: Lineation lengths (coloured red-green by quantiles) reveal shorter (red) forms lateral to each dataset; there is a central corridor of longer (green) lineations, up to >14 km in length. Location of Figs. 6A & 6B marked.
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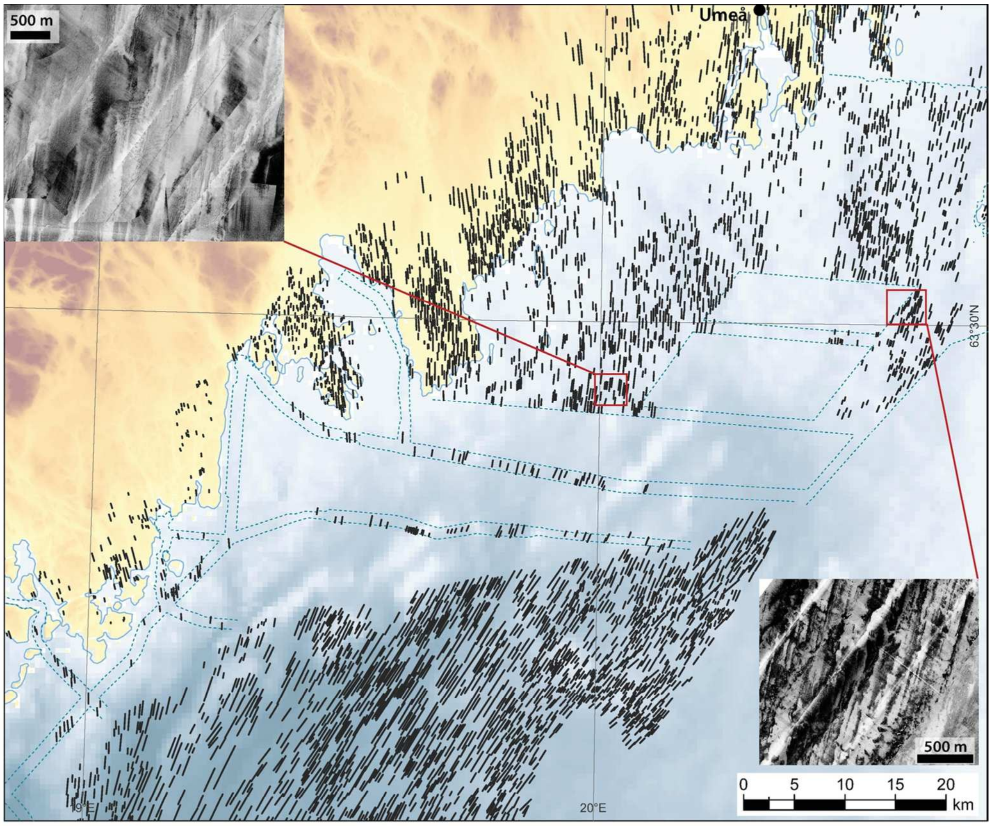
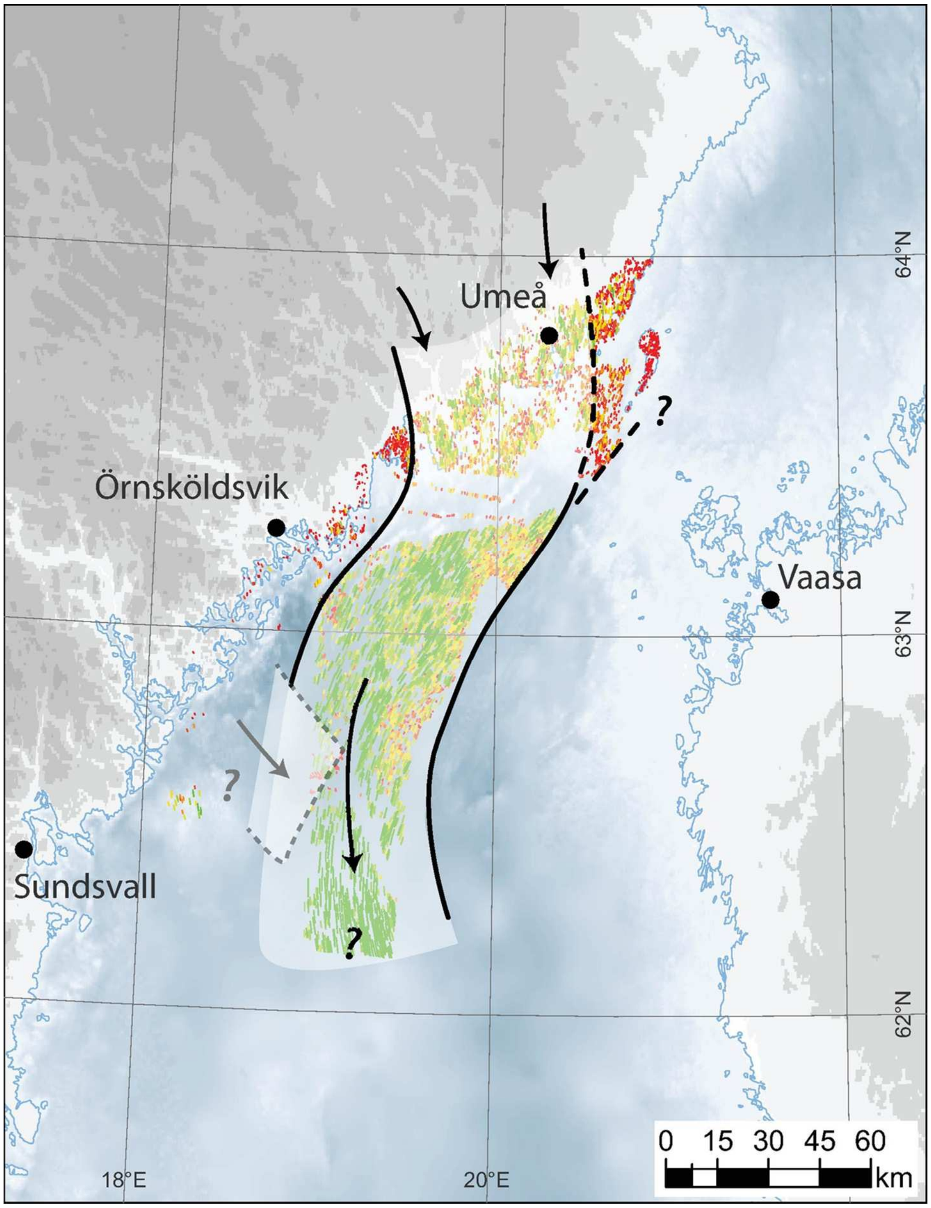


Figure 4: Inspection of sidescan sonar data shows a progression of lineation form and orientation between the areas in which we have LiDAR and multibeam coverage, and we interpret a continuous palaeo-ice flowline. The dashed blue lines mark the bounds of the sidescan sonar data, inset panels give examples of the imagery.
130x116mm (300 x 300 DPI)



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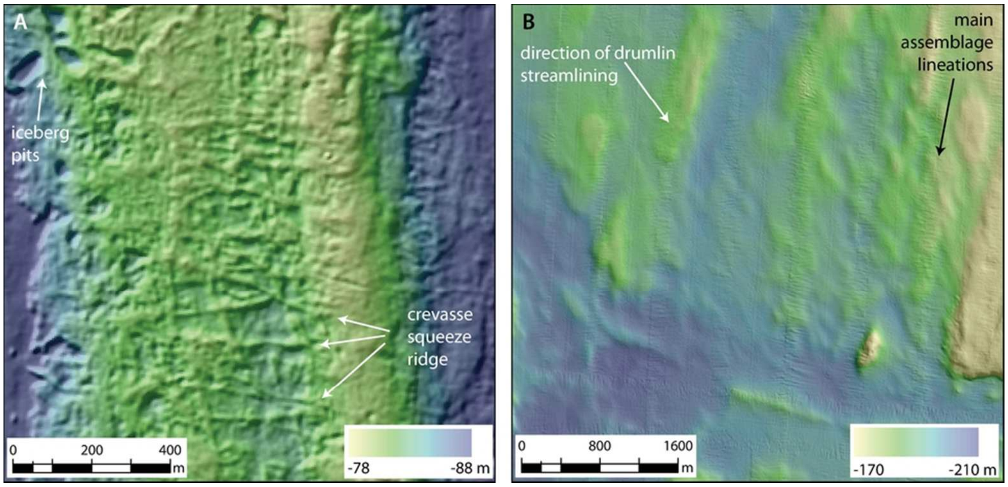

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81x39mm (300 x 300 DPI)