The Gulf of Bothnia is a shallow, elongate basin dividing Sweden and Finland, and is located in the centre of the terrain formerly occupied by the Fennoscandian Ice Sheet (FIS). It is considered to have hosted a variety of different glaciodynamic environments during the evolution of the FIS, but direct glacial geological or geomorphological evidence from the Gulf itself is almost entirely lacking. Recent acquisition of high-resolution multibeam data enables direct investigation of the basin for the first time. These data reveal a wealth of glacial landforms in the Gulf of Bothnia including glacial lineations, ribbed moraine, eskers, meltwater channels, moraines, crevasse-squeeze ridges and iceberg ploughmarks with a variety of different morphologies. Distinct landform assemblages record multiple ice-flow events or phases of differing glaciodynamic character. Two contrasting glacial landform assemblages are presented from the western and northern Bothnian Sea.

Description
Assemblage 1, located in the western Bothnian Sea (Fig. 1), comprises an 80 km long field of approximately 950 pronounced, elongate and aligned mounds (Jakobsson et al. 2016). These mounds have a typified length of about 900 m, width of c. 300 m and amplitude of c. 6 m, and are formed in glacial till, often clustered locally with multiple individuals formed in/of a single till patch. Many mounds appear to be bedrock-cored, however, with preferential till accumulation over bedrock obstacles (Fig. 1e). Within this population, the mounds show progressive downstream elongation. Overall, they possess a SSE orientation, with some slight southward shift in the downstream and western parts of the assemblage. The SSE-oriented features are cross-cut and terminated at their downstream end by a SW-oriented group of much narrower (<50 m), lower-amplitude (c. 1–4 m) and elongate lineations (Fig. 1h). A well-developed channelized landform system weaves southward through the streamlined mounds (Fig. 1i), comprising both incised channel forms and positive-relief ridges of comparable scale. The system evolves from small stream-like forms in the north (e.g. c. 30–50 m wide, c. 1–2 m incised depth), through moderately sized and interconnected channel-ridge segments, to large sinuous and connected ridges (e.g. c. 150 m wide, c. 15 m amplitude) at the distal, SE end of the system. In the north, the small channels occupy troughs between streamlined mounds, while downstream the larger channel components override and incise through the mounds. At the far northern end of the assemblage, low-amplitude transverse ridges (WSW–ENE, Fig. 1d) are superimposed on the southward-directed landforms. Such transverse forms are absent from the rest of the area. Postglacial sedimentation has preferentially filled the lower-lying troughs of Assemblage 1, leaving minimal to no drape on landform crests.

Assemblage 2, in the northern Bothnian Sea (Fig. 1c), is similar in size to Assemblage 1, but is defined mainly by a striking swarm of highly elongate and parallel lineations (Greenwood et al. 2015; Fig. 2). These lineations trend first SW, then south in the distal part of the assemblage and have lengths up to 14 km, the longest of which are located in the centre of the assemblage (Fig. 2b). Laterally and towards the head of the swarm, lineations transition to shorter and wider aligned hills (Fig. 2c), whereas they display an increase in their length downstream to the south (Fig. 2d). This lineation assemblage has been traced onto land, using terrestrial LiDAR elevation data and side-scan sonar images in the nearshore area. Incised channels are also widely present in Assemblage 2, but the channelized system contrasts markedly with that in the western assemblage. This system comprises both erosional and depositional landform elements, but these are disorganized and without any systematic trend. Channels are 0.5–4 km wide and up to c. 85 m deep, whereas a glaciomarine deposit, subsequently incised and partially eroded, measures c. 3 × 4.5 km (Fig. 2e). The largest erosional corridor is floored with glaciomarine sediments and lined with a sinuous ridge deposit, alongside which are numerous irregular depressions about 200 m wide and 10–20 m deep (Fig. 2f). These wide, incised corridors cut obliquely (SE) through the lineation field. Similarly to the western Bothnian Sea, there are few signs of any transverse ridges overprinting the approximately south-oriented landforms.

Interpretation
Both assemblages comprise elongate sedimentary landforms, interpreted as ice-flow directed drumlins and mega-scale glacial lineations (MSGLs), interwoven with a network of subglacial meltwater channels and eskers. However, the assemblages differ in form and arrangement of these landforms, leading to contrasting palaeo-ice dynamic and palaeo-hydrological interpretations.

Assemblage 1 is dominated by a drumlin field overprinted by a glaciomarine lineament network (Fig. 1). Drumlins are usually interpreted as indicators of warm-based ice-sheet flow. The increasing downstream elongation of drumlins in Assemblage 1 points to an acceleration of the overriding ice (cf. Hart 1999; Stokes & Clark 2002) which flowed from the southern part of the Swedish High Coast towards the southern exit of the Gulf of Bothnia. The accompanying meltwater landform system also displays a progressive evolution from small streams, through interconnected channels and eskers, to increasingly large eskers (Fig. 1b, f). The glacial hydrological network was therefore well connected, appears to represent a coherent system and its flow direction is aligned approximately with that of the drumlins. Since the meltwater channels incise and eskers overprint drumlins (Fig. 1f), the geomorphic development of the meltwater landforms must post-date cessation of drumlin shaping, either immediately upon stabilization of a deforming substrate or at a later stage of ice flow. The simpler interpretation is the former: that the drumlins and meltwater landforms represent the same phase of ice flow and that the meltwater landforms are the final geomorphic imprint of this episode. The systematic downstream development of the meltwater landforms, and the absence of moraines or obvious glaciomarine fans throughout most of the length of the assemblage, suggests that this group of landforms may reflect a single, operational hydrological system rather than one which has developed incrementally by headward extension during ice retreat. The length of the interpreted channelized and connected meltwater system (c. 50–60 km) is towards the upper limit of what may be considered physically plausible (e.g. Chandler et al. 2013), and suggests a high and sustained meltwater-discharge regime.

The sequence of events for Assemblage 1 in the western Bothnian Sea is interpreted as follows (Fig. 1g): (1) drumlinization of a mobile subglacial sediment layer that became anchored on bedrock knobs, under ice of a moderate flow velocity that increased downstream to a margin position some distance beyond our assemblage; (2) meltwater-landform development shortly after, and potentially the cause of, cessation of drumlinization as subglacial meltwater conduits became an efficient mode of drainage and
Fig. 1. Landform Assemblage 1, western Bothnian Sea. (a) Multibeam-bathymetric data collected for the Swedish Maritime Administration by FUGRO. Acquisition system Kongsberg EM 2040, frequency 200–400 kHz in the southern part and Reson 7125 SV, frequency 200/400 kHz in the north. Grid-cell size 5 m. (b) Landform mapping derived from multibeam data. (c) Study area (red box; map from GEBCO_08). Bo.S, Bothnian Sea; Bo.B, Bothnian Bay, together forming the Gulf of Bothnia. (d) Moraines orientated WSW–ENE (solid white arrows) drape underlying drumlins. (e) Geological Survey of Sweden-interpreted seismic profiles show many drumlins are bedrock cored: profile lines in white with sedimentary bedrock blue, till orange and postglacial sediments in yellow. (f) A well-developed meltwater system drapes/incises drumlins. (g) Palaeo-glacial interpretation of landform assemblage. Black dashed line marks the lateral boundary of distal cross-cutting and red lines mark retreating margin positions. (h) Drumlins are cross-cut at the distal end of the assemblage by spindle-like lineations.
Fig. 2. Landform Assemblage 2, northern Bothnian Sea. (a) Multibeam-bathymetric data collected for the Swedish Maritime Administration by FUGRO. Acquisition system Kongsberg EM 2040, frequency 200–400 kHz in the southern part and Reson 7125 SV, frequency 200/400 kHz in the north. Grid-cell size 5 m. (b) Glacial landform mapping derived from multibeam bathymetry (coverage outlined), side-scan sonar data and terrestrial LiDAR data. Lineations extend downstream from (c) drumlins to (d) mega-scale glacial lineations (MSGLs). (e) A large meltwater system cuts through the lineations. Channels up to 500 m wide (labelled) feed a 4 km wide meltwater corridor (dashed lines) that is floored with glacifluvial sediments. Geological Survey of Sweden-interpreted seismic profiles show the corridor cuts through till and pre-last-glacial sediments, whereas the eastern corridor flank is pinned on a bedrock step (sedimentary bedrock blue, lacustrine sediments pale blue, till orange, glacifluvial sediments green and post-glacial sediments yellow). (f) A small esker and depressions interpreted as kettle holes line the bottom of the meltwater corridor. (g) Interpreted ice-stream pathway (from Greenwood et al. 2015). (h) Study area (red box; map from GEBCO_08). Bo.S, Bothnian Sea; Bo.B, Bothnian Bay, together forming the Gulf of Bothnia.
sediment consequently stiffened; (3) retreat of the ice margin across the assemblage without pause, the margin only beginning to deposit retreat moraines as it approached the headward extent of the assemblage (e.g. Fig. 1d), towards the higher topography and crystalline bedrock of the present land and nearshore areas; and (4) at some stage, the timing unknown, the southern end of the assemblage is cross-cut from the NE by a second, independent set of glacial lineations. While it is likely that Assemblage 1 formed in a deglacial sequence, it was not the final ice-flow event in this area.

Assemblage 2, dominated by MSGLs and erosional meltwater landforms an order of magnitude larger than in Assemblage 1, represents a different dynamic setting. Downstream elongation of MSGLs and their lateral transition to drumlins in the north of the assemblage are interpreted by Greenwood et al. (2015) to mark the onset zone or upper tributary of a Bothnian Sea ice stream. The upper trunk width is approximately 40 km, and both the lateral transition to less elongate forms and the non-ice-streaming environment recorded by Assemblage 1 indicate that this ice stream did not occupy the whole basin. Onshore extension of Assemblage 2 indicates a supply of ice from northern Sweden (Fig. 2b, g). Flow was initially directed SSE but, immediately offshore of the present-day coast, swung abruptly SSW along the coastline before turning southwards into the central Bothnian Sea. The glaciﬂuvial elements of Assemblage 2 are less closely tied to the bedforms than in Assemblage 1. There is no systematic arrangement of meltwater landforms, which instead cut through the lineation assemblage in various directions. The size of the large meltwater corridor suggests a high-energy and high-discharge system, and/or a long-term (multiple glaciation?) route for meltwater. Sediment stratigraphy suggests the former interpretation (although the two are not mutually exclusive): the eastern flank of the corridor is pinned on a bedrock step, but the western flank is unconstrained by bedrock and the corridor cuts through both the most recent till and the sediments below (Fig. 2e). The corridor morphology is therefore taken to indicate a large erosive capacity. Retreat from this corridor was probably rapid; we tentatively interpret the depressions alongside the esker as kettle holes formed by abandoned blocks of ice (Fig. 2f). Comparable kettle–esker relationships are observed widely on land in Sweden in similarly sized glaciﬂuvial corridors. At the head of the corridor, a large, irregular glaciﬂuvial deposit (Fig. 2e) suggests a sudden dump of sediment, possibly corresponding to a subglacial conduit terminating at a grounding line.

We interpret the following sequence of events for Assemblage 2 in the northern Bothnian Sea (Fig. 2): (1) onset of ice streaming, which diverted ice flow off the Swedish coast from its SSE trajectory into the northwestern and central Bothnian Sea towards a distal margin position; (2) cessation of streaming, leaving a pristine bedform imprint during rapid retreat without pause of the ice margin; and (3) retreat accompanied by (driven by?) rapid melting of the ice surface, which provided extremely high volumes of meltwater to be discharged subglacially in high-energy, erosive and topologically chaotic corridors. The retreating ice margin probably stabilized close to the present-day coast, where De Geer moraines become widespread in the modern terrestrial realm.

**Discussion**

The landform composition of both assemblages leads to their interpretation as belonging to the retreat phase of the FIS through the Gulf of Bothnia. The conventional deglaciation pattern for the Finnish–Swedish sector of the FIS depicts a series of SE-directed lobes crossing the Gulf of Bothnia and spilling across the low relief of Finland (Punkari 1980; Johansson et al. 2011). Whereas Assemblage 1 could correspond to the so-called Baltic Sea lobe, Assemblage 2 is wholly inconsistent with this configuration. Greenwood et al. (2015) favour an interpretation of a late-stage ice-event which was short-lived and rapid, indicating a brief reconfiguration of the ice-sheet flow structure. Such a reconfiguration is also recorded in the overprinting of Assemblage 1 at its distal end by a group of elongate, spindle-like lineations. The timeframe for ice-sheet retreat through the whole Gulf of Bothnia is suggested to be limited to about 1 ka (Hughes et al. 2016; Stroeven et al. 2016). To fit this, any events reconstructed within the Bothnian Sea must be rapid and retreat highly dynamic. Full data coverage of the Gulf of Bothnia is required to assess the relationship in both space and time between the two landform assemblages reported here and the wider, terrestrial deglaciation sequence.

Ice-flow behaviour in the Gulf of Bothnia is demonstrably non-uniform and spatially variable. The ice stream recorded by Assemblage 2 is limited to a width of approximately 40 km, and Assemblage 1 reveals that more moderate ice-sheet velocities occupied the western part of the basin. The ice stream does not follow the larger-scale bathymetry closely; it crosses the head of the trough that defines the eastern side of the Bothnian Sea. Ice flow in this marine basin is therefore governed by a varied set of controls. This is further demonstrated by the composition of the landform assemblages. Drumlins, eskers and meltwater channels are more typical of terrestrial ice-sheet landscapes than continental shelf marine environments. Marine areas are, on the contrary, usually characterized by highly elongate lineations indicative of ice streaming, and a subglacial hydrological system in which meltwater delivery is often ascribed to porewater flow through an unconsolidated sedimentary substrate (e.g. Ò Cofaigh et al. 2002; Wellner et al. 2006). Landform assemblages in the Gulf of Bothnia therefore caution against treating all marine ice-sheet sectors in the same way, or expecting a similar set of controls on marine ice-sheet dynamics. We hypothesize that surface melting was a strong control on deglacial dynamics in the Bothnian Sea and may have been a stronger influence than iceberg calving as a form of ablation and driver of deglaciation.

**References**


