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Ribbed moraines formed during deglaciation of the Icelandic Ice Sheet: implications for ice-stream dynamics

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Investigations of the geomorphological fingerprints of palaeo-ice streams are essential for enhancing our understanding of ice-stream behaviour. Cross-cutting flowsets of palaeo-ice streams, during and following the Last Glacial Maximum, have been suggested in northeast Iceland based on the mapping of streamlined subglacial bedforms (SSBs). To increase our understanding of the dynamics of the Icelandic Ice Sheet (IIS) during deglaciation, we investigate transverse ridges, together with glacifluvial and ice-marginal landforms, within the largest flowset. The main emphasis is on the transverse ridges, which are primarily interpreted as ribbed moraines – the first to be described in Iceland. Morphological data are combined with sedimentological analyses of the ribbed moraines. Our results show that the ribbed moraines are composed of pre-existing material, often exhibiting a base of stratified glacifluvial sediments draped with subglacial till. Deformation and thrust structures within both units suggest compressional flow during the formation of the ridges. Our results suggest the ribbed moraines develop due to velocity gradients under the lateral shear margin of an ice stream based on their distribution and often oblique orientation in relation to SSBs. The ribbed moraines superimpose and thus post-date the SSBs, signifying the waning stage of ice streaming. We suggest that the ridges formed during ice-stream shutdown following the Younger Dryas and/or Preboreal re-advances. Eskers and ice-marginal landforms imply channelized water drainage during the final deglaciation interrupted by short-lived re-advances. This study has implications for the style of deglaciation associated with ice streaming in the northeastern part of the IIS. We characterize the role of ribbed moraines within the ice sheet and identify directions for future work.

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Ribbed moraines, also termed Rogen moraines, subglacial ribs, or traction ribs, are clusters of subglacial ridges, formed transverse or oblique to ice flow, often occurring as elongated tracts (e.g. Lundqvist 1969; Aylsworth & Shilts 1989; Dunlop & Clark 2006; Stokes *et al*. 2016; Ely *et al*. 2023). The landforms have been considered characteristics of the core areas of former ice sheets (Kleman & Hättestrand 1999) but also occur within the trunk-flow zones of ice streams and in their marginal settings (Lundqvist 1969, 1989; Aylsworth & Shilts 1989; Dunlop & Clark 2006). Furthermore, the occurrence of ribbed moraines is suggested to relate to the ice-stream onset zones and the waning stages of ice streaming (e.g. Dyke *et al*. 1992; Stokes *et al*. 2008, 2009). Originally, it was suggested that ribbed moraines formed at the ice margin, reflected by their name (Frödin 1954; Cowan 1968), but further research indicated subglacial origin (e.g. Lundqvist 1969; Bouchard 1989; Hättestrand & Kleman 1999; Vérité *et al*. 2021). Typically, ribbed moraines are described as closely spaced, straight, or arcuate ridges, transverse to former ice flow (Hättestrand & Kleman 1999). However, their morphological characteristics can vary significantly, both between and within areas, thus being more complex than previously thought (e.g. Dunlop & Clark 2006). Their internal composition is also highly variable, ranging from different types of tills to glacifluvial sediments, often found in proximity to the landforms, and glaciotectonic structures are common but not always present (e.g. Bouchard 1989; Hättestrand 1997; Lundqvist 1997; Möller 2006). Drumlins often occur in proximity to ribbed moraines and examples of both ribbed moraines that have undergone drumlinization and 'ribbed' drumlins are common (e.g. Lundqvist 1989; Dunlop & Clark 2006).

The wide range of composition and morphological characteristics has led to several hypotheses of their formation without consensus on whether their formation can be explained by a unifying theory or not (Hättestrand & Kleman 1999; Dunlop *et al*. 2008; Chapwanya *et al*. 2011; Möller & Dowling 2018). The most prevalent theories invoke fracturing and extension of frozen beds related to extensional stress at transition from cold- to warm-based ice (Hättestrand 1997; Hättestrand & Kleman 1999; Sarala 2006), modification of pre-existing sediments by overriding ice (Boulton 1987; Lundqvist 1989; Möller 2006), subglacial outburst

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floods (Fisher & Shaw 1992) or deformation related to shearing and stacking of subglacial till (Bouchard 1989; Lindén *et al*. 2008; Stokes *et al*. 2008). Others tend to favour the instability theory for subglacial bedforms, which argues that ribbed moraines are formed by the natural instability formed in the coupled flow of ice and till (e.g. Dunlop *et al*. 2008; Chapwanya *et al*. 2011; Fowler & Chapwanya 2014; Ely *et al*. 2023). Consequently, correlating ice-sheet dynamics to the formation of ribbed moraines can be challenging due to contradicting hypotheses (Hättestrand & Kleman 1999). A better comprehension of the formation of ribbed moraines is therefore of utmost significance to increase our insight into glacier dynamics and ice-stream behaviour (Stokes 2018).

Ice streams are dynamic components of ice sheets that have a substantial effect on their stability and mass balance. The mechanisms controlling their fast flow are complex and largely governed by processes occurring at the ice-bed interface (e.g. Bennett 2003; Alley *et al*. 2004; Stokes *et al*. 2007). As a result of these processes, distinct and variable subglacial bedforms are developed at the ice-stream bed. After deglaciation, these bedforms can be mapped and used to reconstruct the behaviour of palaeo-ice streams (e.g. Stokes & Clark 1999, 2001; Bingham *et al*. 2017). Owing to the complexity of directly monitoring processes operating under ice sheets and ice streams (Kamb 2001; Bennett 2003; Smith *et al*. 2021), glacial geomorphology is essential for our understanding of processes occurring at the ice-bed interface and for palaeoglaciological reconstructions (Livingstone *et al*. 2012; Stokes 2018).

Ice-stream behaviour within the Icelandic Ice Sheet (IIS) has been reconstructed based on numerical modelling (Bourgeois *et al*. 2000; Hubbard *et al*. 2006; Patton *et al*. 2017), large-scale geomorphology and mapping of certain glacial landforms (e.g. Norðdahl & Pétursson 2005; Spagnolo & Clark 2009; Principato *et al*. 2016; Norðdahl *et al*. 2019; Benediktsson *et al*. 2022b). Mapping of subglacial landforms in northeast Iceland indicates cross-cutting palaeo-ice streams during the maximum extent of the IIS during the Last Glacial Maximum (LGM; 28.1–22.8 cal. ka BP) and ice-stream shutdown during the subsequent deglaciation (Fig. 1A, B; Benediktsson *et al*. 2022a; Aradóttir *et al*. 2023a). Here we expand our research on the ice-stream dynamics during the deglaciation of the IIS in northeast Iceland by investigating glacial landforms within the Vopnafjörður-Jökuldalsheiði flowset with a focus on transverse ridges. We present detailed mapping, morphological and spatial analyses, as well as sedimentological investigations of transverse ridges within the flowset. Parts of the ridges have previously been interpreted as ribbed moraines (Helgadóttir 2020) – the first to be described in Iceland. The motivation for this study is the lack of knowledge of transverse ridges, including ribbed moraines, within the IIS, and their significance for palaeoglaciological reconstructions.

Study area

The study area is located within the Vopnafjörður fjord-valley system in northeast Iceland and can be divided into three subareas: the highland plateaus of Jökuldalsheiði and Hauksstaðaheiði, as well as the Selárdalur valley and its surroundings (Fig. 1B, C). A vast highland plateau, situated mostly between 450 and 600 m a.s.l., extends from the northeast-trending valley, Hofsárdalur, far into the highland interior (Figs 1C, 2A). Most of the plateau is termed Jökuldalsheiði and for simplicity, we use that for the whole plateau. The Hauksstaðaheiði plateau is situated upvalley of Selárdalur and Vesturárdalur and east of the Dimmifjallgarður mountain range. The plateau is relatively flat, with elevations ranging between 350 and 550 m a.s.l., and gradually extends down to sea level in the narrow, northeast-trending valleys of Selárdalur and Vesturárdalur (Figs 3A, 4A). Heath- and peatlands characterize the study area and highland lakes are present on both plateaus (Figs 2–4, 6). The Jökuldalsheiði and Hauksstaðaheiði bedrocks consist primarily of basalt lavas (3.3–0.8 million years old) with intercalated sediments and glacially sculptured hyaloclastite ridges. Closer to the coast in Selárdalur, the age of the basalt lavas increases (>3.3 million years old). The mountain range to the west of the area consists of younger hyaloclastite ridges and interglacial basalt lavas with intercalated sediments (<0.8 million years old) (Sæmundsson 1977; Jóhannesson & Sæmundsson 2009).

Within the Vopnafjörður-Jökuldalsheiði flowset, palaeo-ice streams have been reconstructed from the mapping of over 300 streamlined subglacial bedforms (SSBs; drumlins and mega-scale glacial lineations (MSGLs)). The SSBs have a converging pattern with variable orientation in the highlands that aligns towards the northeast in the central part, parallel to the Vopnafjörður fjord and valley (Fig. 1B, C; Benediktsson *et al*. 2022a). Most of the drumlins in proximity to the study area are considered to have a sedimentary origin (Benediktsson *et al*. 2022a; Aradóttir *et al*. 2023b). The Bustarfell drumlin field is located on a plateau between Jökuldalsheiði and Hauksstaðaheiði. It consists of well-defined sedimentary drumlins that are consistent in shapes and sizes and contain a core of deformed glacifluvial sediments draped with till (Fig. 1B, C; Aradóttir *et al*. 2023b). The transverse ridges on Hauksstaðaheiði were previously interpreted as ribbed moraines by Helgadóttir (2020) and her findings are synthesized in this study.

During the LGM the IIS reached its maximum extent probably at the shelf edge, followed by a deglaciation of the marine sector from around 21.8 cal. ka BP (e.g. Norðdahl & Pétursson 2005; Norðdahl & Ingólfsson

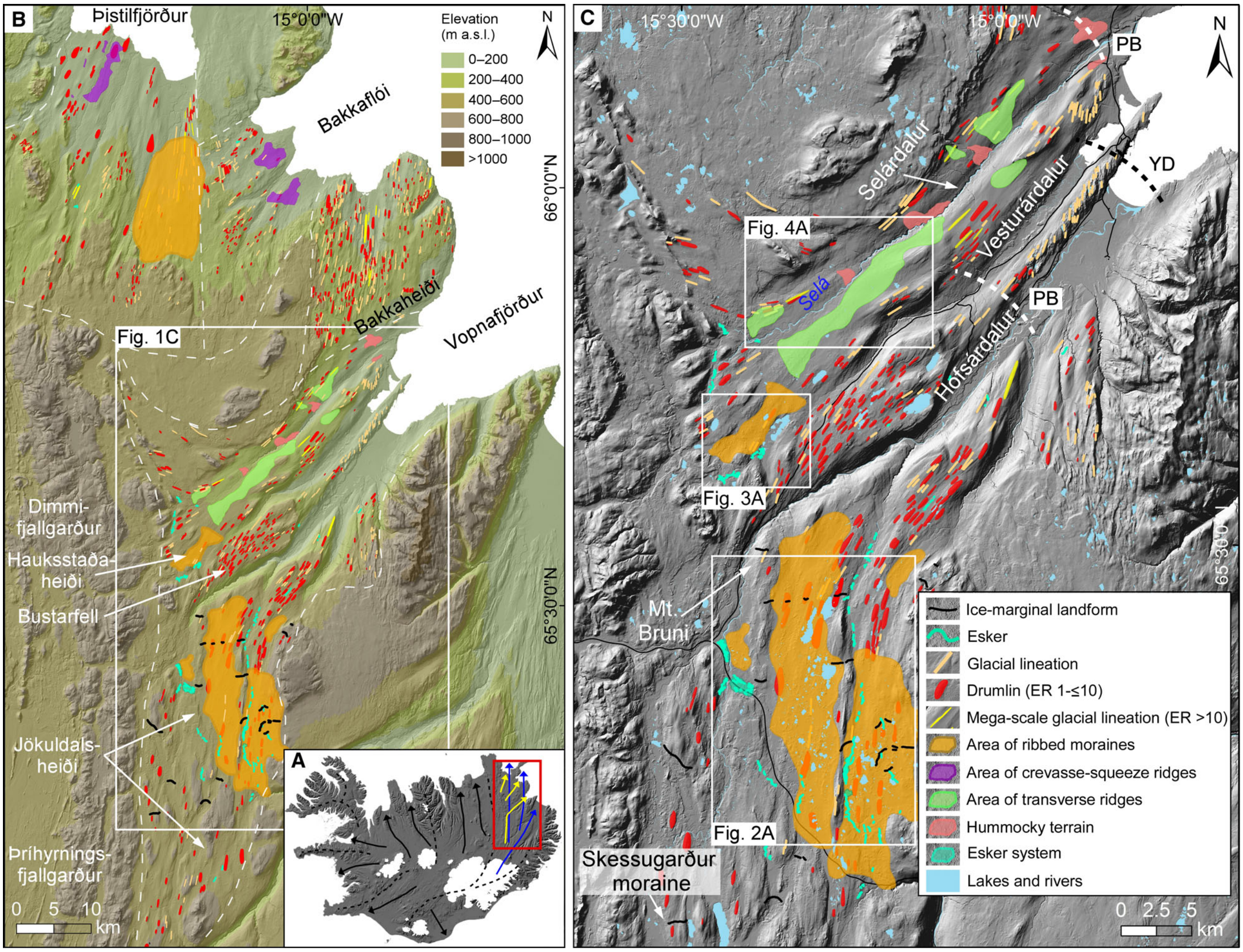

Fig. 1. A. Major ice streams of the Iceland Ice Sheet represented by arrows (Bourgeois *et al.* 2000; Stokes & Clark 2001; Principato *et al.* 2016; Benediktsson *et al.* 2022a). Panel B is outlined in red. Within the red box the blue arrows indicate an older generation of ice flow during maximum glaciation while the yellow arrows represent a younger generation of flow during deglaciation (Benediktsson *et al.* 2022a). B. Geomorphological map of northeastern Iceland (modified from Benediktsson *et al.* 2022a; Aradóttir *et al.* 2023a). The white dashed lines indicate boundaries between three ice-stream flowsets; (1) Vopnafjörður-Jökuldalsheiði, (2) Bakkaheiði, and (3) Bakkaflói and Þistilfjörður. The study area is located within the white box (Panel C). C. Geomorphological map of the Vopnafjörður-Jökuldalsheiði flowset. Ice-marginal positions during the Younger Dryas (YD) and Preboreal (PB) are indicated based on Sæmundsson (1995) together with a post-PB stillstand near Mt. Bruni. Other ice-marginal landforms within the PB position are based on Aðalsteinsson (1985, 1987) and Bjarkason (2024), which were mapped in more detail within the study area. Place names referred to in the text are marked and the main roads are indicated with a black line. The map legend applies to panels B and C.

2015; Benediktsson *et al.* 2022b, 2023a). Chronological constraints on the deglaciation of the IIS in northeast Iceland are minimal but the abrupt warming during the initiation of the Bølling-Allerød interstadial likely caused the collapse of the ice sheet offshore between 15.3 and 14.6 cal. ka BP. The extent of retreat inland is largely unknown (Ingólfsson & Norðdahl 2001; Norð dahl & Ingólfsson 2015; Benediktsson *et al.* 2023b). Following the initial deglaciation, the IIS began to re-expand during the Younger Dryas period (YD; 12.9–11.7 cal. ka BP; Benediktsson *et al.* 2023c). The ice margin is considered to have reached the coast in Vopnafjörður based on truncated raised shorelines (Sæmundsson 1995). Another re-advance of the IIS occurred during the Preboreal period (PB; 11.3–10.4 cal. ka BP; Benediktsson *et al.* 2024a). Ice-marginal deltas in Vesturárdalur and Hofsárdalur, northeast of Bustarfell, have been associated with that re-advance. In Selárdalur, the ice margin during the PB period is suggested to have terminated at the outermost hummocky moraine close to the mouth of the valley (Fig. 1C). Consequently, the YD ice margin is considered to have terminated further out based on correlations of raised shorelines (Sæmundsson 1995).

Ice-marginal landforms have previously been mapped between the suggested PB position and the present northern margin of the Vatnajökull ice cap, indicating punctuated retreat during the final deglaciation (Fig. 1C; Aðalsteinsson 1985, 1987; Sæmundsson 1995; Bjarkason 2024). They often consist of low-relief moraines sometimes

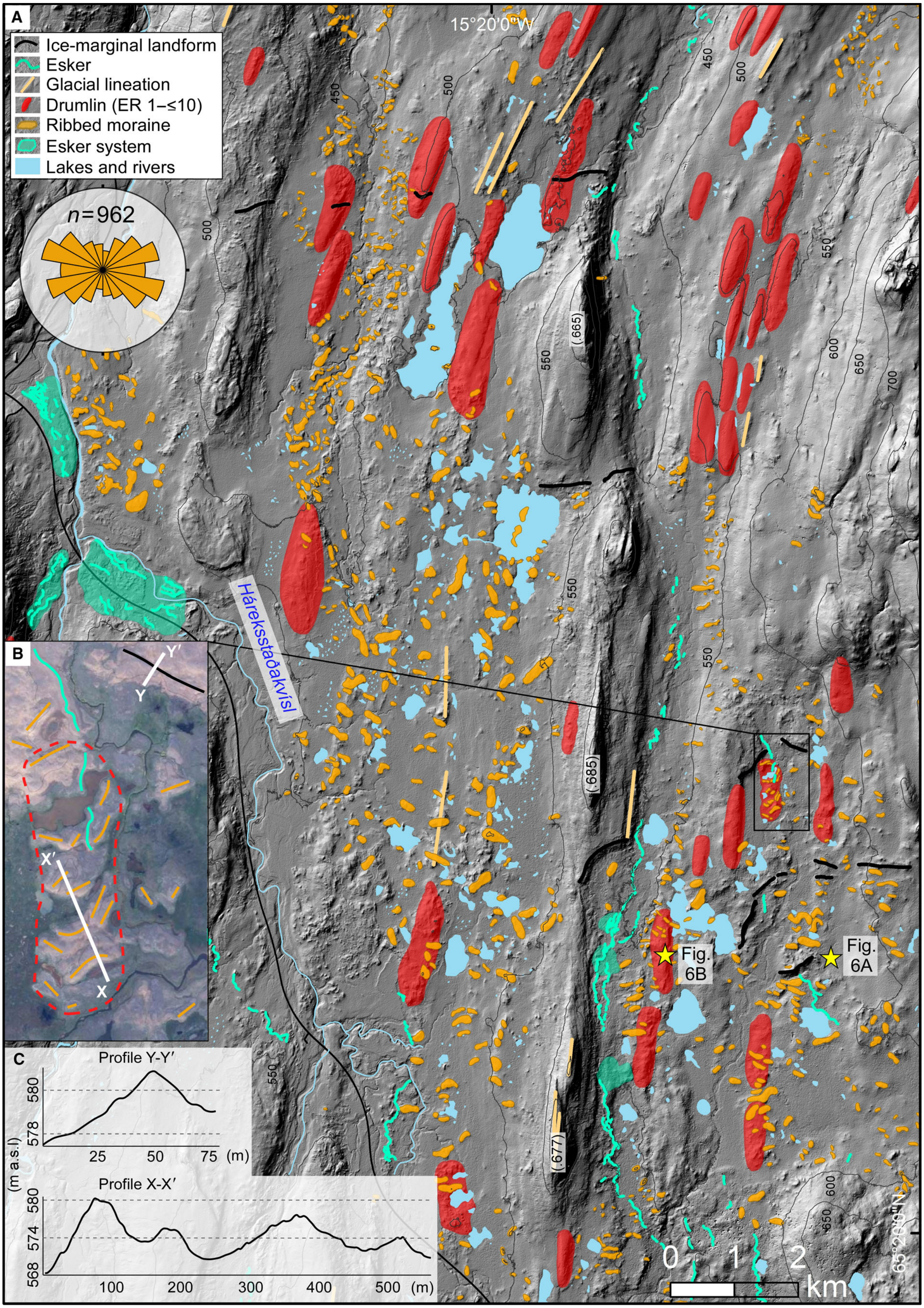
A
Ice-marginal landform
Esker
Glacial lineation
Drumlin (ER 1–≤10)
Ribbed moraine
Esker system
Lakes and rivers
n=962
15°20'0"W
Háreksstaðakvísl
Fig. 6B
Fig. 6A
0 1 2 km
B
Y'
Y
X'
X
C
Profile Y-Y'
(m a.s.l.)
580
578
25 50 75 (m)
Profile X-X'
580
574
568
100 200 300 400 500 (m)

Fig. 2. A. Map of glacial landforms on Jökuldalsheiði. The rose diagram shows the orientation of the mapped 962 ribbed moraines (median 93°–273°). The stars mark the locations where Fig. 6A, B were taken. Contour intervals are 50 m. B. Aerial image of a 'ribbed' drumlin with a superimposed esker. The straight ridge on its distal side is interpreted as an ice-marginal moraine. C. Two terrain cross profiles that are marked in B. The ridges interpreted as ribbed moraines are usually between 0.5 and 5 m in relief with both symmetrical and asymmetrical cross profiles and curved crests. In contrast, the ridge interpreted as an ice-marginal moraine has an asymmetrical cross profile with a steeper proximal side.

combined with ice-marginal channels, depression on their proximal side, and fluvial deposits on their distal side (Aðalsteinsson 1985, 1987; Sæmundsson 1995; Bjarkason 2024). Within our study area, five positions have been suggested. The outermost position is located near Mt. Bruni on the northwestern part of Jökuldalsheiði, just up-ice from the Bustarfell drumlin field (Sæmundsson 1995). The Skessugarður end moraine, a prominent ridge consisting solely of large boulders (1–3 m in diameter), is located approximately 25 km inside Mt. Bruni and is the innermost moraine within our study area (Aðalsteinsson 1985, 1987). This transect is part of an ongoing project constraining the deglaciation history in the area from the coast of Vopnafjörður to near the northern margin of Vatnajökull (Benediktsson *et al.* 2024b).

Material and methods

Geomorphological mapping

The geomorphological mapping was based on the Arctic digital elevation model (ArcticDEM) with a 2-m vertical and <1-m horizontal resolution (Porter *et al.* 2018; corrected and mosaicked by the National Land Survey of Iceland (NLSI), the Icelandic Met Office and the Polar Geospatial Center). Mapping was aided by infrared Spot satellite images with 2.5-m resolution from NLSI and aerial images from Loftmyndir ehf. The geomorphological mapping was done by a combination of fieldwork and remote sensing. Analysis of the data and mapping were conducted in ESRI ArcGIS 10.5-8 and finalized in Canvas X. The main emphasis was on mapping the transverse ridges, which were mapped at scale 1:3000, but eskers and ice-marginal landforms were also mapped. The mapping of SSBs and crevasse-squeeze ridges (CSRs) was conducted by Benediktsson *et al.* (2022a) and Aradóttir *et al.* (2023a), respectively. Previously mapped ice-marginal landforms by Aðalsteinsson (1985, 1987), Sæmundsson (1995) and Bjarkason (2024) were digitized, and additional ice-marginal landforms were mapped within the study area.

Morphological and spatial analyses

To investigate the morphology of the transverse ridges, the length of the long axis, the width orthogonal to the long axis, and the orientation of the long axis were measured using the minimum bounding geometry tool in ArcGIS, as described by Napieralski & Nalepa (2010). Their morphometrics, such as shape, dimensions, spacing, and relationship between the ridges and other bedforms (Dunlop & Clark 2006), were also taken into consideration. The ridge prominence and symmetry were examined with the 3D profile tool in ArcGIS and the spacing between the ridges was measured using the average nearest neighbour tool in ArcGIS. To calculate the density of the ridges a point was created in the centre of each bedform and the number of ridges within each km^2 grid cell was calculated. In addition, qualitative descriptions of the transverse ridges and other mapped landforms are presented.

Sedimentology

Natural sections exposing the sediments in the transverse ridges were documented at a scale of 1:20, using the data chart by Krüger & Kjær (1999) for glacial sediments. Strike and dip of beds and structures were measured. To examine the clast morphology, a minimum of 50 clasts with an a-axis between 1.5 and 10 cm were collected from a 25 × 25 cm surface. The *a* (long)-, *b* (intermediate)- and *c* (short)-axes were measured (Evans & Benn 2004) and plotted in a ternary diagram. In addition, the roundness and texture of the clasts were estimated (Powers 1953; Evans & Benn 2004). The clast morphology and roundness are displayed with C_{40} index (percentage of clasts with c:a axis ratio ≤0.4) and RA index (percentage of angular and very angular clasts), respectively (Benn & Ballantyne 1993). The sections and additional data were illustrated in Canvas X.

Results

The geomorphology of the three subareas, Jökuldalsheiði, Hauksstaðaheiði and Selárdalur (Figs 1C, 2–4), is described separately with emphasis on the transverse ridges and their cross-cutting relationship with other landforms. Additionally, the sedimentology of the ridges on Hauksstaðaheiði is described.

Morphology

Jökuldalsheiði. – On Jökuldalsheiði, 962 ridge segments were mapped. Their distribution is mostly confined to two plateau areas that are over 20 km long and 5 km wide, oriented south–north, at elevations ranging from 430 to 660 m a.s.l. They are separated by south–north trending hyaloclastite mountains that are glacially sculptured. The ridges are generally broad and arcuate. Examples of ridges with hummocky appearance are

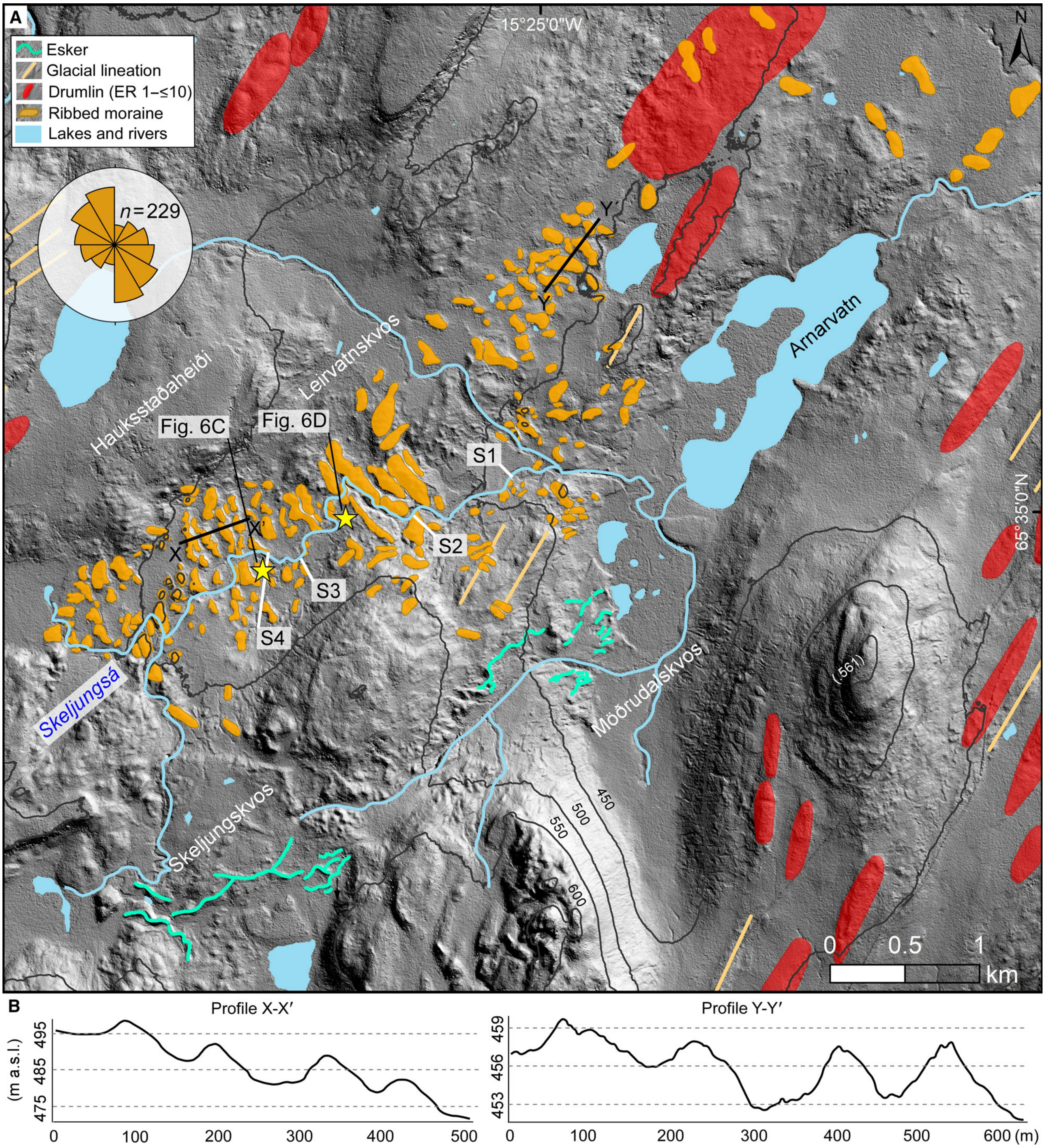

Fig. 3. A. Map of glacial landforms on Hauksstaðaheiði. The rose diagram shows the orientation of the mapped 229 ribbed moraines (median 114°–294°). The locations of the sections are marked (S1–4). The stars mark the locations where Fig. 6C, D were taken. Contour intervals are 50 m. B. Two terrain cross profiles that are marked on the map. The ribbed moraines are usually between 0.5 and 10 m in relief with both symmetrical and asymmetrical cross profiles and curved crests.

observed in the northwest part of the area. Some of the ridges have a fragmented appearance, making them challenging to map (Fig. 2A). Their median length is 127 m with a range of 28–657 m, median width is 64 m with a range of 17–282 m, and median elongation ratio is 2.0:1 with a range of 1.1:1–4.4:1. Further information on the morphology is listed in Fig. 5 and Table 1. The relief of the ridges varies between 0.5 and 15 m, but they are generally between 0.5 and 5 m high and their cross profile appears to be both symmetrical and asymmetrical,

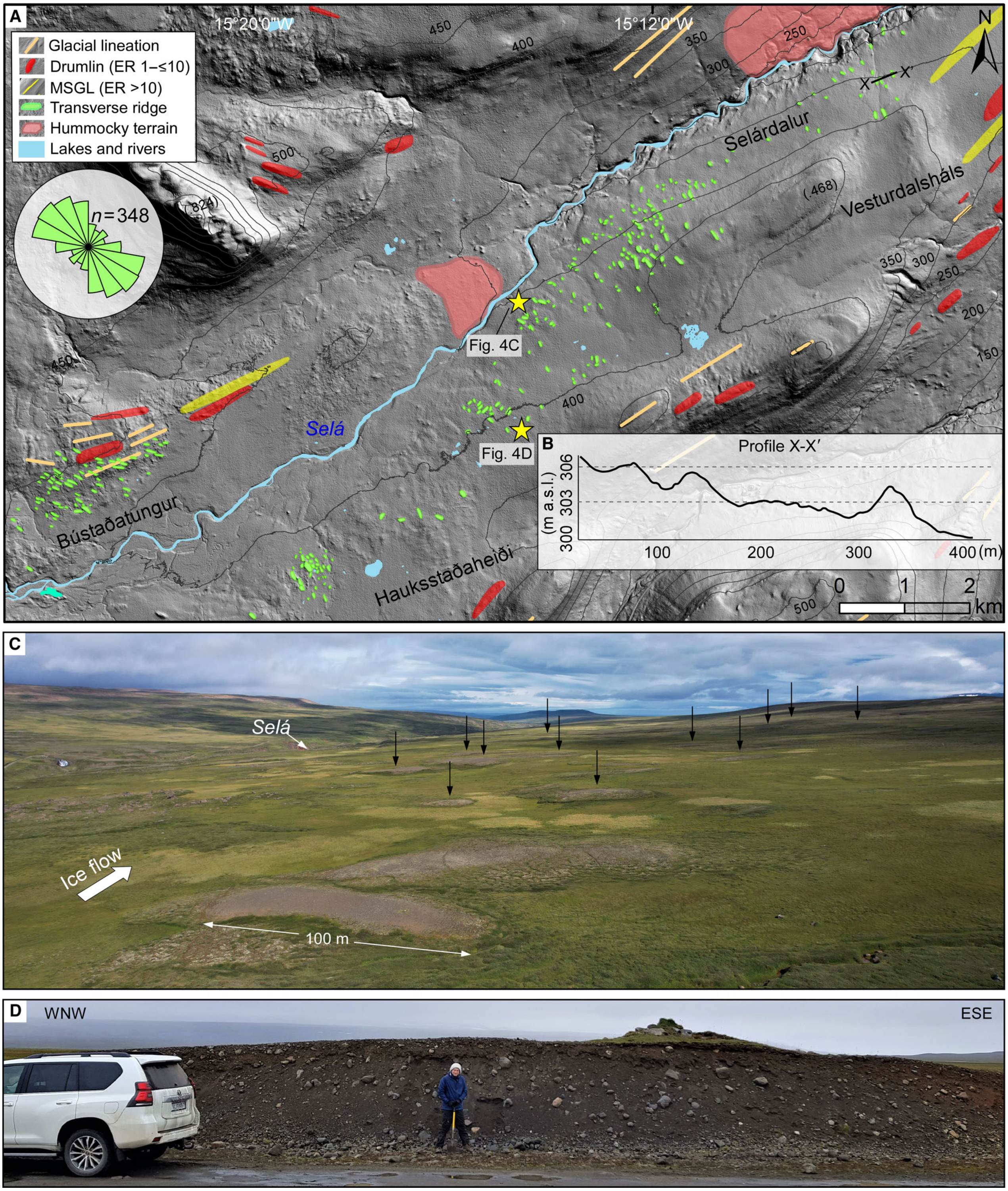

Fig. 4. A. Map of glacial landforms in Selárdalur and the highlands above. Note that the map does not cover the whole subarea. The rose diagram shows the orientation of the mapped 348 transverse ridges (median 128°–308°). The stars mark the locations where panels C and D were taken. Contour intervals are 50 m. B. A terrain cross profile of the ridges that is marked on the map. The ridges are usually <1 m in relief with symmetrical cross profiles and curved crests. C. Cluster of ridges at the head of Selárdalur. Two ridges are obvious in the foreground and arrows point at other prominent ridges in the distance. D. A roadcut into one of the ridges up on the plateau. The ridge is orientated oblique to the former ice flow and the section is perpendicular to the ridge. A brief examination of the sediments in the ridge indicates that it is composed of rather homogenous diamict.

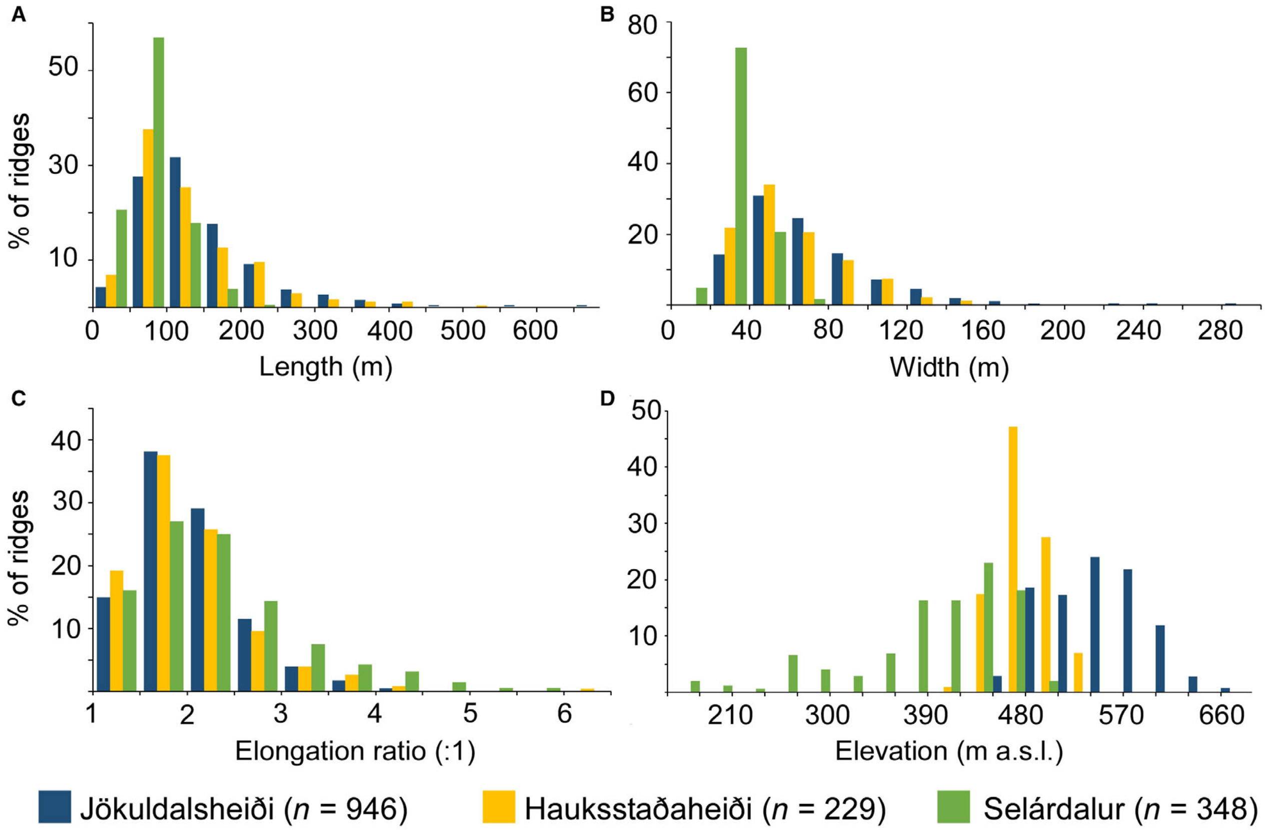

Fig. 5. Size-frequency (A) length, (B) width, (C) elongation ratio, and (D) elevation distribution of the morphometrics of the ridges on Jökuldalsheiði and Hauksstaðaheiði and in Selárdalur.

generally with a curved crest (Fig. 2C). The median orientation of the ridges is east to west (93°–273°), or generally transverse or oblique to the mapped SSBs. In the north and northeastern parts of the area, the ridges are orientated more towards northwest–southeast, which corresponds to changes in the orientation of the SSBs with a more constant southwest–northeast orientation, parallel to the trend of the fjord-valley (Fig. 2A, Table 1). The mean density of ridges is 0.4 ridges per km^2 with a maximum density of 32 ridges per km^2 (Table 1). The highest density of the ridges occurs in the northwestern part of the area where they are generally smaller in size than the median value for the entire area (Fig. 2A). Their crest spacing is not considered systematic by visual observation but due to the fragmented nature of the ridges, it is difficult to calculate their actual crest spacing. Large boulders, up to 3 m in diameter, are common on the surface of the ridges. The boulders are generally blocky and angular to subangular. They are not evenly distributed but appear in clusters, both on the ridges and between them (Fig. 6A, B).

The drumlins in the area are occasionally segmented into transverse ridges and somewhat chaotic transverse ridge fields. Transverse channels, both active and inactive, frequently dissect the drumlins, which might explain some of the discontinuous drumlins (Figs 2B, 6A). The transverse ridges occasionally occur superimposed on drumlins or in connection with them, especially in the southeastern part of the area (Fig. 6B). Sinuous and straight ridges with rounded crests that are generally parallel to the SSBs are frequent in the area (Figs 2A, B, 6A). Investigations from several gravel pits along the ring road in the southern part of the area reveal that the eskers consist of gravel and sand, recorded up to 5 m in thickness. Usually, the gravel overlies the sand, and horizontal layering was observed in some of the pits (The Icelandic Road and Coastal Administration 2023). They are interpreted as eskers and usually occur as single ridges, but esker systems are also present. At the eastern side of the hyaloclastite mountains, there are esker segments that are aligned in a row and together they are over 30 km long. At the southwestern margin of the area is a sharp boundary where the ridges abruptly terminate. This boundary coincides with a gentle depression and the river Háreksstaðakvísl, followed by a slight rise in the elevation up to higher plateaus. Inactive outwash plains and channels together with esker segments and esker systems are found within the depression. The eskers follow the topography and are orientated parallel to the depression and the present-day river, or towards the

Table 1. Morphometrics of transverse ridges on Jökuldals- and Hauksstaðaheiði and in Selárdalur.

		Jökuldalsheiði	Hauksstaðaheiði	Selárdalur
n		962	228	348
Length (m)	Median	127	105	70
	Mean	145	131	78
	Min.	28	32	20
	Max.	657	539	220
	Q_1	90	74	53
	Q_3	181	164	97
Width (m)	Median	64	60	33
	Mean	71	64	34
	Min.	17	23	14
	Max.	282	156	18
	Q_1	47	44	28
	Q_3	86	78	39
Elongation ratio (:1)	Median	2	1.9	2.1
	Mean	2	2	2.3
	Min.	1.1	1	1
	Max.	4.4	6	5.6
	Q_1	1.7	1.5	1.7
	Q_3	2.3	2.3	2.7
Orientation (°)	Median	93	114	129
	Mean	92	107	122
	Min.	0	0	6
	Max.	179	178	179
	Q_1	56	68	107
	Q_3	126	153	151
Density (no. of ridges km^{-2})	Mean	0.38	2.1	2.3
	Max.	32	54	44

northwest to north-northwest (Fig. 2A). Examples of eskers that continue into inactive channels are found in the southwestern part of the area. The eskers occur superimposed on the ridges but large boulders that are frequently on the ridges are never found on top of the eskers (Figs 2A, B, 6A).

In addition to the previously mapped ice-marginal landforms of Early Holocene age (Fig. 1C; Aðalsteinsson 1985, 1987; Sæmundsson 1995; Bjarkason 2024), additional ice-marginal landforms are suggested. These constitute ridges that are generally more prominent and straighter with an asymmetrical cross profile and steeper proximal sides, as compared to the other mapped transverse ridges. Inactive channels are often found in connection with the ridges and the eskers sometimes terminate at them. Their surface consists of unsorted sediments and large and angular boulders are also present on them, like the ridges described above (Figs 2A–C, 6A). Based on these characteristics and their lateral correlation across the area, the ridges are interpreted as end moraines. The distance between the inferred ice-marginal positions ranges from ~1.5 up to 10 km (Fig. 1C).

Hauksstaðaheiði. – On Hauksstaðaheiði, 229 ridge segments were mapped where their distribution is mostly confined within a southwest–northeast shallow basin, Leirvatnskvos, and adjacent hills, at elevations ranging from 415 to 515 m a.s.l. (Fig. 3A). The ridges are generally broad arcuate or rectangular, but examples of anastomosing ridges also occur (Figs 3A, 6C, D). Their median length is 105 m with a range of 32–539 m and the median width is 57 m with a range of 23–156 m. Their median elongation ratio is 1.9:1 with a range from 1.0 to 6.1:1 (Fig. 5, Table 1). The relief of the ridges varies between 0.5 and 10 m with generally higher segments in the southwestern part of the basin. Their cross profile appears to be both symmetrical and asymmetrical, with steeper distal and proximal sides, and generally has a curved crest (Fig. 3B). The median orientation of the ridges is south-southeast to north-northwest (114°–294°), or generally transverse or oblique to the mapped SSBs. The ridges in the southwestern part of the basin have a more distinct transverse orientation as well as a higher elongation ratio (Fig. 3A, Table 1). The ridges are clustered with an observed average crest-to-crest distance of 115 m, generally increasing down-ice. The mean density of ridges is 2.1 ridges per km^2 with a maximum density of 54 ridges per km^2 (Table 1). Large (up to 2 m in diameter), blocky, and angular to subangular boulders are common on the surface of the ridges, similar to Jökuldalsheiði. The boulders are not evenly distributed and seem to occur in clusters, but only on the ridges (Figs 6A, B, 9A).

The ridges occur superimposed on drumlins and glacial lineations. At the northeastern side of the mapped area, there are examples of ridges that resemble drumlins that have been dissected, like Jökuldalsheiði, although they are not as prominent (Fig. 3A). Sinuous to straight ridges made up of sorted sediments, with rounded crests, are observed in two basins, Skeljungsdalskvos and Möðrudalskvos, southeast of the ridges, and further to the north (Figs 1C, 3A). These are interpreted as eskers. The direction of the eskers is generally the same as the drumlins in the area (southwest to northeast) or follows the topography. There are no inferred ice-marginal positions within the area.

Selárdalur. – In total, 348 ridge segments were mapped in Selárdalur valley and the highlands above at elevations ranging from 126–460 m a.s.l. The ridges are generally linear, especially on Bústaðatungur, and when their distribution is dense enough, they have an interconnected network (Fig. 4A, C). The median length is 70 m with a range of 20–220 m and the median width is 33 m with a range of 14–78 m. The median elongation ratio is 2.1:1 with a range from 1.0 to 5.6:1 (Fig. 5, Table 1). The ridges are low in relief (<1 m), often only tens of centimetres prominent, and their cross profile appears to be generally symmetrical with a curved crest, although it can be difficult to determine due to their low relief (Fig. 4B). The median ridge orientation is southeast to northwest (128°–308°), or generally transverse or oblique to the mapped SSBs and the orientation of the valley (Fig. 4A, Table 1). However, the orientation of some segments can be difficult to determine as they have a low elongation ratio and show signs of erosion. The ridges are

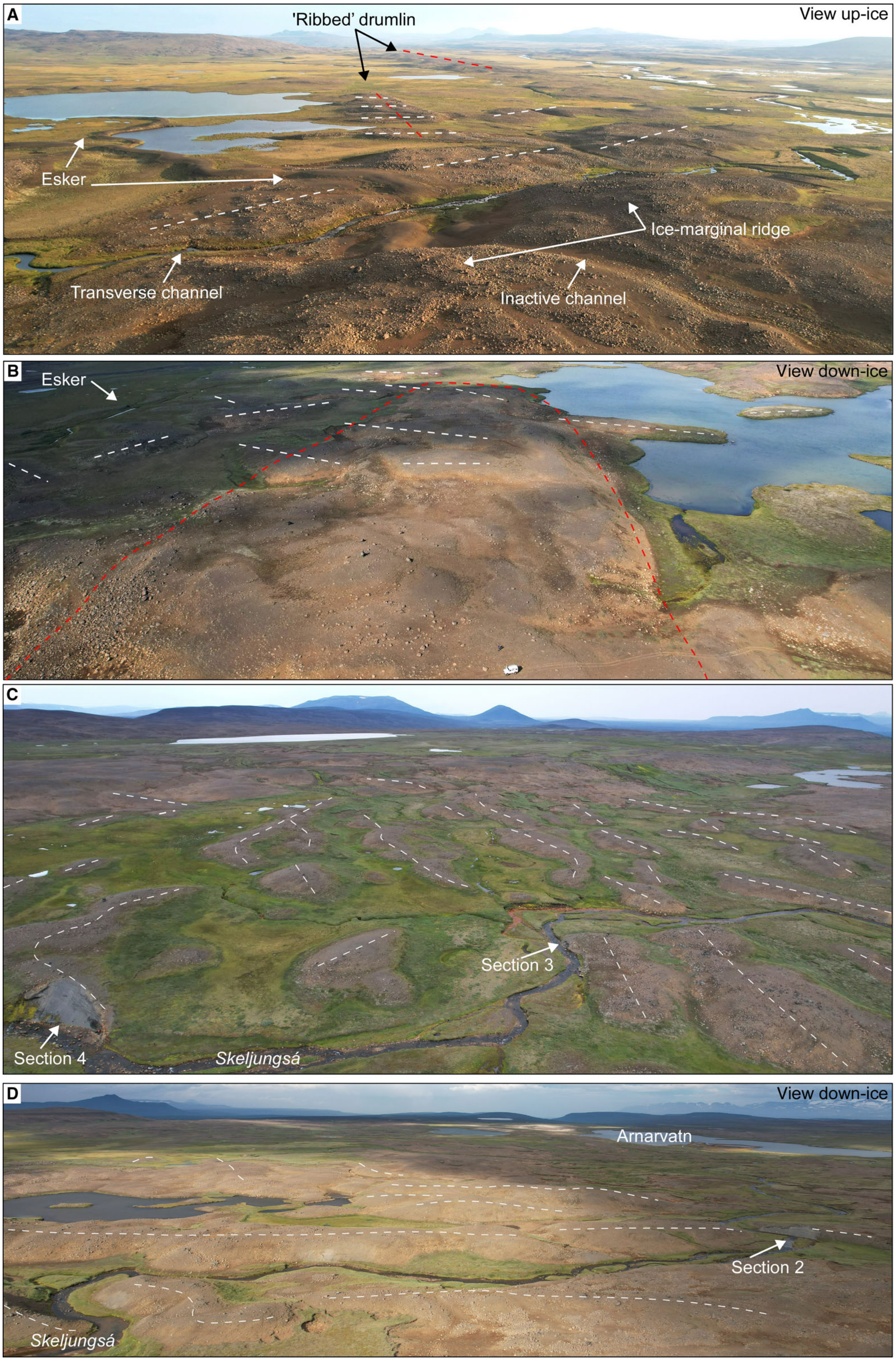

Fig. 6. A. Ribbed moraines (white dashed lines) on Jökuldalsheiði at the proximal side of one of the ice-marginal positions where an esker terminates and changes into an inactive channel (up to 15 m wide). Note the 'ribbed' drumlin (red dashed lines). The view is up-ice. B. The lee side of a large drumlin (red dashed line) on Jökuldalsheiði with superimposed and adjacent ribbed moraines (white dashed lines). An esker lies parallel to the drumlin on the western side (left of the image). Note the large and angular boulders on both figures from Jökuldalsheiði and the car for scale at the bottom. C. Ribbed moraines in the upper part of the basin on Hauksstaðaheiði with a view towards the north. Sections 3 and 4 (30 m long) are marked. Note the broad arcuate and rectangular, and anastomosing shape of the ridges. D. Down-ice overview of the ribbed moraines on Hauksstaðaheiði. Section 2 is marked (45 m long) and the most prominent ridges are highlighted with white dashed lines.

dispersed within the area, but four clusters occur. Most of the ridges are situated on a gentle slope at the southeastern side of the head of the valley and the highlands above, down-ice from the transverse ridges on Hauksstaðaheiði. Within the individual clusters of ridges, the orientation is relatively consistent (Fig. 4A). The mean density of ridges is 2.3 ridges per km^2 with a maximum density of 44 ridges per km^2 and an average crest-to-crest distance of 115 m (Table 1).

On Bústaðatungur, there are examples of ridges superimposed on SSBs and esker segments occur up-ice from those ridges and around Selá (Fig. 4A). The surface of the ridges is composed of diamict, with subangular to subrounded boulders. There are no large angular boulders found on top of the ridges in the valley, distinguishing them from the ridges on Jökuldalsheiði and Hauksstaðaheiði, but further up on the highlands, boulders occur both on and around the ridges. However, the sediment is comparable to sediments on the surface of drumlins on Bustarfell and CSRs in Bakkaflói and Þistilfjörður (Aradóttir *et al.* 2023a, b). The ridge sediments were investigated briefly in one roadcut and a few gravel pits. They were composed of homogenous matrix-supported diamict, and striations were observed on a few clasts (Fig. 4C, D). Based on these data we interpret the ridges to be composed of till, although we acknowledge that our sedimentological data are limited.

Areas with hummocky morphology, similar to those described by Sæmundsson (1995) from the Early PB re-advance (Fig. 1C), are mapped at four new locations: three within the Selárdalur valley and one on the northern part of Hauksstaðaheiði. The areas within the valley are all located on the northwestern side of Selá and distributed from the centre of the valley to its mouth (Figs 1C, 4A). These areas usually comprise poorly sorted sediments on the surface with subangular to subrounded boulders but sorted sediments were also observed.

Sedimentology of the transverse ridges

The internal architecture of the transverse ridges on Hauksstaðaheiði was studied in four river-cut sections (1–4) (Fig. 3A). Four units were identified: (1) matrix-supported diamict; (2a) interbedded sand and gravel layers; (2b) horizontally laminated silt and fine sand; (3) brown, massive, clast-supported diamict; (4) partly stratified, clast-rich, matrix- to clast-supported, firm diamict. Those are described and interpreted in Table 2.

Section 1 is located furthest downstream in Skeljungsá, closest to Lake Arnarvatn. The ridge remnant with the section is 40 m long and 30 m wide and trending ~NW–SE (Fig. 3A). The section is in total 20 m long and 9 m high, orientated transverse to the ridge crest (56° 236°) and two units (2a and 4) are identified within it (Fig. 7A, B). Unit 2a (Gh/m/Sh) is up to 6 m thick and composed of glacifluvial sediments (Table 2). The layers within the unit are 1–20 cm thick and clasts are mostly blocky (C_{40} = 2) and subrounded to subangular (RA = 7.7) with no striations observed (S1_u2). Small-scale deformation structures and ripple marks occur within sand layers and lenses. Vague fissile structures are observed close to the sharp and conformable boundary to unit 4 (Db/sC(m_3/c)4), which is up to 1.5 m thick diamict (Table 2). The clasts within the diamict are usually blocky (C_{40} = 0), subrounded to angular (RA = 9.3), and striated clasts, facets, and or/bullet-shaped clasts are present (S1_u4). The largest boulders in both units are up to 40 cm in diameter. The larger boulders are usually more angular than the smaller ones. Based on the characteristics of unit 4 it is interpreted as subglacial traction till (Table 2). Layers in both units are dipping (6° 20°) transversely or obliquely outwards from the ridge crest (Figs 7B, C, 11A).

Section 2 is located ~700 m upvalley from section 1 in a ridge composed of three segments, with a total length of ~950 m, oriented SE–NW (Figs 3A, 6D). The ridge segment with the section is 180 m long and 170 m wide. The section is 50 m wide and up to 15 m high, aligned transverse to the composite ridge (30°–210°). Three units were identified within the section (2a, 3 and 4; Fig. 8A–D). The base of the ridge (<5 m thick) is composed of unit 2a (G/Sm/h), glacifluvial sediments similar to those in unit 2a of section 1, although the gravel is more massive and coarser. The clasts are generally between 1 and 10 cm in diameter (largest up to 40 cm in diameter) and are mostly blocky (C_{40} = 0) and subrounded to subangular (RA = 0) (S2_u2). Occasional ripple marks are observed in the sand layers and lenses (Table 2). Gravel layers, dipping towards the southwest, at the southwestern part of the unit are truncated by a clast-rich diamict (unit 3; DmM/C(c)4) with an erosional boundary. Unit 3 is therefore interpreted as subglacial traction till. It is less than 1 m thick, brown in colour and clasts are mostly blocky (C_{40} = 0) and subrounded to subangular (RA = 0) (S2_u3), up to 30 cm in diameter (Table 2). A gradational boundary separates unit 4 (Db/sC(m_3)4) at the top of the section, from units 2a and 3. It has a similar appearance to unit 4 in section 1, interpreted as subglacial traction till based on its characteristics, and is up ~5 m thick (Table 2). The clasts are usually blocky (C_{40} = 8) and subrounded to angular (RA = 9.3) (S2_u4). The layers within unit 4 at the southwestern end are dipping towards the southwest, or down-ice (270°/26° and 280°/15°; Figs 8B, C, 11B, C).

Section 3 is located >1.2 km upvalley from section 2. The ridge segment is 116 m long and 50 m wide, orientated SSE–NNW (Fig. 3A). The section is located at the edge of the ridge and is orientated almost parallel to the ridge crest, or 170°350°, and is 15 m wide and up to 3 m high. The section has a similar stratigraphy to section 1, composed of units 2a and 4 (Fig. 9A, B). Unit 2a is 1.8 m

Table 2. Lithofacies identified within units in transverse ridges on Hauksstaðaheiði. Lithofacies codes are according to Krüger & Kjær (1999).

Unit no. – lithofacies code	Location and description	Interpretation	References
1 – DmM(m_2)3	Section 4 Up to 1.2 m thick unit. Massive, matrix-supported diamict. Grey in colour. Deformed sand and silt lenses. Fissile structure.	Subglacial traction till Deposited beneath the active ice.	Krüger & Kjær (1999), Evans *et al.* (2006)
2a – G(h)/S(m)/S(h)/r	Sections 1–4 Up to 6 m thick. Coarse gravel with interbedded, stratified sand and gravel layers. Massive and horizontally laminated sediments. Clasts are mostly blocky and subrounded to subangular. Vague fissile structure. Small-scale deformation structure. Occasional ripple marks in sand layers and lenses. Stratified fine sand veins perpendicular to stratification and horizontal silt sills (clastic dykes). Layers dipping transversely or obliquely outwards from the ridge crest.	Glacifluvial sediments Variable flow regime. Overridden by glacier based on deformation and fissile structure and erosional boundary. Clastic dykes indicate high water pressure at the glacier bed. Signature of multiple coupling/decoupling events.	van der Meer *et al.* (1999), Evans *et al.* (2006)
2b – Fl/Sh	Section 4 ~1-m-thick unit. Horizontally laminated silt and fine sand. Dissorted sediments. Few outside clasts. Not continuous within the section.	Fluvial fines Deposited from running water at low flow regime.	Evans *et al.* (2006)
3 – DmM/C(c)4	Section 2 <1-m-thick unit. Massive, clast-supported diamict. Brown in colour. Clasts are mostly blocky, subrounded to subangular. Erosional boundary with unit 2a and gradational with unit 4.	Subglacial traction till Deposited beneath the active ice. Clast-rich indicates debris-rich ice.	Krüger & Kjær (1999), Evans *et al.* (2006)
4 – Db/sC(m_3/c)3/4	Sections 1–4 Up to 5 m thick. Matrix- to clast-supported diamict. Clast-rich with mostly blocky, subrounded to angular clasts some striated, facets, and bullet-shaped. Mostly heterogeneous and partly stratified with layers and lenses of sorted sediments. Firm to extremely firm. Deformation and fissile structure. Stratified fine sand veins perpendicular to overall stratification (clastic dykes). Layers dipping transversely or obliquely outwards from the ridge crest. Sharp conformable boundary with unit 2a.	Subglacial traction till Deposited beneath the active ice. Clast-rich indicates debris-rich ice. Till is partly interpreted as deposited during melt-out based on stratification and sorted sediments. Clastic dykes indicate high water pressure at the glacier bed.	van der Meer *et al.* (1999), Krüger & Kjær (1999); Evans *et al.* (2006)

thick and is composed of glacifluvial sediments (Gh/Sh/r) (Table 2). Ripples are visible both in sand lenses within the gravel and in the sand layers. The clasts are up to 20 cm in diameter and are mostly blocky (C_{40} = 0) and subrounded to angular (RA = 17.3) (S3_u2). At the top of the section is a diamict (unit 4; Db/sC(m_3/c)3) (<3 m thick) similar to that observed in the other sections (Table 2). A sharp conformable boundary is between units 2a and 4. A clastic dyke, perpendicular to the general stratification of the till, occurs at the up-ice side of the ridge. It consists of stratified fine sand, is <2 cm wide, and extends downwards. Clast morphology measurements show mostly blocky clasts (C_{40} = 4) that are subrounded to angular (RA = 14.5). Based on its appearance the diamict is interpreted as subglacial traction till (Table 2). Layers in both units generally dip towards the west or southwest, or outwards from the ridge crest (Figs 9B, C, 11D).

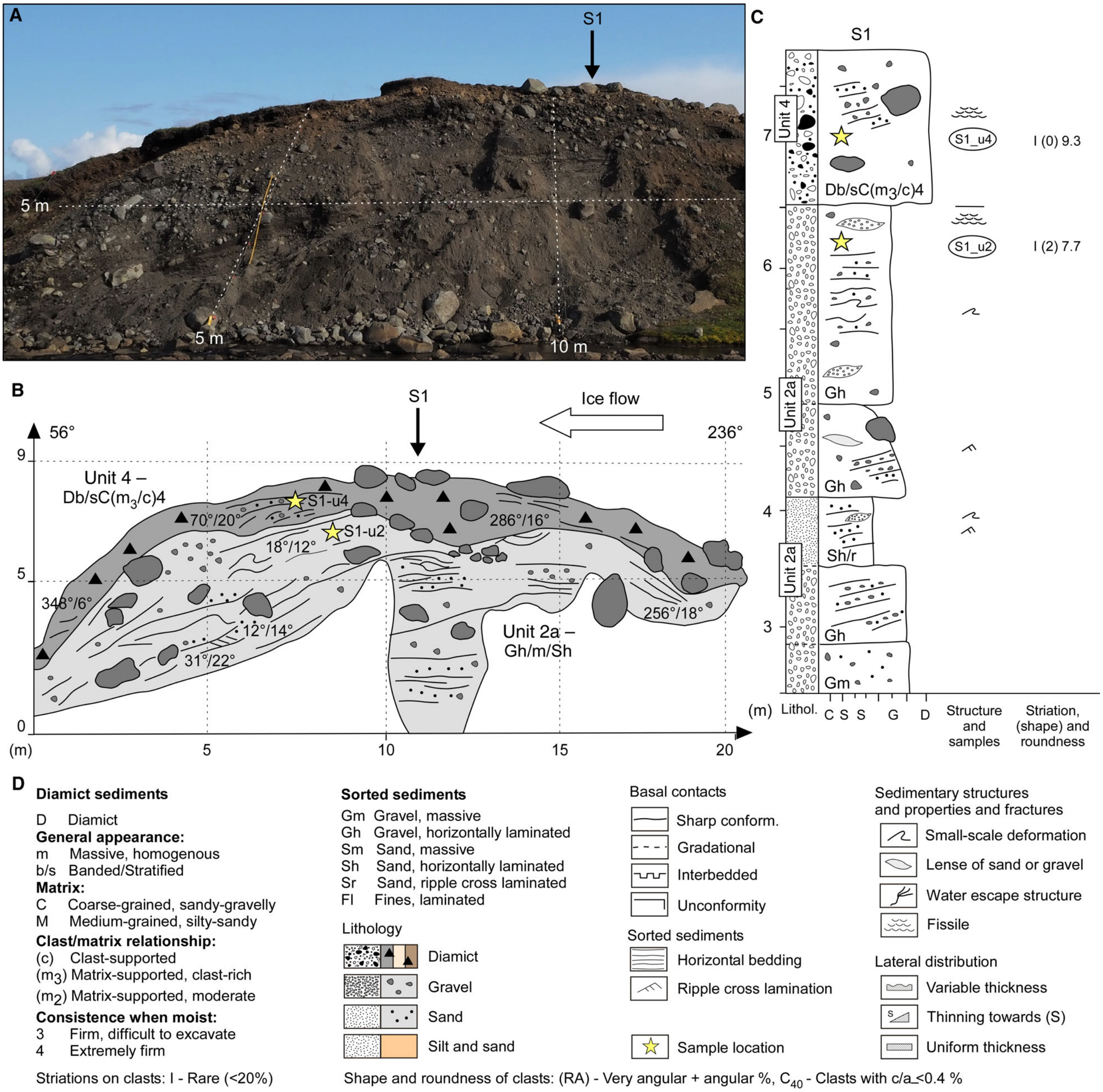

Fig. 7. A. Section 1 on Haukssta∂aheiði. Note the dipping of the layers at the distal (left) side of the ridge. B. Diagram of the section. The location of log S1 is marked. C. Stratigraphical log from S1. D. Legend and lithofacies codes used here and for other logs and diagrams in the paper, following Krüger & Kjær (1999).

Section 4 is the southwestern-most section, located ~250 m upvalley from section 3. The ridge segment is 190 m long and 100 m wide (Fig. 3A). The orientation of the ridge is SSE–NNW and most of the section is orientated 93°–270°, or oblique to the ridge crest. The orientation of the southeastern part of the section changes to 146°–326°, almost perpendicular to the ridge crest. The section is 35 m wide and up to 15 m high (Fig. 10A–C). This section has more complex stratigraphy than the other sections, with four units identified. At the base of the section is unit 1, a layer up to 1.2 m thick of diamict with deformed sand and silt lenses and fissile structure (DmM(m_2)3), interpreted as subglacial traction till (Table 2). Above the till is ~1 m of laminated fine/medium sand and silt (Fl/Sh) that has been distorted (unit 2b). A few outsized clasts, up to 3 cm in diameter, are found within the sand and silt. This unit does not continue to the southeast in the section and could therefore be a lens within unit 2a. The most prominent unit in the section is composed of glacifluvial sediments (unit 2a) comparable to those observed in the other sections (Table 2). The unit is visible through most of the

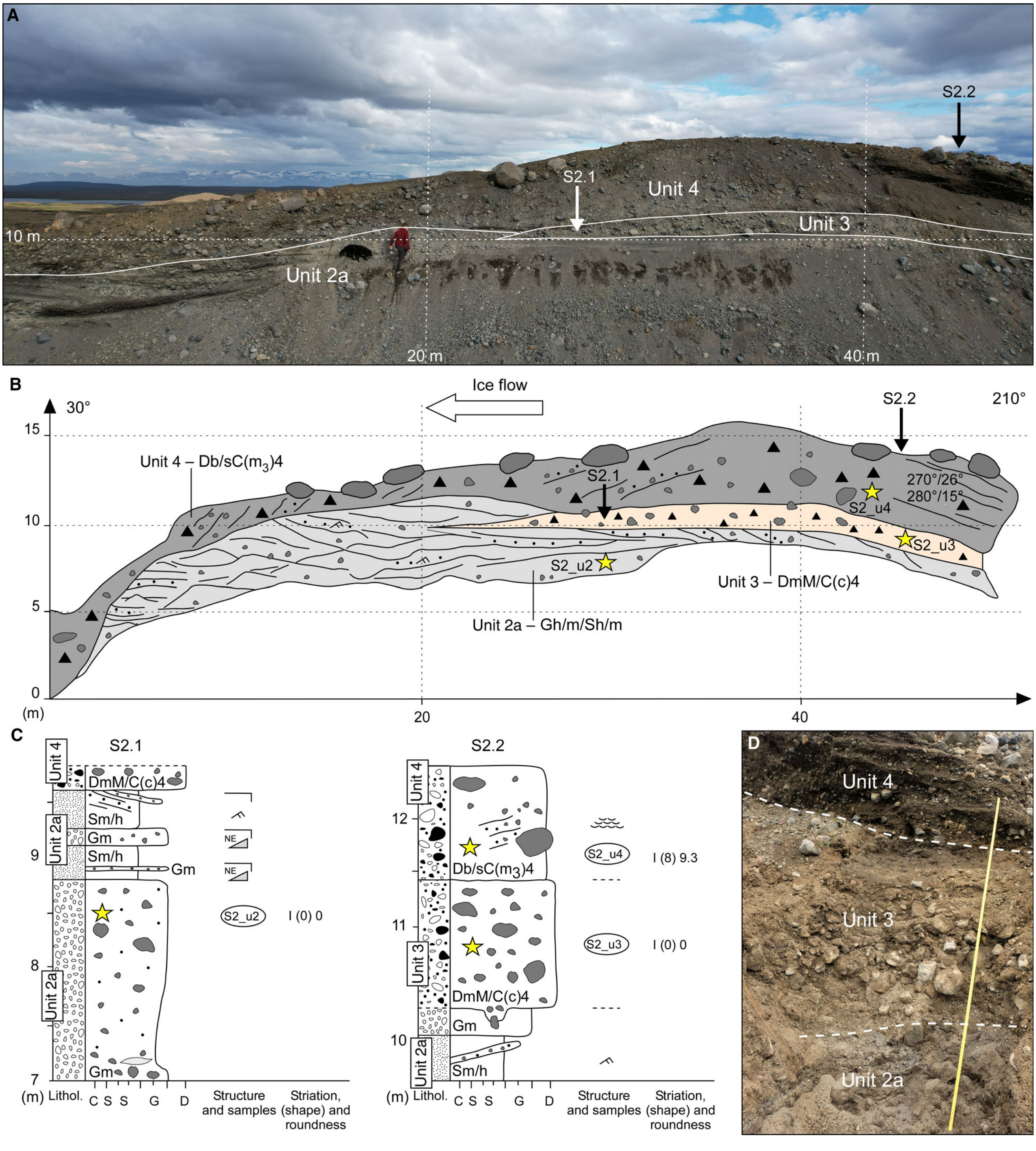

Fig. 8. A. Section 2 on Hauksstaðaheiði. Three different units were identified in section 2 that are highlighted. Note the person and dog for scale in the middle of the section. B. Diagram of the section. The location of logs S2.1 and S2.2 are marked. C. Stratigraphical log from S2.1 and S2.2. D. Part of section S2.2 where all three units (2a, 3 and 4) are observed.

section, over 5 m thick in the middle but thinner at the southeastern side where the log was made. In general, the unit coarsens upwards and ripples are observed in sand lenses within the gravel. Clastic dykes are also found within the unit, both consisting of fine sand veins (<2 cm) perpendicular to the overall stratification of the layers and as thin horizontal silt layers (<1 cm) that separate some of the gravel and sand layers. The sills are usually discontinuous but can continue over several metres in the section. The stratified sand and gravel layers are generally steeply dipping (22°–69°) towards the north-northeast, obliquely to the ridge crest or down-ice. At the

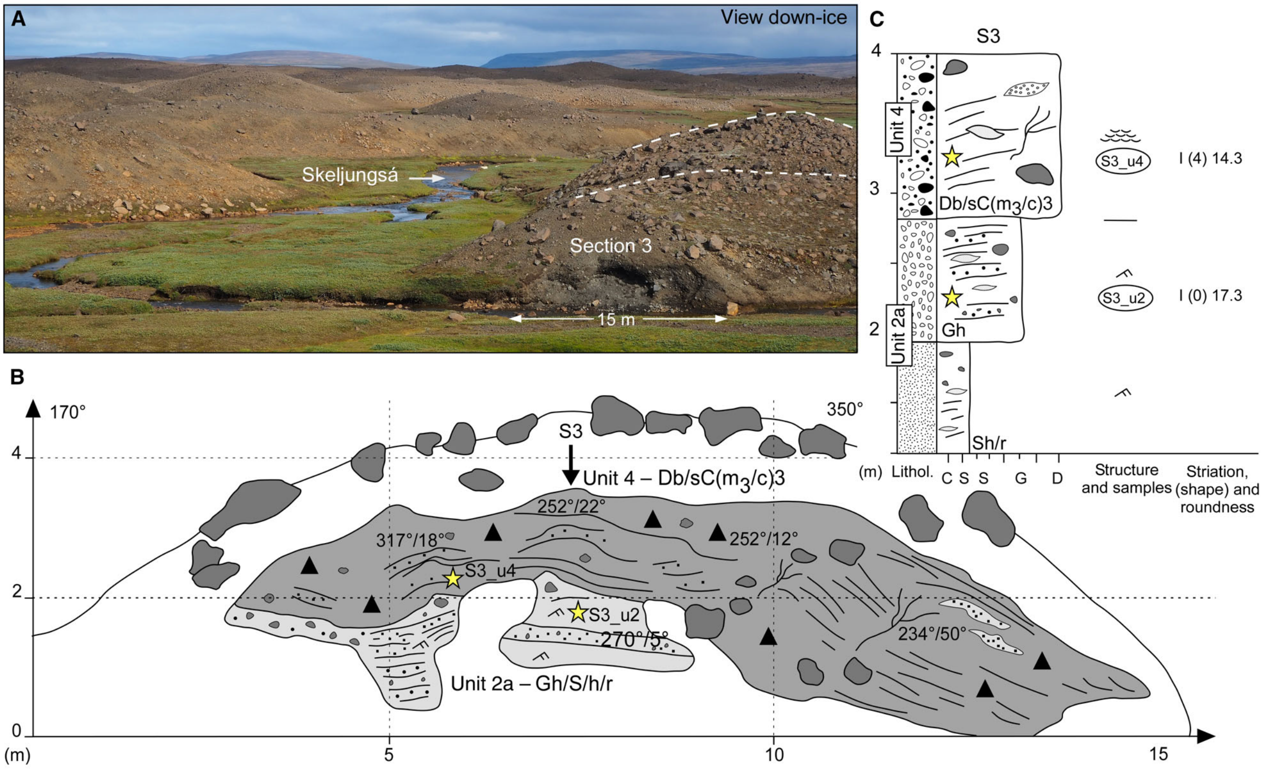

Fig. 9. A. Section 3 on Hauksstaðaheiði. The white dotted lines highlight the ridge crest and the adjacent ridge that lies parallel to it. Note the large angular boulders on top of the ridges. B. Diagram of the section. The location of log S3 is marked. C. Stratigraphical log from S3.

top of the section is unit 4, a diamict (Db/sC(m_3)3), similar to the uppermost unit in the other sections and therefore interpreted as subglacial traction till based on its characteristics (Table 2). The underlying sorted sediments are thrusted into the till and lenses of sand and gravel are frequent in the lower part of the unit. Deformation and fissile structures are visible. Clast samples were not taken here but clasts are usually blocky and angular to subrounded. The unit is up to 4 m thick (Figs 10C, D, 11E, F).

Discussion

Interpretation of transverse ridges

The transverse ridges on Hauksstaðaheiði and Jökuldalsheiði were described by Helgadóttir (2020) who interpreted them as ribbed moraines based on morphological resemblance to a comprehensive analysis of ribbed moraines by Dunlop & Clark (2006). Our results agree with that interpretation based on the morphological characteristics of the ridges. The ridges' appearance on Hauksstaðaheiði is most similar to what Dunlop & Clark (2006) classified as broad arcuate or rectangular ribbed moraines although some can be classified as anastomosing ribbed moraines. On Jökuldalsheiði, some of the ribbed moraines show similarity to the ridges on Hauksstaðaheiði, while the remainder have a hummocky appearance. The median size of the ribbed moraines is similar between the two areas, but they are more closely spaced and have a higher distribution density on Hauksstaðaheiði. The transverse ridges in Selárdalur were also previously interpreted as ribbed moraines by Helgadóttir (2020), but because they exhibit different morphological characteristics compared to the ribbed moraines on Hauksstaðaheiði and Jökuldalsheiði, we speculate that they may have a different origin (Rivers *et al.* 2023). These transverse ridges appear as linear, interconnected segments with symmetrical crests, generally orientated transverse to former ice flow, and show more resemblance to previously described crevasse-squeeze ridges (CSRs) in Bakkaflói and Þistilfjörður (Aradóttir *et al.* 2023a). Their linear shape and interconnected network could also suggest that they are recessional moraines (e.g. Bennett 2001; Chandler *et al.* 2016). However, their generally symmetrical cross profile and lack of other associated ice-marginal landforms rather suggest a CSR origin (e.g. Sharp 1985; Evans & Rea 1999, 2003; Rivers *et al.* 2023). Consequently, that implies deposition during an ice-stream shutdown or a surge event (e.g. Evans *et al.* 2016; Kurjanski *et al.* 2019; Benn 2021; Lamsters *et al.* 2021).

We are aware that ribbed moraines and ice-marginal moraines can be hard to distinguish in places. This especially applies to Jökuldalsheiði where their fragmented

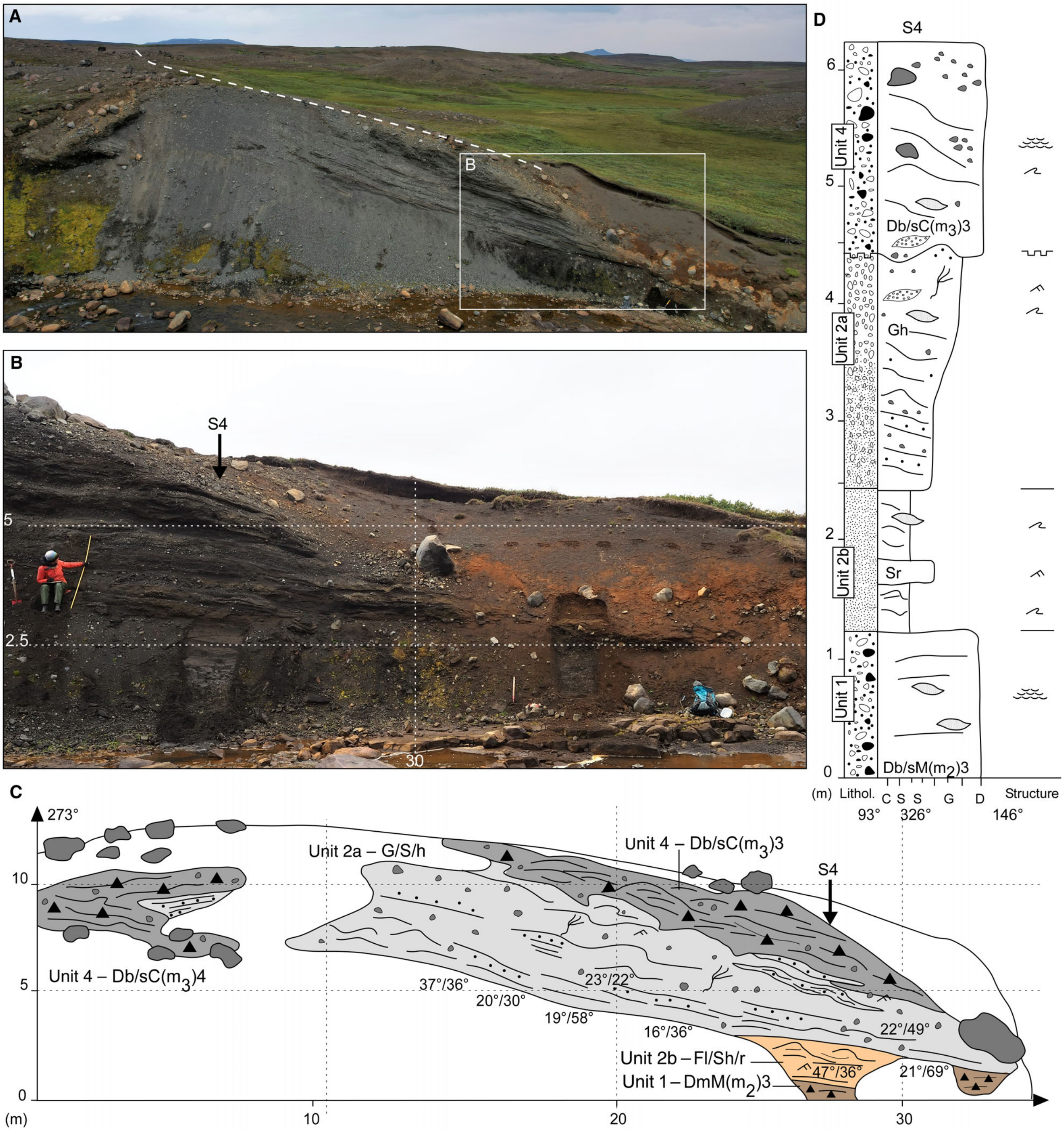

Fig. 10. A. Section 4 on Hauksstaðaheiði. The white dashed line highlights the ridge crest. B. The eastern part of the section where the logging was conducted. The orientation of the section changes slightly from W–E to NW–SE. C. Diagram of the section. The location of log S4 is marked. D. Stratigraphical log from S4.

appearance and high frequency make them difficult to differentiate. However, ice-marginal channels are usually associated with ice-marginal moraines, which can help distinguish between these two types of ridges. It should also be noted that the primary morphology of all the transverse ridges has been altered (lower relief and subdued appearance) due to postglacial sedimentation, erosion (Dunlop & Clark 2006; Finlayson 2013), and accretion of peat (Aradóttir *et al.* 2023b).

In general, the sections in the ribbed moraines on Hauksstaðaheiði have similar stratigraphy; core of glacifluvial sand and gravel (unit 2) draped with massive to stratified, clast-rich subglacial traction till (unit 4) (Table 2). The till at the base of section 4 (unit 1) was only

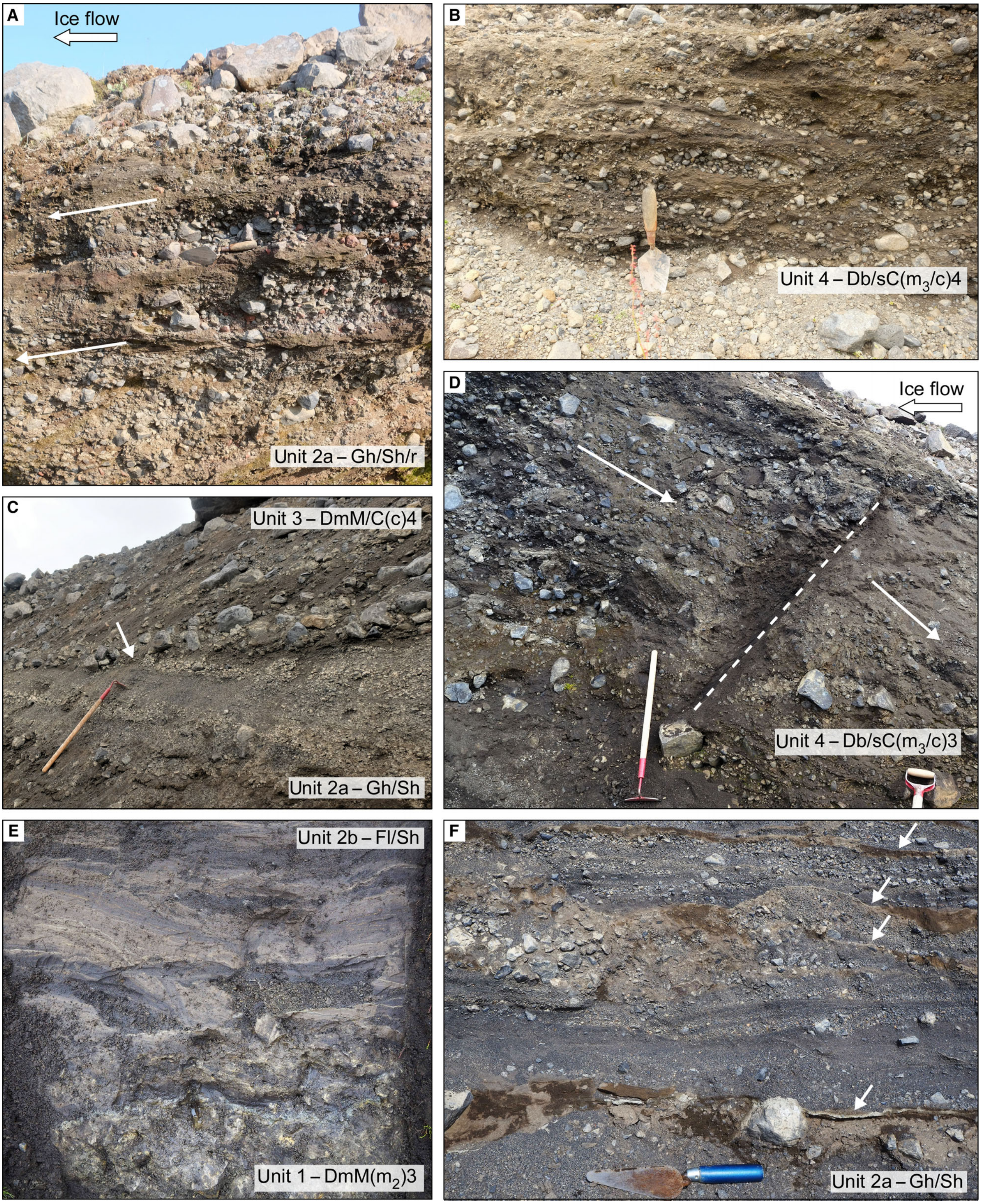

Fig. 11. A. Dipping sand and gravel layers towards north-northeast (down-ice), or outwards from the centre of the ridge in section 1. Arrows indicate dip direction. B. Stratified diamict in section 2. C. Unconformity (arrow) between units 2a and 3 in section 2. D. Stratified diamict in section 3 dissected with clastic dyke (white dashed line). Note the layers dipping towards southwest/south-southwest or up-ice (arrows). E. Deformed laminated silt and fine sand on top of a massive diamict with deformed sand and silt lenses at the base of section 4. F. Laminated sand and gravel in section 3. Note the silt layers (clastic dykes) between the layers (arrows) with minor deformation structures.

observed with limited spatial extent but its subglacial origin may suggest that it is widespread in the whole basin of Hauksstaðaheiði. The glacifluvial sediments (unit 2) are interpreted to have been deposited in a proglacial setting based on the widespread distribution and thickness. The subglacial traction till of units 3 and 4 with erosional lower contact with the underlying glacifluvial sediments indicates that the glacifluvial sediments were overridden by ice together with deformation structures. The clast-rich subglacial traction till at the top of all the ridges (unit 4) suggests debris-rich basal ice (Evans *et al.* 2006; Möller 2006). The partly stratified characteristics of the uppermost till (unit 4) and the layers and lenses of sorted sediments within it, indicate syn-depositional influence of water during melt-out (Evans *et al.* 2006). The clastic dykes further indicate high water pressure at the base of the glacier, as they suggest the downward intrusion of fluidized sediments and the sills' multiple coupling/decoupling at the base of the glacier (van der Meer *et al.* 1999, 2009). Fabric measurements were not feasible in the till because of its clast-rich nature and compactness, and therefore the method could not be used to further determine its origin.

The sedimentology of the ribbed moraines on Hauksstaðaheiði shows resemblance to ribbed moraines described in Sweden, Norway, Finland and Scotland, where deformed glacifluvial sediments, subglacial traction till and melt-out till have been described (e.g. Lundqvist 1989, 1997; Raunholm *et al.* 2003; Möller 2006, 2010; Sarala 2006; Finlayson & Bradwell 2008). These and other studies (e.g. Hättestrand 1997; Hättestrand & Kleman 1999) agree that the sediments within the ridges appear unrelated to the landshaping process. Consequently, the ribbed moraines in northeast Iceland are thought to be formed through the remoulding of pre-existing sediments.

Implication for glacier dynamics

The ribbed moraines on Hauksstaðaheiði and Jökuldalsheiði are located upstream from fields of well-defined drumlins and occasionally superimposed on them. On Jökuldalsheiði, the ridges are surrounded by drumlins of various shapes and sizes, some of which can be classified as 'ribbed' drumlins, but there are no examples of ribbed moraines that have undergone drumlinization. Based on this cross-cutting relationship and that the ridges have not been overridden by rapidly moving ice, we interpret them to be formed during ice-stream deglaciation rather than in the ice-stream onset zone (e.g. Raunholm *et al.* 2003; Sarala 2006; Stokes *et al.* 2008; Delaney *et al.* 2023). As we do not see any remoulding of pre-existing landforms, besides the 'ribbed' drumlins, we do not consider the ribbed moraines to be formed by modification of pre-existing landforms (Lundqvist 1989, 1997; Möller 2006). A ~90° change in flow direction responsible for their formation, as suggested by Boulton (1987), is also highly unlikely in the area based on the inferred flow direction from the mapping of SSBs (Benediktsson *et al.* 2022a).

The formation of ribbed moraines has generally been associated with compressive ice flow (e.g. Shaw 1979; Bouchard 1989; Finlayson & Bradwell 2008; Stokes *et al.* 2008; Vérité *et al.* 2021) or attributed to the fracturing of frozen pre-existing till sheets due to extensional basal ice flow at the boundary between cold- and warm-based conditions (Hättestrand 1997; Hättestrand & Kleman 1999; Raunholm *et al.* 2003; Sarala 2006). The deformation and thrust structures in the sections on Hauksstaðaheiði support compressive flow, although the lack of large-scale folds or faults does not imply shearing and stacking, as proposed by Lindén *et al.* (2008) for the formation of ribbed moraines. The general dipping of the layers up- and down-ice, i.e. outwards from the ridge crests, is difficult to interpret but we surmise that this indicates compressive flow in line with other deformation structures identified in the sections. Individual ridges in this study do not fit together like a jigsaw puzzle, as would be the case for till sheets that got ripped apart under extensional flow at the transition between warm-based and cold-based ice (Hättestrand 1997; Hättestrand & Kleman 1999; Sarala 2006). In addition, there is no morphological evidence of cold-based ice in this region, thus disputing the fracturing hypothesis for the ribbed moraines in northeast Iceland.

Recent modelling experiments by Vérité *et al.* (2021) attribute the formation of ribbed moraines to changes in glacial dynamics and soft-bed deformation in areas with high lateral or longitudinal velocity gradients. They are formed in marginal settings due to compression, with transverse ridges below frontal lobes but oblique ridges beneath lateral shear margins (Vérité *et al.* 2021). Based on the topography and distribution of glacial landforms on Hauksstaðaheiði and Jökuldalsheiði, the ribbed moraines appear to have formed near the shear margins of the ice streams rather than below the frontal lobe, although they occur both transverse and oblique to the former ice flow. However, the orientation of the ridges in the area is affected by the topography and is thus expected to show more variations than modelling experiments on a flat substrate. Other studies have also attributed changes in glacier dynamics and ice velocity to the formation of ribbed moraines (Raunholm *et al.* 2003; Finlayson & Bradwell 2008; Stokes *et al.* 2008). Based on the above arguments, we consider the most reasonable explanation for the formation of ribbed moraines in northeast Iceland to be related to lateral and longitudinal velocity gradients, which results in changes in glacial dynamics and basal processes, such as compressive flow. Furthermore, this explanation would suggest that their formation is associated with ice-stream shutdown, as proposed by other studies (e.g. Sarala 2006; Stokes *et al.* 2008; Delaney *et al.* 2023).

Subglacial hydrological modelling highlights the importance of subglacial meltwater corridors for the development of landforms (Vérité *et al*. 2023). The ribbed moraines in northeast Iceland are likely located within or adjacent to meltwater corridors, as they often occur juxtaposed with eskers. The well-defined drumlins on Bustarfell and further down-ice from Jökuldalsheiði indicate that those areas are outside the main meltwater corridor (Fig. 12B). Eskers described from palaeo-ice sheets are generally interpreted as deglacial landforms, indicating that the water drainage changed from distributed to channelized drainage during the deglaciation. The long and well-organized esker systems on Jökuldalsheiði reflect time transgressive formation and relatively constant channelized drainage during the retreat (e.g. Stokes *et al*. 2007; Margold *et al*. 2011; Storrar *et al*. 2014a, b). This agrees with the model by Vérité *et al*. (2021) where the formation of ribbed moraines is associated with extensive areas of ice-bed coupling due to changes in the channelized and effective subglacial drainage (Fig. 12B). It is generally agreed that large and angular boulders on the surface of ribbed moraines may be explained by the quarrying of bedrock in areas with thin till sheets and englacial transport from

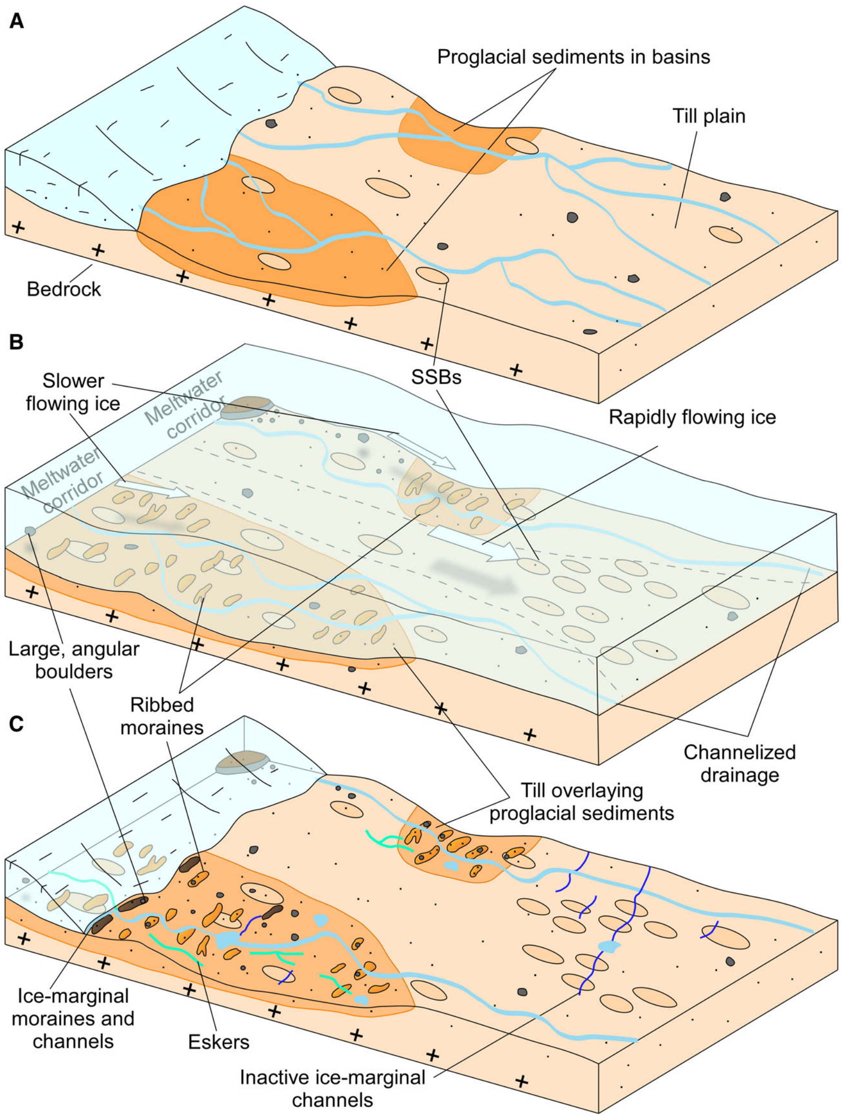

Fig. 12. Conceptual landsystem model illustrating ribbed moraines formed within Vopnafjörður-Jökuldalsheiði flowset, northeast Iceland. A. Deglaciation. SSBs that formed during the last ice advance are exposed and glacifluvial material is deposited, especially in basins. B. Ice stagnation following glacier re-advance. Formation of SSBs continued within the ice-stream trunk during the re-advance. Ribbed moraines are formed at the lateral shear margin of the ice stream due to changes in basal processes related to the spatial velocity difference within the ice during stagnation. Large and angular boulders are transported englacially from local bedrock outcrops during the final phase of the formation of the ridges. Eskers are formed as the drainage changes from distributed to channelized during deglaciation, enhancing ice-bed coupling. C. Deglaciation. Ice-marginal positions indicate a stepwise retreat. SSBs are more fragmented due to fluvial erosion around the ribbed moraines due to their locations within or closer to the meltwater corridor.

nearby bedrock plateaus (Möller 2006). Sarala (2006) suggested that the freeze–thaw process between the ribbed moraines caused quarrying of the bedrock that was subsequently deposited on the next ridge based on changes in the lithology of the boulders. As our data do not suggest that the ridges were formed due to freeze–thaw processes, we rather consider the boulders to be deposited during the final stages of the ribbed moraine formation through englacial transport from local bedrock plateaus (Möller 2006). The higher frequency of boulders in some areas can therefore simply be explained by proximity to bedrock outcrops or knobs under a thin veneer of till, but the thicker accumulation of peat might also prevent them from being observed in the inter-ridge areas.

Glacial history and timing of the landform formation

The chronological constraints on the deglaciation history in the area are limited and therefore the absolute timing for the formation of the ribbed moraines is not known. However, their relative time of formation can be established based on a morphostratigraphical approach. Considering the cross-cutting relationship of the landforms, the ribbed moraines post-date the drumlins but pre-date the eskers and the ice-marginal landforms. As the ribbed moraines are situated inside the suggested PB ice margin and bear no signs of having been overridden, the simplest explanation is that they were formed during the PB period. Due to chronological and geographical uncertainties on how far the glacier retreated between the YD and PB periods, we cannot exclude that the ribbed moraines formed in association with the YD re-advance, or that they were formed time transgressively over those two periods. Glacifluvial sediments within the drumlins of Bustarfell were previously suggested to have been deposited proglacially during the Bølling-Allerød interstadial (Aradóttir *et al*. 2023b). Consequently, the subglacial traction till below may be from a previous ice advance, i.e., the LGM, while the till on top from the YD re-advance. We hypothesize that the glacifluvial sediments in the ribbed moraines were likewise deposited in a proglacial setting simultaneously with those at Bustarfell. As a result, the most probable timing of the deposition of the uppermost till and the formation of the ribbed moraines is during the YD or PB periods, possibly during ice-stream shutdown related to changes in velocity gradients within the ice (Fig. 12B). This could conceivably be tested with additional sedimentological and chronological data and stratigraphical correlations.

The transverse ridges in Selárdalur, suggested to be CSRs, are most likely formed during the deglaciation following the PB based on the suggested ice-marginal position close to the mouth of the valley (Sæmundsson 1995). The three hummocky areas inside the outermost moraine suggest stillstands or small re-advances during the retreat. It might also be speculated that the landform assemblage of several hummocky areas and CSRs in the valley resembles evidence for repeated cycles, comparable to a surge signature, which could provide a new perspective on the relationship between the style of deglaciation and climate forcing (Benn 2021). However, we acknowledge that due to the ridges' low relief and lack of cross-sections, it was difficult to assess the symmetry of their cross profile and study their internal architecture in detail. Thus, further studies are necessary to test if these ridges in Selárdalur are CSRs.

The ice-marginal landforms (end moraines and ice-contact features) on Jökuldalsheiði and in Selárdalur (hummocky moraines), inside the suggested PB margin, signify retreating ice margins with minor re-advances or stillstands during the final deglaciation (Fig. 12C). This is supported by even more pronounced ice-marginal positions and larger moraines, e.g. the Skessugarður moraine, farther inland (Fig. 1C; Aðalsteinsson 1985, 1987; Benediktsson *et al*. 2024b).

This first description of ribbed moraines in Iceland suggests that they are associated with the Lateglacial and/or Early Holocene deglaciation of the IIS. Further investigations of ribbed moraines in Iceland are thus of great importance for providing new insights into the evolution of the IIS and advancing our understanding of palaeo-ice stream dynamics and subglacial processes during ice-sheet decay.

Conclusions

- Broad arcuate or rectangular ridges are mapped in shallow basins on the Hauksstaðaheiði and Jökuldalsheiði plateaus within the Jökuldalsheiði-Vopnafjörður palaeo-ice stream flowset in northeastern Iceland. Based on their morphology, internal architecture, and general orientation transverse and/or oblique to the former ice flow, they are interpreted as ribbed moraines, the first to be described in Iceland.
- The ridges in the Selárdalur valley and the highlands above are more linear and do not resemble ribbed moraines in their morphology but show more similarity to CSRs. However, further studies are required to confirm their origin.
- The investigated ribbed moraines on Hauksstaðaheiði are composed of glacifluvial sand and gravel layers draped with partly stratified, clast-rich subglacial till. Both the glacifluvial sediments and till units exhibit deformation and thrust structures. Furthermore, the strata are characterized by an outward dip from the ridge crest, which we interpret as being a result of compressional flow.
- Other glacial landforms in the area are SSBs, eskers, ice-marginal moraines, and meltwater channels. The superimposition of ribbed moraines on drumlins and the ribbed appearance of some drumlins indicate that

the ribbed moraines post-date the formation of the drumlins. Eskers superimposed on ribbed moraines indicate channelized water drainage during the deglaciation and suggest that the ribbed moraines develop within or proximal to areas that were or later became meltwater corridors. The eskers frequently terminate at ice-marginal positions on Jökuldalsheiði, implying an active retreat interrupted by short-lived re-advances during the final deglaciation.

- We suggest that ribbed moraines develop due to spatial ice velocity gradients within the lateral shear margins of a palaeo-ice stream. These velocity gradients lead to changes in glacial dynamics, particularly in basal processes and meltwater drainage, which enhance ice-bed coupling. The oblique orientation of the moraines supports this hypothesis, indicating that the interaction between fast-flowing ice and surrounding slower-moving ice plays a key role in their development.
- Based on a morphostratigraphical correlation of landforms with reference to the known glacial history in northeast Iceland, we suggest that the ribbed moraines formed during ice-stream shutdown following the YD and/or PB re-advance.
- Further work should focus on mapping ribbed moraines elsewhere in Iceland and their correlation with other glacial landforms, such as eskers, to increase our understanding of the deglaciation history and help constrain future modelling of the IIS.

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Data availability statement. – The data that support the findings of this study are available from the corresponding author upon reasonable request.

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