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Using GIS and streamlined landforms to interpret palaeo-ice flow in northern Iceland

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The properties of streamlined glacial landforms and palaeo-flow indicators in the valleys of Víðidalur, Vatnsdalur and Svínadalur in northern Iceland were quantified using spatial analyses. Drumlins and mega-scale glacial lineations (MSGL) were visually identified using satellite imagery from Google Earth, the National Land Survey of Iceland (NLSI) Map Viewer and Landsat satellites, and using aerial photographs from the NLSI. A semi-automated technique was developed using ENVI to determine regions in northern Iceland likely to contain streamlined landforms. The outlines of the identified landforms were manually delineated in Google Earth, and all analyses were conducted in ArcGIS using a 20 m digital elevation model (DEM) of Iceland from the NLSI. Smaller features such as flutes, grooves and striations were measured in the field. At least 543 drumlins and 90 MSGL were identified in the three valleys. Average elongation ratios for Víðidalur, Vatnsdalur and Svínadalur are 4.3:1, 5.2:1 and 6.7:1, respectively. The average density of streamlined landforms is 2.34 landforms per 1 km^2. Striations and orientation data of the drumlins and MSGL demonstrate ice flow to the northwest into Húnaflói. Parallel conformity is higher in the valley of Svínadalur (9° standard deviation) than in Víðidalur (12°) and Vatnsdalur (16°). Packing values are generally higher in the centre of each valley. The properties of streamlined landforms in the valleys of Víðidalur, Vatnsdalur and Svínadalur support the presence of palaeo-ice stream activity on northern Iceland. Palaeo-ice streams flowed from these regions into Húnaflói, supplying ice to the margin of the Iceland Ice Sheet during the Last Glacial Maximum. These palaeo-ice streams provide a mechanism for ice centres from the mainland of Iceland to reach the shelf-slope break.

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Streamlined landforms are one of the most common features formed beneath modern and palaeo-ice sheets (e.g. Chorley 1959; Piotrowski & Smalley 1987; Clark 1993; Smalley & Warburton 1994; Colgan & Mickelson 1997; Knight & McCabe 1997; Briner 2007; Clark *et al.* 2009; Johnson *et al.* 2010; Spagnolo *et al.* 2011; Ó Cofaigh *et al.* 2013; Stokes *et al.* 2013; Evans *et al.* 2015). They are useful features in understanding palaeo-ice sheets, providing information about ice extent, flow paths and ice-sheet dynamics (e.g. Clark 1997; Colgan & Mickelson 1997; Briner 2007; Dowdeswell *et al.* 2010). In particular, many studies use the distribution of elongate streamlined landforms, such as drumlins and mega-scale glacial lineations (MSGL), to identify and interpret regions of fast ice flow beneath former ice sheets (e.g. Clark 1993; Bourgeois *et al.* 2000; Stokes & Clark 2001, 2002; Clark *et al.* 2003; Ottesen *et al.* 2008; Stokes *et al.* 2013; Spagnolo *et al.* 2014). Identifying the location of modern and palaeo-ice streams is important for understanding global climate change, as ice streams have the ability to drain large volumes of ice from and influence the stability of ice sheets, as well as impact global sea level (e.g. Livingstone *et al.* 2012).

Bourgeois *et al.* (2000) and Stokes & Clark (2001) proposed the locations of palaeo-ice streams as part of the former Iceland Ice Sheet. Both studies noted that the presence of ice streams is plausible, but uncertain in some regions of northern Iceland (Fig. 1). Marine core records and seismic studies on the north Iceland shelf support the advance of the Iceland Ice Sheet to the shelf-slope break during the Last Glacial Maximum (LGM; Andrews *et al.* 2000; Andrews & Helgadóttir 2003; Andrews 2005; Principato *et al.* 2005; Spagnolo & Clark 2009). It is also commonly assumed that two independent ice sheets were present in Iceland during the LGM, one covering the mainland and one covering Vestfirðir, the northwest peninsula of Iceland (Hoppe 1982; Norðdahl 1991; Principato & Johnson 2009; Brynjólfsson *et al.* 2015). Principato *et al.* (2006) suggested a shear margin separating restricted ice on Vestfirðir from ice flowing from the mainland of Iceland, supporting previous interpretations of large volumes of ice flowing to the shelf-slope break from Húnaflói and the adjacent region of northern Iceland. However, none of these previous studies based their ice-stream interpretation on terrestrial geomorphic evidence for proposed ice streams. Principato & Johnson (2009) documented the distribution of ice scour lakes and striations to interpret basal flow regimes of the Iceland Ice Sheet in northern Iceland, but analysis of streamlined landforms was not part of their study.

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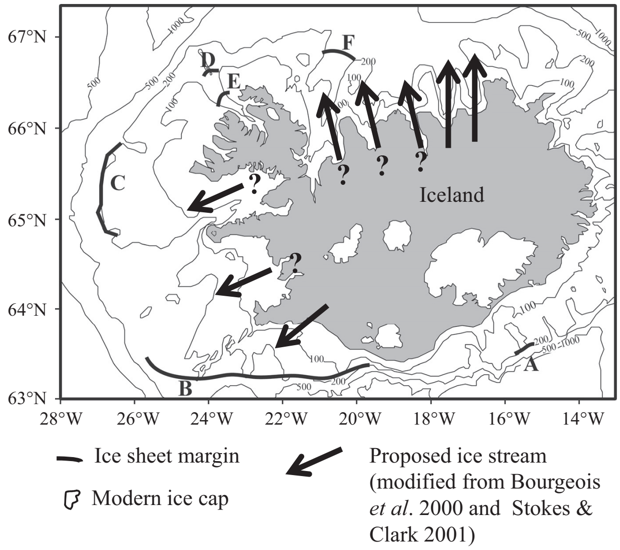

Fig. 1. The location of proposed ice streams on Iceland by Bourgeois *et al.* (2000) and Stokes & Clark (2001) and inferred LGM ice margins around Iceland shown as black lines with the following references: A = Boulton *et al.* (1988); B = Egloff & Johnson (1979); C = Ólafsdóttir (1975), Syvitski *et al.* (1999); D = Geirsdóttir *et al.* (2002); E = Andrews *et al.* (2002); F = Andrews *et al.* (2000), Andrews & Helgadóttir (2003).

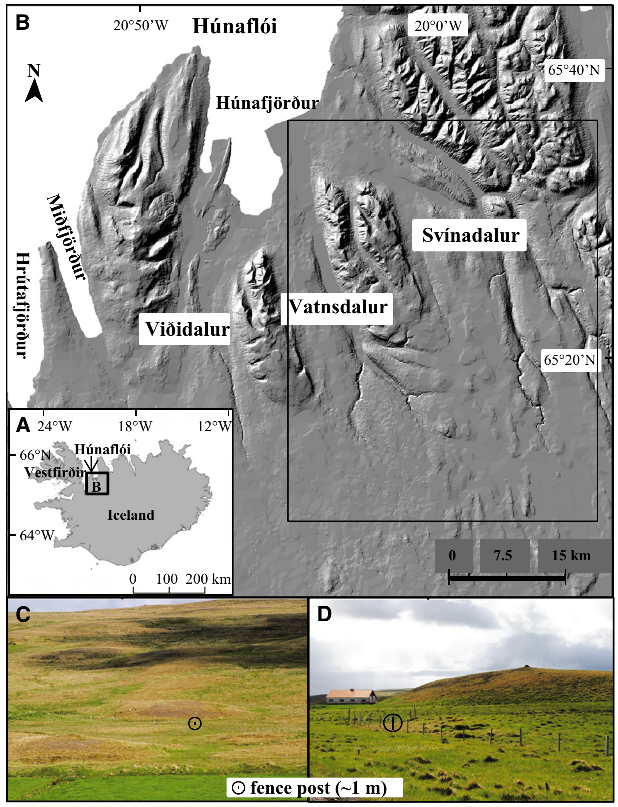

Fig. 2. A. Map of Iceland showing location of study area. B. Shaded relief map of the study area. Húnaflói is a wide bay to the north of the study area. Box indicates area described in Fig. 3. C. Oblique photograph of streamlined landforms in Víðidalur with fence post for scale. D. Close-up of part of a streamlined landform in Víðidalur with fence post for scale.

The purpose of this study was to evaluate the locations of proposed palaeo-ice streams by Bourgeois *et al.* (2000) and Stokes & Clark (2001) in part of northern Iceland where the presence of palaeo-ice streams is uncertain (Fig. 1). Identifying the presence of palaeo-ice streams in northern Iceland fills in a gap in the glacial record of Iceland and inform interpretations of part of the Iceland Ice Sheet during the LGM. We present a quantitative analysis of streamlined landforms on northern Iceland, providing a better understanding of palaeo-ice flow paths and ice-sheet dynamics in the region. A combination of remote sensing, spatial analysis and fieldwork was used to document palaeo-ice flow in this region. The dynamics of the Iceland Ice Sheet are sensitive to changes in North Atlantic oceanographic and atmospheric conditions (Malmberg 1969, 1985; Ruddiman & McIntyre 1981; Stötter *et al.* 1999; Eiríksson *et al.* 2000), which make these analyses important from a local and regional perspective.

Study area

The study area is located south of Húnaflói bay in northern Iceland (Fig. 2). Detailed analyses of streamlined landforms focused on three valleys, Víðidalur, Vatnsdalur and Svínadalur (Fig. 2). Svínadalur is the widest of the three valleys with an average width of 20 km, compared to Víðidalur and Vatnsdalur, which have approximate widths of 12 and 8 km, respectively. The bedrock geology of the three valleys is similar and consists primarily of a mixture of Tertiary and lower Pleistocene plateau basalts with the exception of at least one rhyolitic mountain (Einarsson & Albertsson 1988; Kristjánsson & Jóhannesson 1994; Sigmundsson & Sæmundsson 2008). The region studied is located more than 60 km from the active rift zone, and volcanic activity did not directly impact basal ice flow in this region of Iceland during the LGM. Kaldal & Víkingsson (1990) performed extensive field mapping in parts of northern Iceland, identifying flutes and megaflutes in part of the study area. Bourgeois *et al.* (2000) used satellite imagery and field mapping data from northern Iceland to make interpretations about ice flow and velocity, proposing the presence of an ice stream in this region. We expanded upon this previous work by identifying additional streamlined landforms and providing a quantitative analysis of their properties.

Methods

A combination of spatial analyses, fieldwork and statistical analyses was used to quantify the properties of streamlined landforms. The distribution, density and elongation of streamlined landforms provide information about the location and movement of ice sheets (e.g. Stokes & Clark 2001; Briner 2007; Dowdeswell *et al.* 2010; Fowler 2010).

Remote sensing and spatial analyses

Two Landsat images were combined to identify regions containing streamlined landforms within the study area. One image from Landsat 5, from August 1994, and one image from Landsat 8, from October 2013, were combined to obtain a final image with a total of 12 spectral bands. The images were corrected for atmospheric scattering and converted to radiance units. A supervised classification was performed in ENVI on the combined image, using regions of interest for the classes of vegetation, glacial depositional landform, and an 'other' category containing bedrock, snow and water. The classification was used to identify regions that are likely to contain drumlins and other subglacial landforms and distinguish them from bedrock features.

Focusing on the regions likely to contain streamlined landforms, as determined by the ENVI classification, individual streamlined landforms were visually identified and mapped using satellite imagery provided by the online map viewer of the National Land Survey of Iceland (NLSI) and Google Earth 6. The map viewer is composed of multiple SPOT-5 satellite images in natural colour and is updated annually by the NLSI. Each landform was delineated by hand in Google Earth and exported as a KML file into ArcGIS, transformed into vector format and superimposed on a 20 m digital elevation model (DEM) of Iceland created by the NLSI. The DEM was generated from the IS 50V data set and is presented in conical Lambert projection with the reference ISN93 or ISN2004 (NLSI). Topography is derived from the 1:50 000 or 1:100 000 map series with contour intervals of 20 m.

Due to resolution limitations of the spatial data, analyses focused on drumlins and MSGL. Flutes and other smaller streamlined landforms are not visible on satellite imagery or the DEM. Spagnolo *et al.* (2014) demonstrated that elongation ratios of MSGL are typically higher than elongation ratios of drumlins, and they suggested that MSGL and drumlins are on a morphological continuum. For simplicity, the definition of MSGL based on elongation ratio by Clark (1993) was used to distinguish between drumlins and MSGL, with MSGL having an elongation ratio >10:1.

The area of each streamlined landform was calculated automatically using ArcGIS. Other properties measured include: the length of the long axis, the maximum width orthogonal to the long axis, the elongation ratio of each landform, the orientation of the long axis, the parallel conformity of landforms and landform density. The length of the long axis and the maximum width orthogonal to the long axis were measured in ArcMap. These values were then used to calculate the elongation ratio for each landform, which is the length of the long axis divided by the maximum width orthogonal to the long axis. The orientation of each landform was measured using the Minimum Bounding Geometry tool in ArcGIS, using the shapefile of the long axes as the input. Orientation values were plotted on a rose plot. Parallel conformity was calculated by taking the standard deviation of all of the orientation values, which determines the similarity of landform orientations overall in the three valleys. In order to measure density (the number of landforms per km^2), a point was created in the centre of each polygon. Density was calculated by counting the number of drumlins in each grid cell of a 1 km^2 fishnet over the study area and also by using the Point Density tool with landform identification (ID) as the population field. Packing (surface area of landform per km^2) was calculated using the Point Density tool with landform area as the population field.

Fieldwork

Landform identification was confirmed in the field for selected regions of the study area. Brunton compasses and Garmin GPS units were used to verify the location and measure the orientation of streamlined landforms where accessible. Detailed sediment analyses are beyond the scope of this study, although fieldwork sampling shows that most of the landforms are composed of gravelly diamicton. Orientations of striations and grooves in exposed bedrock in the study area were also measured and plotted on a rose diagram. Parallel conformity of striations was calculated as the standard deviation of the orientation values.

Statistical analyses

Statistical analyses were performed using VASSARSTATS and R in order to determine the significance of the results as well as to identify relationships between the variables quantified. Histograms and boxplots of streamlined landform long-axis length, width orthogonal to the long axis, and elongation ratio were created in R to visually identify any skews in the data set. A standard *t*-test (unequal sample sizes, assumed equal variance) was performed for elongation ratios, orientations, packing and density. Summary statistics were calculated, including mean, median, mode and standard deviation, to describe the landform data set. Linear regressions were performed between long-axis length and width orthogonal to the long axis, long-axis length and elongation ratio, and width orthogonal to the long axis and elongation ratio to determine any significant relationships between variables.

Results

Using satellite images classified in ENVI, a central region of high-density glacial depositional landforms was identified (Fig. 3). A series of lakes was also identified in the central region of the study area, with vegetation dominating the northern part of the image, and bedrock exposed in the southeastern corner. The central landforms correspond to a drumlin field identified visually through analysis of aerial photographs and Google Earth images. The average accuracy of the classification was calculated by visually and manually verifying the identity of 50 cells in another satellite image. The classification was accurate for 91.3% of the verified cells. Although the results generated from the ENVI analysis did not identify individual landforms, it was useful in determining regions that should be investigated in more detail with manual identification and landform delineation.

Using the ENVI classification as a first step in locating streamlined landforms, detailed analyses revealed at least 633 streamlined landforms in the study area (Fig. 4A, B). Additional streamlined landforms are present, and we have subsampled the population of streamlined landforms in the study area. The long axes of additional streamlined landforms are mapped to show flowlines through the lineated landscape (Fig. 4C). These additional streamlined landforms, primarily in Vatnsdalur and Viðidalur, were not quantifiable because the resolution of the satellite images and DEM for these valleys was too low. In addition, drumlins and MSGL commonly experience postglacial erosion (e.g. Spagnolo *et al.* 2014), and in this study area, many landforms are dissected by streams. Due to postglacial erosion and limitations of imagery resolution, the outlines of these additional streamlined landforms were not distinct. Detailed morphological parameters, including area, were difficult to quantify accurately when the landform did not show continuity and had a fragmented outline (following criteria used by Spagnolo *et al.* 2014). The online map viewer of the NLSI has much higher resolution satellite imagery of Svínadalur.

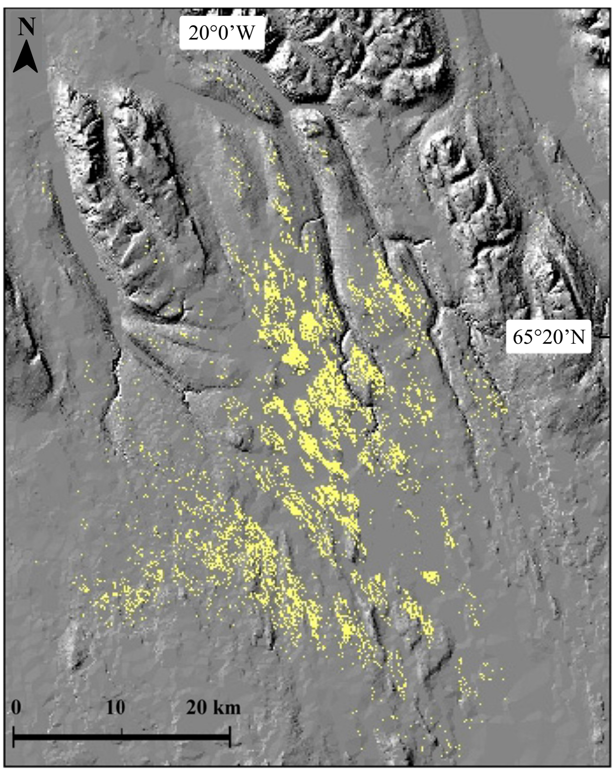

Fig. 3. Regions identified by the ENVI classification to be visually inspected for drumlins and MSGL. Yellow indicates areas where streamlined landforms are likely to be present.

Histograms of streamlined landform long-axis length, width and elongation ratio all demonstrate unimodal distributions with strong positive skews, results that have been observed for large numbers of streamlined landforms (Fig. 5; e.g. Clark *et al.* 2009; Stokes *et al.* 2013). The average long-axis length is approximately 507 m with a range of 21 to 3497 m, and the average width is approximately 92 m with a range of 7 to 576 m (Table 1). The average elongation ratio of all streamlined landforms measured is 6.4:1. There is no significant relationship between elongation ratio and position along the flowline interpreted from distance to coast.

There is a statistically significant positive relationship between long-axis length and width ($p<0.001$), with width accounting for approximately 69% of the variation in length. This result suggests that wider landforms also tend to be longer (Fig. 6A). Elongation ratio and length are expected to be strongly correlated, as length is used to calculate elongation. However, there is only a weak positive correlation between the two ($r^2 = 0.03$, $p<0.001$), suggesting that a landform of a certain length could have a wide range of potential elongation ratios (Fig. 6B). The linear regression between elongation ratio and width reveals a weak, negative correlation ($r^2 = 0.06$, $p<0.001$), but demonstrates that features with the largest elongation ratios (>20:1) are also the narrowest in the data set (Fig. 6C).

The orientation of long axes of streamlined landforms is generally southeast–northwest (Fig. 7). The parallel conformity for all of the landforms in the three valleys is approximately 12°. The average density of landforms is 2.83 landforms per 1 km^2. The concentration of drumlins and MSGL is most dense in the middle of the valleys, although there is also a high concentration of drumlins near the mouth of Svínadalur (Fig. 8). The average distance between streamlined landforms and the coastline is approximately 38 km. Packing is generally tightest in the

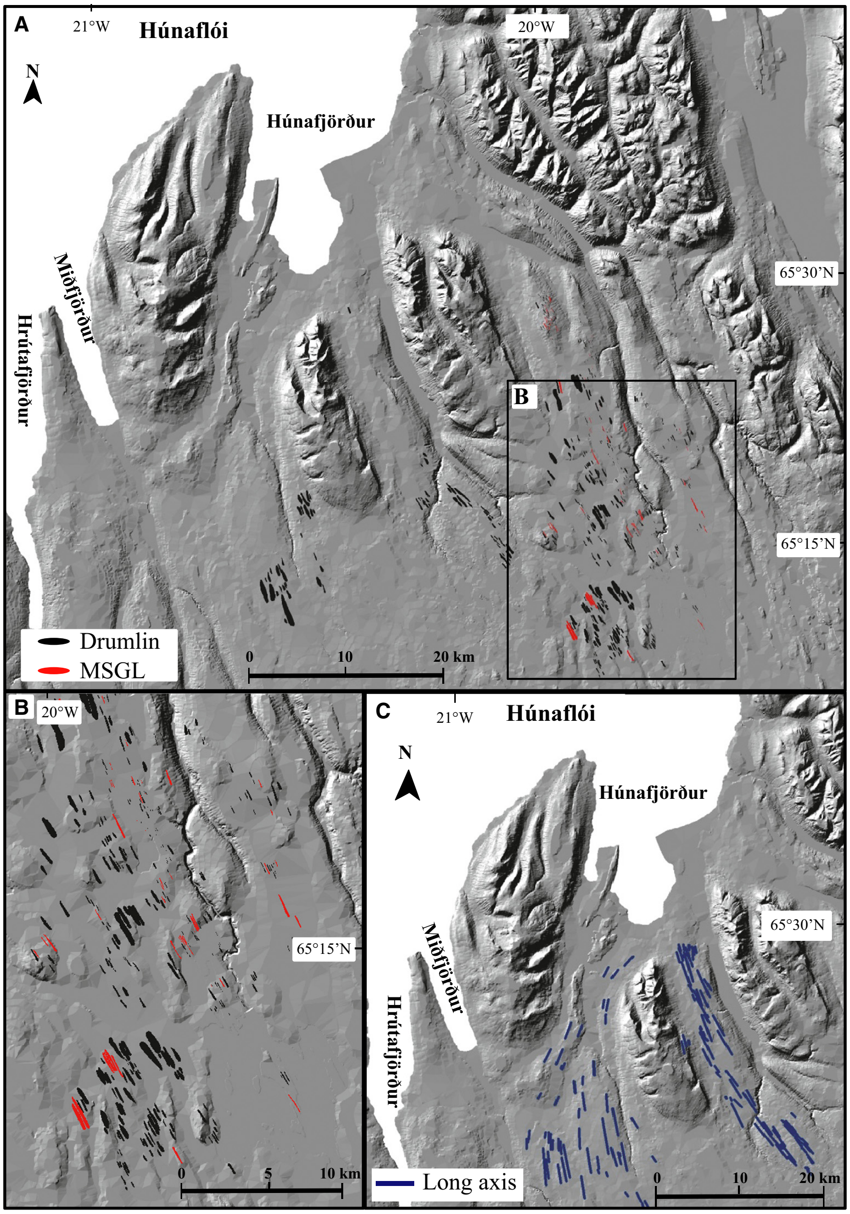

Fig. 4. A. Location of drumlins (black) and MSGL (red) mapped using ArcGIS, Google Earth and the online map viewer of the NLSI. B. Close-up of drumlins (black) and MSGL (red) in Svínadalur from boxed area in Fig. 4A. C. Long axes of additional streamlined landforms are mapped, but these landforms have fragmented outlines and their areas are unclear at the resolution of the available imagery.

middle of the valleys, although there is a region with high packing in the southern part of the study area (Fig. 9).

Of the streamlined landforms identified, 543 (86%) were classified as drumlins and 90 (14%) as MSGL. There is a statistically significant difference in elongation ratios (p<0.001) between drumlins and MSGL, which have average ratios of 5.2:1 and 13.6:1, respectively. There is also a statistically significant difference in orientation (p<0.001) between the landform classes, with drumlins having a parallel conformity of 12° and MSGL of 6°. In general, the MSGL are located further from the coast than the drumlins, but there is no statistically significant difference.

Striation and groove orientations are similar to drumlin and MSGL orientations and generally suggest ice-flow directions parallel to the valleys where they are present (Fig. 10). Grooves are generally present in regions separate from the streamlined landforms at the margins of valleys proximal to the modern coastline, while striated bedrock is present in some of the flat areas in between streamlined landforms (Fig. 10). The grooves vary in length from approximately 2 up to 19 m, with an average length of approximately 5 m.

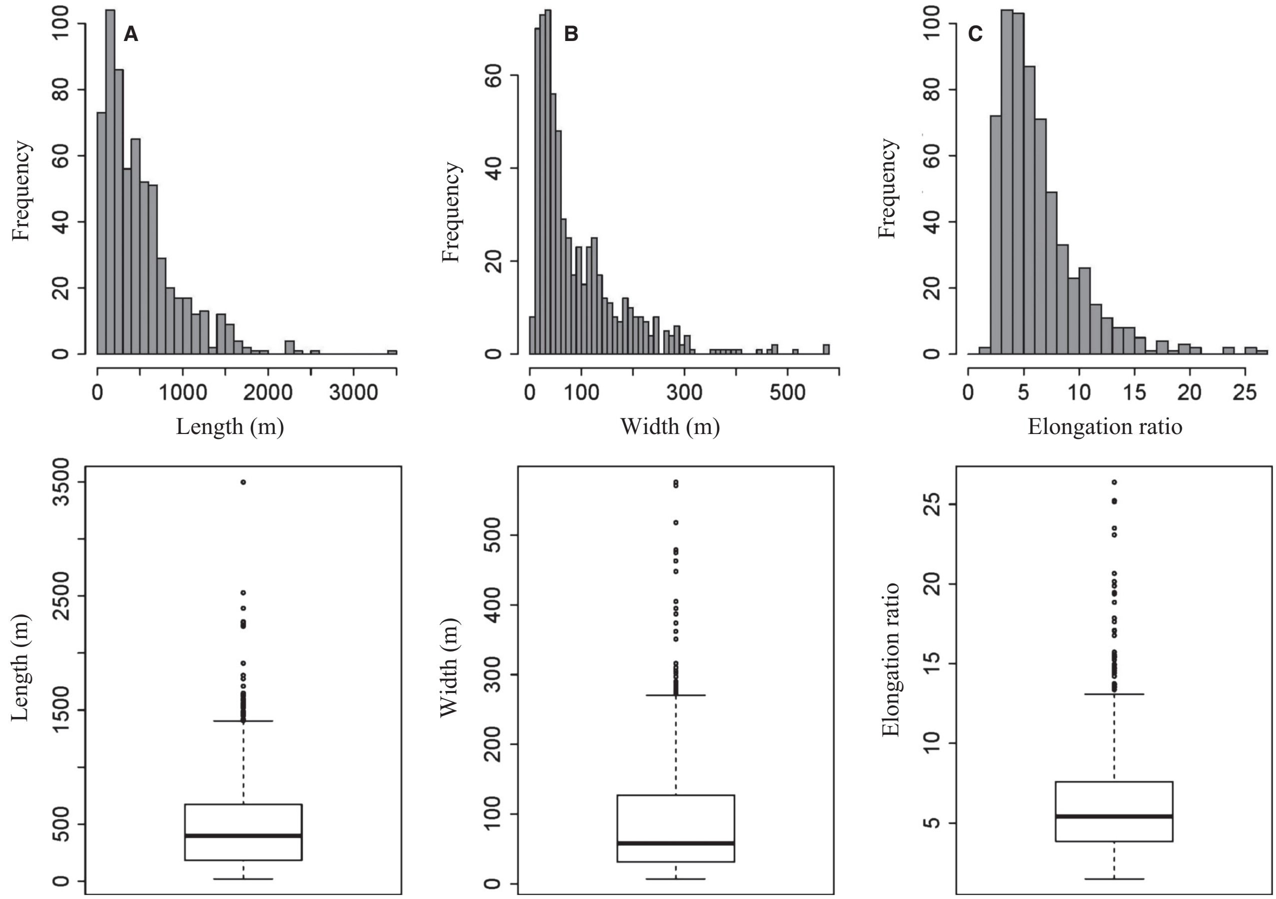

Fig. 5. Histograms and boxplots of streamlined landforms. A. Long-axis length. B. Width. C. Elongation ratio.

Table 1. Mean values of length, width, area, elongation ratio, distance to the coastline and orientation of streamlined landforms, separated by valley and for the combined data set. MSGL refers to the number of MSGL in each valley and total for the entire study area.

	Viðidalur	Vatnsdalur	Svínadalur	All landforms
n	31	85	517	633
Length (m)	1058	742	434	507
Width (m)	248	148	73	91
Area (m^2)	327 381	129 443	55 256	78 544
Elongation	4.3	5.2	6.7	6.4
Distance to coastline (km)	23	43	38	38
Orientation (°)	153	137	154	152
Parallel conformity (°)	12	16	9	12
MSGL	0	3	87	90

They have an average elongation ratio of approximately 12:1.

There are some differences within the subsampled population of streamlined landform characteristics examined amongst the three valleys. Landform elongation ratios are significantly higher in Svínadalur (6.7:1) compared to those identified in Viðidalur (4.3:1; $p<0.01$) and in Vatnsdalur (5.2:1; $p<0.01$), with 97% of the MSGL present in Svínadalur. There are no MSGL present in Viðidalur and only three in Vatnsdalur. The highest density of landforms and the lowest parallel conformity (approximately 9°) are observed in Svínadalur, and Vatnsdalur has the highest parallel conformity of approximately 16°.

Discussion

Interpretation of streamlined landforms in northern Iceland

The properties of streamlined landforms in the valleys of Viðidalur, Vatnsdalur and Svínadalur support the presence of palaeo-ice streams in parts of northern Iceland as proposed by Bourgeois *et al.* (2000) and Stokes & Clark (2001). The characteristics of the landforms identified are in agreement with the characteristics of the landforms mapped by previous studies in parts of the study area (Kaldal & Víkingsson 1990; Bourgeois *et al.* 2000), although additional streamlined landforms were identified beyond the area mapped by Kal-

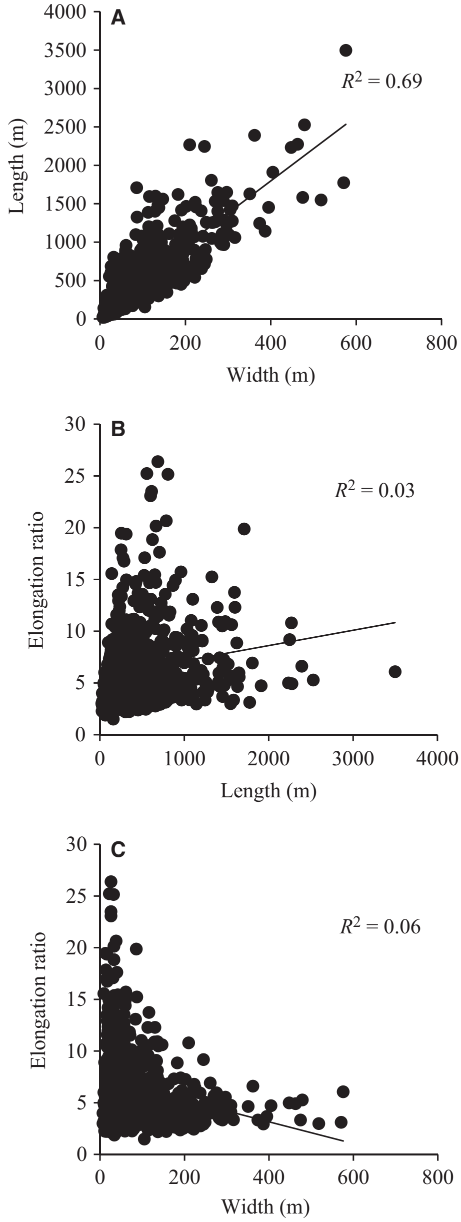

Fig. 6. Linear regressions between landform length and width (A), elongation ratio and length (B) and elongation ratio and width (C).

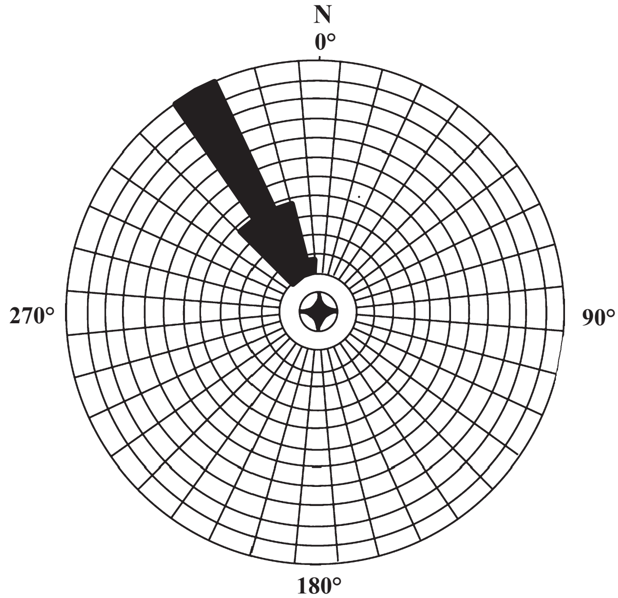

Fig. 7. Rose plot showing orientations of drumlins and MSGL.

dal & Víkingsson (1990). The resolution of the DEM and satellite data used in this study was not high enough to identify small flutes as in previous studies. However, the use of Google Earth and ArcGIS facilitated the identification of MSGL, which were not quantified in previous studies. It is likely that the most significant ice stream with the fastest flow and largest area was present in Svínadalur, as that valley contains the highest abundance of streamlined landforms, highest elongation ratios, highest density and the lowest standard deviation of orientation of streamlined landforms of the three valleys examined. In addition, 97% of the MSGL in the study area are present in Svínadalur. The presence of MSGL suggests the presence of a palaeo-ice stream, as the landforms are interpreted to have formed as a result of fast-flowing ice in many regions of the world (e.g. Clark 1993; Bourgeois *et al.* 2000; Stokes & Clark 2001, 2002; Clark *et al.* 2003; Ottesen *et al.* 2008; Stokes *et al.* 2013; Spagnolo *et al.* 2014). MSGL have also been observed in the active Rutford Ice Stream in Antarctica, providing a further connection between MSGL and ice-stream activity (King *et al.* 2009).

Ice streams in these three valleys may also have been influenced by the topography of the region, as streamlined landforms are not present on the mountainous upland regions in between the three valleys. Orientations of striations and streamlined landforms suggest that the ice was channelled into Viðidalur, Vatnsdalur and Svínadalur, avoiding the higher elevation between the valleys (Fig. 10). It is also likely that these ice streams coalesced in Húnaflói. Streamlined landforms commonly have cross-cutting patterns, which are indicative of variations in ice flow, such as surging or retreat, or may be the result of a different glaciation (Clark 1993; Ottesen *et al.* 2008). However, no cross-cutting landforms or striations were identified in the study area, suggesting that the ice flow in this region during the LGM was uniform and that any evidence from previous glaciations was removed by the ice sheet during the LGM. The lack of cross-cutting landforms and striations is consistent with the landforms identified and mapped by Kaldal & Víkingsson (1990), which also had a NW–SE orientation.

The standard deviation of orientation is the lowest in Svínadalur and suggests that the palaeo-ice stream

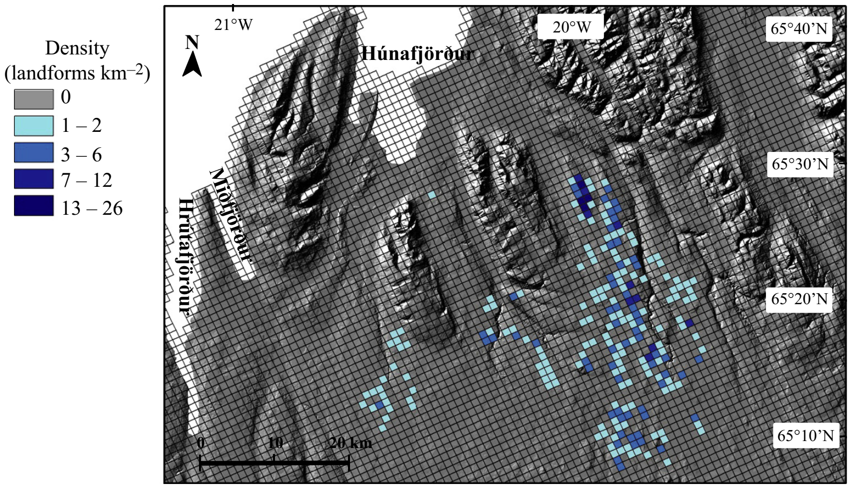

Fig. 8. Map showing density of drumlins and MSGL.

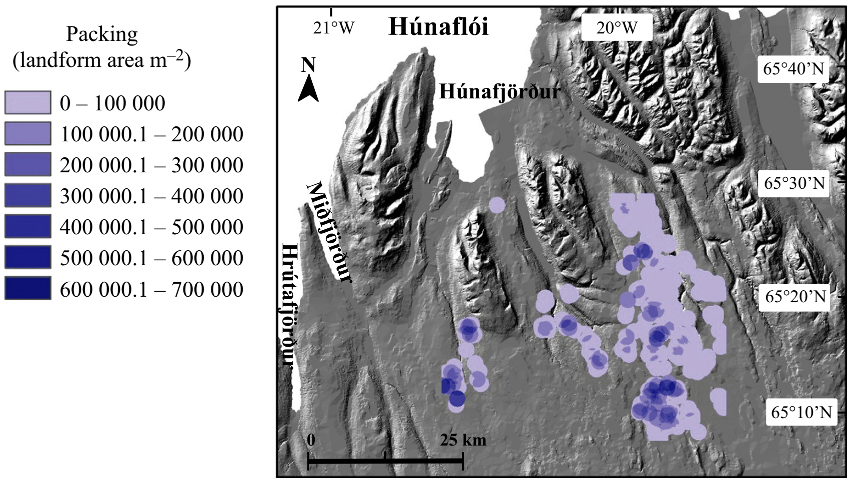

Fig. 9. Map showing packing of drumlins and MSGL.

in this valley followed one primary flow path. The larger spread in orientation in Vatnsdalur could be interpreted as changes in ice-flow direction over time and possibly represents different flow events or it might simply represent convergent ice-flow patterns (Clark 1997; Stokes & Clark 2001, 2002; Ottesen *et al.* 2008). Combining the flow paths interpreted from striations, grooves and streamlined landforms, it is likely that the ice-flow path in Viðidalur shifted direction close to the coastline. The convergence of flow patterns, especially evident in Viðidalur (Fig. 4C), suggests the presence of a palaeo-ice stream (Stokes & Clark 2001). According to Stokes & Clark (2002), high parallel conformity is indicative of fast ice flow, as seen in a Canadian drumlin field, which had a standard deviation of only 3.8°. Landforms formed by slower ice take longer to form and reflect changes in the flow path during formation, showing a lower parallel conformity than landforms formed by faster ice (Stokes & Clark 2002). The parallel conformity of the landforms in the three valleys of this study is relatively high, with a mean of 12° over the entire study area. This value contrasts significantly with the modern Múlajökull drumlins in central Iceland, which have a fan distribution, in an arc of 180°, with very low parallel conformity (Johnson *et al.* 2010; Jónsson *et al.* 2014). The Múlajökull drumlins formed at the outlet of a surge-type glacier and proximal to the ice margin (Johnson *et al.* 2010; Jónsson *et al.* 2014), which partly explains the difference in parallel conformity of landforms in central vs. northern Iceland.

Drumlin density is commonly used to interpret subglacial pressure, with high-density regions being areas of low effective pressure that are favourable for

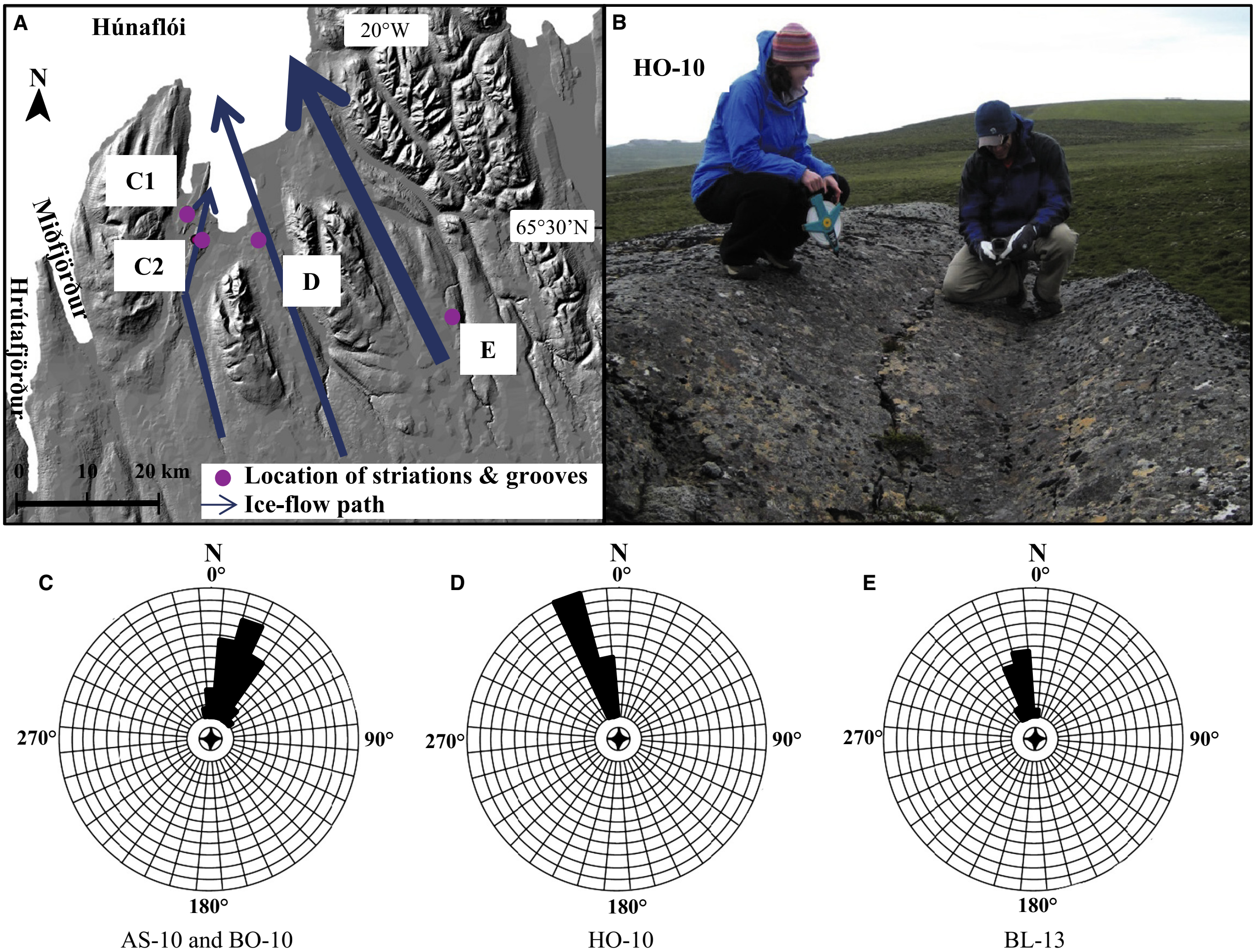

Fig. 10. A. Reconstructed ice-flow paths. Dots represent locations of striation and groove sites. Arrows represent path of palaeo-ice stream, with largest ice stream located on Svínadalur. B. Photograph of groove at HO-10 site. C. Rose plot for striations and grooves in Viðidalur (AS-10 and BO-10). D. Rose plot for striations and grooves in Vatnsdalur (HO-10). E. Rose plot for striations and grooves in Svínadalur (BL-13).

drumlin formation (e.g. Vernon 1966; Smalley & Warburton 1994). The beds of ice streams also experience very low effective pressure, which is nearly zero because the water pressure is close to the ice overburden pressure (e.g. Kamb 1991; Stearns 2002). Therefore, if drumlins are favourably formed in areas of low effective pressure, it can be inferred that these areas of high drumlin density are also areas of fast palaeo-ice flow. The high density of streamlined landforms in the centre of the valleys further supports the interpretation that fast ice flow occurred in each valley, with the fastest ice flowing down the central axis of each valley.

Packing also provides information about palaeo-ice flow velocity. Clark & Stokes (2001) found that packing increased in the down-ice direction of the M'Clintock Channel Ice Stream, hypothesizing that this tight packing of drumlins was a geomorphic product of ice stream shut-down. Streamlined landforms in Viðidalur, Vatnsdalur and Svínadalur do not display the trend of increased packing moving down-ice. The highly packed streamlined landforms in the southeast region of the study area are more proximal to the ice divide than the other landforms.

Comparison with other drumlin fields

Clark *et al.* (2009) provided a comprehensive analysis of the size and shape of drumlins from many parts of the world, including Ireland, Canada, the USA, Finland, Denmark, Sweden and Iceland. The streamlined landforms in Viðidalur, Vatnsdalur and Svínadalur have a lower mode for length and width but are more elongate than those in the data set provided by Clark *et al.* (2009). A maximum elongation limit is observed (Fig. 11A), similar to that of Clark *et al.* (2009), dependent on the landform length. According to Clark *et al.* (2009), for a given length, the elongation ratio will not exceed $E_{max} = L^{1/3}$. The streamlined landforms from this study show a similar trend. However, Dowling *et al.* (2015) suggested performing a log

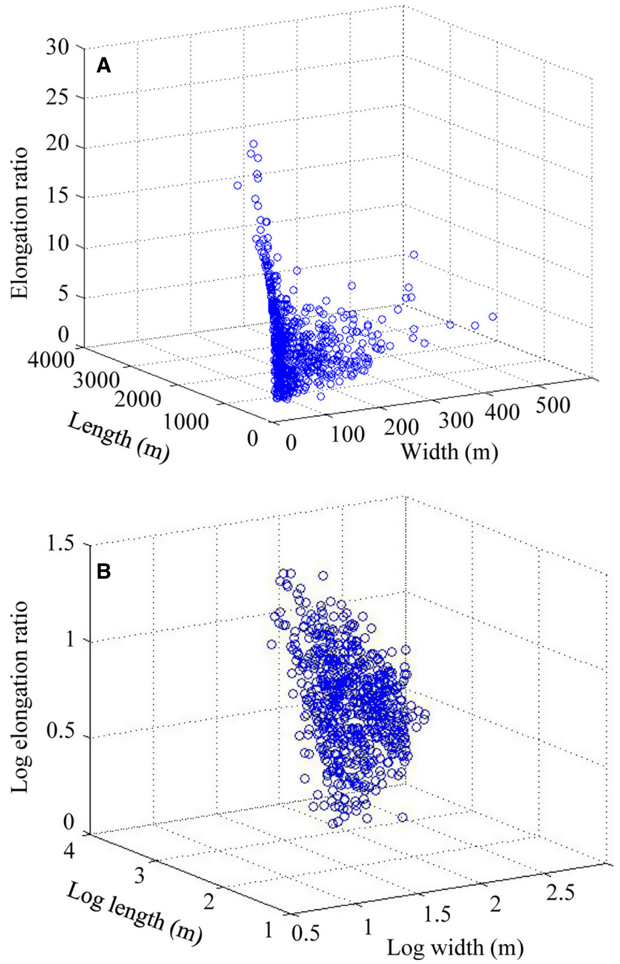

Fig. 11. A. Width, length and elongation ratio follows pattern of Clark *et al.* (2009). B. Log transformation of width, length and elongation ratio shows no pattern, similar to Dowling *et al.* (2015).

transformation of the data, and this transformation results in a clustering of the data without a well-defined boundary layer (Fig. 11B).

The elongation ratios in this study are similar to those in other regions with palaeo-ice streams (Table 2). Hess & Briner (2009) calculated the elongation ratios of a large sample of landforms in the New York Drumlin Field. The patterns of elongation and orientation were used to suggest that there were zones of fast-moving ice. The elongation ratio of the landforms in the New York Drumlin Field is 4.8:1, while the drumlins in this study have an elongation ratio of 6.4:1. Other studies have determined the drumlins formed by ice streams in the Laurentide Ice Sheet to have elongation ratios ranging from 2:1 up to 12:1 (e.g. Stokes & Clark 2001). Dyke & Morris (1988) examined drumlins in the Canadian Arctic and calculated an elongation ratio of 5:1, similar to the value determined in this study. Colgan & Mickelson (1997) showed that the elongation ratio of drumlins formed by the Green Bay Lobe of the southern Laurentide Ice Sheet increase in an up-ice direction, but there is not a monotonic increase of elongation ratios in northern Iceland. Drumlins from the Skeena Valley, formed by an ice stream in the Cordilleran Ice Sheet, have an average elongation ratio of 8.3:1 (Hicock & Fuller 1995). Another set of drumlins, in central and south Finland, formed by an ice stream in the Scandinavian Ice Sheet, has an average elongation ratio of 5.6:1 (Dongelmans 1996), also similar to the results of this study. Bourgeois *et al.* (2000) discussed glacial landforms formed by the entire Iceland Ice Sheet, with an average elongation ratio of 7.5:1. This value is slightly higher than the value of 6.4:1 obtained for Viðidalur, Vatnsdalur and Svínadalur separately from the rest of the country, which may be related to the size of the ice streams in different locations around Iceland during the LGM.

Table 2. Comparison of elongation ratios with selected other studies that used streamlined landforms to identify palaeo-ice streams.

Study site	Elongation ratio	Reference
New York, USA	4.81:1	Hess & Briner (2009)
Canadian Arctic	5:1	Dyke & Morris (1988)
Skeena Valley, Canada	8.3:1	Hicock & Fuller (1995)
Finland	5.6:1	Dongelmans (1996)
Iceland (whole country)	7.5:1	Bourgeois *et al.* (2000)
Viðidalur, Iceland	4.3:1	This study
Vatnsdalur, Iceland	5.2:1	This study
Svínadalur, Iceland	6.7:1	This study

Palaeo-ice stream significance in Iceland Ice Sheet reconstructions

Results of previous studies of marine sediment cores and seismic studies suggest that the outer margins of the Iceland Ice Sheet were offshore around northwest Iceland during the LGM (Andrews *et al.* 2000, 2002; Geirsdóttir *et al.* 2002; Andrews & Helgadóttir 2003; Andrews 2005; Principato *et al.* 2005; Spagnolo & Clark 2009). It is also commonly assumed that two independent ice sheets were present on Iceland during the LGM, one covering the mainland and one covering Vestfirðir, the northwest peninsula of Iceland (Hoppe 1982; Norðdahl 1991). GIS analyses by Principato & Johnson (2009) demonstrated different patterns of glacial erosion that support the presence of independent ice sheets. Ice streams and ice divides have been proposed for the Iceland Ice Sheet during the LGM (Bourgeois *et al.* 1998, 2000; Hubbard *et al.* 2006). This study provides terrestrial geomorphic evidence for at least three ice streams feeding into Húnaflói. It is interpreted that these ice streams merged into one fast-flowing tongue of ice in Húnaflói, providing a mechanism for ice to advance to the shelf-slope break as interpreted by Andrews *et al.* (2000), Andrews & Helgadóttir (2003) and Principato *et al.* (2005). Spagnolo & Clark (2009) identified MSGL in troughs on the Iceland shelf, providing evidence for palaeo-ice streams extending from land onto the shelf. The presence of MSGL on the shelf suggests that landforms in Viðidalur, Vatnsdalur and Svínadalur represent the onset region for the ice stream and illustrates a long flow path to the MSGL identified on the shelf (Spagnolo & Clark 2009). The large volume of ice advancing out of Húnaflói does not require an equally large volume of ice from Vestfirðir, and it supports the presence of two independent ice sheets on Iceland during the LGM with a shear margin separating the two ice sheets (Hoppe 1982; Norðdahl 1991; Principato *et al.* 2006; Principato & Johnson 2009). The locations of the drumlins and MSGL suggest that they are the product of the LGM glaciation, rather than another glaciation event. The Iceland Ice Sheet reached its furthest extent during the LGM and subsequent re-advances probably did not reach the study area (Geirsdóttir *et al.* 2009; Ingólfsson *et al.* 2010). The sensitive location of Iceland in the north Atlantic region makes these ice-sheet reconstructions important to consider when analysing global changes in ocean circulation and ice volume.

Conclusions

The properties of drumlins and MSGL in the valleys of Viðidalur, Vatnsdalur and Svínadalur provide geomorphic evidence in support of proposed palaeo-ice streams in part of northern Iceland. Density and packing of streamlined landforms are generally higher in the centre of each valley than the edges and suggest that the palaeo-ice streams were influenced by topography. Orientation of long axes of streamlined landforms matches orientation of grooves and striations measured in the field, with a preferred southeast–northwest direction. The orientation measurements suggest that ice was channelled into Viðidalur, Vatnsdalur and Svínadalur, avoiding the higher elevation between the valleys. The largest ice stream with the fastest flow was located in Svínadalur, based on the highest elongation ratios, parallel conformity, density and packing, as compared to the other two valleys studied. It is likely that these ice streams coalesced in Húnaflói. Streamlined landforms in Viðidalur, Vatnsdalur and Svínadalur have a lower mode for length and width and higher elongation ratio compared to global data sets of drumlins comprehensively analysed by Clark *et al.* (2009). Elongation ratios of streamlined landforms in northern Iceland are similar to streamlined landforms in other regions where zones of fast-moving ice or palaeo-ice streams have been interpreted. The palaeo-ice streams in the valleys of Viðidalur, Vatnsdalur and Svínadalur are important for understanding the glacial history of Iceland because they provide a mechanism for ice centres from the mainland of Iceland to reach the shelf-slope break offshore during the Last Glacial Maximum.

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