Scottish Geographical Journal

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/rsgj20

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To cite this article: Jodie A. S. Geldard, Tom Bradwell & Douglas I. Benn (28 Nov 2024): Megaflutes in the Menteith Hills, central Scotland, Scottish Geographical Journal, DOI: 10.1080/14702541.2024.2432317

To link to this article: https://doi.org/10.1080/14702541.2024.2432317

Published online: 28 Nov 2024.

SCOTTISH GEOGRAPHICAL JOURNAL
https://doi.org/10.1080/14702541.2024.2432317

Megaflutes in the Menteith Hills, central Scotland

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ABSTRACT

'Flutings' or 'flutes' are elongated, flow-parallel subglacial bedforms associated with relatively fast flowing glaciers. Analysis of recently acquired high-resolution (50 cm) LiDAR data has identified the presence of large, very low-relief flutings on the Menteith Hills in Central Scotland. These subtle landforms, up to 1 km in length and 10s of metres wide, are interpreted as 'megaflutes', falling in between the accepted definition of flutes and the much longer mega-scale glacial lineations. This new geomorphological mapping suggests that the palaeo Teith Glacier grew thick enough to breach the local watershed, forcing a branch of glacier ice to flow into the Forth Valley. The megaflutes are located near the accepted Loch Lomond Stadial (Younger Dryas Stadial) limits in the area, yet are currently undated. Flutes are difficult to identify in the field, on aerial imagery or digital elevation models with ≤ 5 m resolution due to their low-relief and often widespread vegetation cover. LiDAR is therefore a valuable tool for revealing these landforms where they would otherwise go unnoticed. This new research offers a fresh perspective for the glacier landform record in a key part of Central Scotland and highlights the importance of high-resolution LiDAR data for mapping glacial geomorphology.

ARTICLE HISTORY
Received 26 April 2024
Accepted 8 November 2024

KEYWORDS
Megaflutes; LiDAR; geomorphological mapping; Younger Dryas; resolution

Introduction

In glacial geomorphology *flutes* or *flutings* are elongated streamlined ridges composed of glacigenic sediment. They form at the glacier bed, often in closely spaced 'swarms' or groups, and are orientated in the direction of former ice flow. Measurements from large datasets (n > 1000) show that glacial flutes in recently deglaciated terrain are typically between 0.1–5 m wide, 0.5–3 m high and up to 100 m long (Benn & Evans, 2010; Ely et al., 2016; Rose, 1987). Flutes belong to a family of larger subglacial bedforms that includes drumlins, mega-scale glacial lineations (MSGLs) and other streamlined depositional forms. Flute formation is still debated. However, most workers agree that they form beneath glaciers by a mechanism of sediment deformation or accretion in small

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This article has been corrected with minor changes. These changes do not impact the academic content of the article.

lee-side cavities – hence their relatively small size and common association with bedrock obstructions (i.e. lodged boulders or bedrock prominences). Large-scale flutings, with individual forms >100 m in length and >5 m in width, are referred to as *megaflutes* (Hambrey & Glasser, 2003). Long megaflutes with high elongation ratios (>10–20:1) may grade into MSGLs. Megaflutes on soft (sediment) beds have been reported from the palaeo-landform record onshore and offshore. Notable examples have been identified in Minnesota, and the Dakotas (Colgan et al., 2003); Ontario (Eyles et al., 2016); offshore Newfoundland, Placentia Bay (Shaw & Potter, 2016), offshore Scotland, Sound of Jura (Dove et al., 2016); and off West Antarctica, Amundsen Sea Embayment (Graham et al., 2016). Examples of sedimentary or soft-bed flutes, or indeed megaflutes, are rare onshore in Scotland and from the bed of the British–Irish Ice Sheet as a whole according to the literature (e.g. Clark et al., 2012; Hughes et al., 2014). However, the small size of most flutes and their low-relief mean they are easily missed on NEXTMap data (5 m pixel size), which is most widely used for geomorphological mapping in the UK due to its extensive spatial coverage. The rarity of megaflutes in the British Isles could be an apparent one, primarily a function of data resolution, rather than a real absence. The wider use of higher resolution elevation data (*e.g.* publicly available LiDAR datasets) is therefore important for addressing this geomorphological gap in glacier bedform mapping.

In this paper we present new evidence of megaflutes and ice-flow patterns in central Scotland. We use high-resolution digital elevation data (LiDAR 50 cm grid) to map and measure their orientation, shape and size, and field surveys to characterise their internal composition. We link megaflute formation in the Menteith Hills with relatively fast or focused flow of ice over a topographic col between adjacent large valleys. We assess why these features, and others, may have been overlooked in the landform record; speculate on their age; and place their formation in a wider glaciological context.

Study area

The Menteith Hills (reaching 427 m a.s.l.) lie east of the town of Aberfoyle and 22 km WNW of Stirling (Figure 1). The hills separate the Teith Valley to the north from the Forth Valley to the south. The prominent SW-NE trending bedrock ridges of the Menteith Hills form part of the Highland Boundary Complex, which runs SW to NE across Scotland bordering the central lowlands to the south and the Highlands to the north. The steeply dipping complex of the Highland Boundary Fault separates the metamorphic Dalradian Group of the Grampian Mountains (Grampian Highlands terrane) from the SW-NE trending parallel ridges of Devonian sedimentary strata (Midland Valley terrane) which form the Menteith Hills and underlie the Upper Forth Valley (Evans, 2021). The Menteith Hills are dominated by Devonian sequences of the Arbuthnott-Garvock Group, with sandstones and conglomerates containing volcanic clasts (British Geological Survey, 2004; Phillips, 2007).

The last glaciers to occupy the Upper Forth and Teith Valleys existed during the Loch Lomond Stadial (LLS, 12.9–11.7 ka BP). Abrupt cooling at the onset of the LLS caused glaciers to regrow, and a major transfluent icefield formed over the western Highlands, known as the 'West Highland Icefield', extending from Torridon in the north to Loch Lomond in the south (Benn, 2021; Bickerdike et al., 2018; Golledge et al., 2008). Ice accumulation centres, such as Rannoch Moor, fed outlet glaciers streaming into sea-

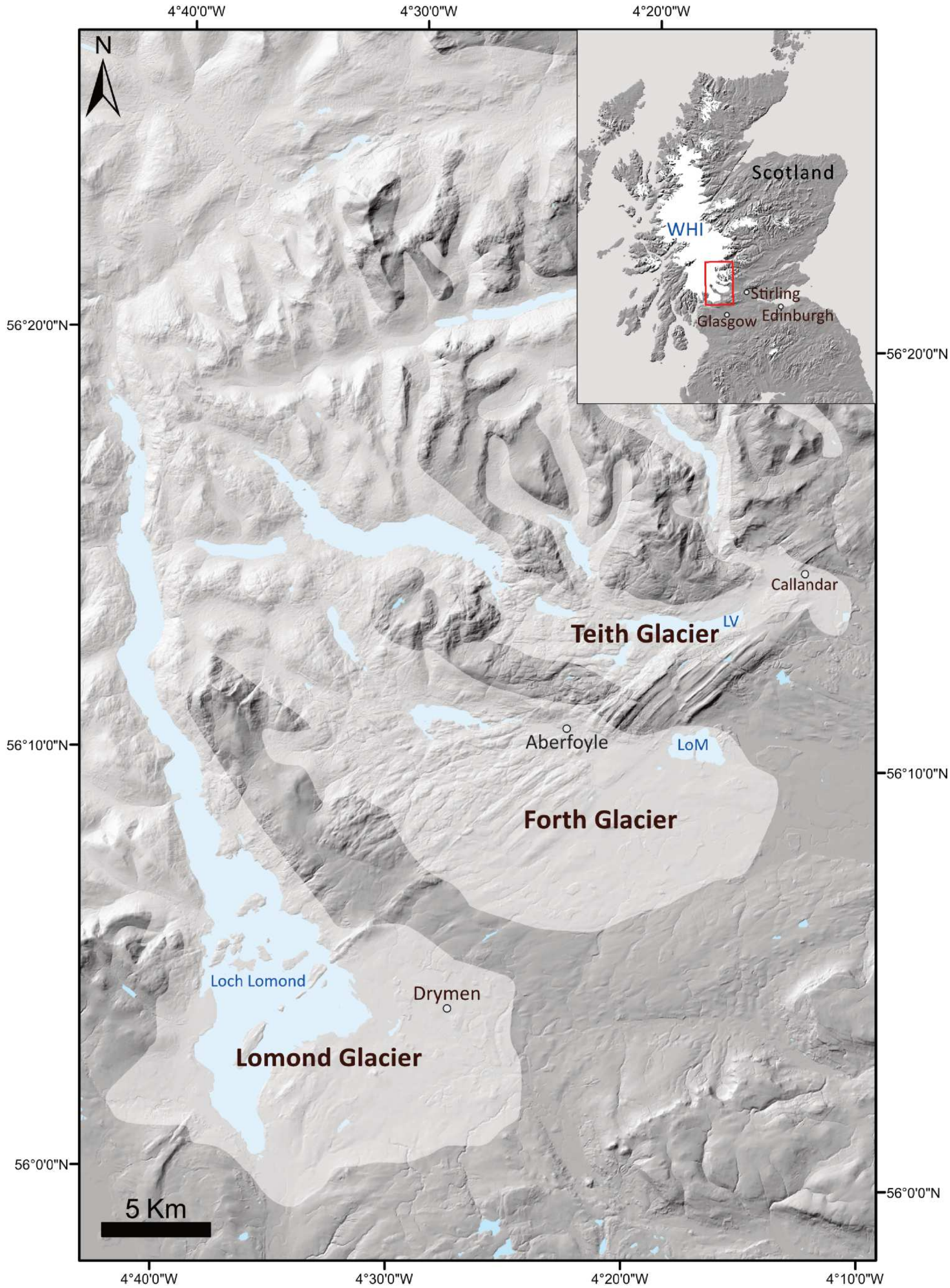

Figure 1. Location of the Menteith Hills, ca. 22 km WNW of Stirling. LoM: Lake of Menteith; LV: Loch Venachar; WHI: West Highland Icefield. The proposed glacier extent during the LLS is shown in white (Bickerdike et al., 2018); present day UK lake extent is in blue (Taylor, 2021). Base map: NEXTMap (Intermap Technologies, 2007); Inset base map: DEM (Pope, 2017).

lochs to the west, and terminating on land and in proglacial lakes to the north, east and south of the West Highland Icefield (Benn, 2021; Peacock & Rose, 2017). Evidence for the dynamics of the Forth and Teith glaciers are preserved in the landform record primarily as terminal moraines, eskers, and meltwater channels (Bickerdike et al., 2016, 2018; Hughes, 2009). Large terminal moraine complexes at the Lake of Menteith and around Callander are proposed to denote the maximum Younger Dryas extents of the Forth and Teith glaciers respectively (Evans, 2021; Thompson, 1972), indicating that these glaciers were anomalously large and extensive compared to the optimal modelled limits (Golledge et al., 2008).

Methods

Features were mapped in ArcGIS 10.8.2 using high-resolution hillshaded digital elevation models (DEMs) sunlit from multiple angles and using different vertical exaggerations (Z-factors), as is standard for mapping glacial landforms of this scale (Ely et al., 2017; Smith & Clark, 2005; Spagnolo et al., 2014). Two remote sensing datasets were used: (i) an airborne LiDAR digital surface model (DSM) and post-processed digital terrain model (DTM) with 50 cm pixel resolution and a vertical accuracy of ± 15 cm root mean square deviation covering part of the Menteith Hills obtained from the DEFRA Data Services Platform (Environment Agency, 2016); and (ii) a LiDAR DEM collected with a DJI Matrice 300 RTK drone and a DJI Zenmuse LiDAR sensor with a 50 cm pixel resolution and expected vertical and horizontal accuracy of < 5 cm which was processed for the purpose of this study. These datasets were merged (Figure 2), and elevation corrections applied, in ArcMap 10.8.2 using the Data Management and Spatial Analyst toolboxes. The joining of the new and existing LiDAR datasets is almost seamless, with the *ca.* 0.1 m vertical offset between the two datasets deemed to be acceptable. The lengths (a-axis) of the elongated features were measured along their crestlines in ArcGIS using the measure function. Widths (b-axis) were determined to be the distance between the lowest points (or furrows) on either side of the elongated crest (Figure 3). Width measurements were taken at approximately 10%, 50% and 90% along the length of the feature and averaged (Figure 3), following the methodology used by Ely et al. (2017). Features were measured to the nearest 0.1 m; however, it is accepted that defining the exact margins of these subtle features can be challenging and therefore not always possible to this level of precision.

Field surveys were conducted in November 2022 and August 2023 to ground-truth the initial mapping. This involved a systematic walkover survey of the hillside, including recording bedrock exposures, glacially-transported boulders, and the sedimentology of a natural stream section eroded into an elongated landform (OS GB grid reference: NN 56297 03062). Bedrock striae were recorded using a GPS and compass to capture their location and orientation. A drone survey was conducted in November 2023 to record additional LiDAR data (*ca.* 1.5 km^2) to the north and east of the existing Environment Agency (2016) dataset. The drone was flown at 10 ms^{-1} at 120 m above the ground surface using the terrain follow option, providing *ca.* 98 points per m^2. The drone is an integrated system where the LiDAR points are geotagged with GNSS data. Processing of the raw LiDAR point cloud to create a DEM was done in DJI Terra.

Results

We map a total of 110 large flutings across the Menteith Hills (see Figure 2B); metrics for these are presented in Table 1. These streamlined landforms have a mean length of 181 m

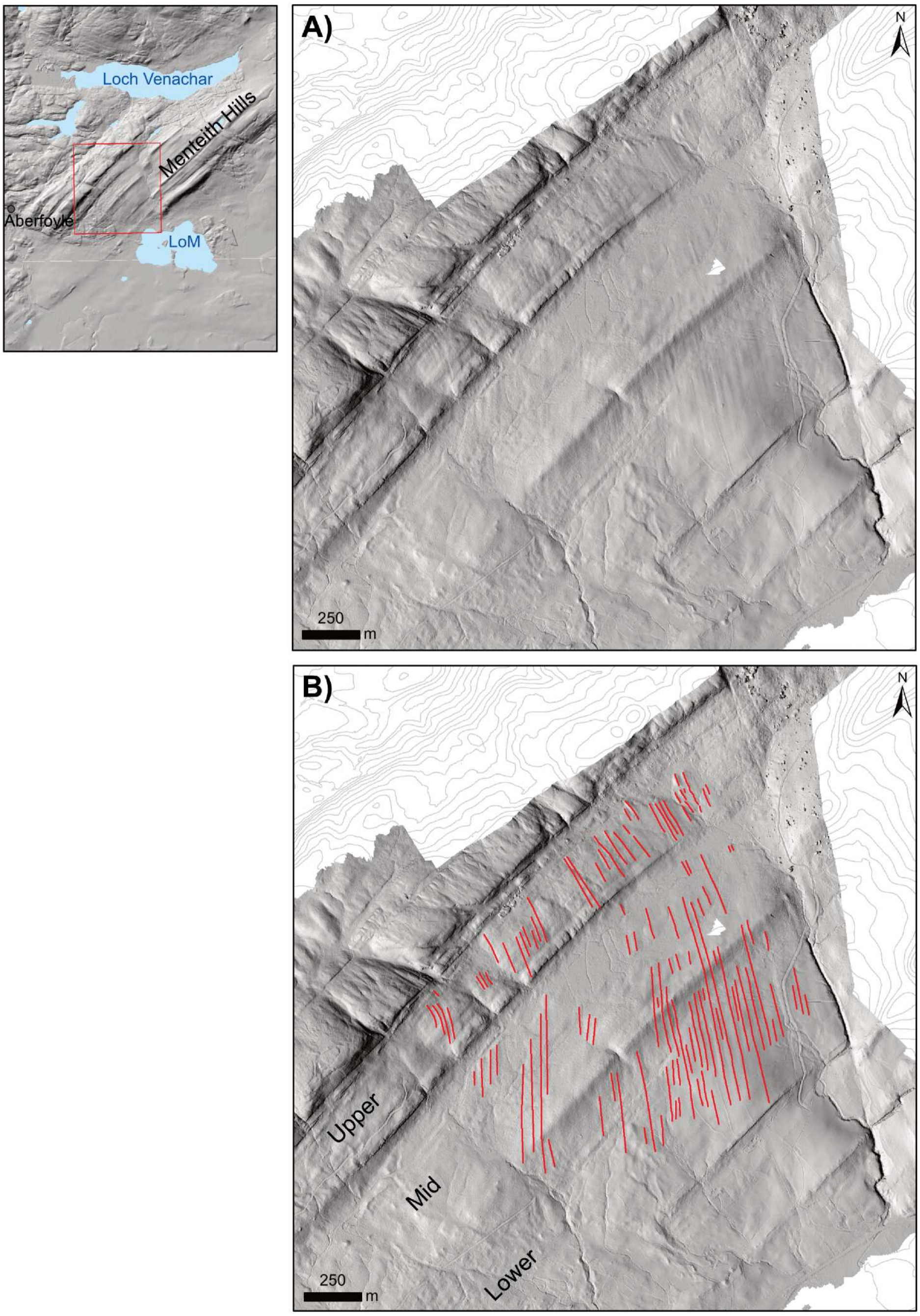

Figure 2. The 50 cm resolution LiDAR data covering the Menteith Hills combining the existing LiDAR data (Environment Agency, 2016) and the newly acquired LiDAR data (this study). LoM: Lake of Menteith. Inset: Location of the Menteith Hills, basemap: NEXTMap (Intermap Technologies, 2007). (A) The merged LiDAR data in the context of the Menteith Hills. The contours are drawn at 10 m intervals. (B) The mapped flutings (red) on the Menteith Hills. The Upper, Mid and Lower slopes (referred to in the text), separated by bedrock ridges of the Highland Boundary Complex, are marked for reference. The LiDAR DEM is hillshaded from a 245° azimuth at 45° altitude with a 4x vertical exaggeration.

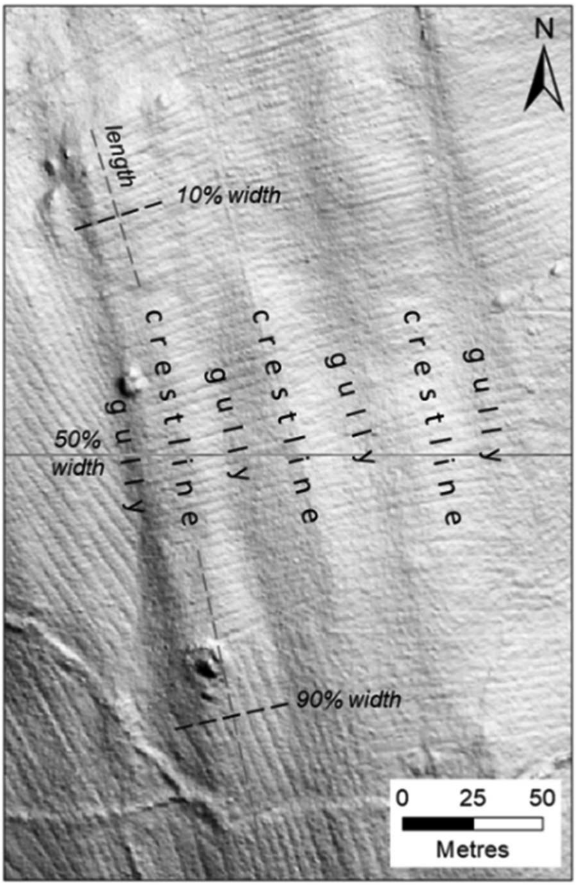

Figure 3. Measuring feature width from gully to gully (or furrow to furrow) at 10%, 50% and 90% along the total length. Basemap: 50 cm LiDAR DTM (Environment Agency, 2016) hillshaded from 45° azimuth with 4x vertical exaggeration.

Table 1. Flute metrics. A-axis = Length; B-axis = Width; Elongation ratio = length divided by width.

	Minimum (metres)	Maximum (metres)	Mean (metres)	Standard Deviation
A-axis	16.2	933.6	181.0	173.6
B-axis	7.2	46.6	23.4	8.1
Elongation ratio (A/B)	1.7: 1	28.9: 1	7.1: 1	4.9

and mean width of 23 m (see Table 1). There is a strong positive correlation between length and width (r = 0.67 for a log-normal relationship: Figure 4). We suggest a log-normal model as the best fit for this distribution due to the data undergoing only one transformation (x, length) and the model having very similar r values to a power-law relationship transformed on both axes (Figure 4). A p-value of 6.98×10^{-16} (log-normal relationship) shows this correlation to be statistically significant at the 99% ($p < 0.01$) confidence level. Table 1 shows that flute length is highly variable (standard deviation of 174 m). This variability in flute length is reflected in the asymmetric box plots

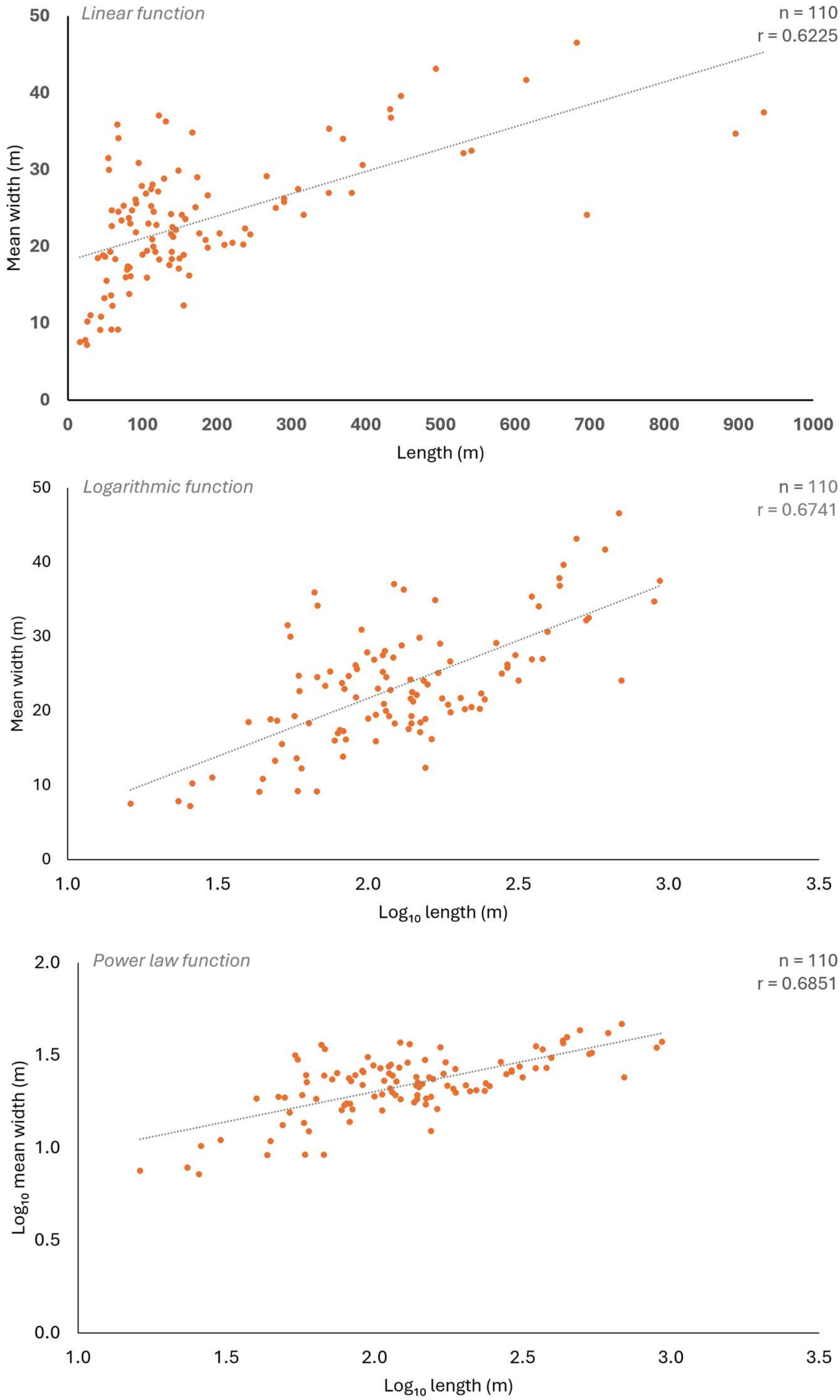

Figure 4. Relationship between flute length and mean flute width, showing a statistically significant positive correlation using 3 different models: (a) Flute length and mean width plotted as a linear relationship ($r = 0.62$, p-value $= 3.87 \times 10^{-13}$); (b) Log-normal relationship of flute length ($\log_{10}$) and mean width ($r = 0.67$, p-value $= 6.98 \times 10^{-16}$); and (c) Power law relationship of flute length ($\log_{10}$) and mean width ($\log_{10}$) ($r = 0.69$).

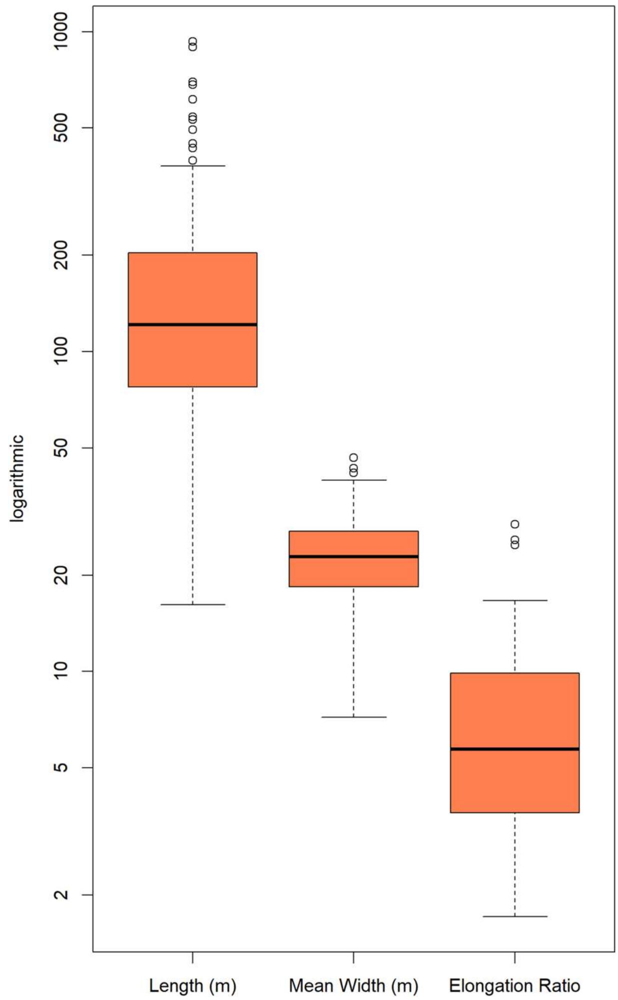

Figure 5. Box plots for flute length, mean width and elongation ratio (*i.e.* length/width).

(Figure 5), with length having a positive skew and several outliers present at the upper range of the data. Flute width is much more consistent (standard deviation = 8 m), showing a more normal distribution and a small interquartile range (Figures 5 and 6). The elongation ratio (flute length divided by width) inherits the positive skew from flute length, and shows a larger interquartile range (Figures 5 and 6). Elongation ratios (Table 1) show that the flutes are elongated features, with a mean length over 7 times that of width. These features have very low vertical relief, commonly between 1 and 2 metres (Figure 7), but up to 4 metres where stream erosion has enhanced vertical relief on one feature on the upper slope.

The flutes cross prominent bedrock ridges of the Highland Boundary Complex, and we therefore split the inter-ridge areas into three segments: the upper, mid, and lower slope (Figure 2B). The flutes are predominantly parallel sided, *i.e.* their widths remain relatively constant along their length and they do not taper. The standard deviation of the widths measured at 10%, 50% and 90% along the flute length averaged at 2.8 m,

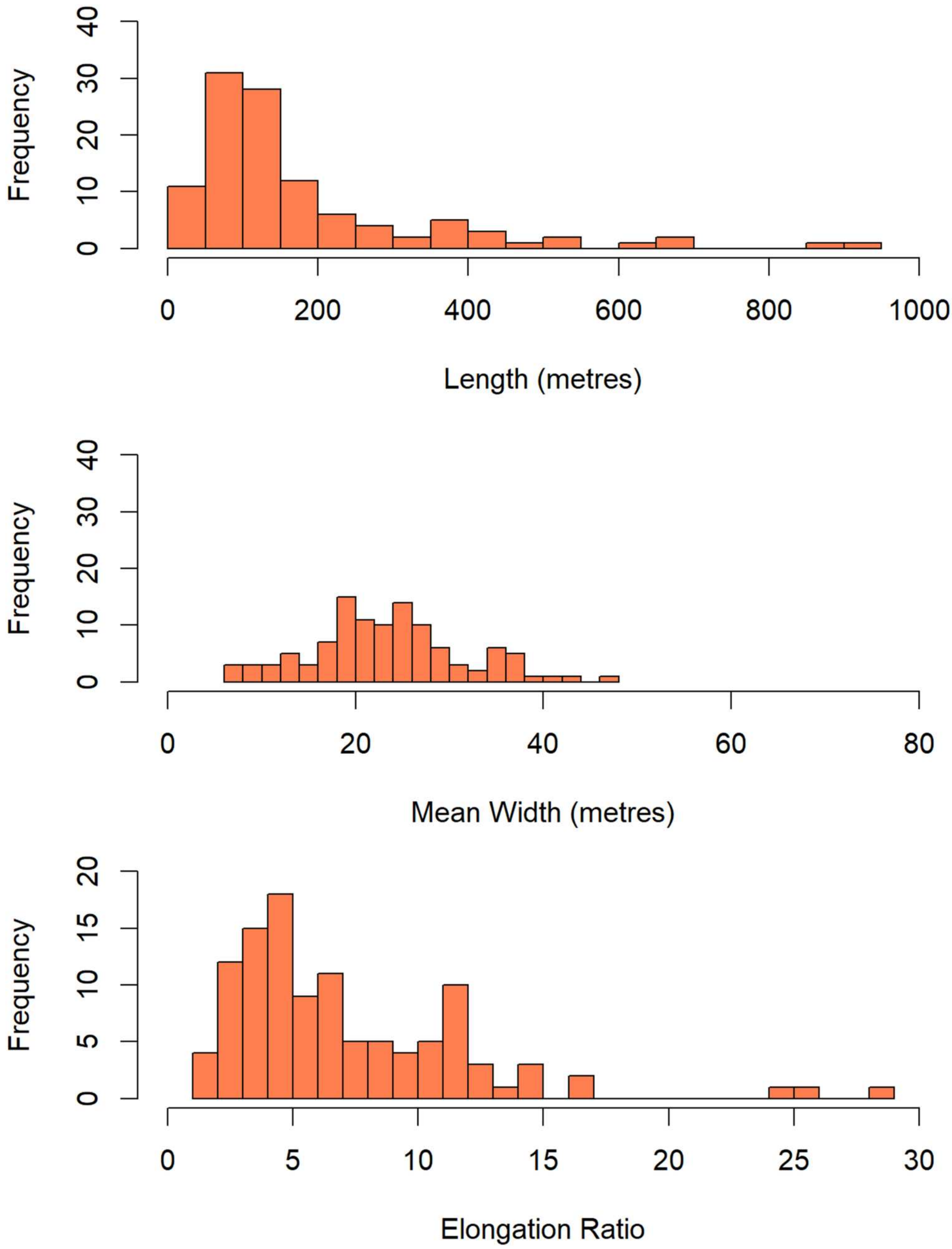

Figure 6. Histograms showing flute length, mean width and elongation ratio.

showing a relatively small amount of variance across the whole flute population. The flutes are mostly straight along their length, although some do curve slightly on the upper slope. Flute crest orientation changes downslope, starting at approximately 154° on the upper slope, 170° on the mid slope, and 168° on the lower slope (Figure 2b). Bedrock striae at a stream crossing on the upper slope are orientated between 140° and 150° (see Figure 8C). Additionally, landform elongation changes downslope, with

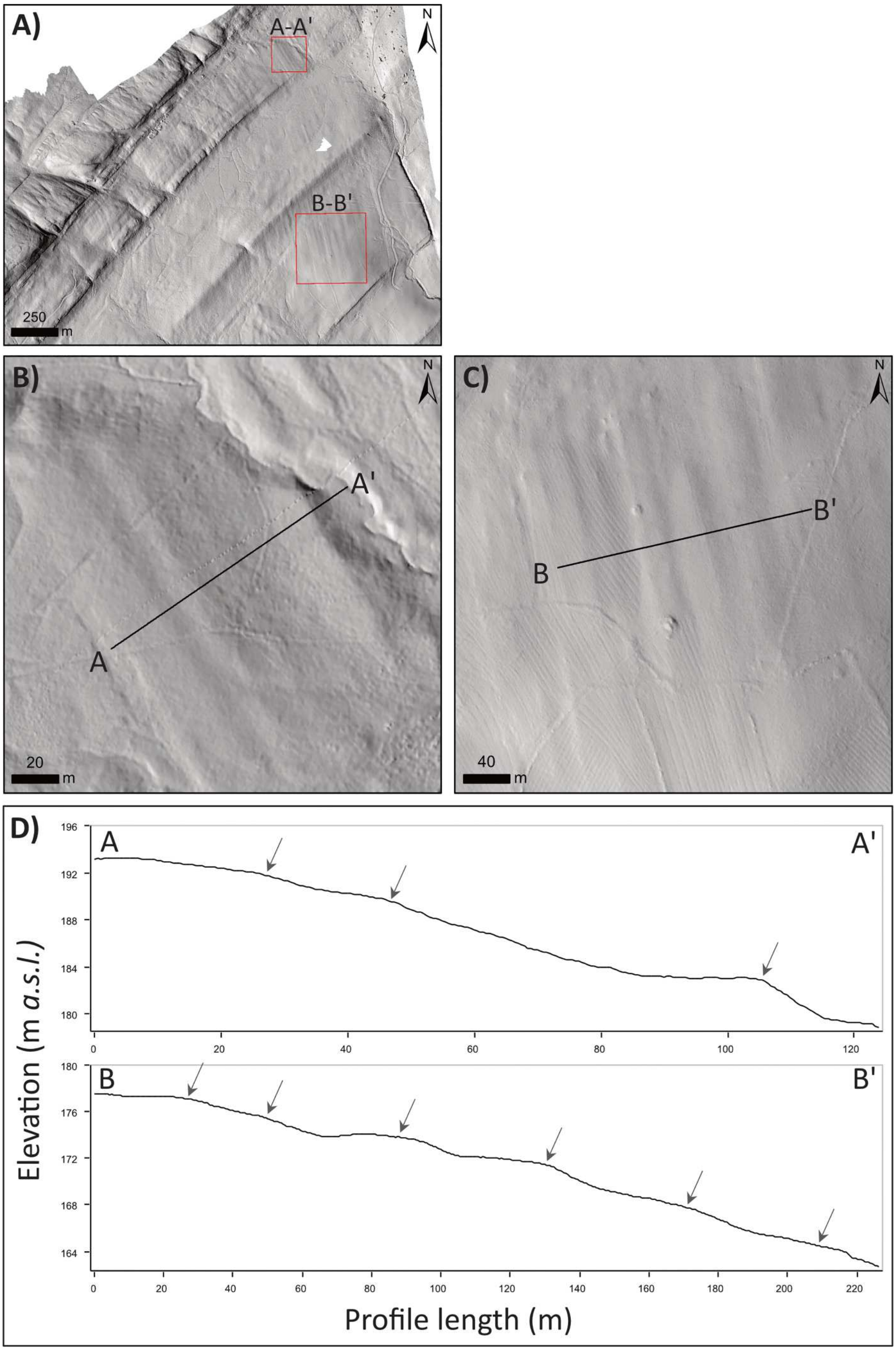

Figure 7. Elevation cross-profiles showing vertical relief of the flutings: (A) Location of the profiles on the flute field; (B) profile A – A′ on the upper slope; (C) profile B – B′ on the lower slope; (D) A – A′ elevation profile showing relief up to *ca*. 3 metres and the B – B′ elevation profile showing relief up to *ca*. 2 metres. Grey arrows indicate the location of flute ridges along the 2 elevation profiles.

Figure 8. (AB) Striated sub-angular to sub-rounded clasts from a stream section eroded into an elongated feature on the upper slope (UK grid reference NN 56297 03062). Clast A: 11 cm x 3.5 cm, clast B: 11.5 cm x 8 cm. (C) Striae eroded into bedrock at a stream crossing orientated at 140° – 150°.

shorter, less-elongate landforms on the upper slope, and longer, more elongate features on the mid and lower slopes. The upper features have elongation ratios (ERs) of up to *ca.* 13:1 (mean *ca.* 6:1), the mid slope landforms have ERs up to *ca.* 29:1 (mean *ca.* 8:1) and the lower slope landforms have ERs of up to *ca.* 17:1 (mean *ca.* 8:1).

The internal composition of these features appears to be a combination of soft-sediment and bedrock. A natural stream section eroded into one of the upper features (OS

GB grid reference NN 56297 03062) shows a matrix-supported diamicton consisting of sub-angular to sub-rounded, striated clasts (see Figure 8A,B). On the lower slopes, bedrock is close to the surface, and even exposed in several places, so we therefore infer that the lower features are bedrock cored. Boulders of non-local geology, *e.g.* Highland schists, are partially buried within the top of the flute ridges on the lower slopes.

Discussion

The elongated streamlined ridges are visible across an area of 2.3 km^2 on the south-facing side of the Menteith Hills, and are identified and mapped for the first time here (see Figure 2B). These features, with lengths up to 934 m and widths up to 65 m, are considerably larger than flutes by the normally accepted definition (*i.e.* ≤ 100 m in length and ≤ 5 m wide; Hambrey & Glasser, 2003), and we therefore categorise them as megaflutes. Their morphology fits with other examples of large glacial flutings, for example from Torridon, Scotland (Bennett, 1995); Tweed Valley, Scotland (Everest et al., 2005); Kuuttilanmäki, Savonlinna, Finland (Putkinen et al., 2017); Hoffellsjökull, Iceland (Evans et al., 2019); Nordenskiöldbreen, Svalbard (Ewertowski et al., 2016); New York State, USA and Ontario, Canada (Briner, 2007; Sookhan et al., 2018); and Lake Viedma, Patagonia, Argentina (Ponce et al., 2019). On the Menteith Hills, the ridges and gullies, or furrows, show high parallel conformity and are orientated in a NNW-SSE direction (mean orientation *ca.* 164°), broadly coinciding with the orientation of bedrock striae at the upper-slope site (Figure 8C). This suggests a palaeo ice-flow direction downslope towards the south-southeast. The megaflutes and bedrock striae indicate basal sliding and subglacial deformation, signifying the presence of warm-based ice (Benn & Evans, 2010; Boulton, 1976; Bradwell, 2006; Glasser & Hambrey, 2001; Ives & Iverson, 2019; Lovell et al., 2015). We use this evidence to infer that ice within the Loch Venachar trough grew thick enough for a branch of the former Teith Glacier to overspill across the Menteith Hills towards the Forth Valley, thereby breaching the watershed. We call this newly identified branch the 'Menteith Hills Glacier'. For clarity, we therefore encourage the previously known 'Menteith Glacier' to be referred to as the 'Forth Glacier', following similar nomenclature to the 'Lomond' and 'Teith' Glaciers.

Flutings are commonly found on contemporary glacial forelands but have poor preservation potential as they are low-relief features susceptible to weathering and modification, *e.g.* by wind or water erosion (Benn & Evans, 2010). The preservation of flutes on the Menteith Hills is therefore unusual and suggests the glacier underwent rapid retreat which was not interrupted by subsequent readvances. Some post-glacial erosion from fluvial and forestry activity has taken place, with streams cross-cutting flutes in some places. This will have likely impacted the continuity of the flutes' appearance today, meaning flutes may be mapped as shorter features than they originally were. This may be a reason why measured flute length is highly variable compared to mean flute width (Figures 5 and 6). The scale of flutes and megaflutes make them difficult landforms to identify in the field, and in the palaeo landscape record of Scotland widespread mixed vegetation cover can obscure these features from view. The Menteith Hills megaflutes are barely visible in the field (Figure 9), from vertical aerial imagery or on digital terrain models with a horizontal resolution of 5 metres or less (*e.g.* NEXTMap: 5 m pixel resolution), explaining why these features have not been previously identified.

Figure 9. Photograph taken from the prominent bedrock ridge between the mid and lower slopes looking south-east across the Lake on Menteith. Yellow arrows indicate the three most prominent flutings.

However, newly acquired high resolution (50 cm) LiDAR data has meant that these features can now be analysed here for the first time. LiDAR-based applications to glacial geomorphology are many and have been responsible for several important advances, such as confirming the existence of morphological bedform continuums (e.g. Eyles et al., 2023; Sookhan et al., 2021, 2022); aiding the discovery of new landforms, such as murtoos (Mäkinen et al., 2017; Peterson et al., 2017); and improving our understanding of palaeo ice dynamics through increased data resolution (e.g. Möller & Dowling, 2015; Seppälä, 2016; Sookhan et al., 2021). However, the use of LiDAR is not ubiquitous, partly due to the differing spatial extent of LiDAR data coverage globally, resulting in a disparity in the use of LiDAR for glacial mapping. The increased capture and use of high-resolution LiDAR data should be encouraged for glacial landform mapping in countries where LiDAR use is currently falling behind the curve, such as in Scotland where coverage is, at present, sporadic. Continuous improvements in the spatial extent of LiDAR data and the development of drone-mounted survey technology make the inclusion of LiDAR data within glacial research more achievable. Additionally, high-resolution (*i.e.* sub-metre) LiDAR data is particularly important for identifying intermediate-scale subglacial bedforms (Goodship & Alexanderson, 2020), such as megaflutes, and we propose its use is vital to ensure landforms of this scale are recognised and adequately mapped.

The bedrock ridges of the Highland Boundary Complex, which comprise the Menteith Hills, are approximately perpendicular to the megaflute ridges (Figure 10), meaning the flutings are not a function of bedrock structure. Sediment cover is thin across much of the Menteith Hills (British Geological Survey, 2004). The thickest identified sediment cover is on the upper slope, where fluted landforms are composed of diamicton, exposed in stream sections. We interpret this matrix-supported diamicton, consisting of striated sub-angular to sub-rounded clasts, to be subglacial till (Evans, 2000). On the lower slopes, bedrock is exposed in multiple places, with prehistoric human rock art known as ‘cup and ring’ marks visible on the bedrock (Van Hoek, 1991). This change in

Figure 10. Oblique aerial photograph of the Menteith Hills looking approximately eastwards, showing the prominent bedrock ridges which make up the hills. The megaflutes can be seen crossing from left to right in the open foreground. Photo: F. I. MacTaggart, British Geological Survey © UKRI (1996), p. 001254.

sediment thickness, from up to *ca.* 4 m thick on the upper slopes to a very thin discontinuous drape <0.5 m thick on the lower slopes, does not appear to interfere with flute formation. The flutes cross from sediment-covered to bedrock-exposed areas uninterrupted, including continuous flutings crossing the most prominent bedrock ridges. The megaflutes are therefore a combination of soft-sediment and bedrock-cored features, suggesting a limited supply of subglacial sediment at the time of glaciation (Ewertowski et al., 2016). This is similar to the flutes seen on the northern proglacial foreland of the retreating Nordenskiöld glacier on Svalbard (Ewertowski et al., 2016). This could also begin to explain why there is no prominent terminal moraine on the Menteith Hills. A short section of moraine was identified to the west of the flutes; however, it is currently unclear whether this relates to the main Forth Glacier or the Menteith Hills Glacier. In addition, the Menteith Hills Glacier may have coalesced with the Forth Glacier, which ended in a large terminal moraine around the eastern shore of the Lake of Menteith (Evans & Wilson, 2006), approximately 3 km southeast of the megaflute field.

The flutes are mostly straight, although do orientate progressively southwards. These slight directional changes appear to correlate with the presence of the main topographic bedrock ridges, suggesting glacier flow may have been affected by topography to some degree. These prominent bedrock ridges, perpendicular to ice-flow, may have enhanced flute formation through the creation of lee-side cavities or promoted basal sliding via stoss-side pressure melting (Boulton, 1976; Krabbendam, 2016). Flutes on the upper slope have lower elongation ratios (< 6:1) and greater vertical relief (up to 4 m high) but become more elongate downslope (ERs up to 29:1) with lower vertical relief (1 – 2 m; see Figure 7). This change in elongation and reduction in height is potentially a function of increasing sliding velocity at the glacier bed (*e.g.* Stokes & Clark, 2002). Faster ice flow is often associated with longer bedforms typically with elongation ratios >10:1 (Stokes & Clark, 2002), as seen on the mid and lower slopes of the Menteith Hills. The increase in elongation could also be a feature of composition, with soft-sediment features (more common on the upper slope) having lower elongation ratios compared to the bedrock-cored features (lower slopes). Sediment-cored flutes are more easily eroded, and this can be seen on the upper slopes where flutes are cut by streams, which may affect elongation ratios here. In addition, grooved surfaces in the direction of movement have been shown to decrease basal friction (Eyles et al., 2023; Stelmakh et al., 2014), explaining how a fluted bed could play a role in increasing sliding velocity through a feedback effect.

Several theories currently exist regarding the evolution and formation of flutes, the most widely accepted being the cavity infill model (Åmark, 1980; Benn, 1994; Benn & Evans, 2010; Boulton, 1976). In this model, weak or deformable sediment flows into a cavity which has formed in the lee of a lodged boulder or rigid obstacle. This evolves into a flow-parallel flute by either cavity propagation or sediment freeze-on to basal ice (e.g. Benn & Evans, 2010; Boulton, 1976). Many, but not all, flutes are associated with a boulder (termed an initiating boulder) or obstacle at their stoss end. However, the megaflutes on the Menteith Hills are not associated with initiating boulders and seem to be a hybrid of soft-sediment and bedrock-cored features (*i.e. composite flutes sensu* Hart et al., 2018), so a cavity infill model cannot fully explain their formation. It is plausible, however, that the large structural bedrock ridges (see Figure 10), with a relief of > 40 m in places, played an important role in flute development at this site. For example, through cavity propagation, initiating faster flow through pressure melting of ice and increased lubrication at the bed, or by increasing bed roughness and enhancing basal shear stress. The hybrid or composite nature of the Menteith Hills megaflutes implies an erosional element to their formation. Erosional control of flute formation may have occurred through transported bedrock blocks protruding from the base of the ice and eroding linear grooves into the underlying substrate, or through erosion from debris-rich basal-ice keels formed through increased bed roughness created by the bedrock ridges and convergent ice flow (Clark et al., 2003). The megaflutes described here may be purely erosional features, or a combination of erosional and depositional processes, formed by focused, relatively fast, unidirectional ice flow over the Menteith Hills.

The megaflutes on the Menteith Hills occur within the existing landform record of the Younger Dryas or LLS in Scotland. During this time, 12.9–11.7 ka BP, the Teith Glacier terminated around Callander (Thompson, 1972; also Figure 1). There are other moraines and hummocky glacial deposits, possibly deposited by the Teith Glacier, mapped on top of the Menteith Hills by the British Geological Survey (1880, 2005), and verified by our field surveys, indicating that the LLS glacier probably reached this thickness. It is therefore possible that ice within the Loch Venachar trough grew thick enough during the LLS to breach the watershed between the Teith and Forth valleys, forming a short overspill glacier lobe – the Menteith Hills Glacier. The Forth Glacier at this time probably terminated in a large thrust block moraine complex to the east of the Lake of Menteith (Evans & Wilson, 2006; Evans, 2021; also Figure 1). We hope, in the near future, to employ cosmogenic-nuclide exposure dating of boulders within the megaflute field to determine the age of this event, and place it firmly within the context of Late Glacial ice-cap fluctuations in Scotland.

The discovery of large flutings (megaflutes) around the margins of the well-established Younger Dryas West Highland Icefield poses important questions about the data resolution used in glacier geomorphological mapping. The spatial extent of NEXTMap data makes it a popular data resource, however its resolution means that subtle landforms, even those large in size like the Menteith megaflutes, can be easily missed (e.g. Bickerdike et al., 2018; Hughes et al., 2010). The increasing extent and availability of sub-metre resolution LiDAR data makes it an important tool for (palaeo-) glaciological researchers filling data gaps in geomorphological mapping.

Conclusions

Recently acquired 50 cm resolution LiDAR data has enabled the identification of a field of over 100 previously unnoticed megaflutes, covering an area of 2 km^2 on the Menteith Hills in Central Scotland. Landform lengths range from around 20 – 1000 m, with widths typically around 20 – 40 m, and heights typically only < 1 – 2 m. These findings highlight the value of high-resolution LiDAR data for mapping subtle glacial landforms in Scotland and elsewhere, and its use is strongly encouraged. The newly identified megaflutes reveal that a branch of the Teith Glacier overtopped the Loch Venachar trough to flow across a col in the Menteith Hills and into the Forth Valley. These large flutings suggest fast or focused flow of ice, following the breach of the watershed. Fieldwork revealed bedrock striae corresponding to the orientation of the flutes and the presence of subglacial till within the depositional flutings, which transition to bedrock-cored features downslope. These composite or hybrid flutings suggest a lack of subglacial sediment supply during formation. This new geomorphological evidence adds a fresh perspective on the glacier dynamics of the West Highland Icefield in Central Scotland during the Late Glacial, and highlights the need to revisit key areas, utilising new high-resolution data. Our study emphasises the importance of sub-metre resolution LiDAR elevation data in glacier geomorphological mapping and its role in improving understanding of palaeo glacier dynamics and the processes operating at the glacier bed.

Acknowledgments

This work was supported by NERC via an IAPETUS2 PhD Studentship awarded to JG. The authors wish to acknowledge the residents of Nether Glenny (Stirlingshire) for allowing access via their private road for the purposes of an aerial survey. Thiago Silva is thanked for his expertise and assistance in the collection and data processing of drone-mounted LiDAR data, and Allan Audsley is thanked for his GIS expertise and accompaniment in the field. The Environment Agency and Scottish and UK Governments are acknowledged for collecting and releasing the original LiDAR dataset available at: https://www.data.gov.uk/dataset/56c928df-2513–42a8-89c6-14d739247e11/50cm-lidar-composite-dsm-dtm-for-scotland. The authors are also especially grateful to the anonymous reviewers for their insightful and constructive comments which helped to improve and clarify an earlier version of this manuscript.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by Natural Environment Research Council [grant number: NE/S007431/1].

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