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# A Glacial Geomorphological Map of the Great Glen Region of Scotland

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A Glacial Geomorphological Map of the Great Glen Region of Scotland

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Abstract

This paper presents a detailed glacial geomorphological map of the Great Glen region of Scotland, UK, covering an area of over 6,800 km\textsuperscript{2} extending from 56°34'7" to 57°41'1" N and from 3°44'2" to 5°33'24" W. This represents the first extensive mapping of the glacial geomorphology of the Great Glen and builds upon previous studies that conducted localised field mapping or ice-sheet wide mapping using remote sensing. Particular emphasis is placed on deriving medium-scale glacial retreat patterns from these data, and examining differences in landsystem assemblages across the region. Features were typically mapped at a scale of 1:8,000 to 1:10,000 and will be used to investigate the pattern and dynamics of the British-Irish Ice Sheet during deglaciation. Mapping was conducted using the NEXTMap digital terrain model. In total, 17,637 glacial landforms were mapped, with 58\% identified as moraines, 23\% as meltwater channels, 10\% as bedrock controlled glacial lineations, 3\% as eskers, 2\% as cirques or arêtes, 2\% as kame topography or kame terraces, and 1\% as drumlins. Additionally, ten palaeo-lake shorelines were identified. Complex landform assemblages in the form of streamlined subglacial bedforms, moraines and glaciofluvial features exist across the region. Extensive subglacial meltwater networks are found over the Monadhliath Mountain Range. Transverse and longitudinal moraine ridges generally arc across valley floors or are located on valley slopes respectively. Hummocky moraines are found almost exclusively across Rannoch Moor. Finally, Eskers, meltwater channels and kame landforms form spatial relationships along the axis of Strathspey. These glacial landsystems reveal the dynamics and patterns of retreat of the British-Irish Ice Sheet during the last deglaciation.

Keywords: Great Glen, Geomorphology, British-Irish Ice Sheet, Deglaciation

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1. Introduction

Glacial landforms are key ingredients for reconstructing the past extent and dynamics of the former British-Irish Ice Sheet (BIIS), which extended across much of Britain and Ireland, and reached the continental shelf edge during the last glaciation about 24,000 years ago (Bowen et al., 2002; Sejrup et al., 2005; 2009; Bradwell et al., 2008a; Chiverrell and Thomas, 2010; Clark et al., 2012). In Scotland, coastal and onshore geomorphology (e.g. Thorp, 1986; Firth, 1989a, b; Merritt et al., 1995; Finlayson, 2006; Finlayson et al., 2010) have been extensively employed to reconstruct flow paths and retreat patterns. The limits of the Younger Dryas (YD) readvance (12.9-11.7 ka BP) are also well known (e.g. Sissons, 1979a; Bennet and Boulton, 1993a; Clark et al., 2004). Terrestrial evidence suggests the configuration of the BIIS was complex and that the ice sheet was characterised by at least four areas of major ice streaming located at the Moray Firth, The Minch, along the eastern coast of England and within the Irish sea basin. These were zones of high flow velocity which drained large volumes of ice from the ice sheet's interior (e.g. Merritt et al., 1995; Bradwell et al., 2008b; Hughes et al., 2010; Clark et al., 2012). Less attention has been given to synthesising terrestrial limits and medium-scale retreat patterns between offshore/coastal and YD ice margin positions. Whilst there are a number of site specific studies of moraines, glaciofluvial landforms, and streamlined subglacial bedforms in Scotland (e.g. McCann, 1966; Peacock, 1971; Young, 1978; Firth, 1989a; Golledge, 2006; Livingstone et al., 2008), the glacial landforms across large sectors of the Scottish landscape have yet to be systematically mapped.

In the Great Glen (GG) and surrounding region a paucity of detailed mapping has precluded an accurate reconstruction of ice sheet retreat from the Scottish coast to the YD maximum extent positions mapped by Clark et al., 2004. However, recent research in the Monadhliath Mountain Range has suggested that ice cover between ~15 ka BP and 11.7 ka BP was more extensive than previously thought (Boston et al., 2013).

The accompanying geomorphological map covers a region of 6,828 km² centred on the Great Glen in Scotland. This builds upon previous mapping efforts (e.g. Clark et al., 2004; Hughes et al., 2010) and is part of ongoing research into the nature of deglaciation through the Great Glen sector of the BIIS including subaqueous geophysical surveys of the lochs in the region (e.g. Turner et al., 2012; 2013a, b).
2. Methods

2.1 Data Sources

The geomorphological map of the Great Glen region has been produced from high-resolution Intermap Technologies NEXTMap digital terrain data which has a horizontal resolution of 5 m and vertical resolution of 1 m. ESRI ArcGIS 9.3 software was used during mapping procedures. An orthogonally illuminated hillshade of the study area was produced (Smith and Clark, 2005). As lineations on the land surface have a predominant south-west/north-east trend, the digital elevation model was initially shaded from an azimuth perpendicular to their orientation (north-west: 315°). To reduce the bias associated with hillshading from a single solar azimuth, a second relief map was produced with a perpendicular north-east (45°) azimuth (e.g. Smith and Clark, 2005). A solar elevation angle of 45° was selected for these images to reveal subtle topography within the study area. To further reduce azimuth biasing, a shaded relief image with an illumination angle of 90° (vertical) was also produced, as suggested by Smith and Clark, (2005).

Additional contextual data from Ordnance Survey MasterMap, available from the Edina ShareGeo website (http://edina.ac.uk/projects/sharegeo/index.shtml), at a scale of 1:2,000 were also used. These data allowed roads, buildings, managed woodland, railway lines, rivers/streams, tree cover and landforms pertinent to this study to be identified. A base map for the remainder of Scotland is provided by NASA Shuttle Radar Topography Mission (SRTM) data, available at http://www2.jpl.nasa.gov/srtm/. This layer is not used in mapping procedures due to its low resolution (90 m - Farr et al., 2007) and vertical elevation errors (5 m - Rodriguez et al., 2005). All map layers were displayed using the British National Grid (OSGB 1936 datum) and projected to the Transverse Mercator, airy spheroid.

2.2 Mapping Procedure

The glacial geomorphological map was generated by visually identifying features of glacial origin from the relief shaded images described above. Across the area 17,637 individual glacial features were systematically located and classified according to common morphological descriptions (see section 3). Landforms were digitised within ArcGIS 9.3 software as colour coded polyline data at a scale of between 1:8,000 and 1:10,000. In cases where a landform was tentatively identified in the imagery, but lacked pronounced relief or was otherwise difficult to see, ESRI ArcScene 9.3 3D
91 visualisation software was used to aid in scrutinising landforms. This helped classify the exact feature
type, or allowed a feature to be rejected as unimportant to the study (e.g. roads, electrical pylons,
buildings).
92
93 Whilst previous mapping has identified a wealth of glacial landforms such as bedrock controlled
94 glacial features (e.g. Peacock et al., 1992; Hughes et al., 2010), drumlins (Hughes et al., 2010)
meltwater channels (e.g. Gordon, 1993; Greenwood et al., 2007; Margold and Jansson, 2012), eskers
(e.g. Young, 1978; Key, 1997), kame features (e.g. Young, 1978; May and Highton, 1998; Russell
and Marren, 1998), moraines (e.g. Bennett and Boulton, 1993a, b; Benn and Lukas, 2006; Dunlop
and Clark, 2006a, b; Smith et al., 2006) and ice dammed palaeo-lake shorelines (e.g. Sissons, 1977b;
1979a, c; Palmer et al., 2010); a new map was required that covers a regional area and synthesises
96 these data at the medium-scale. The descriptions of landforms given in the above references have
also provided criteria for identification of previously unmapped glacial landforms in the region. Where
a landform was confirmed from visual identification of the relief imagery they were included on the
final geomorphological map. The source references for such features were added to the attribute
table entry during mapping. It is estimated that 80% of the landform record presented in the glacial
gemorphological map has not been identified previously.
99
100 All features were further subdivided into 3 'certainty categories' (cf. Greenwood, 2007).
101 Category 1 ('definite') denotes a given landform possesses most of the characteristic attributes
described in the literature for that landform type. Category 2 ('probable') refers to those landforms
which are most likely of a particular feature type but some uncertainty remains as not all classic
characteristics may be present. The final category 3 ('possible') landforms display only a few of the
typical characteristics of its type or, alternatively, possess characteristics of two or more landform
types and could potentially be misidentified. Category 3 landforms are omitted from the final
gemorphological map. Statistical information for each landform type was drawn from examples
classified as ‘definite’ or ‘probable’ (Table 1).
103
104 A short ground truthing field excursion was also conducted to verify several landform types.
105 Locations included the northern and southern shores of Loch Ness, several locations within the
Monadhliath Mountain Range and Glen Roy.
106
107 The palaeo-shorelines of ice dammed lakes, which previously occupied glens, were produced
by first identifying the palaeo-shoreline from the hillshaded NEXTMap data based on descriptions by
Sissons (1977b; 1979a, c) and Palmer et al. (2010). Where the surface elevation of a palaeo-shoreline was known, an isoline of the appropriate elevation above sea-level was generated in the GIS using a geoprocessing tool in order to keep elevation error to a minimum. The extent of the resulting palaeo-lake was therefore delineated primarily by topography, but also from associated moraine limits. A caveat to this is that the NEXTMap digital elevation model retains all natural and anthropogenic features in addition to the relief of the land surface; therefore where the lake shores disappear under tree cover, the mapping algorithm would map tree elevation instead of palaeo-shoreline elevation. Forested areas are therefore omitted from the elevation analysis. Glacio-isostatic adjustment is not accounted for, but given the relatively small size of the lakes, this is unlikely to be a problem.

3. Glacial Geomorphology

3.1 Cirques/Arêtes

Cirques are erosional hollows in mountainous terrain with concave slopes bounded upstream by a sharp arcuate headwall and sharp valley side ridges (arêtes) (Gordon, 2001; Evans, 2006) and are flat floored and open at the downstream end (Evans and Cox, 1974; Benn and Evans, 2010) (Fig. 2a, b). In the Great Glen region, clusters of cirques exist in the vicinities of Loch Ericht, Ben Nevis Mountain Range, Loch Arkaig, Loch Loyne and Loch Affric (Fig. 1). These locations lie within YD ice cap limits as defined by Clark et al. (2004). Three clusters of cirques occur outside the YD limit in proximity to Loch Laggan, Strathossian and Strathconon (Fig. 1). It should be noted that the YD ice limits presented here are based on Clark et al. (2004). However, recent work in the Monadhliath Mountain Range suggests a more extensive ice limit during the YD cold event (Boston et al., 2013).

3.2 Streamlined bedrock

Streamlined bedrock features are highly elongate, (e.g. Table 1) ice flow parallel landforms (Bradwell et al., 2008b), possessing sharp crest lines in cross-profile and gentle long-profile morphology (Jansson et al., 2003). The highest concentration occurs over the mountainous areas surrounding Loch Ness (e.g. Fig. 2c, d); other concentrations are located on the western side of Strathspey and on peaks overlooking Glens Moriston, Roy and Spean. These fields of streamline
bedrock ridges predominantly occur outside the YD ice limit. Within the YD limit, the streamlined features are located in the vicinities of Lochs Aber, Affric, Garry, Loyne (Fig. 1).

3.3 Crags and Tails

Crags and tails are ice moulded bedrock outcrops with indistinct or sharp crests and a leeward tail/ridge of un lithified material (usually till) tapering in the direction of ice flow (Smith et al., 2006; Greenwood and Clark, 2008; Hughes et al., 2010) (Fig. 2c, d). They are have a relatively high elongation ratio (Table 1) and are found outside the YD ice limits over elevated terrain, and surround the northern portion of Loch Ness. Other fields are found in proximity to Glen Affric, Strathconon, the Clava river valley, and on peaks overlooking Strathspey (Fig. 1). Additionally, the northern Affric/Ness clusters surround the peripheries of drumlin fields discussed below.

3.4 Drumlins

Drumlins are streamlined, commonly described as asymmetric, ovoid hills aligned parallel to ice flow with gentle stoss and lee slopes which may also be spindle-like, parabolic or barchanoid in planview (Mitchell and Riley, 2006; Smith et al., 2006; Greenwood and Clark, 2008; Hughes et al., 2010). In this region, they are more elongate when compared to other types of glacial lineations (Table 1). They encircle the northern and eastern shores of Loch Ness, and they surround the northern and southern shorelines of Beauly Firth and west of Cromarty Firth.

3.5 Transverse moraines

Transverse moraines are ridges deposited perpendicular to ice flow which may be single ridges or broken into linear chains arcing across valley floors (Sissons, 1979c, Benn and Lukas, 2006; Golledge, 2006; Smith et al., 2006). The mean length of transverse moraines has been calculated to be ~128 m (Table 1). A characteristic cluster has been identified at the Blackwater Reservoir (Fig. 3a, b). Other fields occur in glens adjacent to Lochs Arkaig, Cluanie, Eil and Quioch with two further clusters located in Glen Spean and north-east of Loch Ness (Fig. 1).

3.6 Longitudinal (ice flow parallel) moraines
Longitudinal moraines occur laterally on valley slopes (lateral moraines) (Sissons, 1979c), on valley floors running parallel to the valley long axis and former ice flow (Benn and Evans, 2010), or extend from central ridges at the confluence of adjacent valleys, showing where two separate glacier systems have merged into one coherent ice mass flowing down-valley (medial moraines) (e.g. Spagnolo and Clark, 2009). They are frequently asymmetrically distributed across opposing valley slopes (Sissons, 1979c). They have also been calculated to possess a slightly longer mean length than transverse moraines, measured at ~149 m (Table 1). A large population is found at the northern end of Loch Ness and close to Foyers, with examples found at the YD limit in Glen Moriston. Further fields are found in proximity to Lochs Arkaig and Ossian, and across Rannoch Moor (Fig. 1).

3.7 Ribbed moraine

Ribbed moraine consist of curved, closely spaced ridges aligned transverse to ice flow with a characteristic anastomosing pattern or ‘ribbing’ (Lundqvist, 1989; Aylsworth and Shilts, 1989; Hättestrand and Kleman, 1999; Dunlop and Clark, 2006a, b) (Fig. 3e, f). They may have multiple sub-crests or singular flat apexes (Dunlop and Clark, 2006a, b; Hughes et al., 2010). Ribbed moraines are exclusively found surrounding the southern tip of the Cromarty Firth, deposited above a 40 m palaeo-sea level shoreline mapped by Firth (1989a) with few examples below this (Fig. 3e, f). They also possess the greatest mean length (measured perpendicular to ice flow direction), at ~243 m (Table 1).

3.8 Hummocky terrain

Hummocky terrain is defined as irregular mounded topography which exhibits varying degrees of order; ranging from unordered (chaotic) assemblages to suites of nested linear elements (Sissons, 1976; Smith et al., 2006). Hummocky terrain commonly occurs in localised depocentres in the form of broad and low ridges in the landscape, which may grade into till sheets (Key, 1997). The largest population was observed in the Rannoch Moor area with other concentrations located in western Strathspey, in the vicinities of Lochs Lochy, Eil and Quioch, and west of the YD ice limit in Glen Affric (Fig. 1).

3.9 Kame topography
Kame and kettle topography are assemblages of mounds and hollows generated through supraglacial or ice contact glaciofluvial deposition which may also represent zones of in situ ice stagnation, wastage, ice-block meltout or jökulhlaups (Sissons, 1976; 1979c; Young, 1978; Russell and Marren, 1998; Fay, 2002; Gordon and McEwen, 1993) (Fig. 4a, b). The largest field is located on the western slopes of Strathspey with another series of features found at the Auchteraw Terrace, close to Fort Augustus (Fig. 1). Another field exists at the head of Loch Treig (Fig. 1).

3.10 Kame terraces

Kame terraces are gently sloping depositional benches perched on valley sides, and are related to the lateral deposition of glaciofluvial outwash (Evans, 2005); or possibly outwash deposition in ice marginal ribbon lakes (Benn and Evans, 2010). They often occur in series and have differing gradients relating to former ice margin morphology (Fletcher et al., 1996; Benn and Evans, 2010). The largest concentration occurs in Glen Moriston on the slopes on either side of the modern river within the YD ice limit. Also within the ice limit, kame terrace fragments are identified north of Loch Treig (Sissons, 1979c) (Fig. 1). Outside of the YD limit, in Strathspey, terrace fragments are observed north of Newtonmore (Young, 1978) and in the northern Findhorn river valley (Fletcher et al., 1996).

3.11 Lateral meltwater channels

Lateral meltwater channels develop parallel to ice margin surfaces and erode distinct lateral or arcuate ‘grooves’ or benches into the topography during deglaciation (Dyke et al., 1992; Kleman et al., 1992; Dyke, 1993; Hättestrand, 1998; Hättestrand and Stroeven, 2002; Solliid and Sørbel, 1994; Smith et al., 2006; Greenwood et al., 2007). Outside the YD ice limit, channels are located at the peripheries of Loch Ness and valleys in the Monadhliath Mountain Range (Fig. 1). Within the ice limit, concentrations are found at Lochs Arkaig, Laggan and Ossian, and around Leum Uilleim (Fig. 4e, f). Statistical information obtained from all meltwater channel types are presented in Table 1.

3.12 Sublateral meltwater channels

Sublateral channels typically have greater angles of dip on the land surface than lateral examples and often occur in series at elevations below major longitudinal moraine ridges and in some instances plunge through down slope chutes or fissures (Sissons, 1967; Greenwood et al., 2007).
Concentrations exist in Glen Moriston, over Leum Uilleim, and at Urquhart Bay and Foyers, Loch Ness (Fig. 1).

### 3.13 Subglacial meltwater channels

Subglacial channels can form in an upslope flow direction and may overtop mountainous peaks/ridges and erode directly into bedrock, due to controls imparted by ice flow direction and hydrostatic pressures (Sissons, 1967; Nye, 1973; Young, 1978; Sharpe and Shaw, 1989; Sugden et al., 1991; Kleman and Borgström, 1996; Kleman et al., 1997; Hättestrand and Stroeven, 2002). They may also preferentially erode into faults in bedrock surfaces and display anastomosing or braided patterns (Margold and Jansson, 2012). The highest density is found over the Monadhliath Mountain Range and on the elevated terrain between Loch Ness and Glen Affric (Fig. 1). These areas are located outside of the YD ice limit. Within the ice limit small clusters are located on the flanks of Leum Uilleim, Loch Treig and Loch Eil (Fig. 1).

### 3.14 Proglacial meltwater channels

Proglacial channels are formed at the termini of glaciers and ice sheets which can form braided and branching channel networks in the proglacial zone (Benn and Evans, 2010). They often rapidly erode pre-existing channels or down-cut into bedrock surfaces and may be difficult to distinguish from modern drainage channels, or, if channels are of low relief, they may have a very weak signature on the land surface (Benn and Evans, 2010; Margold et al., 2011). Only three features have been confirmed as proglacial channels. These are located in the Glen Roy area, eroded through a series of transverse moraines and into the top of a proglacial fan complex known as the Glen Turret Fan (Chen and Rose, 2008).

### 3.15 Over-col spillway channels

Over-col spillways (Fig. 4f) are deep channels or gorges incised into bedrock which are often found in association with former ice dammed lakes (Margold and Jansson, 2012). Four of the spillways are associated with the former ice dammed lakes in Glens Spean, Roy and Gloy, with further spillways located near Beinn a’Bha’ach Ard and Sgurr na Ruaidhe between Strathconnon and Strathfarrar and at Leum Uilleim (Fig. 1).
3.16 Eskers

Eskers are well-defined, sub-linear to sinuous ridges which may have smooth or sharp crests and are often associated with lakes, kame and kettle topography. They typically trend in the direction of former meltwater flow which may not necessarily be the same as the regional ice flow direction (Smith et al., 2006; Margold and Jansson, 2012). They can form supraglacially, englacially or subglacially (Banerjee and McDonald, 1975) via sustained deposition over long timescales or via single high-magnitude events (jökulhlaups) (Burke et al., 2008; 2010). Eskers are observed in proximity to Glens Moriston and Spean, Strathossian, and on slopes overlooking Lochs Erich, Lochy, Oich, and Treig. Elsewhere, eskers are found in the vicinities of Strathspey, Loch Laggan and the Clava and Findhorn river valleys. A small number of eskers located at the northern end of Loch Ness are larger in scale.

3.17 Paleo-lake shorelines

Palaeo-lake shorelines are laterally continuous valley side terraces, notches or benches that are the result of wave erosion and beach deposition at a former long-lived palaeo-water-level which also often occur in series (Darwin, 1839; Sissons, 1977a; 1978; Sissons and Cornish, 1982; Chen and Rose, 2008; Margold and Jansson, 2012). Six shorelines are identified in Glen Doe at 510 m, 406 m, 359 m, 334 m, 324 m and 305 m above sea-level (a.s.l.) (Fig. 5a-f). A 355 m a.s.l. shoreline is identified in Glen Gloy and crosses two sets of transverse moraine deposited within the valley bottom, resulting in possible minimum and maximum extents (Fig. 5g, h). Three are traced in Glen Roy where they are laterally extensive and occur at 350 m, 325 m and 260 m a.s.l. (Fig. 5i-k). The 260 m a.s.l. shoreline is also traced in Glen Spean (Fig. 5j, k).

4. Conclusions

The map accompanying this article is the first detailed map of the glacial geomorphology of the Great Glen region of Scotland. This map builds upon and extends previous work by both field researchers, cartographers and the BRITICE data set by synthesising small-scale mapping efforts at the medium-scale, including previously unmapped landform assemblages, to produce a detailed regional pattern of glacial landforms which can be used to reconstruct the dynamics and retreat...
patterns of the former BIIS in this sector of Scotland. Complex landform assemblages exist across the study area especially on the eastern side of the Great Glen, where a larger number of landforms appear to have been preserved. In total 17,637 individual features were mapped in the 6828 km$^2$ study area; 58% of these are moraine, 23% are meltwater channels, 10% are bedrock lineations, 3% are eskers, 2% are cirques or arêtes, 2% are kame and kettles or kame terraces and 1% are drumlins.

Where mountainous areas are present, glacial erosion has produced cirques, marking initial accumulation areas and final deglacial enclaves of the former ice cover in Scotland. Over elevated ground, streamlined bedforms dominate, with drumlins occupying lower ground to the north-east. Extensive subglacial meltwater networks are found over the Monadhliath Mountain Range. Across low elevation terrain in the southern extremity of the study area, in western Rannoch Moor, moraine ridges are the prevailing landforms. Transverse and longitudinal moraine ridges are generally located across valley floors or deposited on valley slopes respectively dispersed across the study area. Longitudinal moraines additionally share a spatial relationship with lateral meltwater channels along the axis of the Great Glen. Eskers, meltwater channels and kame landforms also form spatial relationships along the axis of Strathspey.

The glacial geomorphological map accompanying this paper synthesises morphological data in order to examine the nature of glaciation in the Great Glen region and the potential evidence of fast flow (ice streaming). Particular emphasis is placed on deriving regional glacial retreat patterns, and finally, examining any differences in morphology or landsystem assemblages occurring within the Younger Dryas ice cap limits.

5. Software

Relief shaded visualisations of the NEXTMap dataset and onscreen digitisation of landforms were done using ESRI ArcGIS 9.3 software. The 3D visualisation tool of ArcScene 9.3 was used to aid assessment of landform features where this was difficult in the planview of ArcGIS 9.3. The final geomorphological map was produced in ArcGIS 9.3 and exported as a PDF document.

6. Acknowledgements
The authors would like to thank Dr. Ian S. Evans of Durham University in helping to find the relevant BGS map sheets for the study area (BGS, 1995; 1997; 2000). We would also like to thank Dr. Mike Lim of Northumbria University for providing Intermap Technologies NEXTMap data for the study area and Dr. Clare M. Boston of Exeter University for fruitful discussions on the landforms of the Monadhliath Mountain Range.

7. Map Design

All glacial landforms were mapped as a series of polyline data, colour coded to feature type for expedient mapping. For meltwater channels, kame features and moraines different colours were also used to differentiate between sub-types (e.g. dark blue for subglacial meltwater channels and lighter blues for lateral and sublateral types). Mapped landforms were overlaid on various hillshaded renditions of the NEXTMap data and coloured white to emphasise the topography of the area and to aid clarity of individual features. Place names were kept to an absolute minimum on the final geomorphological map to avoid cluttering the map and obscuring geomorphological features. This accompanying paper contains a figure with all relevant place names mentioned in the text.

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### 9. Tables

#### Table 1 – Statistical properties calculated for glacial landforms.

<table>
<thead>
<tr>
<th>Glacial Landform</th>
<th>N</th>
<th>Mean Length (m)</th>
<th>Mean Width (m)</th>
<th>L/W Ratio</th>
<th>Mean Orientation (°)</th>
<th>Mean Area (km²)</th>
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</thead>
<tbody>
<tr>
<td><strong>Cirques</strong></td>
<td>277</td>
<td>1155 ± 811</td>
<td>1038 ± 553</td>
<td>1.4:1</td>
<td>89.2 ± 50.98</td>
<td>1.42 ± 1.78</td>
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<tr>
<td><strong>Arêtes</strong></td>
<td>77</td>
<td>1804 ± 1462</td>
<td>-</td>
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<tr>
<td><strong>Eskers</strong></td>
<td>553</td>
<td>222 ± 202</td>
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<td><strong>Glacial Lineations</strong></td>
<td>1977</td>
<td>290 ± 377</td>
<td>158 ± 132</td>
<td>4.2:1</td>
<td>47.9 ± 23.9</td>
<td>0.13 ± 0.26</td>
</tr>
<tr>
<td><strong>Crag &amp; Tail</strong></td>
<td>314</td>
<td>482 ± 400</td>
<td>111 ± 82</td>
<td>4.4:1</td>
<td>49.1 ± 37.5</td>
<td>0.5 ± 0.09</td>
</tr>
<tr>
<td><strong>Drumlins</strong></td>
<td>181</td>
<td>778 ± 750</td>
<td>189 ± 154</td>
<td>3.9:1</td>
<td>46.4 ± 22.2</td>
<td>0.18 ± 0.33</td>
</tr>
<tr>
<td><strong>Streamlined Bedrock</strong></td>
<td>1482</td>
<td>268 ± 260</td>
<td>55 ± 35</td>
<td>5.0:1</td>
<td>47.4 ± 18.2</td>
<td>0.01 ± 0.07</td>
</tr>
<tr>
<td><strong>Kames</strong></td>
<td>387</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Kame &amp; Kettle</strong></td>
<td>337</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
</tr>
<tr>
<td><strong>Kame Terraces</strong></td>
<td>50</td>
<td>355 ± 252</td>
<td>-</td>
<td>-</td>
<td>76.6 ± 34.5</td>
<td>-</td>
</tr>
<tr>
<td><strong>Meltwater Channels</strong></td>
<td>4117</td>
<td>413 ± 347</td>
<td>-</td>
<td>-</td>
<td>74.7 ± 46.2</td>
<td>-</td>
</tr>
<tr>
<td><strong>Lateral</strong></td>
<td>2468</td>
<td>310 ± 293</td>
<td>-</td>
<td>-</td>
<td>76.8 ± 46.3</td>
<td>-</td>
</tr>
<tr>
<td><strong>Sublateral</strong></td>
<td>221</td>
<td>377 ± 323</td>
<td>-</td>
<td>-</td>
<td>94.2 ± 49.4</td>
<td>-</td>
</tr>
<tr>
<td><strong>Subglacial</strong></td>
<td>1418</td>
<td>560 ± 413</td>
<td>-</td>
<td>-</td>
<td>68.0 ± 44.3</td>
<td>-</td>
</tr>
<tr>
<td><strong>Proglacial</strong></td>
<td>3</td>
<td>229 ± 68</td>
<td>-</td>
<td>-</td>
<td>112.9 ± 7.8</td>
<td>-</td>
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<tr>
<td><strong>Over-col</strong></td>
<td>7</td>
<td>858 ± 449</td>
<td>-</td>
<td>-</td>
<td>58.6 ± 50.1</td>
<td>-</td>
</tr>
<tr>
<td><strong>Moraines</strong></td>
<td>10227</td>
<td>116 ± 114</td>
<td>-</td>
<td>-</td>
<td>90.0 ± 52.3</td>
<td>-</td>
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<tr>
<td><strong>Transverse</strong></td>
<td>3397</td>
<td>128 ± 107</td>
<td>-</td>
<td>-</td>
<td>98.8 ± 55.6</td>
<td>-</td>
</tr>
<tr>
<td><strong>Longitudinal</strong></td>
<td>3478</td>
<td>149 ± 143</td>
<td>-</td>
<td>-</td>
<td>77.8 ± 46.5</td>
<td>-</td>
</tr>
<tr>
<td><strong>Hummocky</strong></td>
<td>3077</td>
<td>62 ± 45</td>
<td>-</td>
<td>-</td>
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<tr>
<td><strong>Ribbed</strong></td>
<td>275</td>
<td>243 ± 180</td>
<td>-</td>
<td>-</td>
<td>105.9 ± 64.3</td>
<td>-</td>
</tr>
</tbody>
</table>

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1 Standard deviations (±) are derived from the square root of the variance within each landform population.
Figure 1 – Map to show locations described in the text with figure extents. CF = Cromarty Firth; MF = Moray Firth; LU = Loch Ussie; SP = Strathpeffer; IF = Inverness Firth; SC = Strathconnon; BF = Beauly Firth; I = Inverness; L = Lochend; D = Dores; LD = Loch Duntelchaig; RC = River Clava; UB = Urquhart Bay; SF = Strathfarrar; LM = Loch Mullardoch; GA = Glen Affric; GU = Glen Urquhart; LN = Loch Ness; SE = Stratherrick; RF = River Findhorn; Laf = Loch Affric; GD = Glen Doe; GM = Glen Moriston; FA = Fort Augustus; AT = Auchteraw Terrace; LC = Loch Cluanie; LQ = Loch Quioch; Lloy = Loch Loyne; Gar = Glen Garry; LG = Loch Garry; LO = Loch Oich; GT = Glen Turret; GR = Glen Roy; Ggl = Glen Gloy; LA = Loch Arkaig; LL = Loch Lochy; La = Loch Laggan; SS = Strathspey; LS = Loch Shiel; LE = Loch Eil; Lab = Loch Aber; FW = Fort William; BN = Ben Nevis; BNM = Ben Nevis Mountain Range; LT = Loch Treig; SO = Strathossian; Los = Loch Ossian; Ler = Loch Erich; BW = Blackwater Reservoir; RM = Rannoch Moor; Lai = Loch Laidon; LB = Loch Ba.
Figure 2 – a) Map data showing glacial valleys surrounding the peak of Mullach nan Coirean, Ben Nevis Mountains. b) Interpreted image with cirque and arête features identified in green. c) Streamlined landforms found on the high ground to the west of Loch Ness. d) Interpreted image with crag and tails (yellow) and streamlined bedrock (red) identified. e) Extract from south of the Beauly Firth (BF). f) Interpreted image with drumlins identified in purple. LB = Loch Bruiceach.
Figure 3 – a) NextMap data showing a field of ridges perpendicular to the long axis of Blackwater Reservoir. b) Interpreted image with transverse moraines identified. c) NextMap data showing ridges aligned parallel to the valley long axis in proximity to Loch Ossian, cross-cut by a modern railway line and coming into contact with valley slopes. d) Interpreted image with longitudinal moraines identified. e) NextMap image showing ridges with an anastomosing pattern from Cromarty Firth. f) Interpreted image with ribbed moraine identified and associated with a palaeo-shoreline mapped by Firth (1989a). g) NextMap data from Rannoch Moor showing a field of chaotically distributed mounds. h) Interpreted image with hummocky moraine identified; no clear linear trends exist. Ice flow directions are indicated. See figure 1 for locations.
Figure 4 –  a) NextMap data showing chaotic surface morphology north of Newtonmore. b) Interpreted image with kame and kettle topography identified. c) NextMap data showing linear terraces aligned parallel to the valley axis in Glen Moriston. d) Interpreted image with kame terraces identified. e) NextMap image showing numerous channelised features around Leum Uilleim, Rannoch Moor. f) Interpreted image with lateral, sublateral, subglacial and over-col spillways identified. g) NextMap data from western Strathspey showing a field of sinuous, sharp crested ridges. h) Interpreted image with eskers identified. See figure 1 for locations.
Figure 5 – Reconstruction of the waning stages of ice dammed lake development based on shorelines mapped in this study and before complete drainage. a) Glen Doe 510 m; b) Glen Doe 406 m; c) Glen Doe 359 m; d) Glen Doe 334 m; e) Glen Doe 324 m; f) Glen Doe 305 m; g) Glen Gloy 355 m maximum extent; h) Glen Gloy 355 m minimum extent; i) Glen Roy 350 m and Glen Spean 260 m; j) Glen Roy 325 m and Glen Spean 260 m. Drainage has been interpreted to be via a series of outburst floods (jökulhlaups) (Sissons, 1977a; 1979b). Dashed lines indicate ice margins.
A Glacial Geomorphological Map of the Great Glen Region, Scotland, UK

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Mapped from Intermap Technologies NEXTMap Data (NERC Earth Observation Data Centre)

Projection: Transverse Mercator, any spheroid, OSGB1936

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