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Glacial geomorphology of the Gaick, Central Grampians, Scotland

Benjamin M. P. Chandler ^a, Sven Lukas ^b, Clare M. Boston ^c and Jon W. Merritt^d

^aSchool of Geography, Queen Mary University of London, London, UK; ^bDepartment of Geology, Lund University, Lund, Sweden;

^cDepartment of Geography, University of Portsmouth, Portsmouth, UK; ^dBritish Geological Survey, The Lyell Centre, Edinburgh, UK

ABSTRACT

The Gaick is an enigmatic glaciated landscape in the Central Grampians, Scotland, dominated by an expansive dissected plateau. Previous studies have postulated widely differing interpretations of the glacial landforms and current understanding of the glacial events in this area is partly restricted by the absence of detailed glacial geomorphological mapping. To address this issue, we present a comprehensive 1: 46,000-scale glacial geomorphological map, covering an area of ~520 km². A combination of detailed field mapping and interpretation of aerial photographs and Digital Surface Models (DSMs) has revealed a variety of glacial, periglacial and fluvial landforms, including an abundance of moraines and meltwater channels within valleys. We also identify a glacial sediment-landform assemblage, dissected glaciogenic material, that has not previously been reported in the Scottish Highlands. The geomorphological map provides the necessary foundation for elucidating the extent, dynamics and timing of former glaciation in the area.

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Glacial geomorphology; remote sensing; field mapping; upland plateau; the Gaick; Scotland

1. Introduction

Geomorphological mapping of glacial landforms in Britain and Ireland has allowed the compilation of vast inventories of geomorphological data that have been used to produce reconstructions of former ice masses and provide insights into former glacier dynamics (see Bickerdike, Evans, Ó Cofaigh, & Stokes, 2016; Bickerdike, Evans, Stokes, & Ó Cofaigh, 2018; Bickerdike, Ó Cofaigh, Evans, & Stokes, 2018; Clark et al., 2004, 2018; Hughes, Clark, & Jordan, 2014, and references therein). In the case of discrete ice masses (corrie glaciers, valley glaciers and icefields) relating to the Younger Dryas (~12.9–11.7 ka), geomorphological mapping has facilitated three-dimensional palaeoglaciological reconstructions and, in turn, calculations of palaeoclimatic variables (e.g. Ballantyne, 2002a, 2007a, 2007b; Barr, Roberson, Flood, & Dortch, 2017; Bendle & Glasser, 2012; Benn & Ballantyne, 2005; Boston, Lukas, & Carr, 2015; Finlayson, Gollidge, Bradwell, & Fabel, 2011; Lukas & Bradwell, 2010). Despite this large body of research, there remain several areas in Britain and Ireland where past glacial events remain poorly constrained, in large part due to the paucity of detailed geomorphological mapping in those areas.

This situation is exemplified by the Gaick, a dissected plateau in the Central Grampians, Scotland (Figure 1). The Gaick has proven to be an enigmatic and rather controversial area, with widely differing interpretations of the glacial sediment-landform record having been

proposed. Three main conceptual models of former glaciation have previously been suggested for the Gaick: (i) an extensive Lateglacial (~14.7–11.7 ka) re-advance which occupied much of the central and southeast Grampians (Charlesworth, 1955); (ii) advance and retreat of an extensive, locally-sourced Younger Dryas plateau icefield (Sissons, 1974); and (iii) retreat of the last British–Irish Ice Sheet across the plateau (Merritt, 2004; Merritt, Lukas, & Mitchell, 2004; Smith, Merritt, Leslie, Krabbendam, & Stephenson, 2011).

The three conflicting interpretations of glacial events in the Gaick partly reflect the absence of a detailed geomorphological map for the area. Although the Quaternary deposits and many associated landforms were mapped at a scale of 1: 25,000 in the 1990s by the British Geological Survey (BGS, 2008a, 2008b; Smith et al., 2011), the maps only depict the spatial coverage of moraine assemblages (i.e. the moraines are mapped as a ‘unit’), rather than individual moraines. Similarly, the earlier geomorphological mapping of Sissons (1974) did not identify individual moraine mounds and ridges, instead identifying entire tracts of ‘hummocky moraine’ using a stippled pattern. Consequently, it is challenging to assess any systematic variations in the moraine patterns (e.g. upvalley changes in moraine orientation, shape and/or style) and concomitant changes in the spatial distribution of other sediment-landform assemblages, which can be important strands of evidence for differentiating

extent, style and (where possible) thickness of prominent phases of glaciation. These three themes will be examined in future publications, drawing on the geomorphological evidence presented here.

Our main research focus is on establishing the extent, style and dynamics of discrete, locally-sourced ice masses (i.e. corrie glacier to ice-cap scale) during the Last Glacial-Interglacial Transition (~16–8 ka), with special reference to potential Younger Dryas ice masses. To this end, the geomorphological mapping focused on sediment-landform assemblages that could potentially be utilised for glacier reconstruction using established morphostratigraphic procedures (see Boston et al., 2015; Lukas, 2006). These sediment-landform assemblages include *inter alia* ice-marginal ('hummocky') moraines, ice-contact deposits (e.g. kame terraces), glaciolacustrine deposits (e.g. Gilbert-type deltas), meltwater channels, upslope limits of glaciogenic sediment cover ('drift limits'), terraces, and periglacial landforms (e.g. solifluction lobes, mountain-top detritus, talus cones). Accordingly,

geomorphological features pertaining to long-term glacial landscape evolution (e.g. glacial breaches) were not included on our map. Long-term landscape evolution has a long history of research in the Gaick and interested readers are directed to previous publications (see Hall & Jarman, 2004, and references therein).

3. Methods

A combination of field mapping and interpretation of remotely-sensed datasets (hereafter 'remote mapping') is typically used to map the geomorphology of alpine and plateau-style ice masses (see Chandler et al., 2018, for review). This permits a holistic approach to mapping that combines the advantages of the different methods and datasets to enhance accuracy and robustness. Following the approach and recommendations synthesised by Chandler et al. (2018), geomorphological mapping of the study area was conducted through a combination of field and remote mapping (Figures 2 and 3).

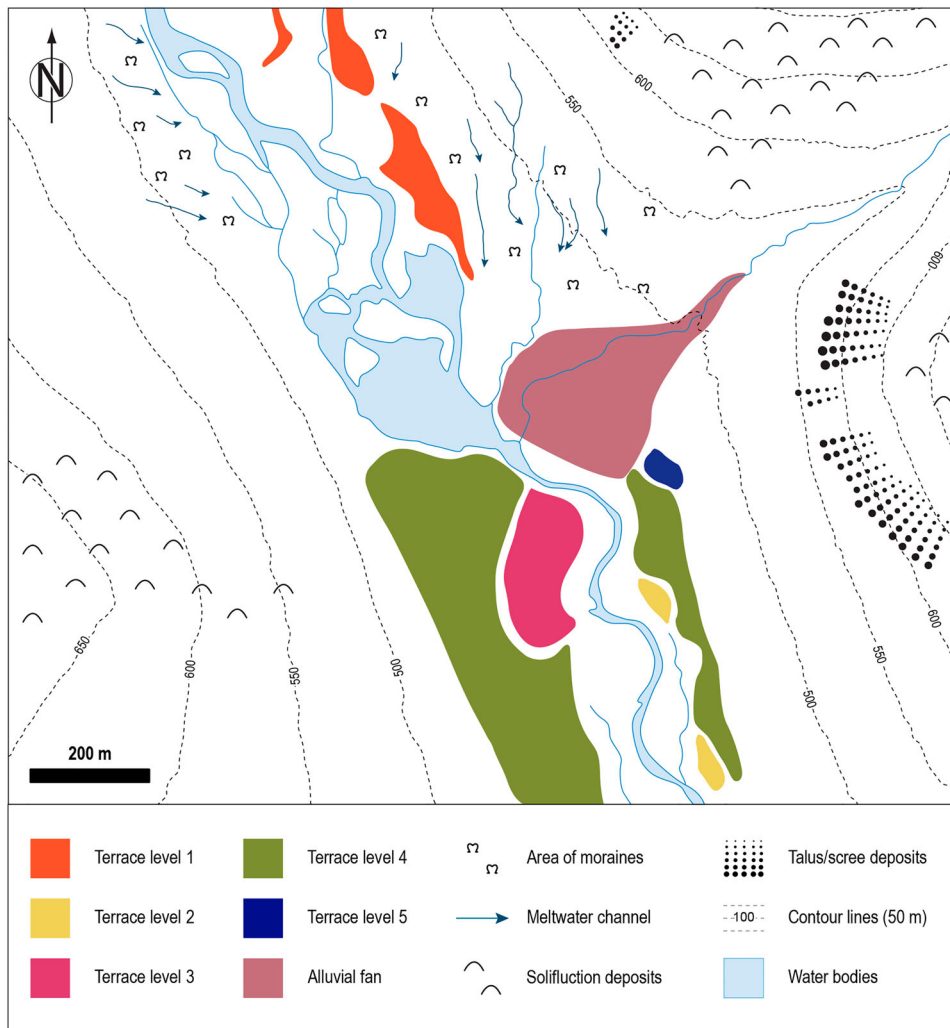


Figure 2. Digitised example of mapping conducted in the field for part of Glen Bruar. Field mapping allowed the distinction between multiple terrace levels that were not identifiable from remotely-sensed data. Note, field mapping of moraines in this study predominantly involved establishing areas of moraines for later detailed mapping using aerial photographs. Mapping of the moraines from the aerial photographs was later verified in the field. Contours were derived from the NEXTMap Great Britain™ dataset (Intermap Technologies®).

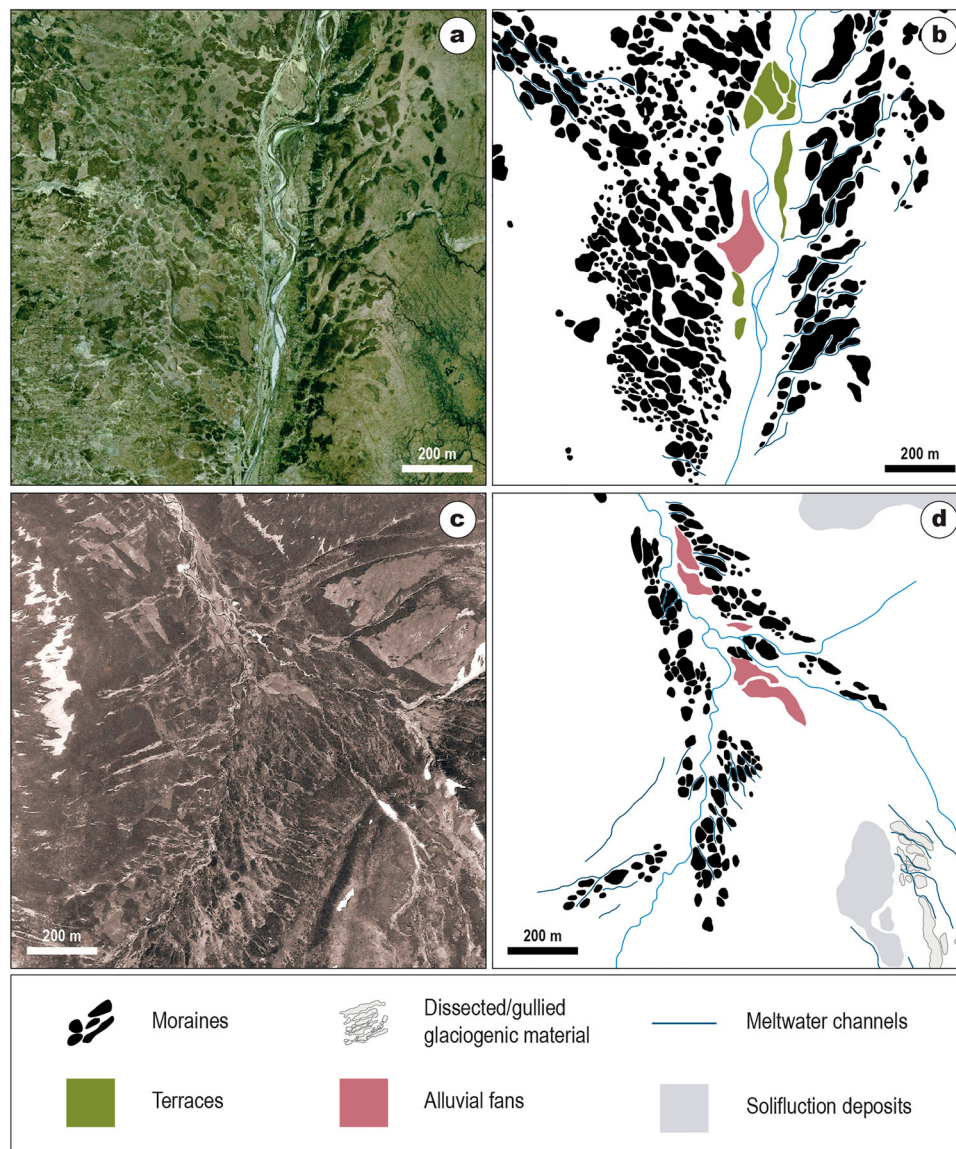


Figure 3. Examples of remote mapping from digital and analogue aerial photographs for Glen Edendon (a and b) and Coire Chais (c and d). (a) Extract from Getmapping® digital aerial photographs for Glen Edendon. (b) Associated digital (on-screen) mapping from the digital aerial photographs. (c) Scanned and georeferenced aerial photograph extract from the All Scotland Survey collection (sortie: 62088; print: 008; date: 10/06/1988). (d) Accompanying digitised version of a scanned and georeferenced acetate overlay.

3.1. Field mapping

Field mapping was performed on topographic base maps with a scale of 1: 10,000 (Figure 2), enlarged from an Ordnance Survey (OS) topographic map (Explorer Sheet 394). The locations of landforms were recorded with reference to ‘landmarks’ that were clearly identifiable both in the field and on the base maps, following standard field mapping procedures (see Chandler et al., 2018). In some cases, locations were verified using a handheld Global Positioning System (GPS; Garmin eTrex® 10), with a horizontal accuracy of ± 3 m. Additional information between these known reference points was then interpolated and marked on the field maps. In addition to contour inflections (which may mark the location and boundaries of prominent ridges, for example), pacing and/or estimation of lengths, heights and widths

was also employed to accurately record the size of landforms on the base maps. The detailed field mapping allowed the identification of features that are difficult or impossible to detect on remotely-sensed data, including ice-flow directional indicators (e.g. striae), low-amplitude moraines, upslope limits of glaciogenic sediment (‘drift limits’) and different terrace altitudes (cf. Lukas & Lukas, 2006).

During field mapping, natural sedimentary exposures were also identified and examined. Detailed analyses of selected exposures were conducted in a targeted approach, although the availability of sedimentary exposures was partly an influence. With the primary focus of our research on the extent and style of glaciation (see Section 2; Chandler, 2018), rather than a spatially extensive examination of a specific landform (e.g. Benn, 1992; Lukas, 2005), sections

through landforms either demarcating or in close proximity to inferred glacial limits were mainly selected for investigation. Detailed sedimentological investigations involved section logging, lithofacies analysis, as well as clast shape and structural geological analyses, following established procedures (e.g. Evans & Benn, 2004; Gribenski et al., 2016; Lukas, 2005; Lukas et al., 2013). Detailed discussions of sedimentary processes and their implications are beyond the scope of this paper; thus, section logs, descriptions and interpretations will be presented in future publications.

3.2. Remote mapping

Three primary remotely-sensed datasets were used in the production of the *Main Map*, namely (i) a Digital Surface Model (DSM) from the NEXTMap Great Britain™ dataset (hereafter 'NEXTMap DSM'), (ii) digital colour aerial photographs, and (iii) hard-copy stereoscopic aerial photographs. Additionally, the primary datasets were supplemented by viewing imagery available via Microsoft® Bing™ Maps and three-dimensional visualisation of landforms in Google Earth™ Pro.

The NEXTMap DSM is a georeferenced topographic model that has a pixel size of 5 m. The horizontal accuracy of the DSM is 2.5 m root mean square error (RMSE), whilst the vertical accuracy is 1.0 m RMSE. For mapping and analytical purposes, the NEXTMap DSM data were converted into hillshaded relief models, using the spatial analyst tools in ESRI® ArcMap™ 10.3.1. An illumination angle of 30° and azimuths of 45° and 315° have been suggested as optimal settings for visualisation (e.g. Smith & Clark, 2005), and these recommendations were followed in the present study. The NEXTMap DSM was primarily used for reconnaissance purposes and to generate the topographic data for the *Main Map*, rather than detailed geomorphological mapping (see Section 4).

Remote mapping was largely conducted using orthorectified, seamless digital aerial photographs with a ground sampled distance (GSD) of 0.25 m per pixel (Getmapping®/UKP), as in recent studies elsewhere in the Scottish Highlands (e.g. Finlayson et al., 2011; Pearce, Rea, Bradwell, & McDougall, 2014). The aerial photographs were made available as pre-processed, orthorectified products, with the processing procedures and errors unknown. To circumvent any potential artefacts/errors in the dataset, a quality assurance check was made by cross-checking the mapping with the NEXTMap DSM and OS topographic data. Mapping from the digital aerial photographs was performed by digitally drawing geomorphological features directly in ESRI® ArcMap™, with individual vector layers created for each feature (Figure 3).

Analogue (hard-copy) aerial photographs (~1:24,000 scale) from the *All Scotland Survey 1988/89* collection were also examined using a mirror stereoscope

with 3x magnification. These panchromatic, vertical aerial photographs generally show a good tonal contrast that is typically superior to that of the Getmapping® digital aerial photographs, thus making them valuable tools in locating small glacial landforms, such as moraines (e.g. Boston, 2012a, 2012b; Lukas, 2003; Lukas & Lukas, 2006). Unfortunately, the aerial photographs did not provide complete coverage of the study area; thus, this dataset was used to check and enhance mapping in selected valleys/corries (where photographs were available). Mapping from the analogue aerial photographs was conducted on acetate overlays, which were scanned and then georeferenced to prominent reference points on the digital aerial photographs using the georeferencing tools in ESRI® ArcMap™.

4. Map production

To produce the *Main Map*, an iterative process was employed, involving several consultations of the field mapping and remotely-sensed data (Figure 4). This provided a robust approach to mapping that has broadly been employed in several previous studies in Scotland (e.g. Benn & Ballantyne, 2005; Boston, 2012a, 2012b; Finlayson et al., 2011; Lukas & Lukas, 2006; Pearce et al., 2014). The process of assimilating the data from the various methods is outlined below.

The initial reconnaissance stages of mapping involved a systematic examination of the NEXTMap DSM, along with consultations of topographic, geological and existing geomorphological maps. Given the superior detectability of landforms on aerial photographs and in the field, no independent mapping *sensu stricto* was undertaken using the NEXTMap DSM to save duplication of effort. However, the latter dataset is useful for identifying meltwater channels (e.g. Evans, Hughes, Hansom, & Roberts, 2017; Hughes, Clark, & Jordan, 2010) and was thus used in tandem with the digital aerial photographs for this purpose.

Following the initial preparatory stage, reconnaissance-level mapping of the study area was conducted using Bing™ Maps imagery before the first field season. This field season initially focused on identifying areas for detailed mapping and route planning, before targeted 1:10,000 scale field mapping was undertaken. Field mapping and aerial photograph interpretation were then conducted in an alternating process: the mapping was performed such that areas specifically targeted for field mapping were subsequently mapped remotely. This enabled consultation of field maps throughout the remote mapping process to ensure all features identified in the field were mapped and to minimise any errors which may arise from misinterpretation of features (cf. Chandler et al., 2018).

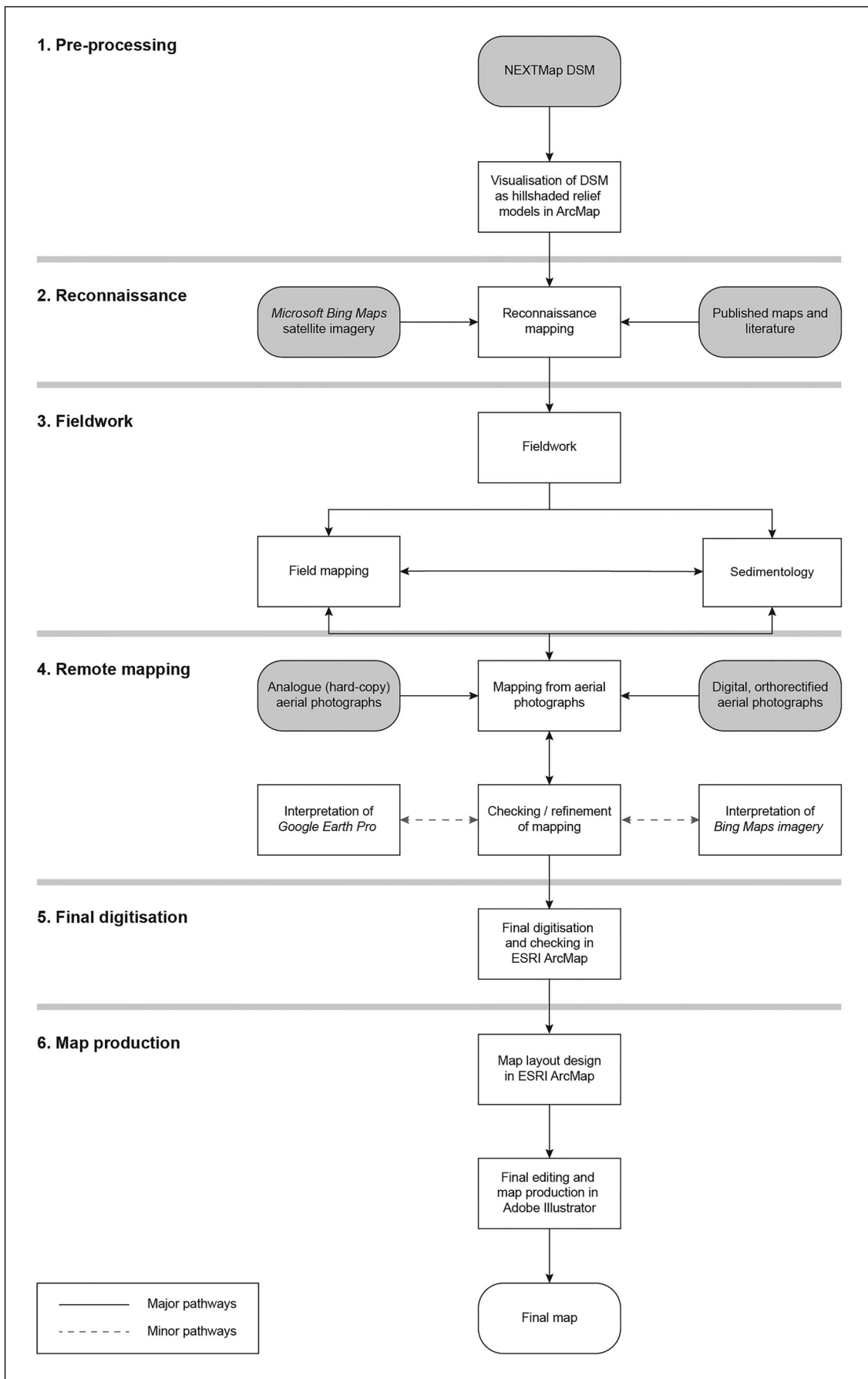


Figure 4. Workflow diagram summarising the datasets and methods used in the production of the final geomorphological map of the Gaick (**Main Map**). Note, fieldwork (3) and remote mapping (4) were carried out alternately as part of an iterative process, as shown by the two-way arrows.

The geomorphological mapping was finalised through aerial photograph interpretation, in consultation with field maps and earlier versions of remote mapping. In particular, moraines, meltwater channels and dissected glaciogenic material (see Table 1) were mapped almost exclusively using the aerial photographs, since these offered the best means of accurately mapping their position and planform (cf. Boston, 2012a, 2012b; Lukas & Lukas, 2006). Conversely, other landforms were more easily and readily mapped in the field (e.g. river terraces, ‘drift limits’). Field mapping was incorporated into the [Main Map](#) by digitising scanned field maps. Thus, the final map is the product of an iterative process that assimilated mapping from several approaches, exploiting their respective advantages (Figure 5).

The [Main Map](#) was created using a combination of GIS and graphics software. Prior to exporting the mapping and map layout from ESRI® ArcMap™, the position of the final geomorphological mapping was cross-checked against the NEXTMap DSM and manually adjusted to match the DSM as necessary. This is to enable direct comparison and future integration of the mapping into databases of glacial landforms in Britain, which commonly use the NEXTMap DSM as a base layer (e.g. Bickerdike et al., 2016; Clark et al., 2018). Following adjustment of the mapping, contours were generated from the NEXTMap DSM and then smoothed using the cartographic tools in ESRI® ArcMap™. The final map layout was initially designed in the GIS software before export to Adobe® Illustrator™ CC, along with all the individual vector layers (geomorphological features and contours). The focus at this stage was on the final map design and ensuring optimal map presentation.

5. Geomorphology

The 1:46,000 scale geomorphological map of the Gaick ([Main Map](#)) records a variety of glacial sediment-landform assemblages that are defined in Table 1 and summarised below. These include moraines, dissected glaciogenic material, meltwater channels, and glaciolacustrine deposits. The [Main Map](#) also includes associated fluvial and periglacial landforms (e.g. river terraces, solifluction lobes), which are potentially useful for differentiating former distinct periods of glaciation (cf. Lukas, 2006).

5.1. Moraines

Several valleys in the Gaick, along with areas around its periphery (e.g. Glen Geldie), contain an abundance of moraines (Figures 3 and 6; [Main Map](#)). Most of the moraines display clear spatial patterns in which the crestlines of mounds and ridges can be extrapolated to form chains that trend obliquely downslope,

frequently forming arcuate or chevron-shaped patterns when linked to moraines on the opposite side of the valley. Thus, most of the moraines are interpreted as ice-marginal (or latero-frontal) moraines, recording former positions of glacier margins (e.g. Bennett & Boulton, 1993a, 1993b; Boston, 2012b; Lukas and Benn, 2006).

The moraines in the Gaick could all be classified under the geomorphological umbrella term ‘hummocky moraine’, as was previously done by [Sissons \(1974\)](#) and by many authors in other regions of Scotland (see [Lukas, 2005, 2006](#), and references therein). However, ‘hummocky moraine’ is not useful as a descriptive term due to potential confusion with the genetically-distinct ‘hummocky moraine’ deposited by ice sheet lobes through widespread *in situ* stagnation (cf. [Eyles, Boyce, & Barendregt, 1999](#); [Hoppe, 1952](#); [Lukas, 2005](#)). Moreover, ascribing the term ‘hummocky moraine’ would be an oversimplification that does not recognise the variations in moraine patterns across the Gaick, which are outlined below.

Overall, two broad moraine patterns can be distinguished in the Gaick. Firstly, in the lower parts of the southern valleys (e.g. Glen Edendon, Glas Choire), topographically-discordant and cross-cutting moraines are observed (Figure 6(d)). Moraines in this category descend obliquely downslope in an *upvalley* direction (i.e. they are topographically-discordant) and occasionally curve towards the centre of the valley. Cross-cutting and overprinted moraines are also present in the northeastern Gaick, documenting eastwards (downvalley) retreat of ice in Glen Geldie. The topographically-discordant and overprinted moraines are inconsistent with outward radial flow of local ice masses from the Gaick and therefore reflect the interplay of regional ice and local, Gaick, ice.

The second, and dominant, spatial pattern observed in the Gaick is that of topographically-concordant moraines (i.e. they descend downslope in a downvalley direction) organised as inset transverse chains. These chains of moraine mounds and ridges can be connected with chains on the opposite slopes to form nested concentric arcuate loops. Moraines of this type occur in the higher parts of the catchments, sometimes continuing to the very upper parts of the catchments and to the plateau edge, providing evidence for plateau-sourced ice (cf. [Boston, 2012b](#); [Boston et al., 2015](#); [McDougall, 2001](#)). This spatial pattern has been observed in many areas throughout upland Britain (e.g. [Benn & Ballantyne, 2005](#); [Bennett & Boulton, 1993a, 1993b](#); [Benn, Lowe, & Walker, 1992](#); [Bickerdike, Ó Cofaigh et al., 2018](#); [Boston, 2012a, 2012b](#); [Finlayson et al., 2011](#); [Lukas and Benn, 2006](#); [McDougall, 2001, 2013](#)).

Within the second overarching category, further variations in the moraine pattern and landform associations are recognised. The outermost moraines in the second category may be restricted to a narrow band

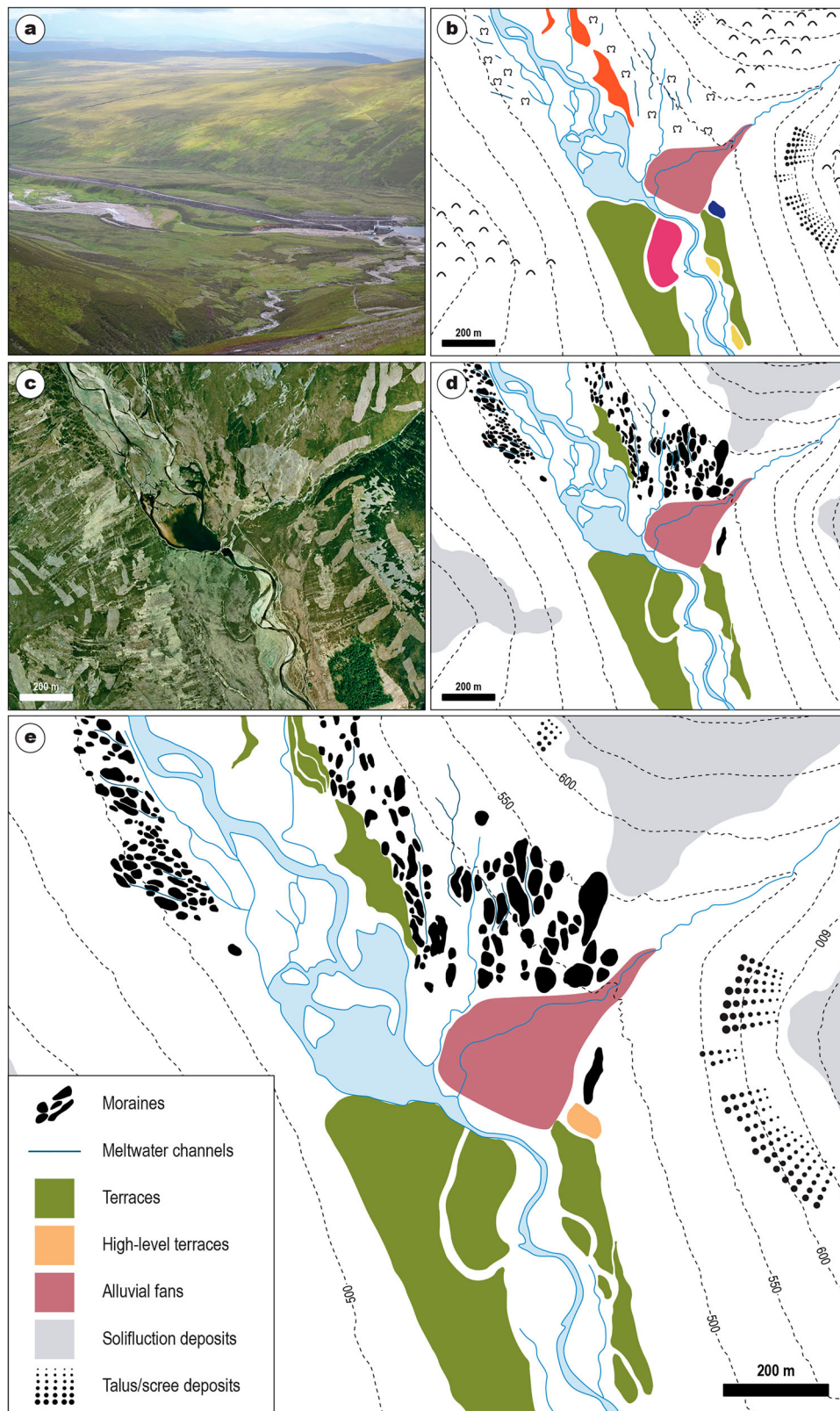


Figure 5. Example from part of Glen Bruar illustrating the assimilation of the field mapping (a and b) and aerial photograph interpretation (c and d) to produce the final geomorphological map (e). Key for (b) is the same as in Figure 2. Note, terrace levels were simplified from the field mapping for the final map. The aerial photograph extract in (c) is from the Getmapping® digital, orthorectified aerial photographs. Contours were derived from the NEXTMap Great Britain™ dataset (Intermap Technologies).

at the slope foot and do not trend up the valley slopes in the lower to middle parts of the Gaick valleys, with chains of moraines exhibiting very shallow average gradients (often ~ 5 m per 100 m). Conversely, in the higher parts of the valleys, transverse chains of

moraines often have considerably steeper average gradients (~ 15 – 20 m per 100 m) and are found ascending the valley slopes. Additionally, there is typically a clear contrast in the slope features, with the shallower, outer moraines associated with scree- or talus-covered

Table 1. Summary of the key landform types depicted on the [Main Map](#) and criteria used to identify them.

Landform type	Morphology / planform	Composition	Interpretation	References
Moraines	<ul style="list-style-type: none"> Ridges and mounds arranged as inset chains that trend obliquely downslope, often curving towards the valley centre 	<ul style="list-style-type: none"> Typically contain stacked layers of debris flows and fluvial 'wash' horizons, with varying degrees of proglacial and subglacial glaciotectionism evident 	<ul style="list-style-type: none"> Deposited as terrestrial ice-contact fans during oscillatory retreat Glaciotectionic structures indicate minor re-advances (proglacial push) and more substantial re-advance (overriding and subglacial shear) 	<p>Benn (1992), Lukas (2005), Benn and Lukas (2006), Boston (2012b) See Chandler (2018) for detailed descriptions and interpretations</p>
Dissected glaciogenic material	<ul style="list-style-type: none"> Positive-relief elements (sediment accumulations) and intervening channels that have 'jigsaw-like' appearances The positive-relief elements are not arranged as chains indicative of former glacier margins (cf. moraines) Typically, they exhibit subdued, low-relief forms (often 1–3 m high) 	<ul style="list-style-type: none"> Glaciogenic sediments of all types possible Sequences of proglacial outwash sediments identified in available exposures 	<ul style="list-style-type: none"> Dissection of pre-existing, undulating glaciogenic sediments into ridges and mounds by fluvial activity Where exposures are available, these indicate a proglacial glaciofluvial environment 	<p>Previously unreported See Chandler (2018) for detailed descriptions and interpretations</p>
Ice-contact deposits	<ul style="list-style-type: none"> Variiously shaped mounds, ridges, terraces and fans Ridges, mounds and terraces occur in isolated clusters on the higher parts of the valley sides These are arranged as chains that trend across the hillsides at low angles Found intimately associated with meltwater channels 	<ul style="list-style-type: none"> Glaciofluvial sediments (inferred) 	<ul style="list-style-type: none"> Positive-relief elements deposited at, or along, an ice-margin by glacial meltwater 	<p>Brodzikowski and van Loon (1991), Livingstone et al. (2010), Evans et al. (2017)</p>
Glaciolacustrine deposits	<ul style="list-style-type: none"> Ridges, mounds and terraces of variable forms containing glaciolacustrine sediments 	<ul style="list-style-type: none"> Various subaqueous sediments, e.g. subaqueous debris flows, gravel clinoforms (foresets), turbidites (bottomsets) 	<ul style="list-style-type: none"> Deposition as Gilbert-type deltas and grounding-line fans Indicative of former ice-damming 	<p>Benn and Evans (1993), Benn (1996), Brazier, Kirkbride, and Gordon (1998), Evans, Hiemstra, and Cofaigh Ó (2012), Evans, Rother, Hyatt, and Shulmeister, (2013) See Chandler (2018) for detailed descriptions and interpretations Lukas (2006)</p>
Upslope limit of glaciogenic sediment ('drift limits')	<ul style="list-style-type: none"> Abrupt transition in the sediment cover, with sediment accumulations either markedly thinner or completely absent in upslope parts 	<ul style="list-style-type: none"> Glaciogenic sediment (undifferentiated) 	<ul style="list-style-type: none"> Represent the vertical limit of a former glacier surface 	
Glacial meltwater channels	<ul style="list-style-type: none"> Erosional benches perched on steep valley slopes ('one-sided channels') Channels <i>sensu stricto</i> ('two-sided channels') cut into sediments or bedrock on valley sides, in valley bottoms or on plateau surfaces Series of (sub)parallel channels that trend obliquely downslope Networks of sinuous channels on plateau surfaces with undulatory long profiles 	<ul style="list-style-type: none"> n/a 	<ul style="list-style-type: none"> <i>Ice-marginal (lateral) meltwater channels:</i> one-sided and two-sided channels that descend obliquely downslope <i>Subglacial meltwater channels:</i> networks of sinuous channels, or chutes that descend directly downslope 	<p>Sissons (1961), Greenwood et al. (2007)</p>

(Continued)

Table 1. Continued.

Landform type	Morphology / planform	Composition	Interpretation	References
	<ul style="list-style-type: none"> Chutes that descend directly downslope 			
Solifluction deposits	<ul style="list-style-type: none"> Sheets of frost-weathered regolith that terminate downslope at a steep step (or 'riser') Solifluction lobes occur where the gradient increases downslope, with lobate sheets overriding each other and isolating individual lobes 	<ul style="list-style-type: none"> Frost-weathered regolith 	<ul style="list-style-type: none"> Represent the downslope movement of boulders, sediments and soils due to seasonal freezing and thawing May indicate ice-free areas during last glacial phase, or areas that were covered by cold-based ice 	Ballantyne and Harris (1994), Lukas (2006), Ballantyne (2008), Boston et al. (2015)
Mountain-top detritus	<ul style="list-style-type: none"> Range of landforms associated with frost-weathered regolith that mantles summits and high plateaux Mountain-top detritus is divisible into two broad categories: (i) block deposits and (ii) debris-mantled surfaces Includes blockfields (or <i>felsenmeer</i>) 	<ul style="list-style-type: none"> Frost-weathered regolith 	<ul style="list-style-type: none"> Reflects intense periglacial activity (frost weathering) May indicate ice-free areas during last glacial phase, or areas that were covered by cold-based ice 	Ballantyne and Harris (1994), Ballantyne (1998), Lukas (2006), Boston et al. (2015)
Scree/talus	<ul style="list-style-type: none"> Accumulations of debris on steep valley slopes at the foot of rockwalls. May take three forms: (i) talus sheets; (ii) talus cones; and (iii) coalescing talus cones, where talus cones intersect laterally 	<ul style="list-style-type: none"> <i>Scree</i>: minor or patchy slope covers of predominantly, unvegetated coarse debris, irrespective of location <i>Talus</i>: accumulations of debris at the foot of rockwalls 	<ul style="list-style-type: none"> <i>Talus sheets</i> indicate fairly uniform delivery of rockfall material <i>Talus cones</i> indicate rockfall has been concentrated or funnelled down a gully 	Ballantyne and Harris (1994), Lukas (2006), Ballantyne (2008), Boston et al. (2015)
Terraces	<ul style="list-style-type: none"> <i>Terraces</i>: raised, relatively flat areas located immediately adjacent to, or near, a stream or river <i>High-level terraces</i>: benches situated away from modern drainage and/or have risers that are of much greater height 	<ul style="list-style-type: none"> Alluvial, glaciofluvial (outwash) or glaciolacustrine sediments 	<ul style="list-style-type: none"> The result of periods of aggradation and incision Distinct changes in terraces may correlate with former glacier limits, reflecting strong upstream control exerted by glaciers 	Lukas (2006), Boston (2012b), Cordier, Adamson, Delmas, Calvet, and Harmand (2017)
Debris cones	<ul style="list-style-type: none"> Cone- or fan-shaped accumulations of sediment at the base of a steep gully, chute or tributary valley Typically, steeper than alluvial fans, which are similar morphologically 	<ul style="list-style-type: none"> Colluvial deposits: poorly sorted debris flow deposits 	<ul style="list-style-type: none"> Record the deposition of successive debris flows 	Brazier, Whittington, and Ballantyne (1988), Ballantyne (2002b, 2008)
Alluvial fans	<ul style="list-style-type: none"> Fan-shaped sediment accumulations located at stream junctions Typically, gentler, low gradient forms than debris cones 	<ul style="list-style-type: none"> Alluvial/fluvial deposits 	<ul style="list-style-type: none"> Reflect lateral spreading out of alluvial/fluvial sediment accumulations at stream junctions, broadening out from a central channel 	Brazier (1987), Summerfield (1991), Ballantyne (2002b)

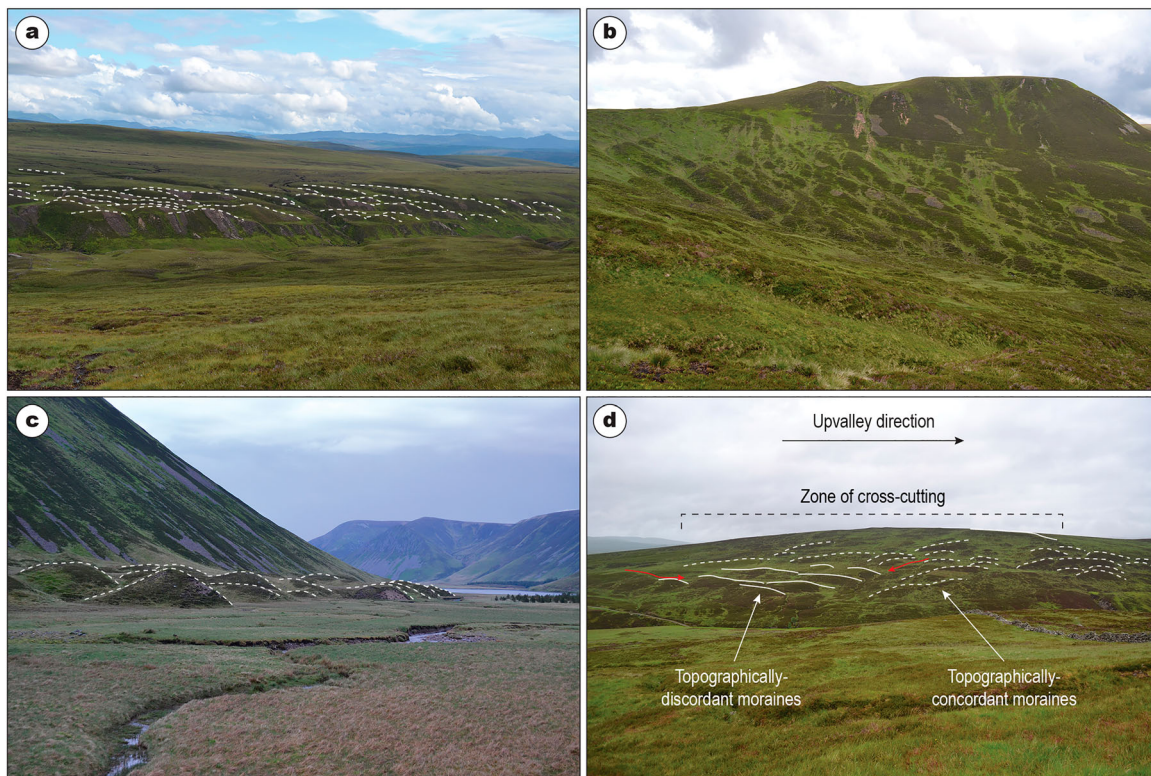


Figure 6. Field photographs of moraine suites in (a) Glen Edendon, (b) Coire Meadair, (c) Gaick Pass and (d) the valley of Allt Glas Choire. *Dashed arrowed lines* show the crestlines of topographically-concordant moraines (i.e. they descend downslope in a down-valley direction), *solid white lines* (in d) show the crestlines of topographically-discordant moraines (i.e. they descend downslope in an upvalley direction), and *red arrowed lines* (in d) indicate meltwater channels. Note the zone of cross-cutting moraines in (d).

slopes. Generally, no clear distinction can be made between moraines purely based on morphological characteristics.

5.2. Dissected glaciogenic material

A distinctive feature of several valleys in the Gaick is the presence of spreads of ‘dissected glaciogenic material’ and intervening channels, with exemplar assemblages evident in Glen Chulaibh, Glas Choire and Glen Tarf (Figure 7; Main Map). This sediment-landform assemblage, as defined in Table 1, has not previously been reported or mapped in the Scottish Highlands. It exhibits a jigsaw-like erosional planform, where a pre-existing, undulating glaciogenic sediment cover has been dissected into mounds and ridges by fluvial activity (i.e. the positive-relief elements are *erosional*, rather than constructional, products). In nearly all cases, dissection was the result of glacial meltwater activity, although pronival (snowmelt), paraglacial and/or postglacial fluvial activity is also likely to have had some influence on the final form of these sediment-landform assemblages. Paraglacial/postglacial processes (e.g. downslope movement and ‘spreading’) has led to final forms that are morphologically similar to moraines and ice-contact deposits. However, dissected glaciogenic material, as defined in this paper, can be clearly differentiated from moraines and ice-contact deposits (i.e. ‘constructional’ landforms)

based on their erosional, jigsaw-like planform (see also Table 1).

Analyses of two sedimentary exposures reveal that the positive surface expression of the dissected surfaces (i.e. the mounds and ridges) in Glas Choire comprise facies consistent with proximal proglacial outwash (Chandler, 2018). The sedimentological evidence, together with the incision of the outwash sediments by shallow meltwater channels, therefore suggest that the sediment-landform assemblage in Glas Choire was formed in a proximal glaciofluvial environment. This contrasts with available sedimentary evidence from moraines in the Gaick that demonstrates they contain stacked debris flows and intercalated fluvial ‘wash’ horizons, with varying degrees of proglacial and subglacial glaciotectionism evident (see Chandler, 2018). Thus, the moraines were constructed as terrestrial ice-contact fans at active glacier margins (cf. Benn, 1992; Boston, 2012b; Lukas, 2005).

The recognition of dissected glaciogenic material in the Gaick potentially has important implications for elucidating the extent and dynamics of former glaciation in the area, since valleys in the Scottish Highlands are typically characterised by ice-marginal moraines indicative of active, oscillatory glacier retreat (e.g. Benn et al., 1992; Bennett & Boulton, 1993a, 1993b; Bickerdike, Ó Cofaigh et al., 2018; Boston, 2012a, 2012b; Lukas and Benn, 2006). By contrast, the

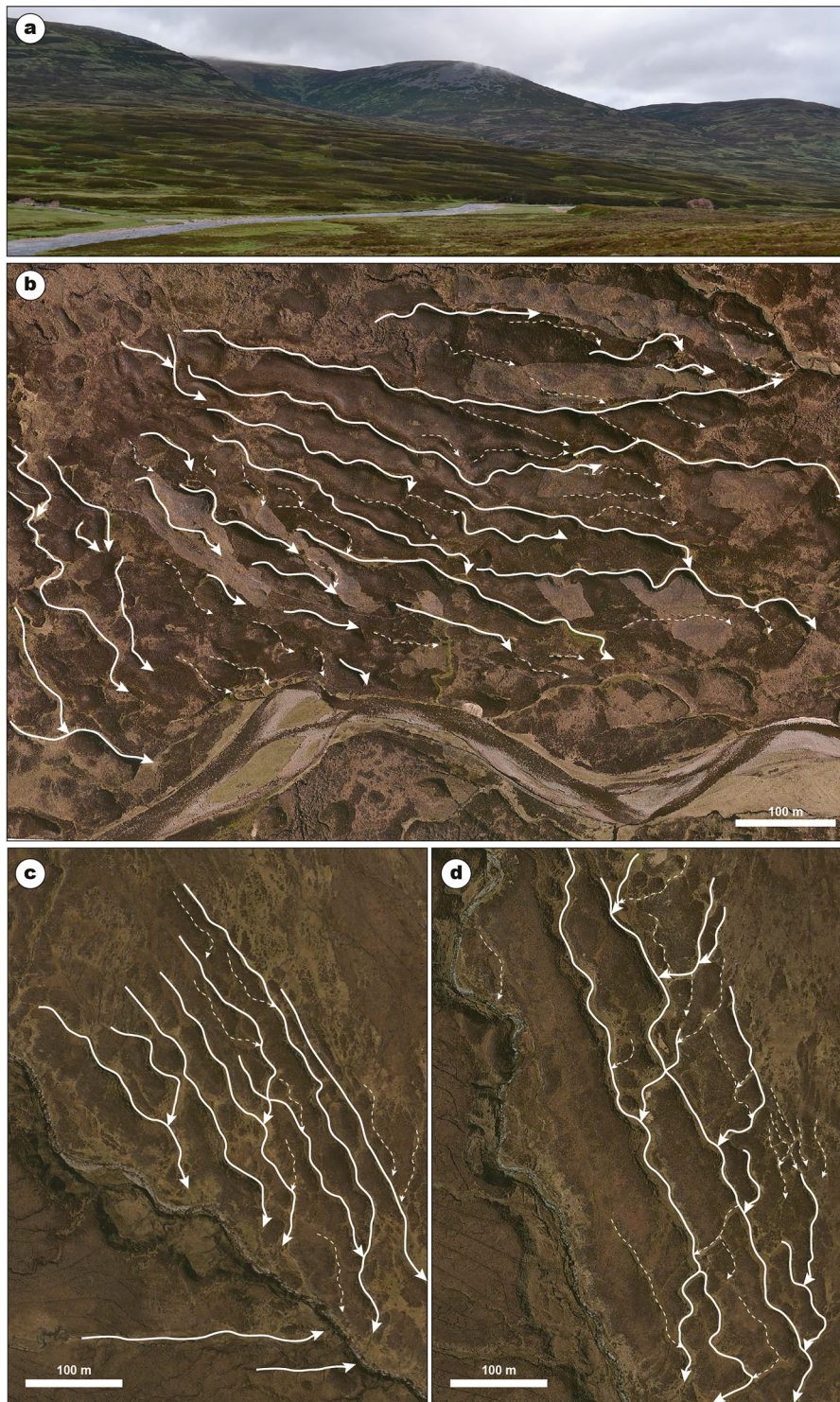


Figure 7. Example images of dissected glaciogenic material in the Gaick. (a) Overview photograph of dissected glaciogenic material on the northern side of Glen Tarf, eastern Gaick. From this angle, the dissected glaciogenic material is deceptively similar to nested lateral moraines. (b) Satellite imagery extract (Microsoft® Bing™ Maps; ©HERE) showing the planform of the assemblage shown in (a), with meltwater channels annotated. From this aerial view, the jigsaw-like appearance of the depositional elements is apparent. (c) and (d) Satellite imagery extracts (Microsoft® Bing™ Maps; ©HERE) showing the planform of dissected glaciogenic material in Glen Chulaibh, southwestern Gaick, with meltwater channels annotated. *Solid arrowed lines* indicate major channels; *dashed arrowed lines* indicate minor channels.

dissected glaciogenic material indicates widespread erosion of pre-existing glaciogenic sediment cover, rather than construction of successive, discrete ice-marginal landforms (moraines) during retreat. This is a very different sediment-landform and glaciodynamic

signature, possibly akin to fluvially-dissected sediment masses evident at High Arctic glaciers on Svalbard (cf. Lovell & Boston, 2017). The potential glaciodynamic implications of dissected glaciogenic material will be examined in detail in a future publication.

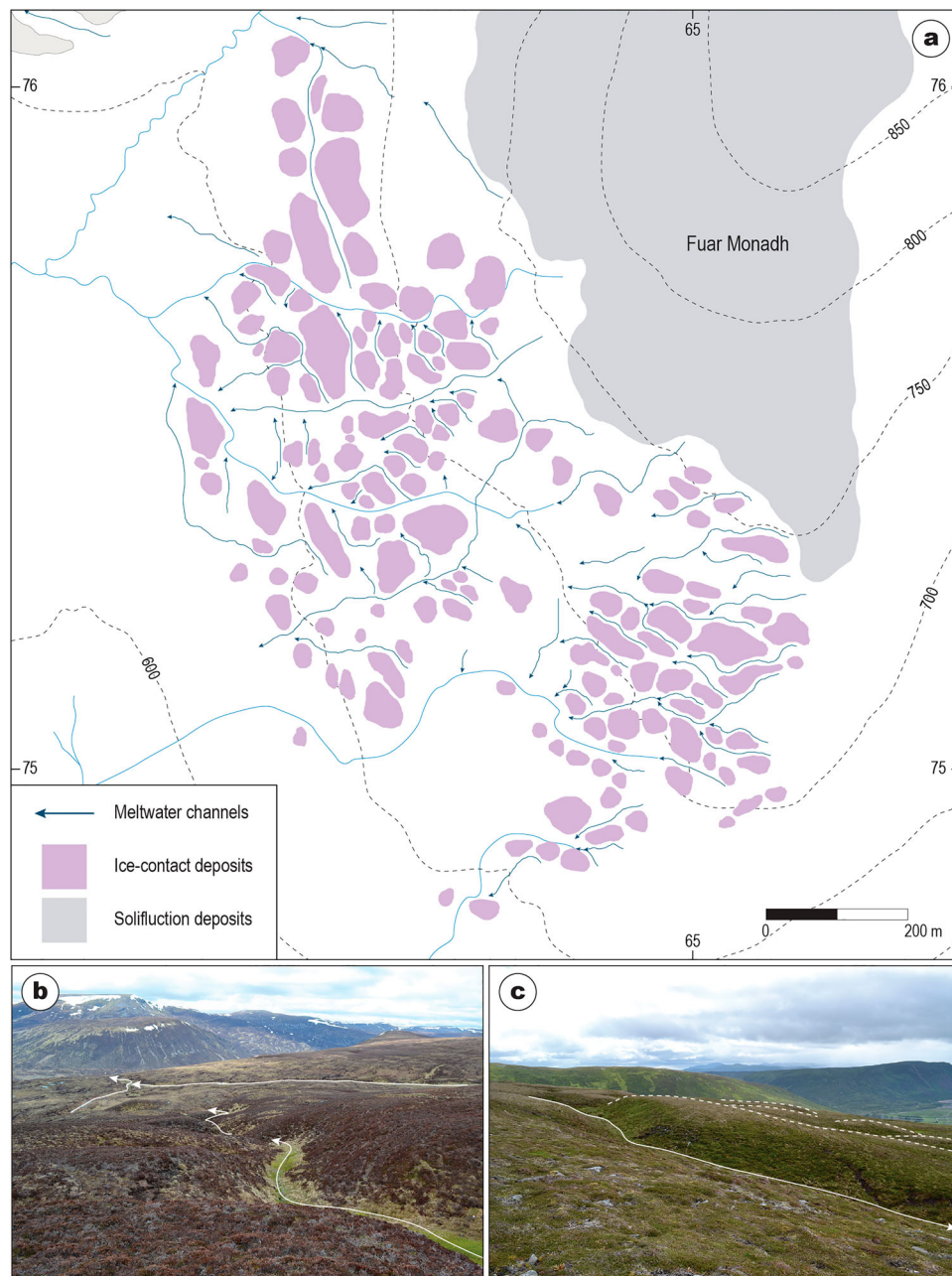


Figure 8. (a) Close-up geomorphological map of the meltwater channels and ice-contact deposits on the slopes of Fuar Monadh, near Coire Mhic-sith. Note how some of the meltwater channels make sharp, 90° turns. (b) Example photograph of the meltwater channels (*white arrowed lines*), illustrating the sharp turns. View is looking approximately west-northwestwards towards the Boar of Badenoch and A'Mharconaich. (c) Field photograph of the ice-contact deposits (*white dashed lines*) and intervening meltwater channels (*white arrowed lines*), looking southeastwards towards Druim Coire Mhic-sith.

5.3. Ice-contact deposits

This sediment-landform assemblage incorporates variously-shaped mounds, ridges, terraces and fans that are inferred to have been formed in intimate association with a glacier margin and deposited as positive-relief elements by glaciofluvial activity, i.e. these features are constructional (as opposed to dissected glaciogenic material: Section 5.2). A prominent area of ice-contact deposits occurs on the slopes of Fuar Mhoadh to the southwest of Coire Mhic-sith (NN 646 753). In this area, numerous flat- or dome-topped mounds and ridges occur (Figure 8; see also Section

5.6). These depositional landforms are ~15–150 m long, ~15–75 m wide and <2 m high, and chains of these mounds and ridges trend relatively uniformly across the hillside at very low angles. The ice-contact deposits are found in intimate association with several single-sided lateral meltwater channels that descend the hillside at similarly low angles, but there are numerous instances where the meltwater channels make sharp (nearly 90°) turns and plunge down the slope (see Section 5.6). Based on the arrangement and trend of the ice-contact deposits, and their association with ice-marginal meltwater channels, these landforms

are interpreted as kame terrace fragments (cf. Brodzkowski & van Loon, 1991; Evans et al., 2017; Livingstone, Evans, Cofaigh Ó, & Hopkins, 2010; Lukas & Merritt, 2004).

A glacial origin for the features described above has previously been contested. Benn and Ballantyne (2005, p. 582) argued that they were ‘produced by rock-mass creep, and the intervening “channels” are tensional crevices formed by downslope block displacement’ (i.e. the assemblage is a rock slope failure). However, no hitherto-recorded rock slope failures in the Gaick and mapped in this study (see *Main Map*) bear any similarity to this area, all of which occur in the psammites that dominate the bedrock geology of the Gaick (cf. Jarman, 2004). There are also no clear comparators elsewhere in Scotland (cf. Jarman, 2006). Notably, there are no strong indicators of failure, with no source scar/cavity, toe bulge or dislocation of drainage evident on the slopes of Fuar Mhonadh (cf. Holmes, 1984; Jarman, 2006). The simplest interpretation of the channels and intervening mounds is that they are meltwater channels and kame terrace fragments, as argued above.

5.4. Glaciolacustrine deposits

Evidence for the existence of former ice-dammed lakes in the Gaick is recognised in Coire Mhic-sith (NN 655 746) and at the site of the present-day Loch an Dùin (NN 723 801). In Coire Mhic-sith, evidence is in the form of glaciotectionised glaciolacustrine sediments, lake shorelines and lake overflow channels (cf. Benn & Ballantyne, 2005; Chandler, 2018; Lukas & Merritt, 2004; Phillips, Merritt, Auton, & Golledge, 2007). Northwards of the present-day Loch an Dùin, evidence for a former ice-dammed lake is found in the form of a Gilbert-type delta and a glaciotectionised grounding-line (or subaqueous outwash) fan (Chandler, 2018).

5.5 Drift limits

Distinct upslope limits of glaciogenic sediment cover (‘drift limits’; cf. Lukas, 2006, and references therein) are rare in the Gaick, with only a few evident. The two most prominent examples occur in Coire Chais (NN 696 840) and Gaick Pass (NN 733 823) (see *Main Map*). In Coire Chais, an upslope limit of the sediment cover, which ascends from ~550 m OD to ~610 m OD on the southwest-facing slope, can be traced from the outer limit of small, low-amplitude (<2 m high) and indistinct moraines. This ‘drift limit’ coincides with the downslope limit of extensive talus deposits. A conspicuous upslope limit of glaciogenic sediment in Gaick Pass grades from the outer moraines on the northern side of the valley, ascending northwestwards into Coire an Dubh-chadha and reaching ~580 m OD. This distinct upper limit coincides with the downslope limit of extensive screes beneath Creag an Dubh-chadha.

5.6. Meltwater channels

A large number of meltwater channels occur in the Gaick, both within the valleys and on the plateau surfaces. Many of the meltwater channels have been identified as ice-marginal (lateral) channels based on their orientation and association with other landforms: these features have downslope trending profiles and often intervene chains of moraines (see Section 5.1), occasionally curving towards the valley centre (cf. Boston, 2012a, 2012b; Greenwood, Clark, & Hughes, 2007). Predominantly, the lateral meltwater channels are shallow (frequently ~1–5 m deep), although they do attain depths of >15 m in some instances. For example, in Glen Edendon, there is a pronounced meltwater channel that is up to ~20 m deep and ~40 m wide (NN 715 765). Meltwater channel length is highly variable across the Gaick, ranging between ~50 m and ~1000 m (average ~170 m).

Subglacial meltwater channels have also been identified on the plateau, in the vicinity of An Sli-gearnach (786 m OD; NN 951 782) (*Figure 9*). The meltwater channels are small (often ~1 m deep and ~2 m wide) and form part a southwestwards-directed system that has a maximum altitude of ~830 m OD and descends to the valley bottom at ~650 m OD. In planform, these channels are arranged as a complex network of sinuous and anastomosing channels that frequently exhibit abrupt beginnings and terminations. Occasionally, some of the channels also take sharp (~90°) turns, with the new channel course heading directly downslope (*Figure 9*). These are all characteristics consistent with subglacial meltwater channels (cf. Greenwood et al., 2007; Sissons, 1961).

On the slopes of Fuar Monadh, near Coire Mhic-sith, there are also meltwater channels that initially formed as ice-marginal channels before descending into the subglacial realm (NN 646 753). This is indicated by their oblique trend across the hillside before abrupt, sharp turns (~90°) to descend directly downslope (cf. Livingstone et al., 2010; Sissons, 1961). Many of these channels also exhibit undulating long profiles, which is consistent with meltwater channels formed under hydrostatic pressure, i.e. subglacially.

5.7. Fluvial landforms

Several fluvial landforms have been recognised in the study area, namely alluvial fans and river terraces. Notable examples of alluvial fans occur in Gaick Pass, with a prominent fan emanating from Allt Bhrodainn and splaying out across the valley floor (NN 750 837) (*Main Map*). In some instances, the alluvial fans partially submerge and obscure moraines.

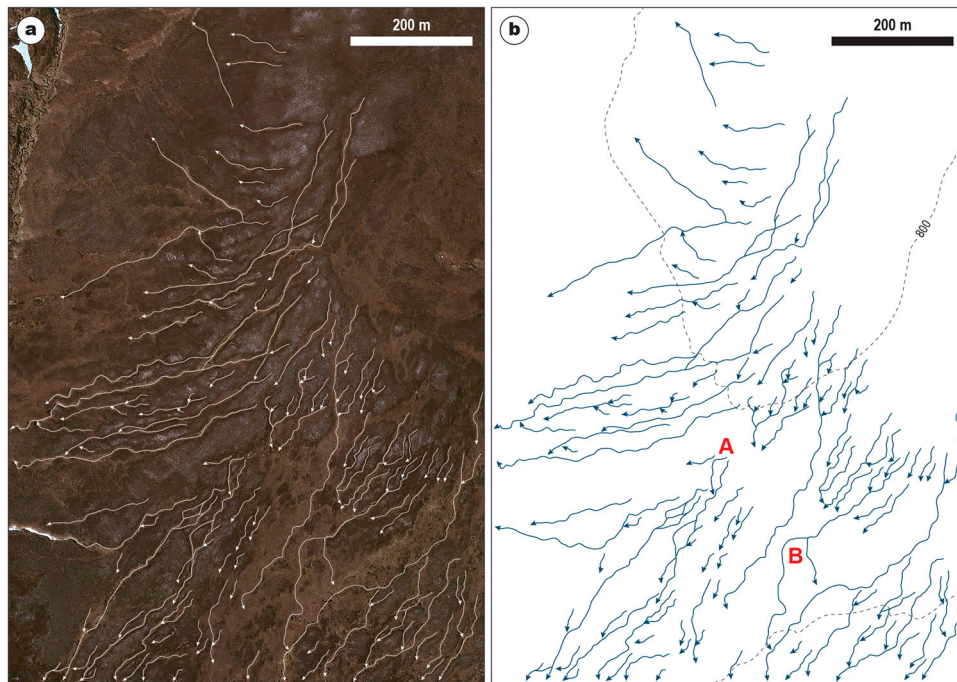


Figure 9. (a) Annotated satellite imagery (Microsoft® Bing™ Maps; ©HERE) showing the meltwater channels on the southern slopes of An Sligearnach. (b) Corresponding thematic geomorphological map of the same area, with the mountain-top detritus and solifluction lobes excluded for clarity (see [Main Map](#)). Capital letters indicate examples of meltwater channels that make sharp turns downslope.

River terraces occur in a number of the glens in the Gaick, with a particularly well-developed river terrace sequence found in Glen Bruar (NN 830 764) (see [Figure 5](#)). Low river terraces (~1–2 m above the current floodplain) extend into the upper parts of some valleys.

5.8. Periglacial landforms

Periglacial features, principally in the form of solifluction lobes and mountain-top detritus, occur on the majority of summits in the area and around the periphery of the plateau surfaces. There is a conspicuous change in the periglacial assemblages on the higher ground from west to east across the Gaick. In the west, solifluction lobes are found on the spurs surrounding the plateau, descending to elevations of ~700 m OD. Discontinuous spreads of mountain-top detritus (frost-shattered regolith) occur around the periphery of the plateau. East of Gaick Pass, solifluction deposits and mountain-top detritus become increasingly prevalent on the higher ground ([Figure 10](#); [Main Map](#)). The detritus comprises blockfields on some summits in the southeastern and northeastern sectors of the Gaick, including on Beinn Dearg (1008 m OD; NN 852 777) and An Sgarsoch (1006 m OD; NN 933 836). Frost-shattered bedrock outcrops are also encountered in the eastern, but not in the western, parts of the Gaick. Thick accumulations of talus/scree can be found in several valleys in the study area, sometimes extending to the slope foot. Extensive

deposits occur in the Gaick Pass, Gleann Diridh and Gleann Mhairc.

5.9. Rock slope failures

Several rock slope failures (RSFs) have been identified in the Gaick, with most of them clustered in the Gaick Pass and in the vicinity of Loch an Dùin ([Main Map](#)). These include arrested to sub-cataclastic slides and compressional slope deformation type RSFs, following criteria defined by [Jarman \(2006\)](#). An exemplar compressional slope deformation is recognised on the flank of A' Chaoirnich (NN 730 810) (see also [Jarman, 2004, 2006](#)), which has similarities with the largest RSF in the Scottish Highlands, Beinn Fhada (see [Jarman & Ballantyne, 2002](#)). The RSFs recorded on the [Main Map](#) have been reported previously (see [Holmes, 1984](#); [Jarman, 2004](#)).

6. Conclusions

The glacial geomorphological map presented here provides a detailed record of the glacial landforms in the Gaick that can be used to significantly enhance our knowledge of glacial and climatic events in the region. The spatial distribution of the glacial sediment-landform assemblages in the Gaick provides compelling evidence for at least one phase of local (valley or icefield) glaciation and the ‘unzipping’ of Gaick-sourced ice and external (regional) ice. Strong evidence for the influence of regional ice lobes includes the

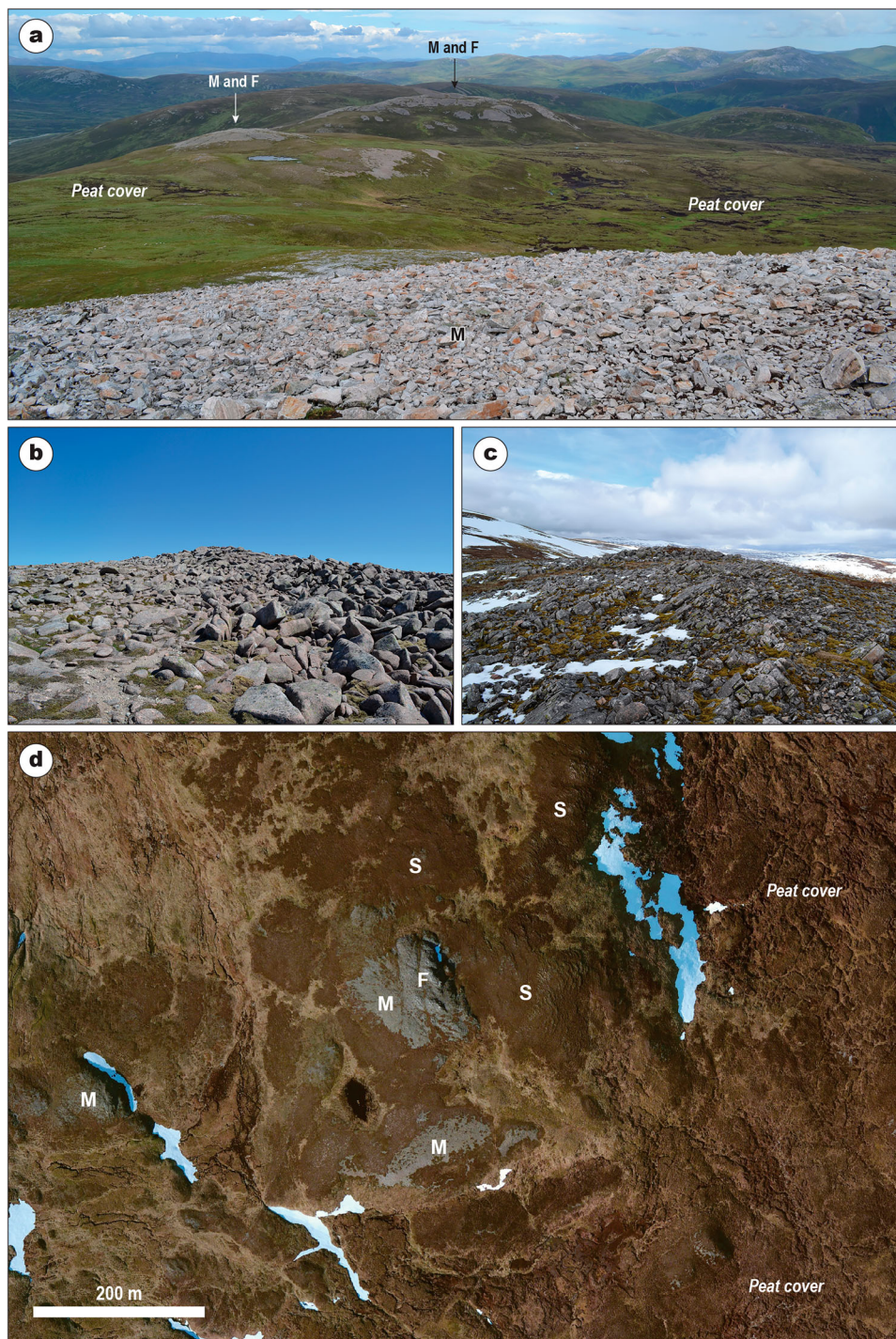


Figure 10. Example images of the periglacial landforms found on the higher ground in the southeastern sector of the Gaick. (a) Overview photograph of the higher ground from the slopes of Carn a' Chlamain, looking towards the northeast. Carn a' Chlamain is strewn with mountain-top detritus (M). Mountain-top detritus, along with frost-shattered bedrock outcrops (F), is evident on the summits of Conlach Bheag (middle ground) and Conlach Mhòr (background). Much of the surrounding ground is covered by peat. (b) Ground view of the blockfield on the slopes of Beinn Dearg. (c) Ground view photograph of a frost-shattered bedrock outcrop on Conlach Bheag. (d) Annotated satellite imagery extract of Conlach Bheag (Microsoft® Bing™ Maps; ©HERE). F = frost-shattered bedrock; M = mountain-top detritus; S = solifluction lobes.

presence of moraines and lateral meltwater channels that are incompatible with outward radial flow from the Gaick (e.g. topographically-discordant moraines in valley bottoms), whilst ‘unzipping’ events are documented by cross-cutting of moraines. Further upvalley, suites of topographically-concordant moraines and meltwater channels are present and provide a record

of former valley/outlet glacier fluctuations. This geomorphological evidence, together with variations in associated fluvial and periglacial landforms, will be employed to establish a morphostratigraphic framework for the Gaick glacial events in a subsequent publication. In turn, this will provide the important foundation for establishing a glacial chronology,

reconstructing the former ice masses, and assessing former glacier dynamics and palaeoclimatic conditions.

Software

ESRI® ArcMap™ 10.3.1 was used to (i) visualise and, where necessary, process the remotely-sensed datasets, (ii) perform on-screen geomorphological mapping, and (iii) assimilate the field and on-screen mapping. The mapping was exported to Adobe® Illustrator™ CC for final map production.

Data availability

The data that support the findings of this study are available from the corresponding author, BMPC, upon reasonable request.

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ORCID

Benjamin M. P. Chandler  <http://orcid.org/0000-0003-1532-9696>

Sven Lukas  <http://orcid.org/0000-0001-7744-9728>

Clare M. Boston  <http://orcid.org/0000-0002-8973-5366>

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