Processes of 'hummocky moraine' formation in the Gaick, Scotland: insights into the ice-marginal dynamics of a Younger Dryas plateau icefield

BENJAMIN M. P. CHANDLER, SVEN LUKAS AND CLARE M. BOSTON

Chandler, B. M. P., Lukas, S. & Boston, C. M.: Processes of 'hummocky moraine' formation in the Gaick, Scotland: insights into the ice-marginal dynamics of a Younger Dryas plateau icefield.

Younger Dryas ice-marginal ('hummocky') moraines in Scotland represent valuable terrestrial archives that can be used to obtain important information on ice-marginal dynamics and glacier thermal regimes during a period of rapid climatic change. In this paper, we present detailed sedimentological studies of Younger Dryas ice-marginal moraines in the Gaick, central Scotland, the former site of a spatially-restricted plateau icefield. Exposures demonstrate that moraines in the Gaick represent terrestrial ice-contact fans, with evidence of proglacial and subglacial glaciotectonisation, as reported elsewhere in Scotland. The exposures also reveal the influence of local hydrogeological conditions, with pressurisation of the groundwater system leading to the formation of hydrofracture fills within some moraines. Clast shape analysis shows that all the moraines contain debris consistent with transport in the subglacial traction zone. The sedimentological data, and the planform arrangement of the moraines as nested arcs or chevrons, indicate that retreat of the Younger Dryas Gaick Icefield outlets was incremental and oscillatory. This evidence strongly suggests a mainly temperate thermal regime and short glacier response times, but with narrow cold-ice zones near the margins facilitating the elevation of basal debris to the glacier surface. Analogous glaciodynamic regimes occur at modern ice-cap and plateau icefield outlets in Iceland and Norway, although there are significant differences in the nature of ice-marginal deposition. The glaciodynamic signature recorded by moraines in the Gaick has allowed us to shed new light on the ice-marginal dynamics and thermal regime of one of the most easterly Younger Dryas icefields in Scotland.

Benjamin M. P. Chandler (email: benjamin.chandler@port.ac.uk), School of Geography, Queen Mary University of London, Mile End Road, London E1 4NS, UK, and School of the Environment, Geography and Geosciences, University of Portsmouth, Buckingham Building, Lion Terrace, Portsmouth PO1 3HE, UK; Sven Lukas, Department of Geology, Lund University, Sölvegatan 12, 223 62 Lund, Sweden; Clare M. Boston, School of the Environment, Geography and Geosciences, University of Portsmouth, Buckingham Building, Lion Terrace, Portsmouth PO1 3HE, UK.

Ice-marginal moraines, as delineators of the position of a glacier margin at a given time, undoubtedly represent some of the most important empirical archives for examining past glacier retreat and ice-marginal dynamics. This is significant in the context of observed and predicted glacier retreat globally (e.g. IPCC 2013; Zemp *et al*. 2015), as moraine sequences potentially offer long-term records of glacier retreat that can considerably extend and/or contextualise short-term (often decadal-scale) observations of contemporary glacier change. Sequences of ice-marginal moraines have been used extensively as the basis for establishing glacier retreat chronologies, spanning a range of timescales from multi-decadal records of ice-marginal retreat during the 20th and 21st centuries (e.g. Bradwell 2004; Beedle *et al*. 2009; Lukas 2012; Bradwell *et al*. 2013; Chandler *et al*. 2016a, b) to centennial and millennial-scale chronologies of Pleistocene and Holocene glacier fluctuations (e.g. Bickerton & Matthews 1993; Bradwell *et al*. 2006; Kelley *et al*. 2014; Garcia *et al*. 2018; Hofmann *et al*. 2019). Moreover, moraines are important for elucidating the maximum limits of former glaciers, a requirement for glacier reconstruction (e.g. Lukas 2006; Boston *et al*. 2015; Chandler *et al*. 2019a).

Observations of moraine formation in modern glacial environments have allowed clear links to be made between processes contributing to moraine formation and ice-marginal dynamics, glacier thermal regime and/or climate (e.g. Price 1970; Sharp 1984; Krüger 1993, 1995, 1996; Matthews *et al*. 1995; Winkler & Nesje 1999; Evans & Hiemstra 2005; Lukas 2012; Reinardy *et al*. 2013; Chandler *et al*. 2016a; Wyshnytzky 2017). Alongside sedimentological analyses, there have also been efforts to establish climatic controls on the spacing between individual moraines (as a proxy for ice-marginal retreat) in multi-decadal moraine sequences on modern glacier forelands (Bradwell 2004; Beedle *et al*. 2009; Lukas 2012; Chandler *et al*. 2016a, b). Together, such investigations of moraines in modern glacial settings have resulted in an advanced understanding of the relationships between particular moraine-forming processes and different glaciodynamic, climatic and other boundary conditions. Applying these modern analogues and the principle of actualism to ancient glacial environments, the sedimentological end products (moraines) can be used to reconstruct past glacier dynamics. Through detailed investigation of the internal architecture and composition of moraines, important information has been obtained on the dynamics and thermal regimes of Pleistocene and

Early Holocene glaciers from the nature of the moraine-forming processes elucidated (e.g. Benn 1992; Lukas 2005, 2007; Benn & Lukas 2006).

In this study, we examine the mechanisms of moraine formation associated with a small Younger Dryas plateau icefield that has recently been identified in the Gaick, Central Scottish Highlands (Fig. 1; Chandler *et al*. 2019a). The Younger Dryas moraines in the Gaick and elsewhere in Scotland are potentially valuable terrestrial archives, as they offer a rare case where the well-preserved nature of the glacial sediment-landform assemblages allows the three-dimensional form and dynamics of relatively small Pleistocene icefields to be studied and linked to palaeoclimatic proxy records (e.g. Brooks & Birks 2000; Brooks *et al*. 2012, 2016). Despite this, there have so far been only a relatively limited number of detailed sedimentological studies of Younger Dryas moraines in Scotland and they have focused primarily on western Scotland (e.g. Benn 1992; Lukas 2005; Benn & Lukas 2006; Golledge 2006). The purpose of this contribution is to use sedimentological data from Younger Dryas moraines in the Gaick to shed light on the ice-marginal dynamics and thermal regime of one of the most easterly Younger Dryas icefields in Scotland.

Study area

The study area comprises a ~40 km^2, gently-undulating plateau and adjoining valleys, located in the Central Grampians, Scotland (Fig. 1). It is situated between latitudes 56.81884 and 56.968842° N and longitudes 4.229708 and 4.049743° W. This relatively small plateau area forms the western part of an extensive, dissected and undulating upland plateau (covering ~520 km^2) collectively referred to as the Gaick (Fig. 1). Fault-guided valleys and a glacial breach dissect the region in the west, disconnecting the western plateau from the plateau areas to the east (cf. Hall & Jarman 2004). The entire area is primarily underlain by a Neoproterozoic Precambrian succession of siliciclastic psammitic and semipelitic rocks (the 'Grampian Group'; see Stephenson & Gould 1995; Leslie *et al*. 2006; Smith *et al*. 2011).

It has long been argued that the Gaick supported a Younger Dryas plateau icefield (Sissons 1974), but the glacial history of the region has been a matter of much debate (cf. Lukas *et al*. 2004; Benn & Ballantyne 2005; Chandler 2018; Chandler *et al*. 2019a). In recent re-investigations of the glacial geomorphology and glacial history of the Gaick, we recognised a distinct morphostratigraphic signature in the western Gaick that differs markedly from sediment-landform assemblages found elsewhere in the area (Chandler *et al*. 2019a, b). On the basis of this distinct sediment-landform signature and independently-tested morphostratigraphic criteria for the Scottish Highlands (cf. Lukas 2006; Boston *et al*. 2015), we argued that only the western Gaick was glaciated during the Younger Dryas and used the distinct sediment-landform signature to reconstruct a spatially-restricted Younger Dryas plateau icefield (Fig. 1; Chandler *et al*. 2019a). Here, we focus on the sedimentology of the Younger Dryas moraines in the western Gaick. The moraines examined in this study are located in the Gaick Pass (Figs 1, 2), a deep valley that was occupied by one of the main outlet glaciers on the eastern side of the Younger Dryas Gaick Icefield.

Methods

Moraines and associated sediment-landform assemblages in the Gaick were mapped using a combination of geomorphological field mapping at 1:10000 scale and aerial photograph interpretation, following standard procedures (see Chandler *et al*. 2018, 2019b). To ensure that the location and planform geometry of individual moraines were represented accurately and precisely on the maps, the final mapping of the moraines was performed digitally: on-screen vectorisation was conducted in ESRI ArcMap using orthorectified aerial photographs with a ground sampled distance (GSD) of 0.25 m per pixel (Getmapping®/UKP).

Available natural exposures through moraines were enlarged and cleaned, before annotated, measured drawings of the cleaned sections were produced on square millimetre paper, following established protocols (e.g. Lukas 2005, 2012; Reinardy *et al*. 2013; Chandler *et al*. 2016a). To ensure maximum planimetric accuracy of the final section logs, photomosaics were also produced for each exposure and the field logs were later transferred and vectorised in Adobe Illustrator. Individual sedimentary units were identified and distinguished in the field based on their physical properties, namely grain size, sorting, compaction, sedimentary structures, bed contacts and unit geometry, following standard procedures and criteria (Evans & Benn 2004). A lithofacies code, modified from Eyles *et al*. (1983), was employed for clear, effective and rapid description on the sedimentary logs. The section logs presented in this paper all use a common style (Fig. 3). Clast shape and roundness were also analysed for each moraine following established methods, with C_{40}, RA and RWR indices calculated for each sample using a modified version of TriPlot (see Benn & Ballantyne 1993, 1994; Midgley *et al*. 2000; Lukas *et al*. 2013).

Moraine geomorphology

The Younger Dryas moraines in the Gaick (‘Type A moraines’ of Chandler *et al*. 2019a) consist of mounds and short ridge fragments that reach heights of ~2 to 15 m, lengths of ~10 to 250 m and widths of ~10 to 85 m. They are widespread features in the valley bottoms and on the lower ~50–150 m of adjacent slopes of the upper western catchments (cf. Chandler *et al*. 2019a, b), and individual moraine mounds and ridges give rise to a hummocky appearance at ground level (Fig. 4). As a consequence, these moraine assemblages have previously been referred to as ‘hummocky moraine’ (see Sissons, 1974), although this earlier classification also included morphologically-similar moraines that pre-date the Younger Dryas (cf. Chandler *et al*. 2019a). The term ‘hummocky moraine’ also belies the inherent organisation within the Younger Dryas moraine sequences in the Gaick: individual moraine mounds and ridges are characteristically aligned as a series of inset transverse chains that trend obliquely downvalley across the slopes towards the valley axis, forming nested arcuate or chevron-shaped patterns (Figs 2, 4). These inset chains of moraines have close spacings, typically between only a few metres to tens of metres. In many cases, shallow meltwater channels (often <5 m deep) occur between the chains of moraines, conforming with the trend of the moraine arcs/chevrons downslope. The morphological characteristics and spatial distribution of the Younger Dryas moraines in the Gaick closely resemble those of Younger Dryas moraines in other areas of upland Britain, where they have been interpreted as ice-marginal moraines and thus represent positions of individual palaeo-ice margins (cf. Benn 1992; Benn *et al*. 1992; Bennett & Boulton 1993a, b; McDougall 2001; Lukas 2003, 2005; Lukas & Benn 2006; Boston & Lukas 2019).

Moraine sedimentology

Below we present four examples of moraine exposures (Fig. 5), all situated in close proximity to the Younger Dryas glacier limit in the Gaick Pass (Figs 1, 2). Natural exposures through the whole width of Younger Dryas moraines in the Gaick are rare, and the Gaick Pass offered the only suitable locality for sedimentological investigations of such moraines. However, the availability of a series of exposures within this single valley offers the opportunity to examine any variations in mechanisms of moraine formation and ice-marginal dynamics following initiation of retreat from the glacier limit. Each section is described separately below in a downvalley (east) to upvalley (west) direction.

Section 1: Moraine BCL-05

The first example, moraine BCL-05 (Fig. 5A; NN 735 821; 457 m a.s.l.), is located on the southern side of Allt Loch an Dùin and nested inside two large moraine ridges (Fig. 2). The moraine is ~70 m long, ~30 m wide and reaches a maximum height of ~5 m. BCL-05 has a relatively smooth, rounded surface (i.e. it is not sharp crested), and the moraine displays an asymmetric cross-profile: the downvalley side is long, rectilinear and gently dipping (~12°) to the east, whilst the upvalley side is shorter and more steeply dipping (up to ~24°) to the west.

Description of moraine BCL-05. – The sedimentary characteristics of the exposure through BCL-05 allow grouping into two lithofacies association (LFAs), those situated on the left-hand (distal) side of the moraine and those on the right-hand (ice-proximal) side. LFA 1, on the distal side of the moraine, consists of decimetre-scale layers of relatively loose, matrix- to clast-supported, stratified diamicts (Dms, Dcs), with silty sandy to sandy matrixes (Fig. 5A). Gently-dipping Dms units are found towards the base of BCL-05, grading upwards to slightly more steeply dipping layers of Dcs. These stacked layers dip gently downvalley, with typical dip angles of ~18°. Individual clasts in the diamicton layers predominantly have *a*-axes between ~1 and 10 cm, but *a*-axes reach up to ~55 cm in the top left-hand (distal) side of the section. Amongst the diamicton layers in LFA 1, a few sporadic, thin (<0.1 m), pebbly, medium to coarse gravels are found. Relatively thin, streaked out lenses (8–15 cm thick) and very thin stringers of sand form interbeds within the diamicts on the left-hand (distal) side of BCL-05, mainly concentrated towards the base of the section (Fig. 5A). Individual sand lenses reach up to ~1.2 m in length, and they comprise silty fine sands to medium grade sands with laminations (Sl). The downvalley dip of these sand lenses and stringers is conformable with the stratification within the diamicts. At the base of the section, on the left-hand (distal) side, a large lens of massive, silty fine sand (Sm) is also found, reaching a maximum width of ~1.4 m and maximum thickness of ~60 cm. Several outsized clasts are embedded in this sand unit, with *a*-axes between 3 and 18 cm.

LFA 2 consists of sandy, matrix-supported, stratified diamicts (Dms), which dip ~22° in an upvalley direction, i.e. they dip slightly more steeply and in the opposite direction to LFA 1 (Fig. 5A). Occasional sorted sediment units (Fl, Gh, Sl) are found interspersed between the Dms layers, but such sorted lenses and stringers are less prevalent and generally thinner in this part of the section than in LFA 1 on the left-hand (distal) side. The boundary between the two LFAs is gradational, with no clearly discernible, abrupt change between downvalley- and upvalley-dipping units. Bedding plane measurements on a thin, streaked-out lens of laminated to horizontally-bedded, medium-grade sands (Sl) near the top of the section indicate this layer strikes 198° and dips 22° to the west. Similarly, bedding plane measurements on one of the thin layers of silty fines (Fl) show that this strikes 192° and dips at 22° in an upvalley direction. Thus, they dip subparallel to the upvalley surface slope of the moraine.

Interpretation of moraine BCL-05. – The stacked layers of relatively loose, stratified variable diamicts (Dms, Dcs) and intercalated, discontinuous sand units (Sl) that conformably dip in a downvalley direction are consistent with interpretations as debris flow units and fluvial ‘wash’ horizons, respectively (cf. Lawson 1982, 1989; Benn 1992; Lukas 2005). This lithofacies association has frequently been identified in ice-marginal moraines in many settings and indicates switches between gravitational and fluvial processes at a former stationary ice margin (e.g. Lawson 1982; Benn 1992; Krzyszkowski & Zieliński 2002; Lukas 2005, 2007, 2012; Evans *et al*. 2010; Lukas *et al*. 2012; Boston & Lukas 2013). The variability in the diamicton units within this part of BCL-05 can be explained by differences in the water content and, consequently, matrix strength of discrete debris flows (cf. Lawson 1979, 1981, 1982). Similarly, the presence of lenses of sand are compatible with fluctuations in water and debris content, with the water content determining whether gravitational or fluvial processes were in operation at any given time (Krzyszkowski & Zieliński 2002; Lukas 2005; Lukas *et al*. 2012). Some of the thin sand lenses may represent the winnowed product of material sourced from diamicton matrices, but the presence of laminations in many of the sand units and their lateral discontinuity suggest episodic deposition in shallow rills (cf. Lawson 1989; Krzyszkowski & Zieliński 2002). Where these lenses consist of thinly laminated silty fine sands, it implies lower flow velocities and sedimentation rates, with deposition possibly through filling of puddles on the gently-dipping debris slope (cf. Krüger 1997; Krzyszkowski & Zieliński 2002; Luka, 2005). The presence of a relatively large wedge of massive sand in the bottom left-hand (distal) part of the exposure is argued to represent the accumulation of sands at the foot of the debris slope following a relatively sustained period of fluvial deposition at the ice margin.

The upvalley-dipping, somewhat steeper lithofacies units (LFA 2) on the right-hand (ice-proximal) side of the exposure are interpreted as the former ice-contact face that formed following gravitational collapse as support by the ice was withdrawn during glacier retreat (Lukas 2005, 2012). This is supported by the relatively loose nature of the diamicts and presence of distinct stratification. The absence of diagnostic meltout/collapse structures in this half of the exposure implies that no dead ice was incorporated into the moraine during retreat of the glacier margin and concomitant collapse of the ice-proximal slope (cf. Benn 1992; Kjær & Krüger 2001; Lukas 2005, 2011, 2012).

Together, the two facies associations in BCL-05 support an interpretation of this moraine as a terrestrial ice-contact fan, following interpretations in previous studies (e.g. Benn 1992; Zieliński & van Loon 2000; Krzyszkowski & Zieliński 2002; Lukas 2005; Evans *et al*. 2010; Lukas *et al*. 2012; Boston & Lukas 2013). This type of terrestrial ice-contact fan corresponds to a scaled version of the terminoglacial fans of Brodzikowski and van Loon (1991), which consist of subaerial mass flow deposits (II-A-3-a) and terminoglacial fluvial facies (II-A-2), and the mass flow deposit-dominated ice-marginal fans (Type A) of Krzyszkowski and Zieliński (2002).

Section 2: Moraine BCL-06

The second moraine (BCL-06; NN 734 822; 463 m a.s.l.) is situated on the northern side of Allt Loch an Dùin and only ~50 m upvalley of moraine BCL-05 (Fig. 2). BCL-06 is ~30 m long, ~15 m wide and up to ~3 m high. The surface slopes dip very gently (maximum slope angles of ~10°) towards the east and west, giving moraine BCL-06 a very subdued, 'smoothed' appearance (Fig. 5B). In cross-section, the moraine has a broadly symmetrical surface. Moraine BCL-06 adjoins a much larger and more pronounced moraine ridge to the west (BCL-07, see below).

Description of moraine BCL-06. – The majority of BCL-06 contains lithofacies unit A, which predominantly consists of a compacted, silty-sandy, clast-supported diamicton that is stratified (Dcs) at the outcrop scale. This diamicton unit reaches up to ~1.2 m in thickness and extends across the entire width of the section. Individual clasts in the Dcs are predominantly small cobbles, with *a*-axes lengths often <5 cm. Intercalated with the diamicton are a number of elongated or attenuated lenses/pods of sorted sediments (Fl, Sd), which extend for up to ~1.5 m and typically have thicknesses of ~15 cm (Fig. 6). These sorted sediment lenses, which make up unit B, frequently bend or wrap around the undersides of larger clasts embedded in the diamicton. Internally, the fine sand units (Sd) exhibit deformed, wavy and gently folded laminations, with some individual laminae of the silt grain size fraction. Occasional flame structures are also present in the sorted sediment lenses. At the section scale, there is evidence of an overturned fold of silty fines (Fl) towards the base of the section and proto-boudinage (Sd) throughout. Unit C occurs in the top left-hand (ice-proximal) part of BCL-06 and comprises a matrix-supported, stratified diamicton (Dms) with a silty sandy matrix (Fig. 5B). The Dms conformably overlies and grades from the Dcs below. Taken together, the diamicts (units A and C) and the sorted sediment lenses (unit B) appear to form part of long-wavelength, low-amplitude anticlines and synclines that do not reflect the almost symmetrical surface of the moraine (Fig. 5B). They curve downwards in the middle part of the section and then arc back up in a zone that is ~2.5 m wide (i.e. forming a syncline). Based on this architecture, the three lithofacies units are grouped together as LFA 3.

Interpretation of moraine BCL-06. – Following similar arguments made above, the presence of diamicton units with interbedded sands and fines (Sd, Fl) in moraine BCL-06 are interpreted as the products of debris flows and fluvial processes, deposited as part of a terrestrial ice-contact fan. The dominance of clast-rich Dcs in this exposure (compared with Dms in BCL-05) can be explained by lower water content and greater debris content in the debris flows that deposited LFA 3 (cf. Lawson 1979, 1981, 1982). In some instances, sand lenses wrap beneath clasts, which may reflect sliding and falling of clasts from the ice surface onto the former fan surface causing localised deformation (Lukas 2005). The finer texture (silty fines, fine sands) and lamination of the sorted sediment units in this moraine exposure are consistent with relatively low flow velocities and sedimentation rates on a gently-dipping fan surface (cf. Krüger 1997; Krzyszkowski & Zieliński 2002; Lukas 2005). There are several deformation structures in the exposure, and these together imply that this moraine has experienced disturbance following deposition as an ice-contact fan. Firstly, the apparent long-wavelength, low-amplitude fold implies that this moraine has experienced large-scale proglacial push and lateral compression (e.g. van der Wateren 1999; Lukas 2005). Secondly, there are several features that suggest glacier overriding and shearing: (i) the moraine has a very subdued form; (ii) the diamicton units are compact, firm and relatively difficult to excavate; and (iii) the sorted sediment units display deformation structures (attenuation, wavy laminations, proto-boudinage) that are indicative of subglacial shear and clearly distinguishable from proglacial deformation (e.g. van der Wateren 1995, 1999; van der Wateren *et al*. 2000; McCarroll & Rijsdijk 2003). On this basis, this moraine is interpreted to have formed during a three-stage process of terrestrial ice-contact fan formation, proglacial folding and subsequent overriding. The deformation events may have occurred either during the same or a later re-advance. This sequence is equivalent to that identified for a suite of moraines on the shore of Loch Shin, northwest Scotland (Lukas 2005).

Sections 3 and 4: Moraines BCL-07 and BCL-04

The final two examples, moraines BCL-07 and BCL-04, contain similar lithofacies associations and add a new variant to the range of sedimentary processes thus far identified as contributing to ‘hummocky moraine’ formation in Scotland (cf. Benn 1992; Lukas 2005; Benn & Lukas 2006). The first of these two moraines, BCL-07 (NN 734 822; 463 m a.s.l.), adjoins the upvalley (western) side of moraine BCL-06 (Fig. 2), which was described above. The final case study, moraine BCL-04, is a moraine mound located ~420 m upvalley of moraine BCL-07 (Fig. 2; NN 731 820; 472 m a.s.l.). It forms part of a chain of moraine mounds that curve around towards the centre of the valley, with BCL-04 situated beside Allt Loch an Dùin.

Description of moraine BCL-07. – Moraine BCL-07 is a large, prominent ridge that reaches ~55 m in length, ~35 m in width, and up to ~9 m in height. The moraine has a distinctly asymmetric cross-profile: the upvalley slope steeply dips (28°) to the west, whereas the downvalley slope dips gently (18°) to the east. This asymmetry is not clearly reflected in the sedimentary log for BCL-07 (Fig. 5C) as the river cutting has only created a partial exposure. Three LFAs (2, 4 and 5) can be distinguished in moraine BCL-07. Firstly, the bulk of the right-hand (distal) side of the exposure comprises matrix-supported stratified diamicton layers (Dms) with silty sandy to sandy matrixes, which constitute LFA 4 (Fig. 5C). Unlike the stratified diamicts found in BCL-05 and -06 (LFAs 1–3), sorted sediment lenses and stringers are rare in LFA 4, restricted to a small pod of deformed fine sand towards the base of BCL-07. The Dms unit contains a series of stacked layers that dip eastwards, sub-parallel to the distal surface slope (~20–22°). On the left-hand (ice-proximal) side of the exposure, upvalley-dipping layers of sandy, matrix-supported diamicton (Dms) and occasional sorted sediment interbeds are evident (Fig. 5C). These lithofacies equate to LFA 2 in moraine BCL-05. The sorted sediment lenses/pods in moraine BCL-07 comprise fine to medium sands with some silty fine layers, all exhibiting deformed laminations (Sd). As in moraine BCL-05, there is no clearly distinguishable boundary between the downvalley- and upvalley-dipping diamicton layers. Finally, the third LFA (LFA 5) occurs in the central portion of the exposure. LFA 5 comprises a series of vertically-orientated dykes (Sd), which attain maximum widths of ~30 cm (Figs 5C, 6). These display wavy/anastomosing, vertical beds of fine sand and laminae to beds of silty fines (Fig. 6). The right-hand lens wraps around the undersides of several clasts, before bending to a vertical orientation again. The left-hand dyke curves in a westerly (upvalley) direction before tapering out up through the section.

Interpretation of moraine BCL-07. – The roughly uniform, downvalley-dipping matrix-supported diamicts (LFA 4) in the right-hand (distal) part of this exposure are consistent with deposition as debris flows (cf. Lawson 1982, 1989; Benn 1992; Lukas 2005). Unlike in BCL-05 and -06, sorted sediment lenses/layers are rare, indicating the dominance of gravitational processes and comparatively lower water content throughout the duration of deposition. The upvalley-dipping units of Dms in the left-hand (ice-proximal) side of the exposure (LFA 2) are interpreted as the former ice-contact face, resulting from gravitational collapse as the ice margin withdrew (as in moraine BCL-05, above). Thus, the sedimentary characteristics of this moraine are consistent with deposition as a mass flow deposit-dominated (Type A) terrestrial ice-contact fan (cf. Benn 1992; Krzyszkowski & Zieliński 2002; Lukas 2003, 2005; Reinardy & Lukas 2009; Evans *et al*. 2010; Lukas & Sass 2011; Boston & Lukas 2013).

The injected layers of sands and fines into the surrounding diamicton units (clastic dykes; LFA 5) are interpreted as hydrofracture fills, reflecting impeded drainage conditions and the escape of pressurised water (e.g. Rijsdijk *et al*. 1999; van der Meer *et al*. 1999, 2009; Lukas 2005; Phillips & Merritt 2008; Phillips *et al*. 2012, 2018; Evans *et al*. 2013). The presence of wavy laminations and beds in these fills may reflect either (i) repeated re-activation of fluid flow associated with fluctuating porewater availability, or (ii) pulsed injection of sediment-laden fluid upwards through the fracture (Larsen & Mangerud 1992; Phillips & Merritt 2008; van der Meer *et al*. 2009; Phillips *et al*. 2012, 2013; Lee *et al*. 2015). We suggest that the wavy, vertical laminae and beds are most likely related to (ii) pulsed injection. The hydrofractures in moraine BCL-07 are simple structures with no cross-cutting hydrofracture fills, break outs of the hydrofracture or faulting of the hydrofracture wall evident, as might be expected for hydrofracture systems that have been repeatedly re-activated (cf. Phillips *et al*. 2013).

Hydrofracture systems have been widely recognised in subglacial to ice-marginal and proglacial environments, and they have often been associated with overriding (e.g. van der Meer *et al*. 1999, 2009; Rijsdijk, 2001; Evans *et al*. 2013). Indeed, small-scale water escape structures have hitherto been reported in terrestrial ice-contact fans elsewhere in Scotland and associated with localised stress transmission during short-lived re-advance (Lukas 2005). However, there is no clear evidence (i.e. deformation structures) to indicate overriding of moraine BCL-07. On this basis, it is argued that the hydrofracture fills reflect elevated porewater pressures in the ice-marginal to proglacial environment. We speculate that the elevation of porewater pressures, and ensuing hydrofracturing, could be linked to three potential factors: Firstly, diurnal and/or seasonal increases in glacial meltwater production may have led to, or exacerbated, the periodic build-up of hydrostatic pressures in the ice-marginal to proglacial environment (cf. Robinson *et al*. 2008; Lee *et al*. 2015). These conditions, combined with a high water table in the Gaick Pass (as is currently the case) and the proximity of the glacier, may have been sufficient to pressurise the hydrogeological system, leading to upward evacuation of pressurised groundwater and infilling of the hydrofractures by sediment-water mixtures. Secondly, seasonal freezing and thawing of ground ice could have resulted in super-saturation and high porewater pressures, leading to hydrofracturing and infilling (cf. French 2007). Alternatively, the presence of a permafrost layer beneath the glacier snout would have reduced hydraulic connectivity and increased porewater pressures, with pressurisation of the groundwater system near the glacier margin leading to hydrofracturing in ice-marginal sediments (cf. Boulton *et al*. 1993, 1995, 1996; Boulton & Caban 1995; Waller *et al*. 2012). Strong upward groundwater flow and high seepage pressures would occur just beyond the permafrost layer/zone or through local gaps in a discontinuous permafrost (cf. Boulton *et al*. 1993, 1996); thus, the presence of permafrost in the Gaick Pass could potentially explain why pressurised groundwater escaped into moraine BCL-07, rather than up through surrounding, lower lying (possibly frozen) areas in the foreland. A caveat to this discussion of the controls on the hydrofracturing is that we do not have any data on the hydraulic conductivity of the subsurface sediments in the transitions from the submarginal to ice-marginal to proglacial environments. The hydraulic conductivity of any permafrost would have been considerably lower than unconsolidated sediment, rendering any permafrozen sediments practically impermeable (cf. Piotrowski, 1997; Ravier & Buoncristiani, 2018). However, the hydraulic conductivity of the subsurface sediments would have varied locally, resulting in a mosaic of areas of low hydraulic conductivity where permafrozen sediments were present and zones of comparatively high hydraulic conductivity in unfrozen sediment bodies.

Description of moraine BCL-04. – Moraine BCL-04 is ~35 m long, ~30 m wide and ~3 m high and has an asymmetric cross-profile, with a steeper (22°) ice-proximal slope and gentler (18°) distal flank. A river cutting through the southern end of the moraine, and perpendicular to the crestline, has exposed the sedimentary units that can be grouped into three LFAs (1, 2 and 5). Firstly, on the right-hand (distal) side of the section fairly compact, silty-sand diamicton layers occur (Fig. 5D). These range from clast-supported, stratified diamicts (Dcs) near the base of the section to crudely stratified, sandier, matrix-supported diamicts towards the top of the exposure (Fig. 5D). The diamicts in this LFA are cobble rich, but also contain several boulder-sized clasts (a-axis lengths up to ~35 cm). Occasional lenses and thin stringers of sorted sediment are found interspersed between the diamicts (Fig. 5D). These sorted sediments comprise massive to laminated, silty fine sands and fine sands (Sm, Sl) that extend up to ~60 cm in length. The association of downvalley-dipping diamicts and occasional sorted sediment lenses on the right-hand (distal) side of BCL-04 is broadly equivalent to sediments observed in moraine BCL-05 (LFA 1).

The second LFA is found in the western (ice-proximal) side of the exposure and consists of upvalley-dipping layers of (i) clast-supported, silty sandy, stratified diamicts (Dcs) in the lower part, and (ii) overlying, loose, matrix-supported, crudely stratified diamicton (Dms) (Fig. 5D). The lower Dcs lithofacies unit reaches a thickness of ~80–90 cm, before grading to Dms. Occasional lenses and stringers of sand are interspersed between the diamicts, which take the form of massive silty to fine sand (Sm) and deformed silty fine sand (Sd). Lenses range in thicknesses from ~10–20 cm, with widths ~25–50 cm. These lithofacies and their relationships equate with LFA 2 found in the upvalley halves of exposures in moraines BCL-05 and -06 (see above); thus, they are recognised as LFA 2.

Lastly, the third LFA comprises silty fines and silty, fine sand units with deformed bedding or laminations (Sd, Fl) in the right-hand (distal) side of moraine BCL-04 (Figs 5D, 7). These lithofacies are equated with LFA 5 in moraine BCL-07. At the base of the section, and upwards for ~65 cm, the lithofacies take the form of deformed sands with wavy, (sub)vertical bedding (Sd) (Fig. 7). This unit has relatively diffuse to sharp boundaries with the surrounding diamicts. It is widest at the base of the exposure (~50 cm) and gradually narrows upwards (to ~20–25 cm wide), before abruptly turning and curving to the right (east) beneath a large clast (Fig. 5D). To the right of this, deformed bedding and greater fine (silt) content is evident. The unit continues to the right but becomes increasingly finer in texture (Fl). Silty fines wrap around clasts and bend beneath the undersides of larger clasts embedded in the diamicton (Dcs), before tapering out amongst a concentration of cobble-sized clasts. Silty very fine sand with deformed laminations (Sd) is also found immediately to the right of the largest clast in the aforementioned cluster, and this trends upwards to wrap around the upper surface of a boulder-sized clast in the right-hand side of the section (Fig. 5D).

Interpretation of moraine BCL-04. – Following arguments made in the interpretations of the three moraines described above, the crudely stratified diamicts (Dms, Dcs) in moraine BCL-04 are interpreted as the products of supraglacial debris flows (cf. Lawson 1982, 1989; Benn 1992; Lukas 2005). The variability of the diamicts, from poorly sorted, cobbly-bouldery, clast-supported diamicts to matrix-supported diamicts, is explained by differences in the water content and, consequently, matrix strength of discrete debris flows units (cf. Lawson 1979, 1981, 1982). Occasional stringers interspersed in the diamicts are interpreted as fluvial 'wash' horizons, which may represent the winnowed product of material sourced from the diamicton matrix or deposition in shallow rills (cf. Lawson 1989; Krzyszkowski & Zieliński 2002; Lukas 2005; Lukas et al. 2012). As in moraines BCL-05 and -07, the upvalley-dipping stratified diamicts (LFA 2) are inferred to relate to collapse of the ice-contact slope following ice margin retreat (Lukas 2005). Thus, the sedimentary characteristics of this moraine are also consistent with deposition as a mass flow deposit-dominated terrestrial ice-contact fan (cf. Benn 1992; Krzyszkowski & Zieliński 2002; Lukas 2005).

As argued in the case of moraine BCL-07, the injected sands and fines (Sd, Fl) are interpreted as hydrofracture fills, resulting from elevated hydrostatic pressures and escape of pressurised water (e.g. Rijsdijk *et al*. 1999; van der Meer *et al*. 1999, 2009; Phillips & Merritt 2008). This hydrofracture fill is considerably larger than that identified in BCL-07, indicating that the system was either (i) in operation for a long period due to sustained pressurisation of the hydrogeological system, and/or (ii) repeatedly re-activated over a period of time as a result of fluctuating porewater pressures. The presence of relatively indistinct hydrofracture margins in parts of the system indicates some initial diffuse fluid flow (cf. Phillips *et al*. 2012) and may also potentially indicate some infiltration of the water-sediment mixture into the adjacent diamicton (cf. Lee *et al*. 2015). No glaciotectonic deformation structures are evident in this moraine; thus, the hydrofractures are again argued to reflect pressurisation of groundwater in the proglacial environment. Changes to groundwater pressures may have been driven by both standard processes that control groundwater systems and seasonal variations in meltwater flux (Robinson *et al*. 2008; Lee *et al*. 2015), with the hydrofracture system being more 'active' during the melt season (cf. Phillips *et al*. 2012). Alternatively, freeze-thaw cycles or the presence of submarginal to ice-marginal permafrost may have elevated porewater pressures near the glacier snout, leading to hydrofracturing in sediments at the glacier margin (cf. Boulton *et al*. 1993, 1996; Boulton & Caban, 1995; French, 2007; Waller *et al*. 2012).

Moraine clast shape

Clast shape analyses were conducted on samples of 50 psammitic clasts taken from downvalley-dipping, stratified diamicton (Dcs, Dms) lithofacies in each of the four moraines described above. The data show that the clasts within the moraines are predominantly sub-angular (SA) to sub-rounded (SR), with low percentages of angular (A) and rounded (R) clasts in each of the samples (RA = 4–6%; RWR = 0–4%) (Fig. 8). Moreover, the clasts mainly have blocky forms (C_{40} = 6–16%); oblate and prolate clasts are almost entirely absent. These characteristics are consistent with active transport in a subglacial environment (cf. Benn & Ballantyne 1993, 1994; Evans & Benn 2004; Lukas *et al*. 2013). Comparison of the moraine samples with ‘control’ samples (subglacial, fluvial and rockfall) on covariance plots of both RA-C_{40} and RWR-C_{40} (Fig. 9) also supports a subglacial transport pathway: all the moraine samples lie close to the subglacial control envelope on both plots. Thus, the clast shape data strongly suggests the debris in the moraines was transported in the subglacial traction zone (cf. Boulton 1978; Benn 1992; Benn & Ballantyne 1994; Benn & Lukas 2006). Taken together with the evidence for primary deposition of the sediments in terrestrial ice-contact fans, the clast shape data further indicate that debris was transported at the glacier bed and then elevated to a supraglacial position prior to deposition in terrestrial ice-contact fans, as found in different landsystems across Scotland (cf. Benn & Lukas 2006).

Synthesis of genetic processes and discussion

Geomorphologically, all the Younger Dryas moraines in the Gaick are organised as discrete chains of mounds and ridges that can be connected to form arcuate or chevron-shaped patterns. The planform arrangement recognised in this study is thus comparable to that observed in many other areas of the Scottish Highlands (e.g. Benn *et al*. 1992; Bennett & Boulton 1993a, b; Lukas 2003; Lukas & Benn 2006; Boston & Lukas 2019).

Sedimentologically, the four moraine exposures reported here all yielded similar lithofacies associations and represent terrestrial ice-contact fans, with evidence for proglacial push, subglacial shearing and complete overriding in one case (moraine BCL-06). These depositional processes are consistent with previous studies of Younger Dryas ‘hummocky moraine’ in Scotland, which have recognised terrestrial ice-contact fan deposits in the vast majority of cases (cf. Benn 1992; Lukas 2003, 2005; Benn & Lukas 2006; Golledge 2006; Boston & Lukas 2013). Although the exposures reported in this paper were concentrated in a small area of the Gaick, the consistency of the genetic processes, and the ubiquity of terrestrial ice-contact fans across the Scottish Highlands, implies that Younger Dryas moraines throughout the present study area are most likely to have also formed by this mechanism.

In two cases, hydrofracture fills were identified, reflecting elevated hydrostatic pressures and escape of pressurised water. The occurrence of these hydrofracture fills is suggested to reflect the influence of relatively high groundwater levels. Hydrofracture systems of this extent have not hitherto been reported from terrestrial ice-contact fans in Scotland (cf. Benn 1992; Lukas 2003, 2005; Reinardy & Lukas 2009; Boston & Lukas 2013), suggesting that local hydrogeological conditions in the Gaick were more important than conditions commonly found in proglacial environments in Scotland. These two examples add a further variant to the range of terrestrial ice-contact fans thus far reported from the Scottish Highlands in which pressurisation of the local groundwater system can lead to evacuation of groundwater into glaciogenic sediments within moraines and, in turn, post-depositional modification of the moraines. The presence of hydrofracture fills within moraines in the Gaick represent rare cases, as such structures are more commonly reported in proglacial and subglacial sedimentary sequences (e.g. Rijsdijk *et al*. 1999; Lee *et al*. 2015).

The lithofacies associations and internal architecture of the moraines reported here indicate they formed by the following sequence of events where groundwater flow away from the glacier is efficient and unconfined (Fig. 10A; cf. Lukas 2005): (A1) basal debris elevated to the ice surface is saturated by meltwater, leading to the formation of supraglacial debris flows. Stacking of these debris flows and intercalated glaciofluvial ‘wash’ horizons results in fan construction at a temporarily stationary glacier margin. Retreat of the glacier margin and loss of support by ice (A2) leads to gravitational collapse and formation of a proximal rectilinear ice-contact slope (as exemplified by moraine BCL-05). Evidence from elsewhere in Scotland (Lukas 2005) indicates that during a re-advance of the glacier margin (A3), the ice-contact fan can be proglacially deformed and, when followed by a phase of retreat, a proximal rectilinear ice-contact slope is formed (A4). During sustained glacier re-advance, partial (A5) or complete (A6) overriding of the ice-contact fan can occur, leading to subglacial shearing of the fan units (as evident in moraine BCL-06). In situations where the hydrogeological system becomes pressurised, upward evacuation of pressurised groundwater into the terrestrial ice-contact fans (moraines) may occur, most likely while the moraine remains in contact with the glacier margin (Fig. 10B). As speculated above, pressurisation of the hydrogeological system could be the result of (i) the close proximity of the glacier, (ii) diurnal/seasonal meltwater fluxes, (iii) a high local water table, (iv) seasonal freeze-thaw cycles, and/or (v) the presence of (discontinuous) permafrost. Evacuation of the groundwater into the moraines leads to hydrofracturing and subsequent infilling of the hydrofractures by sediment-water mixtures (B3). This is reflected in moraines BCL-04 and BCL-07. Theoretically, the groundwater-modified terrestrial ice-contact fans could later experience proglacial and/or subglacial deformation. The Younger Dryas ice-marginal moraines in the Gaick therefore represent terrestrial ice-contact fans that have been subject to varying degrees of glaciotectonism/post-depositional modification.

Implications for ice-marginal dynamics

The evidence for ice-marginal sedimentation in the form of terrestrial ice-contact fans, together with the dense spacing and planform arrangement of the moraine mounds and ridges (discontinuous arcs or chevron-shaped chains), indicates that the Younger Dryas glaciers in the Gaick experienced active, oscillatory retreat that was punctuated by minor stillstands or re-advances, as has been documented at many Younger Dryas glaciers in Scotland (e.g. Benn 1992; Benn *et al*. 1992; Bennett & Boulton, 1993a, b; Lukas 2003, 2005; Lukas & Benn 2006; Finlayson *et al*. 2011; Boston & Lukas 2019). Sedimentary evidence from moraine BCL-06, in the form of proglacial and subglacial glaciotectonism, indicates that a more substantial re-advance of the Gaick Glacier (Fig. 1) occurred at some stage during the Younger Dryas. The occurrence of an undeformed terrestrial ice-contact fan (moraine BCL-05) to the east (downvalley) of the overridden ice-contact fan (moraine BCL-06) indicates either the re-advance limit did not extend as far downvalley as moraine BCL-05 (hence the absence of deformation structures) or that the undeformed terrestrial ice-contact fan records a former ice-marginal position related to the re-advance event, i.e. moraine BCL-05 may have been deposited after the glacier had re-advanced and overridden moraine BCL-06.

Exposures at the northern end of the nearby Loch an Dùin (see Fig. 1B) have revealed a grounding-line fan that has also been subject to proglacial push and subglacial shearing (Chandler 2018). This exposure and moraine BCL-06 are located in close proximity to the former Younger Dryas glacier limits and exhibit equivalent sequences of deformation events (proglacial push followed by subglacial shearing). On this basis, it is tentatively suggested that the re-advances of the divergent Gaick and northern Loch an Dùin lobes (Fig. 1C) were broadly coeval, subject to testing through absolute dating. This glaciodynamic signature closely resembles that exhibited by Younger Dryas outlets elsewhere in Scotland (e.g. Lukas 2005), and it could be a manifestation of the two-phased Younger Dryas advance reported in other regions of Scotland (cf. Peacock *et al*. 1989; Merritt *et al*. 2003; Pearce, 2014; Boston *et al*. 2015). In the Gaick, this takes the form of a re-advance, rather than the stillstand reported elsewhere (e.g. Boston *et al*. 2015). To summarise, the evidence suggests that the main Gaick outlet glaciers displayed highly dynamic ice-marginal responses and oscillatory behaviour during the Younger Dryas.

Implications for basal thermal regime

The spatial pattern (i.e. closely-spaced, nested, discontinuous moraine arcs) exhibited by the moraine assemblages in the Gaick (and elsewhere in Scotland) broadly resembles moraine patterns formed by modern temperate glaciers in maritime settings (e.g. Boulton 1986; Bickerton & Matthews 1993; Krüger 1994, 1995; Winkler 1996; Winkler & Nesje 1999; Evans & Twigg 2002; Lukas 2007; Chandler *et al*. 2016a). In such maritime environments, temperate glaciers react dynamically at short timescales to climatic fluctuations, with the ice-marginal moraines documenting minor winter re-advances and/or more extensive re-advances in response to (multi-)annual climatic fluctuations. Thus, the geomorphological evidence from the Gaick implies that the Younger Dryas outlet glaciers had a predominantly wet-based (temperate) thermal regime. The occurrence of proglacial and subglacial glaciotectonic structures within moraine BCL-06 indicates dynamic ice-marginal responses in the Gaick and thus provides sedimentary evidence for incremental, oscillatory retreat of predominantly temperate Younger Dryas outlet glaciers.

The characteristics of clast shape samples from the moraines (dominantly blocky, edge-rounded clasts; Figs 11, 12) are consistent with debris transport in the subglacial traction zone, which is also characteristic of temperate glacier systems (cf. Benn & Ballantyne 1994; Benn & Lukas 2006; Lukas 2007; Lukas *et al*. 2013). However, the abundance of closely-spaced moraines inside the Younger Dryas glacier limits in the Gaick requires a mechanism that is able to continuously elevate subglacially-transported debris to the ice surface. Possible mechanisms for elevating basal debris at temperate glaciers, such as freeze-on by glaciohydraulic supercooling (cf. Cook *et al*. 2006 and references therein) and englacial thrusting (cf. Hambrey *et al*. 1997; Bennett *et al*. 1998; Swift *et al*. 2006, 2018), are associated with specific topographic boundary conditions, namely overdeepenings and reverse bedrock slopes (cf. Benn & Lukas 2006 for detailed discussion). These topographic boundary conditions do not occur in the Gaick and thus those debris transport mechanisms are unable to explain the sedimentary evidence. An internal, glaciological control is therefore required that allows both (i) efficient elevation of material to the glacier surface and (ii) deposition of moraines regardless of special topographic conditions. For Younger Dryas glaciers in the northwest Highlands and on Skye, Benn & Lukas (2006) invoked polythermal conditions to explain the elevation of basal debris, proposing that narrow zones of cold-based ice existed near the glacier margins. These cold-ice zones would have enabled folding and thrusting at the boundary between warm-based and cold-based ice and thus elevation of basal debris to the glacier surface. The cold-ice zones would also effectively migrate with the receding glacier margins, thereby providing a consistent mechanism for debris elevation and moraine genesis via debris flows originating from the glacier surface.

The presence of narrow cold-ice zones near the margins of the Younger Dryas outlet glaciers in the Gaick could explain (i) the widespread geomorphological evidence for a temperate glacier thermal regime, (ii) the sedimentological evidence for active transport of debris in the subglacial traction zone and its elevation to supraglacial positions, (iii) the absence of any geomorphological or sedimentological evidence for dead-ice meltout (cf. Benn & Lukas 2006), and (iv) the frequent occurrence of ice-marginal meltwater channels between moraine arcs. With respect to the latter, ice-marginal (lateral) meltwater channels are commonly associated with, and best developed at, cold-based glacier margins where surface meltwater flow is routed along frozen glacier margins (e.g. England 1986; Dyke 1993; Ó Cofaigh *et al*. 1999; Skidmore & Sharp 1999; Hättestrand & Stroeven 2002; Atkins & Dickinson 2007). Although Syverson & Mickelson (2009) argued that lateral meltwater channels can occur at temperate glacier margins, the presence of narrow cold-ice zones at the glacier margins (at least seasonally) would readily explain the lateral meltwater channels (cf. Dyke 1993). In this situation, the frozen zone at the glacier margins could have favoured the routing of meltwater along the glacier margin, leading to lateral channel formation at periods between moraine formation.

General support for the presence of (seasonal) cold-ice zones near the margins of otherwise temperate outlet glaciers can be found at modern temperate glaciers in maritime areas. The penetration of a winter cold wave and seasonal cold-based conditions have been recognised as playing an important role at temperate glacier margins, although the mechanism of moraine formation (basal freeze-on) is different to those recognised in the Gaick (see Andersen & Sollid 1971; Krüger 1993, 1995, 1996; Matthews *et al*. 1995; Evans & Hiemstra 2005; Reinardy *et al*. 2013; Chandler *et al*. 2016a). Recent geophysical investigations have also revealed that plateau icefield outlets may be thermally complex, with the identification of cold-ice zones within a temperate outlet (Midtdalsbreen) of Hardangerjøkulen, Norway (Reinardy *et al*. 2019). The presence of these cold-ice zones, together with the penetration of permafrost beneath the glacier margin, is thought to be crucial to the transport of basal material to englacial and supraglacial positions (see also Etzelmüller & Hagen 2005).

Based on the totality of available geomorphological and sedimentary evidence from the Gaick, together with evidence from modern analogues, we therefore suggest that the Younger Dryas outlets in the Gaick had predominantly temperate basal thermal regimes but with cold-based ice in the marginal zone. The presence of narrow cold-ice zones would have facilitated the elevation of basal debris to the ice surface, which was subsequently deposited in terrestrial ice-contact fans.

Conclusions

The 'hummocky' moraines formed during the Younger Dryas in the Gaick, Central Scottish Highlands, are characteristically aligned as a series of inset transverse chains that trend obliquely downvalley across the slopes towards the valley axis, forming nested arcuate or chevron-shaped patterns. These inset chains of moraines have close spacings, typically between only a few metres to tens of metres. Four exposures (BCL-04 to BCL-07) through moraines located near the margin of the one of the main outlet glaciers in the Gaick (the 'Gaick Glacier') have been logged. Based on the geomorphological evidence and sedimentological data, the following key conclusions were drawn.

- The sediments within all the moraines primarily consist of stacked matrix- and clast-supported, stratified diamicts (Dms, Dcs), with intercalated, discontinuous sand units (Sl, Sd). On the downvalley (distal) sides of the exposures, these diamicton and intercalated sand units dip conformably downvalley, whereas the units on the upvalley (ice-contact) sides dip upvalley. The downvalley-dipping diamicton and sands units are interpreted as debris flow units and fluvial 'wash' horizons formed at a temporarily stationary glacier margin, respectively. The upvalley-dipping lithofacies are interpreted as former ice-contact faces that formed following gravitational collapse as support by the ice was withdrawn during ice retreat. The sedimentary evidence thus indicates that the moraines in the Gaick represent terrestrial ice-contact fans.
- Deformation structures within one moraine (BCL-06) indicate that the ice-contact fan was subject to large-scale proglacial push and subglacial shearing and overriding, leading to the

formation of a low-relief, overridden terrestrial ice-contact fan. This evidence indicates that the Younger Dryas outlet glacier in Gaick Pass underwent a re-advance at some stage.

- In two cases (moraines BCL-04 and BCL-07), hydrofracture fills occur within the moraines, but there are no deformation structures to indicate deformation and glaciotectonisation of these moraines. We argue that these hydrofracture fills represent pressurisation of groundwater in the proglacial environment. Pressurisation of the groundwater potentially relates to (i) the close proximity of the glacier, (ii) seasonal meltwater fluxes, (iii) a high local water table, (iv) seasonal freezing and thawing of ground ice, and/or (v) the presence of (discontinuous) permafrost. Pressurisation of the local hydrogeological system led to groundwater being evacuated into the ice-contact fans, with the hydrofractures then filled by a sediment-water mixture. These findings indicate the role that local hydrogeological conditions can play and adds a further variant to the range of terrestrial ice-contact fans reported from Scotland.
- The geomorphological and sedimentological evidence from the moraines in the Gaick is only compatible with dynamic, predominantly temperate glaciers that underwent oscillatory retreat, with retreat punctuated by re-advances into previously-formed terrestrial ice-contact fans. Moreover, the close spacing of the moraines and the sedimentological data indicate that the Younger Dryas outlet glaciers had short response times, being closely coupled with climate.
- Although the evidence indicates a predominantly warm-based thermal regime, we argue for the presence of narrow cold-ice zones (at least seasonally) near the glacier margins in order to facilitate the continuous elevation of basal debris to the glacier surface, as required by evidence from clast shape analyses. This thermal structure is entirely consistent with that recently recognised at Midtdalsbreen, a temperate plateau icefield outlet in Norway.

Acknowledgements. – This research was funded by a Queen Mary Natural and Environmental Science Studentship as well as a small grant from the International Association of Sedimentologists to BMPC, which are hereby gratefully acknowledged. We are thankful to Jon Merritt for support and discussion during this research, and to BGS Edinburgh for providing access to resources. BMPC would also like to thank Colm Ó Cofaigh and Steph Mills for valuable discussions of an earlier version of this work. We are grateful to the reviewers, Anders Schomacker and Stephen Livingstone, for constructive comments that helped to improve this paper and to Jan A. Piotrowski for his thorough editorial work.

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

Author contributions. – Conceptualisation: BMPC, SL and CMB; Methodology: BMPC and SL; Investigation: BMPC; Analysis: BMPC, SL and CMB; Writing – Original Draft: BMPC; Writing – Review & Editing: BMPC, SL and CMB; Visualisation: BMPC, SL and CMB; Supervision: SL and CMB; Funding Acquisition: BMPC.

References

Andersen, J. L. & Sollid, J. L. 1971: Glacial Chronology and Glacial Geomorphology in the Marginal Zones of the Glaciers, Midtdalsbreen and Nigardsbreen, South Norway. *Norsk Geografisk Tidsskrift - Norwegian Journal of Geography 25*, 1–38.

Atkins, C. B. & Dickinson, W. W. 2007: Landscape modification by meltwater channels at margins of cold-based glaciers, Dry Valleys, Antarctica. *Boreas 36*, 47–55.

Beedle, M. J., Menounos, B., Luckman, B.H. & Wheate, R. 2009: Annual push moraines as climate proxy. *Geophysical Research Letters 36*, L20501. doi: 10.1029/2009GL039533.

Benn, D. I. 1992: The genesis and significance of ‘hummocky moraine’: evidence from the Isle of Skye, Scotland. *Quaternary Science Reviews 11*, 781–799.

Benn, D. I. & Ballantyne, C. K. 1993: The description and representation of particle shape. *Earth Surface Processes and Landforms 18*, 665–72.

Benn, D. I. & Ballantyne, C. K. 1994: Reconstructing the transport history of glacigenic sediments: a new approach based on the co-variance of clast shape indices. *Sedimentary Geology 91*, 215–27.

Benn, D. I. & Ballantyne, C. K. 2005: Palaeoclimatic reconstruction from Loch Lomond Readvance glaciers in the West Drumochter Hills, Scotland. *Journal of Quaternary Science 20*, 577–592.

Benn, D.I. & Lukas, S. 2006: Younger Dryas glacial landsystems in North West Scotland: an assessment of modern analogues and palaeoclimatic implications. *Quaternary Science Reviews 25*, 2390–2408.

Benn, D. I., Lowe, J. J. & Walker, M. J. C. 1992: Glacier response to climatic change during the Loch Lomond Stadial and early Flandrian: geomorphological and palynological evidence from the Isle of Skye, Scotland. *Journal of Quaternary Science 7*, 125–144.

Bennett, M. R. & Boulton, G. S. 1993a: A reinterpretation of Scottish 'hummocky moraine' and its significance for the deglaciation of the Scottish Highlands during the Younger Dryas or Loch Lomond Stadial. *Geological Magazine 130*, 301–318.

Bennett, M. R. & Boulton, G. S. 1993b: Deglaciation of the Younger Dryas or Loch-Lomond Stadial ice-field in the northern Highlands, Scotland. *Journal of Quaternary Science 8*, 133–145.

Bennett, M. R., Hambrey, M. J., Huddart, D. & Glasser, N. F. 1998: Glacial thrusting & moraine-mound formation in Svalbard & Britain: the example of Coire a' Cheud-chnoic (Valley of hundred hills), Torridon, Scotland. *Quaternary Proceedings 6*, 17–34.

Bickerton, R. W. & Matthews, J.A. 1993: ‘Little Ice Age’ variations of outlet glaciers from the Jostedalsbreen ice-cap, southern Norway: a regional lichenometric-dating study of ice-marginal moraine sequences and their climatic significance. *Journal of Quaternary Science 8*, 45–66.

Boston, C. M. & Lukas, S. 2013: The sedimentology of Younger Dryas moraines in the vicinity of Loch Killin. *In* Boston, C. M., Lukas, S. & Merritt, J. W. (eds.): *The Quaternary of the Monadhliath Mountains and the Great Glen: Field Guide*, 121–128. Quaternary Research Association, London.

Boston, C. M. & Lukas, S. 2019: Topographic controls on plateau icefield recession: insights from the Younger Dryas Monadhliath Icefield, Scotland. *Journal of Quaternary Science 34*, 433–451.

Boston, C. M., Lukas, S. & Carr, S. J. 2015: A Younger Dryas plateau icefield in the Monadhliath, Scotland, and implications for regional palaeoclimate. *Quaternary Science Reviews 108*, 139–162.

Boulton, G. S. 1978: Boulder shapes and grain-size distributions of debris as indicators of transport paths through a glacier and till genesis. *Sedimentology 25*, 773–799.

Boulton, G. S. 1986: Push-moraines and glacier-contact fans in marine and terrestrial environments. *Sedimentology 33*, 677–698.

Boulton, G. S. & Caban, P. 1995: Groundwater flow beneath ice sheets: Part II—Its impact on glacier tectonic structures and moraine formation. *Quaternary Science Reviews 14*, 563–587.

Boulton, G. S., Slot, T., Blessing, K., Glasbergen, P., Leijnse, T. & Van Gijssel, K. 1993: Deep circulation of groundwater in overpressured subglacial aquifers and its geological consequences. *Quaternary Science Reviews 12*, 739–745.

Boulton, G. S., Caban, P. E. & Van Gijssel, K. 1995: Groundwater flow beneath ice sheets: Part I—Large scale patterns. *Quaternary Science Reviews 14*, 545–562.

Boulton, G. S., Caban, P. E., Van Gijssel, K., Leijnse, A., Punkari, M. & Van Weert, F. H. A. 1996: The impact of glaciation on the groundwater regime of Northwest Europe. *Global and Planetary Change 12*, 397–413.

Bradwell, T. 2004: Annual Moraines and Summer Temperatures at Lambatungnajökull, Iceland. *Arctic, Antarctic and Alpine Research 36*, 502–508.

Bradwell, T., Dugmore, A. & Sugden, D. 2006. The Little Ice Age glacier maximum in Iceland and the North Atlantic Oscillation: evidence from Lambatungnajökull, southeast Iceland. *Boreas 35*, 61–80.

Bradwell, T., Sigurdsson, O. & Everest, J. 2013: Recent, very rapid retreat of a temperate glacier in SE Iceland. *Boreas 42*, 959–973.

Brodzikowski, K. & van Loon, A. J. 1991: *Glacigenic Sediments*. 673 pp. Elsevier, Amsterdam.

Brooks, S. J. & Birks, H. J. B. 2000: Chironomid-inferred Late-glacial air temperatures at Whitrig Bog, Southeast Scotland. *Journal of Quaternary Science 15*, 759–764.

Brooks, S. J., Matthews, I. P., Birks, H. H. & Birks, H. J. B. 2012: High resolution Lateglacial and early-Holocene summer air temperature records from Scotland inferred from chironomid assemblages. *Quaternary Science Reviews 41*, 67–82.

Brooks, S. J., Davies, K. L., Mather, K. A., Matthews, I. P. & Lowe, J. J. 2016: Chironomid-inferred summer temperatures for the Last Glacial-Interglacial Transition from a lake sediment sequence in Muir Park Reservoir, west-central Scotland. *Journal of Quaternary Science 31*, 214–224.

Chandler, B. M. P. 2018: *Extent, style and timing of former glaciation in the Gaick, Central Grampians, Scotland, and implications for palaeoclimate*. Ph.D. thesis, Queen Mary University of London, 354 pp.

Chandler, B. M. P., Evans, D. J. A. & Roberts, D. H. 2016a: Characteristics of recessional moraines at a temperate glacier in SE Iceland: Insights into patterns, rates and drivers of glacier retreat. *Quaternary Science Reviews 135*, 171–205.

Chandler, B. M. P., Evans, D. J. A. & Roberts, D. H. 2016b: Recent retreat at a temperate Icelandic glacier in the context of the last ~80 years of climate change in the North Atlantic region. *arktos 2*, 24. doi: 10.1007/s41063-016-0024-1.

Chandler, B. M. P., Lovell, H., Boston, C. M., Lukas, S., Barr, I. D., Benediktsson, Í. Ö., Benn, D. I., Clark, C. D., Darvill, C. M., Evans, D. J. A., Ewertowski, M. W., Loibl, D., Margold, M., Otto, J. -C., Roberts, D. H., Stokes, C. R., Storrar, R. D. & Stroeven, A. P. 2018: Glacial geomorphological mapping: A review of approaches and frameworks for best practice. *Earth-Science Reviews 185*, 806–846.

Chandler, B. M. P., Boston, C. M. & Lukas, S. 2019a: A spatially-restricted Younger Dryas plateau icefield in the Gaick, Scotland: Reconstruction and palaeoclimatic implications. *Quaternary Science Reviews 211*, 107–135.

Chandler, B. M. P., Lukas, S., Boston, C. M. & Merritt, J. W. 2019b: Glacial geomorphology of the Gaick, Central Grampians, Scotland. *Journal of Maps 15*, 60–78.

Cook, S. J. Waller, R. I. & Knight, P. G. 2006: Glaciohydraulic supercooling: The process and its significance. *Progress in Physical Geography 30*, 577–588.

Dyke, A. S. 1993: Landscapes of cold-centred Late Wisconsinan ice caps, Arctic Canada. *Progress in Physical Geography 17*, 223–247.

England, J. 1986: Glacial erosion of a high arctic valley. *Journal of Glaciology 32*, 60–64.

Etzelmüller, B. & Hagen, J. O. 2005: Glacier–permafrost interaction in Arctic and alpine mountain environments with examples from southern Norway and Svalbard. *In* Harris, C. & Murton, J. B. (eds.): *Cryospheric Systems: Glaciers and Permafrost*, 11–27. *Geological Society, London, Special Publications 242*.

Evans, D. J. A. & Benn, D. I. (eds.) 2004: *A Practical Guide to the Study of Glacial Sediments*. 266 pp. Arnold, London.

Evans, D. J. A. & Hiemstra, J. F. 2005: Till deposition by glacier submarginal, incremental thickening. *Earth Surface Processes and Landforms 30*, 1633–1662.

Evans, D. J. A. & Twigg, D. R. 2002: The active temperate glacial landsystem: a model based on Breiðamerkurjökull and Fjallsjökull, Iceland. *Quaternary Science Reviews 21*, 2143–2177.

Evans, D. J. A., Shulmeister, J. & Hyatt, O. 2010: Sedimentology of latero-frontal moraines and fans on the west coast of South Island, New Zealand. *Quaternary Science Reviews 29*, 3790–3811.

Evans, D. J. A., Rother, H., Hyatt, O. M & Shulmeister, J. 2013: The glacial sedimentology and geomorphological evolution of an outwash head/moraine-dammed lake, South Island, New Zealand. *Sedimentary Geology 284-285*, 45–75.

Eyles, N., Eyles, C. H. & Miall, A. D. 1983: Lithofacies types and vertical profile models. An alternative approach to the description and environmental interpretation of glacial diamict and diamictite sequences. *Sedimentology 30*, 393–410.

Finlayson, A. G. 2006: Glacial geomorphology of the Creag Meagaidh Massif, western Grampian Highlands: implications for local glaciation and palaeoclimate during the Loch Lomond Stadial. *Scottish Geographical Journal 122*, 293–307.

Finlayson, A. G., Golledge, N., Bradwell, T. & Fabel, D. 2011: Evolution of a Lateglacial mountain icecap in northern Scotland. *Boreas 40*, 536–554.

French H. M. 2007: *The Periglacial Environment*. 458 pp. John Wiley & Sons, Chichester.

García, J. -L., Hein, A. S., Binnie, S. A., Gómez, G. A., González, M. A. & Dunai, T. J. 2018: The MIS 3 maximum of the Torres del Paine and Última Esperanza ice lobes in Patagonia and the pacing of southern mountain glaciation. *Quaternary Science Reviews 185*, 9–26.

Golledge, N. R. 2006: The Loch Lomond Stadial glaciation south of Rannoch Moor: new evidence and palaeoglaciological insights. *Scottish Geographical Journal 122*, 326–343.

Golledge, N. R. 2010: Glaciation of Scotland during the Younger Dryas stadial: a review. *Journal of Quaternary Science 25*, 550–566.

Graham, D. J. & Midgley, N.G. 2000: Graphical representation of particle shape using triangular diagrams: an Excel spreadsheet method. *Earth Surface Processes and Landforms 25*, 1473–1477.

Hall, A. M. & Jarman, D. 2004: Quaternary landscape evolution - Plateau dissection by glacial breaching. *In* Lukas, S., Merritt, J. W. & Mitchell, W. A. (eds.): *The Quaternary of the Central Grampian Highlands: Field Guide*, 26–40. Quaternary Research Association, London.

Hambrey, M. J., Huddart, D., Bennett, M. R. & Glasser, N. F. 1997: Genesis of 'hummocky moraines' by thrusting of glacier ice: evidence from Svalbard and Britain. *Journal of the Geological Society of London 154*, 623–632.

Hättestrand, C. & Stroeven, A. P. 2002: A relict landscape in the centre of Fennoscandian glaciation: Geomorphological evidence of minimal Quaternary erosion. *Geomorphology 44*, 127–143.

Hofmann, F. M., Alexanderson, H., Schoeneich, P., Mertes, J. R., Léanni, L. & Aster Team (Aumaître, G., Bourlès, D. L. & Keddadouche, K.). 2019: Post-Last Glacial Maximum glacier fluctuations in the southern Écrins massif (westernmost Alps): insights from ^{10}Be cosmic ray exposure dating. *Boreas 148*, 1019–1041.

IPCC. 2013: Climate Change 2013: The Physical Science Basis. *In* Stocker T. F., Qin, D., Plattner, G-. K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. & Midgley, P.M. (eds.): *Contribution of Working Group I to the Fifth Assessment Report of the*

Intergovernmental Panel on Climate Change. 1535 pp. Cambridge University Press, Cambridge.

Kelley, S. E., Kaplan, M. R., Schaefer, J. M., Andersen, B. G., Barrell, D. J. A., Putnam, A. E., Denton, G. H., Schwartz, R., Finkel, R. C. & Doughty, A. M. 2014: High-precision 10Be chronology of moraines in the Southern Alps indicates synchronous cooling in Antarctica and New Zealand 42,000 years ago. *Earth and Planetary Science Letters 405*, 194–206.

Kjaer, K. H. & Kruger, J. 2001: The final phase of dead-ice moraine development: processes and sediment architecture, Kotlujokull, Iceland. *Sedimentology 48*, 935–952.

Krüger, J. 1993: Moraine-ridge formation along a stationary ice front in Iceland. *Boreas 22*, 101–109.

Krüger, J. 1994: Glacial processes, sediments, landforms and stratigraphy in the terminus region of Mýrdalsjökull, Iceland. *Folia Geographica Danica 21*, 1–233.

Krüger, J. 1995: Origin, chronology and climatological significance of annual-moraine ridges at Myrdalsjökull, Iceland. *The Holocene 5*, 420–427.

Krüger, J. 1996: Moraine ridges formed from subglacial frozen-on sediment slabs and their differentiation from push moraines. *Boreas 25*, 57–64.

Krüger, J. 1997: Development of minor outwash fans at Kötlujökull, Iceland. *Quaternary Science Reviews 16*, 649–659.

Krzyszkowski, D. & Zieliński, T. 2002: The Pleistocene end moraine fans: controls on their sedimentation and location. *Sedimentary Geology 149*, 73–92.

Lawson, D. E. 1979: Sedimentological Analysis of the Western Terminus Region of the Matanuska Glacier, Alaska. *Cold Regions Research and Engineering Laboratory, Report 79-9*. 122 pp. Hanover, NH.

Lawson, D. E. 1981: Distinguishing characteristics of diamictons at the margin of the Matanuska glacier, Alaska. *Annals of Glaciology 2*, 78–84.

Lawson, D. E. 1982: Mobilization, movement and deposition of active subaerial sediment flows, Matanuska Glacier, Alaska. *Journal of Geology 90*, 279–300.

Lawson, D. E. 1989: Glacigenic resedimentation: Classification concepts and application to mass movement processes and deposits. *In* Goldthwait, R. P. & Matsch, C.L. (eds.): *Genetic Classification of Glacigenic Deposits*, 147–169. Balkema, Rotterdam.

Lee, J. R., Wakefield, O. J. W., Phillips, E. & Hughes, L. 2015: Sedimentary and structural evolution of a relict subglacial to subaerial drainage system and its hydrogeological implications: an example from Anglesey, north Wales, UK. *Quaternary Science Reviews 109*, 88–110.

Leslie, A. G., Krabbendam, M. & Smith, R. A. 2006. The Gaick Fold Complex: large-scale recumbent folds and their implications for Caledonian structural architecture in the Central Grampian Highlands. *Scottish Journal of Geology 42*, 149–159.

Lukas, S. 2003: Scottish Landform Example No. 31: the moraines around the Pass of Drumochter. *Scottish Geographical Journal 119*, 383–394.

Lukas, S. 2005: A test of the englacial thrusting hypothesis of 'hummocky' moraine formation: case studies from the northwest Highlands, Scotland. *Boreas 34*, 287–307.

Lukas, S. 2006: Morphostratigraphic principles in glacier reconstruction: a perspective from the British Younger Dryas. *Progress in Physical Geography 30*, 719–736.

Lukas, S. 2007: Early-Holocene glacier fluctuations in Krundalen, south central Norway: palaeo-glacier dynamics and palaeoclimate. *The Holocene 17*, 585–598.

Lukas, S. 2011: Ice-cored moraines. *In* Singh, V.P., Singh, P., Haritashya, U.K. (eds.): *Encyclopedia of Snow, Ice and Glaciers*, 616–618. Springer, Dordrecht.

Lukas, S. 2012: Processes of annual moraine formation at a temperate alpine valley glacier: insights into glacier dynamics and climatic controls. *Boreas 41*, 463–480.

Lukas, S. & Benn, D. I. 2006: Retreat dynamics of Younger Dryas glacier in the far NW Scottish Highlands reconstructed from moraine sequences. *Scottish Geographical Journal 122*, 308–325.

Lukas, S. & Bradwell, T. 2010: Reconstruction of a Lateglacial (Younger Dryas) mountain ice field in Sutherland, northwestern Scotland, and its palaeoclimatic implications. *Journal of Quaternary Science 25*, 567–580.

Lukas, S. & Sass, O. 2011: The formation of Alpine lateral moraines inferred from sedimentology and radar reflection patterns: a case study from Gornergletscher, Switzerland. *Geological Society, London, Special Publications 354*, 77–92.

Lukas, S., Merritt, J. W. & Mitchell, W. A. (eds.) 2004: *The Quaternary of the central Grampian Highlands: Field Guide*. 227 pp. Quaternary Research Association, London.

Lukas, S., Graf, A., Coray, S. & Schlüchter, C. 2012: Genesis, stability and preservation potential of large lateral moraines of Alpine valley glaciers – towards a unifying theory based on Findelengletscher, Switzerland. *Quaternary Science Reviews 38*, 27–48.

Lukas, S., Benn, D. I., Boston, C. M., Brook, M., Coray, S., Evans, D. J. A., Graf, A., Kellerer-Pirklbauer, A., Kirkbride, M. P., Krabbendam, M., Lovell, H., Machiedo, M., Mills, S. C., Nye, K., Reinardy, B. T. I., Ross, F. H. & Signer, M. 2013: Clast shape analysis and clast transport paths in glacial environments: A critical review of methods and the role of lithology. *Earth-Science Reviews 121*, 96–116.

Matthews, J. A., McCarroll, D. & Shakesby, R. A. 1995: Contemporary terminal-moraine ridge formation at a temperate glacier: Styggedalsbreen, Jotunheimen, southern Norway. *Boreas 24*, 129-139.

McCarroll, D. & Rijsdijk, K. F. 2003: Deformation styles as a key for interpreting glacial depositional environments. *Journal of Quaternary Science 18*, 473–489.

McDougall, D. A. 2001: The geomorphological impact of Loch Lomond (Younger Dryas) Stadial plateau icefields in the central Lake District, northwest England. *Journal of Quaternary Science 16*, 531–543.

van der Meer, J. J. M., Kjær, K. H. & Krüger, J. 1999: Subglacial water-escape structures and till structures, Sléttjökull, Iceland. *Journal of Quaternary Science 14*, 191–205.

van der Meer, J. J. M., Kjær, K. H., Krüger, J., Rabassa, J. & Kilfeather, A. A. 2009. Under pressure: clastic dykes in glacial settings. *Quaternary Science Reviews 28*, 708–720.

Merritt, J. W., Coope, G. R. & Walker, M. J. C. 2003: The Torrie Lateglacial organic site and Auchenlaich pit, Callander. *In* Evans, D. J. A. (ed.): *The Quaternary of the Western Highland Boundary: Field Guide*, 126–133. Quaternary Research Association, London.

Graham, D. J. & Midgley, N. G. 2000: Graphical representation of particle shape using triangular diagrams: an Excel spreadsheet method. *Earth Surface Processes and Landforms 25*, 1473–1477.

Ó Cofaigh, C., Lemmen, D. S., Evans, D. J. A. & Bednarski, J. 1999: Glacial landform-sediment assemblages in the Canadian High Arctic and their implications for late Quaternary glaciation. *Annals of Glaciology 28*, 195–201.

Peacock, J. D., Harkness, D. D., Housley, R. A., Little, J. A. & Paul, M. A. 1989: Radiocarbon ages for a glaciomarine bed associated with the maximum extent of the Loch Lomond Readvance in west Benderloch, Argyll. *Scottish Journal of Geology 25*, 69–79.

Pearce, D. 2014: *Reconstruction of Younger Dryas glaciation in the Tweedsmuir Hills, Southern Uplands, Scotland: Style, dynamics and palaeo-climatic implications*. Ph.D. thesis, University of Worcester, 229 pp.

Phillips, E. & Merritt, J. 2008: Evidence for multiphase water-escape during rafting of shelly marine sediments at Clava, Inverness-shire, NE Scotland. *Quaternary Science Reviews 27*, 988–1011.

Phillips, E., Everest, J. & Reeves, H. 2012: Micromorphological evidence for subglacial multiphase sedimentation and deformation during overpressurised fluid flow associated with hydrofracturing. *Boreas 42*, 395–427.

Phillips, E., Lipka, E. & van der Meer, J. J. M. 2013: Micromorphological evidence of liquefaction and sediment deposition during basal sliding of glaciers. *Quaternary Science Reviews 81*, 114–137.

Phillips, E. R., Evans, D. J. A., van der Meer, J. J. M. & Lee, J. R. 2018: Microscale evidence of liquefaction and its potential triggers during soft-bed deformation within subglacial traction tills. *Quaternary Science Reviews 181*, 123–143.

Piotrowski, J. A. 1997: Subglacial groundwater flow during the last glaciation in northwestern Germany. *Sedimentary Geology 111*, 217–224.

Price, R. J. 1970: Moraines at Fjallsjökull, Iceland. *Arctic and Alpine Research 2*, 27–42.

Reinardy, B. T. I. & Lukas, S. 2009: The sedimentary signature of ice-contact sedimentation and deformation at macro- and micro-scale: A case study from NW Scotland. *Sedimentary Geology 221*, 87–98.

Reinardy, B. T. I., Leighton, I. & Marx, P. J. 2013: Glacier thermal regime linked to processes of annual moraine formation at Midtdalsbreen, southern Norway. *Boreas 42*, 896–911.

Reinardy, B. T. I., Booth, A. D., Hughes, A. L. C., Boston, C. M., Åkesson, H., Bakke, J., Nesje, A., Giesen, R. H. & Pearce, D. M. 2019: Pervasive cold ice within a temperate glacier – implications for glacier thermal regimes, sediment transport and foreland geomorphology. *The Cryosphere 13*, 827–843.

Rijsdijk, K. F. 2001: Density-driven deformation structures in glaciogenic consolidated diamicts: examples from Traeth y Mwnt, Cardiganshire, Wales, U.K. *Journal of Sedimentary Research 71*, 122–135.

Rijsdijk, K. F., Owen, G., Warren, W. P., McCarroll, D., & van der Meer, J. J. M. 1999: Clastic dykes in over-consolidated tills: evidence for subglacial hydrofracturing at Killiney Bay, eastern Ireland. *Sedimentary Geology 129*, 111–126. Elsevier, Amsterdam.

Ravier, E. & Buoncristiani, J. -F. 2018: Chapter 12 – Glaciohydrogeology. *In* Menzies, J. & van der Meer, J. J. M. (eds.): *Past Glacial Environments*, 431–466.

Robinson, Z. P., Fairchild, I. J. & Russell, A. J. 2008: Hydrogeological implications of glacial landscape evolution at Skeiðarársandur, SE Iceland. *Geomorphology 97*, 218–236.

Sharp, M. 1984: Annual moraine ridges at Skálafellsjökull, south-east Iceland. *Journal of Glaciology 30*, 82–93.

Sissons, J. B. 1974: A lateglacial ice cap in the central Grampians, Scotland. *Transactions of the Institute of British Geographers 62*, 95–114.

Sissons, J. B. & Sutherland, D. G. 1976: Climatic inferences from former glaciers in the south-east Grampian Highlands. *Journal of Glaciology 17*, 325–346.

Skidmore, M. L. & Sharp, M. J. 1999: Drainage system behaviour of a high arctic polythermal glacier. *Annals of Glaciology 28*, 209–215

Smith, R. A., Merritt, J. W., Leslie, A. G., Krabbendam, M. & Stephenson, D. 2011: Bedrock and Superficial Geology of the Newtonmore – Ben Macdui district: Description for Sheet 64 (Scotland). *British Geological Survey Internal Report, OR/11/055*. 122 pp.

Standell, M. R. 2014*: Lateglacial (Younger Dryas) glaciers and ice-sheet deglaciation in the Cairngorm Mountains, Scotland: glacier reconstructions and their palaeoclimatic implications*. Ph.D. thesis, Loughborough University, 403 pp.

Stephenson, D. & Gould, D. 1995: *British Regional Geology: the Grampian Highlands*. 261 pp. HMSO, London.

Swift, D. A., Evans, D. J. A., Fallick, A. E. 2006: Transverse englacial debris-rich ice bands at Kvíárjökull, southeast Iceland. *Quaternary Science Reviews 25*, 1708–1718.

Swift, D. A., Cook, S. J., Graham, D. J., Midgley, N. G., Fallick, A. E., Storrar, R., Toubes Rodrigo, M., Evans, D. J. A. 2018: Terminal zone glacial sediment transfer at a temperate overdeepened glacier system. *Quaternary Science Reviews 180*, 111–131.

Syverson, K. M. & Mickelson, D. M. 2009: Origin and significance of lateral meltwater channels formed along a temperate glacier margin, Glacier Bay, Alaska. *Boreas 38*, 132–145.

Waller, R. I., Murton, J. B. & Kristensen, L. 2012: Glacier–permafrost interactions: Processes, products and glaciological implications. *Sedimentary Geology 255*, 1–28.

van der Wateren, F. M. 1995: Structural geology and sedimentology of push moraines - processes of soft sediment deformation in a glacial environment and the distribution of glaciotectonic styles. *Mededelingen Rijks Geologische Dienst 54*, 1–168.

van der Wateren, F. M. 1999: Structural geology and sedimentology of the Heiligenhafen till section, Northern Germany. *Quaternary Science Reviews 18*, 1625–1639.

van der Wateren, F. M., Kluiving, S. J. & Bartek, L. R. 2000: Kinematic indicators of sub glacial shearing. *In* Maltman, A. J., Hubbard, B. & Hambrey, M. J. (eds.): *Deformation of Glacial Materials,* 259–278. *Geological Society of London Special Publications 176*.

Winkler, S. 1996: Front variations from outlet glaciers of Jostedalsbreen, western Norway, during the 20th century. *Norges Geologiske Undersnkelse Bulletin 431*, 33–47.

Winkler, S. & Nesje, A. 1999: Moraine Formation at an Advancing Temperate Glacier: Brigsdalsbreen, Western Norway. *Geografiska Annaler 81A*, 17–30.

Wyshnytzky, C. E. 2017: *On the mechanisms of minor moraine formation in high-mountain environments of the European Alps*. Ph.D. thesis, Queen Mary University of London, 329 pp.

Zieliński, T. & van Loon, A. 2003: Pleistocene sandur deposits represent braidplains, not alluvial fans. *Boreas 32*, 590–611.

Zemp, M. & 38 others. 2015: Historically unprecedented global glacier decline in the early 21st century. *Journal of Glaciology 61*, 745–762.

Figure captions

Fig. 1. Location and palaeoglaciological context of the study area. A. Map showing the location of the Gaick, central Scotland, relative to other Younger Dryas ice masses in the wider region, based on data in Sissons and Sutherland (1976), Benn & Ballantyne (2005), Finlayson (2006), Golledge (2010), Standell (2014), Boston *et al*. (2015) and Chandler *et al*. (2019a). B. Principal topography of the Gaick, Central Grampians, Scotland. The location of the geomorphological map shown in Fig. 2 is indicated by a white frame. Scale and orientation in (B) are provided by British National Grid (10 km intervals). C. Reconstruction of the 'mid-range' Younger Dryas Gaick Icefield (after Chandler *et al*. 2019a). Underlying hillshade relief models in (B) and (C) were derived from the NEXTMap BritainTM dataset (Intermap Technologies Inc.). Modified from Chandler *et al*. (2019a).

Fig. 2. Glacial geomorphological map extract for southern Gaick Pass (NN 731 820), with the Younger Dryas glacier limit and locations of moraine exposures (BCL-04 to BCL-07) also indicated. The map extract is adapted from the geomorphological map presented by Chandler *et al*. (2019b). Underlying hillshade relief model was derived from the NEXTMap Britain$^{\mathrm{TM}}$ dataset (Intermap Technologies Inc.).

Fig. 3. Lithofacies codes and symbols used on the section logs presented in this paper. The lithofacies codes are adapted from Eyles *et al*. (1983).

Fig. 4. Morphology and arrangement of Younger Dryas 'hummocky moraine' in the Gaick, Scotland. A.–D. Annotated field photographs of moraines in (A) Gaick Pass, (B) Glen Edendon, and (C and D) Coire Chais. The white solid lines indicate moraines crestlines; the black dashed line in (A) indicates the upslope limit of the glaciogenic sediment cover (or 'drift limit'). E. Aerial imagery showing the planform arrangement of moraines in Glas Choire. The imagery is from Microsoft® Bing™ Maps.

Fig. 5. A. Section log of moraine BCL-05 (NN 735 821; 457 m a.s.l.). B. Section log of moraine BCL-06 (NN 734 822; 463 m a.s.l.). C. Section log of moraine BCL-07 (NN 734 822; 463 m a.s.l.). The black frame in (C) indicates the approximation location of the photograph shown in Fig. 6A. D. Section log of moraine BCL-07 (NN 734 822; 463 m a.s.l.). The black frame in (D) indicates the approximation location of the photograph shown in Fig. 7A. The locations of the different lithofacies units/associations described in the text are indicated in the top right diagrams on each section log. For locations of the exposures, see Fig. 2; for key, see Fig. 3. See text for detailed descriptions of the sections.

Fig. 6. A. Annotated field photograph of the largest clastic dyke within moraine BCL-07. The black frame shows the location of the photograph in B. For location, see Fig. 5B. B. Close-up photograph showing the sediments within the largest clastic dyke. Trowel for scale; the blue handle is 12 cm long.

Fig. 7. A. Annotated field photograph of the clastic dyke within moraine BCL-04. The black frame shows the location of the photograph in (B). Trenching tool for scale; the painted red and white intervals are 10 cm long. For location, see Fig. 5C. B. Close-up photograph showing the sediments within the largest clastic dyke. Trowel for scale; the blue handle is 12 cm long.

Fig. 8. Results of the moraine clast shape analyses conducted on samples obtained from the moraines presented in this paper. Ternary diagrams and indices were derived using a modified version of TriPlot (Graham & Midgley, 2000). Roundness classes for the frequency distribution plots follow the scheme of Benn & Ballantyne (1994). See text for description.

Fig. 9. Covariance plots displaying (A) the RA-index plotted against the C_{40}-index and (B) the RWR-index plotted against the C_{40}-index for the various control samples and moraines. Samples from the moraines suggest they contain subglacially-transported material. See text for further details.

Fig. 10. Schematic representation of the sequence of events involved in the formation of terrestrial ice-contact fans, modified from Lukas (2005). A. Terrestrial ice-contact fan formation where groundwater drainage is efficient: A1. Fan construction along a temporarily stationary ice margin by stacking of supraglacial debris flows and glaciofluvial sediments. A2. Formation of the rectilinear ice-contact face where material is at the angle of repose as a result of partial collapse following withdrawal of ice support. A3. Short-lived re-advance of the glacier margin causing widespread deformation within the fan and occasionally the addition of new material. A4. Formation of a new ice-contact face and abandonment of the fan. A5. Partial overriding of the proximal part of a moraine leading to partial glaciotectonisation. A6. Larger-scale overriding leading to smoothing and alteration of the original moraine asymmetry and complete glaciotectonisation. B. Terrestrial ice-contact fan formation in situations where the hydrogeological system becomes pressurised: B1. Fan formation, as in (A1). B2. The local hydrogeological system becomes pressurised after meltwater fluxes saturate the substrate. B3. Pressurised groundwater is evacuated into the fan while it is still in contact the glacier margin, resulting in a hydrofracture within the moraine. B4. Formation of the rectilinear ice-contact face, as in (A2). Note: Pressurisation of the groundwater system likely occurs only in specific situations (see text).

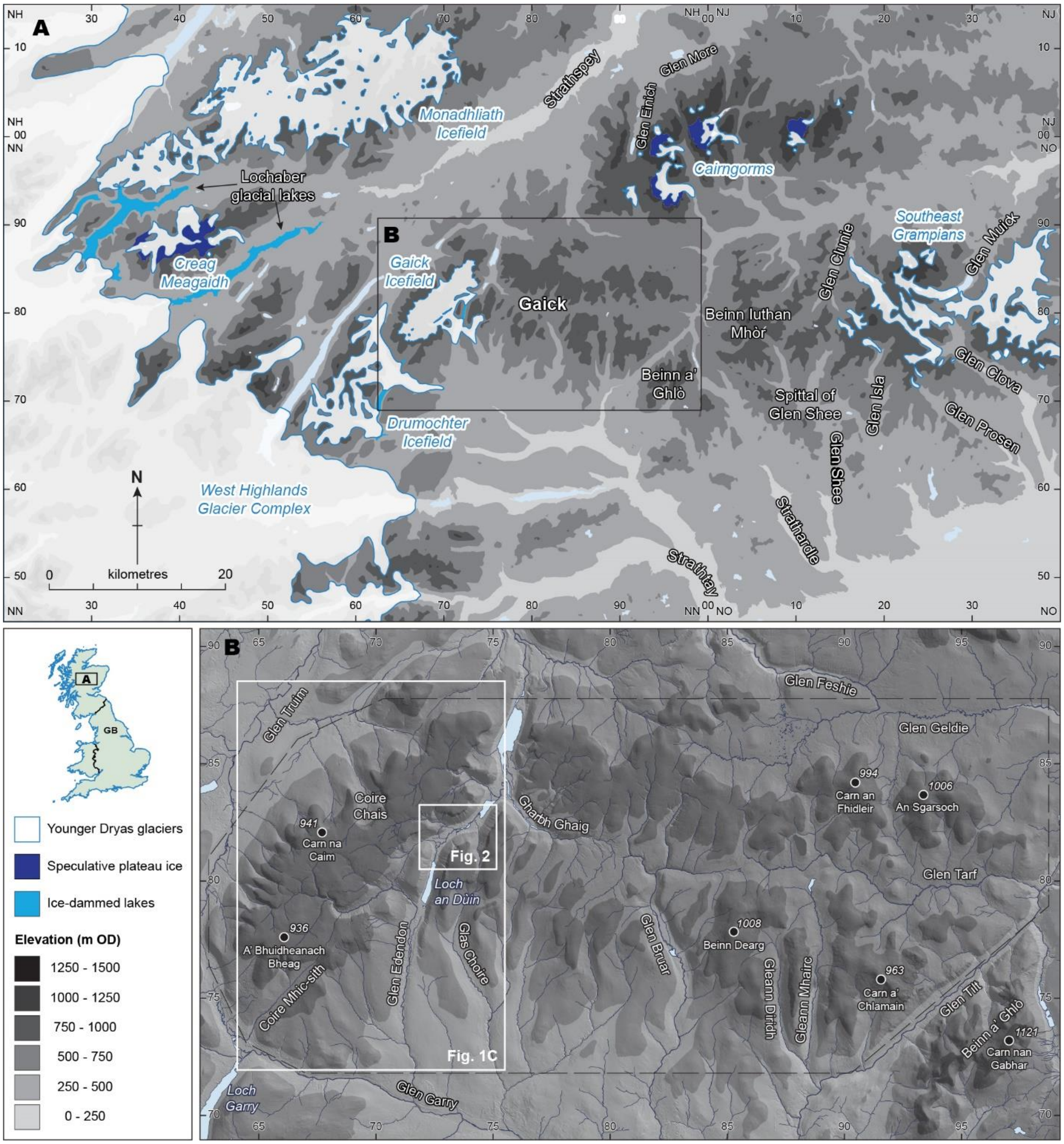


Fig. 1. Location and palaeoglaciological context of the study area. (A) Map showing the location of the Gaick, central Scotland, relative to other Younger Dryas ice masses in the wider region, based on data in Sissons and Sutherland (1976), Benn & Ballantyne (2005), Finlayson (2006), Golledge (2010), Standell (2014), Boston *et al*. (2015) and Chandler *et al*. (2019a). (B) Principal topography of the Gaick, Central Grampians, Scotland. The location of the geomorphological map shown in Fig. 2 is indicated by a white frame. Scale and orientation in (B) are provided by British National Grid (10 km intervals). (C) Reconstruction of the 'mid-range' Younger Dryas Gaick Icefield (after Chandler *et al*. 2019a). Underlying hillshade relief models in (B) and (C) were derived from the NEXTMap BritainTM dataset (Intermap Technologies Inc.). Modified from Chandler *et al*. (2019a).

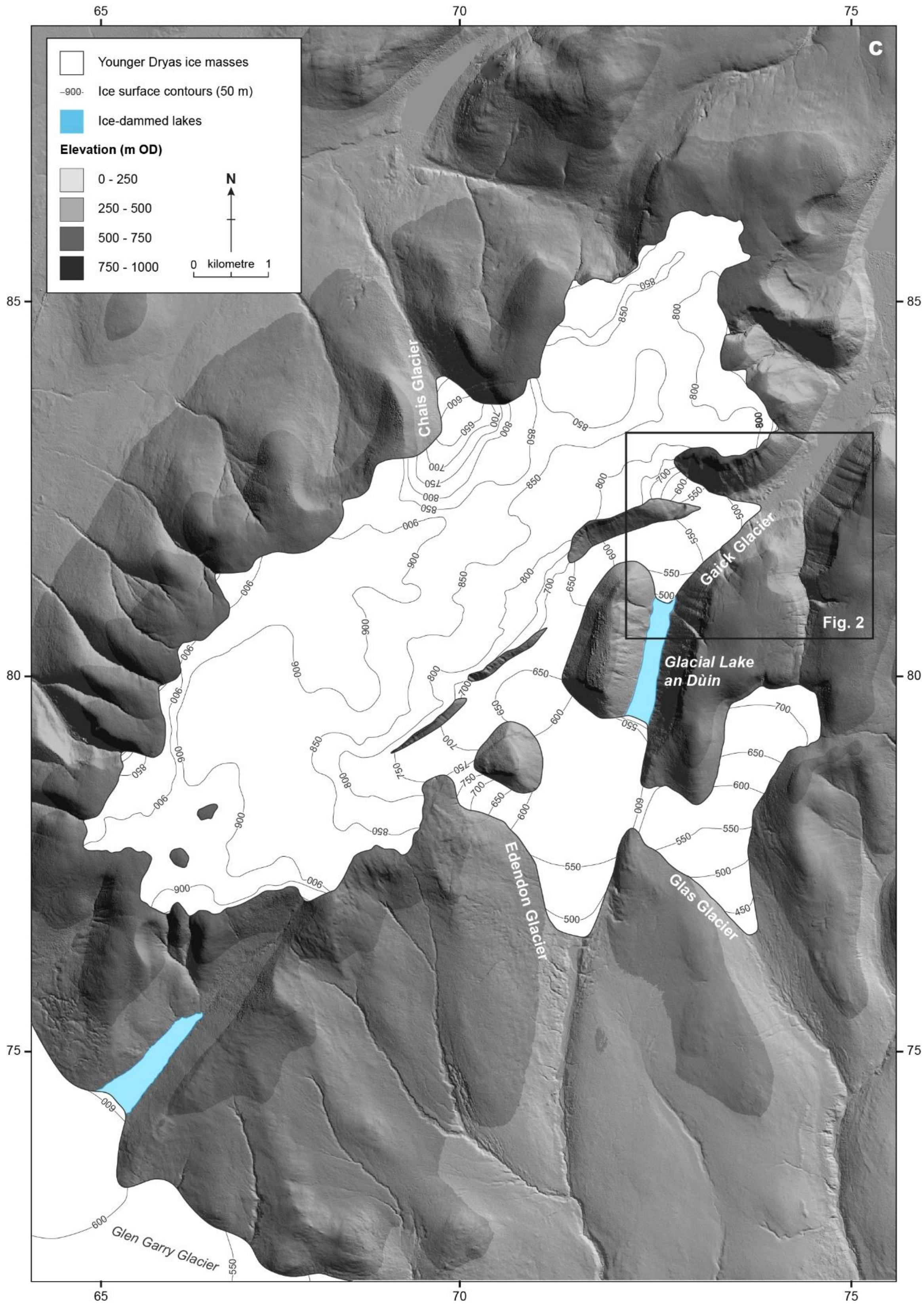


Fig. 1. Continued

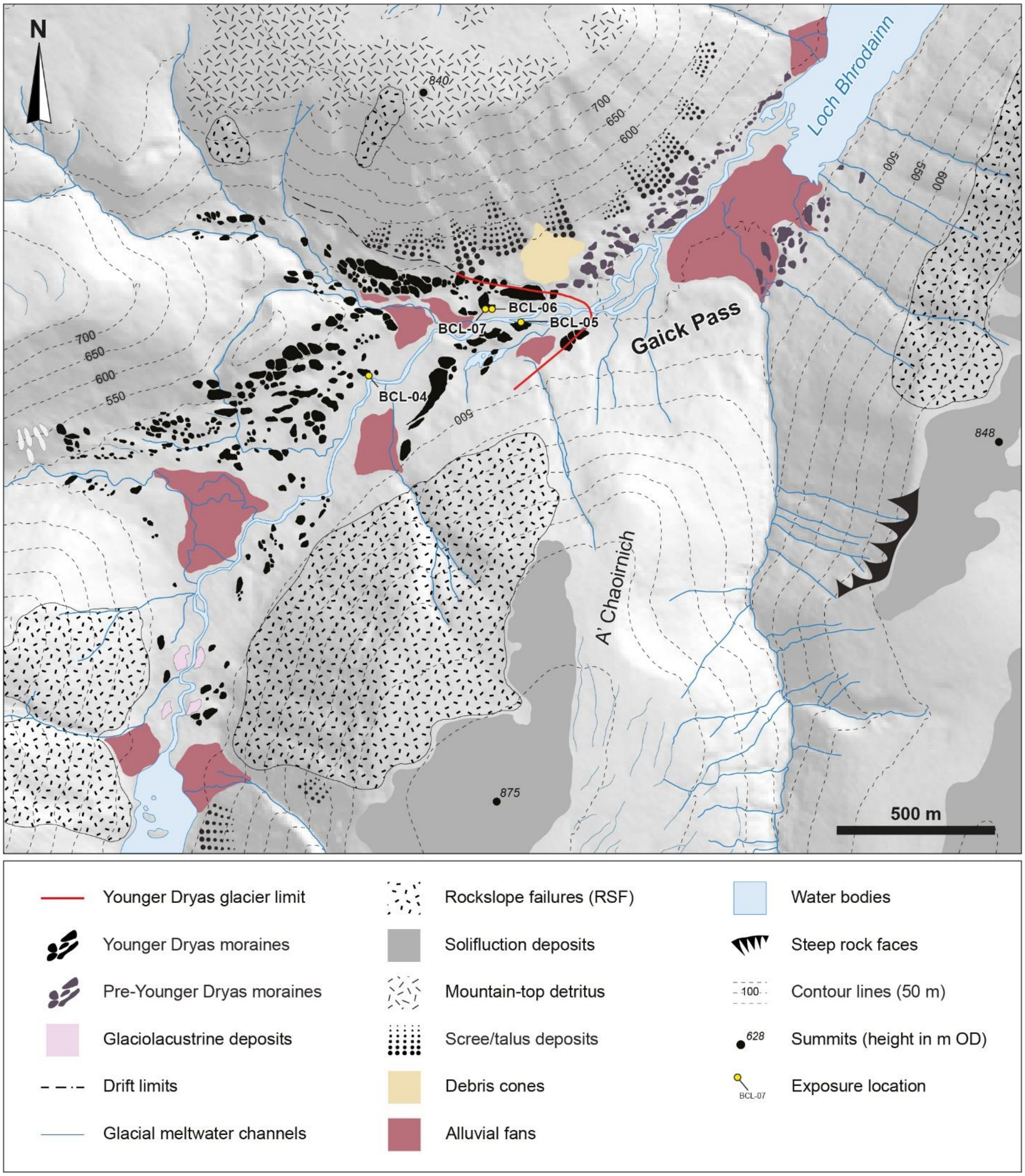


Fig. 2. Glacial geomorphological map extracts for southern Gaick Pass (NN 731 820), with the Younger Dryas glacier limit and locations of moraine exposures also indicated. The map extract is taken from the glacial geomorphological map presented by Chandler *et al*. (2019b). Underlying hillshade relief model was derived from the NEXTMap Britain™ dataset (Intermap Technologies Inc.).

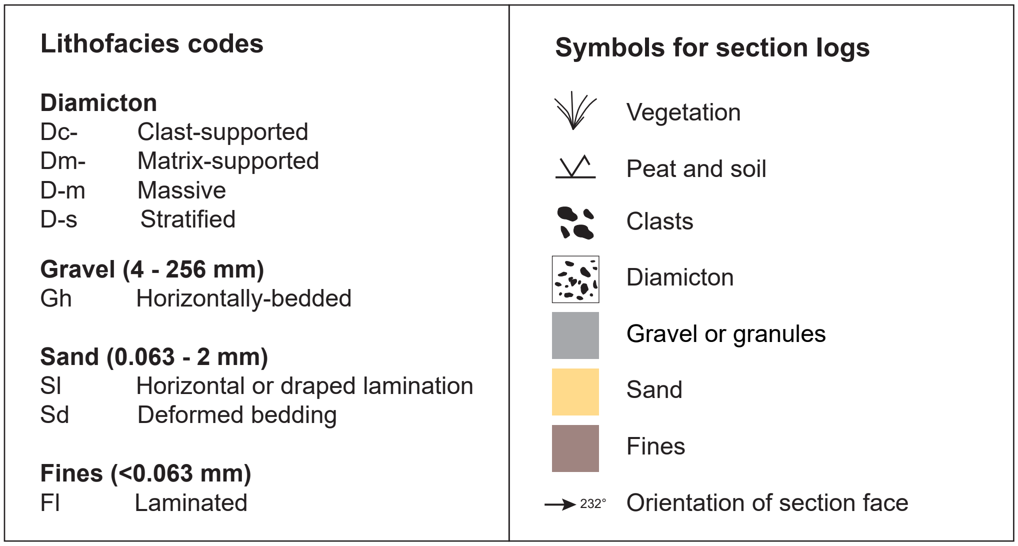


Fig. 3. Lithofacies codes and symbols used on the section logs presented in this paper. The lithofacies codes are adapted from Eyles *et al*. (1983).

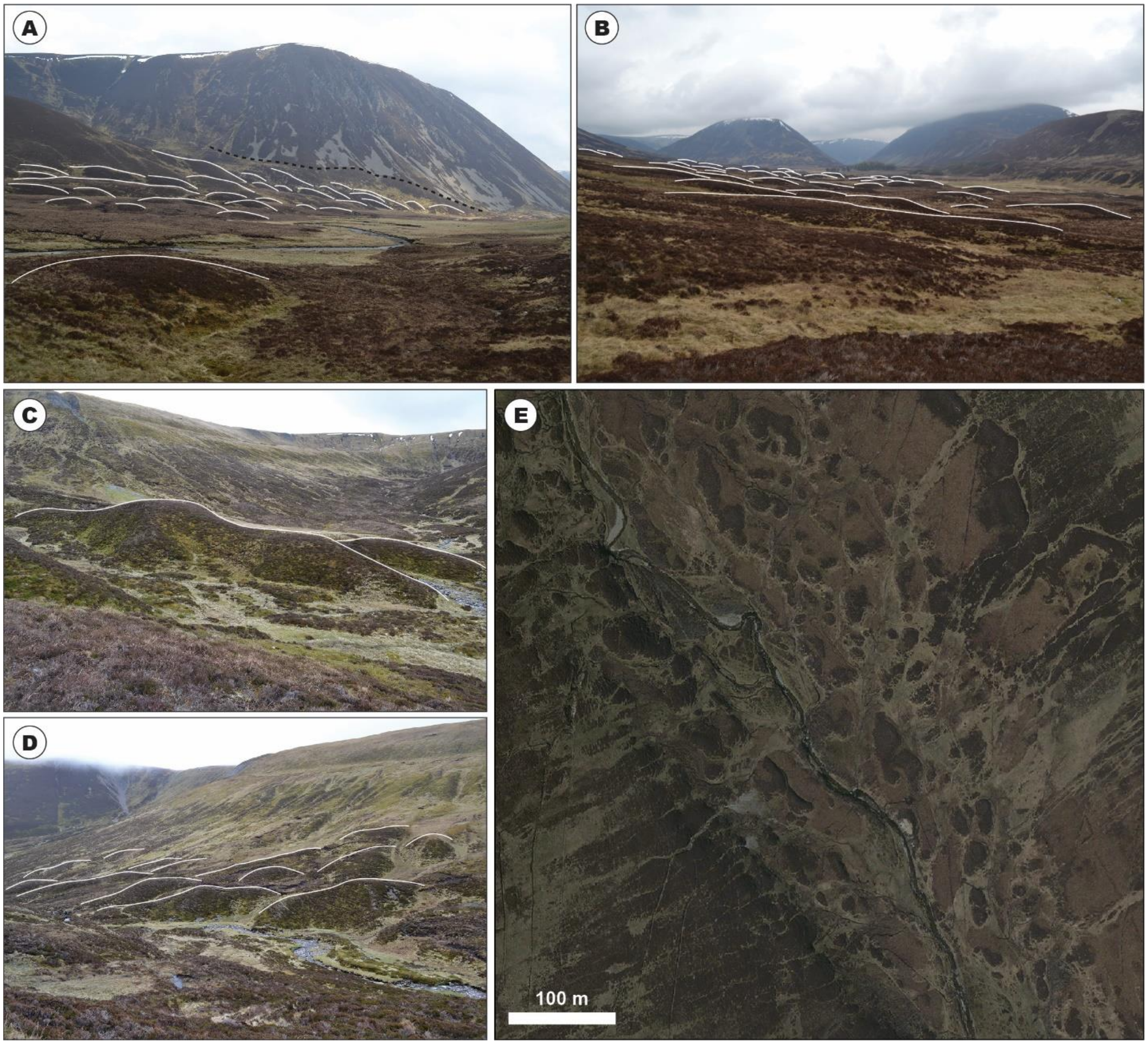
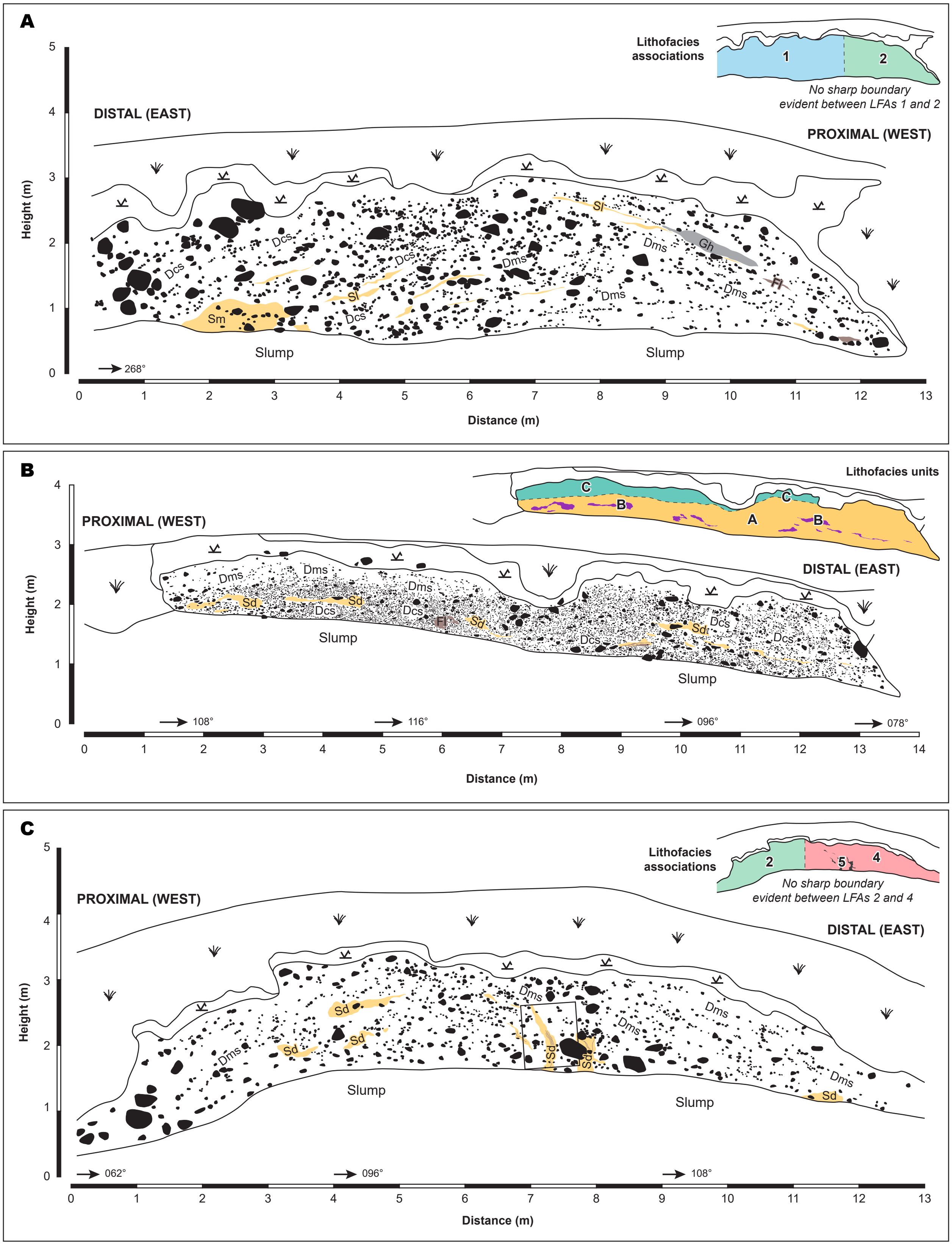


Fig. 4. Morphology and arrangement of Younger Dryas ‘hummocky moraine’ in the Gaick, Scotland. (A–D) Annotated field photographs of moraines in (A) Gaick Pass, (B) Glen Edendon, and (C and D) Coire Chais. The white solid lines indicate moraines crestlines; the black dashed line in (A) indicates the upslope limit of the glaciogenic sediment cover (or ‘drift limit’). (E) Aerial imagery showing the planform arrangement of moraines in Glas Choire. The imagery is from Microsoft® Bing™ Maps.


A
Lithofacies associations
1
2
No sharp boundary evident between LFAs 1 and 2
DISTAL (EAST)
PROXIMAL (WEST)
Height (m)
Dcs
Sl
Dms
Gh
Fl
Sm
Slump
268°
Distance (m)
B
Lithofacies units
C
B
A
PROXIMAL (WEST)
DISTAL (EAST)
Dms
Sd
Dcs
Fl
Slump
108°
116°
096°
078°
Distance (m)
C
Lithofacies associations
2
5
4
No sharp boundary evident between LFAs 2 and 4
PROXIMAL (WEST)
DISTAL (EAST)
Dms
Sd
Slump
062°
096°
108°
Distance (m)

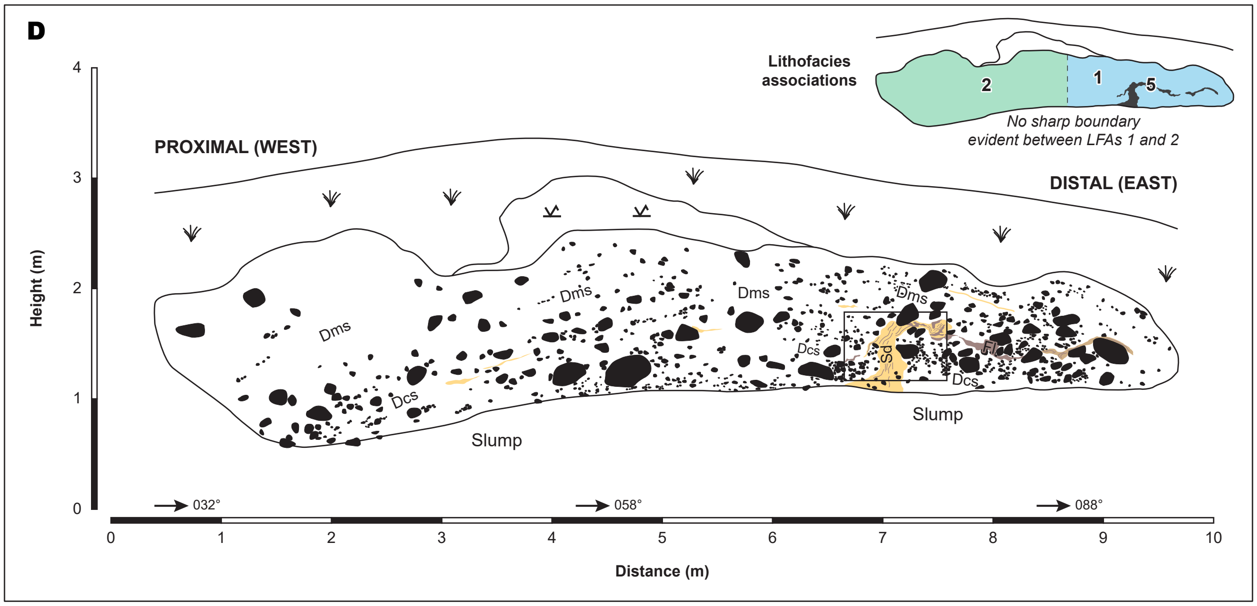


Fig. 5. A. Section log of moraine BCL-05 (NN 735 821; 457 m a.s.l.). B. Section log of moraine BCL-06 (NN 734 822; 463 m a.s.l.). C. Section log of moraine BCL-07 (NN 734 822; 463 m a.s.l.). The black frame in (C) indicates the approximation location of the photograph shown in Fig. 6A. D. Section log of moraine BCL-07 (NN 734 822; 463 m a.s.l.). The black frame in (D) indicates the approximation location of the photograph shown in Fig. 7A. The locations of the different lithofacies units/associations described in the text are indicated in the top right diagrams on each section log. For locations of the exposures, see Fig. 2; for key, see Fig. 3. See text for detailed descriptions of the sections.

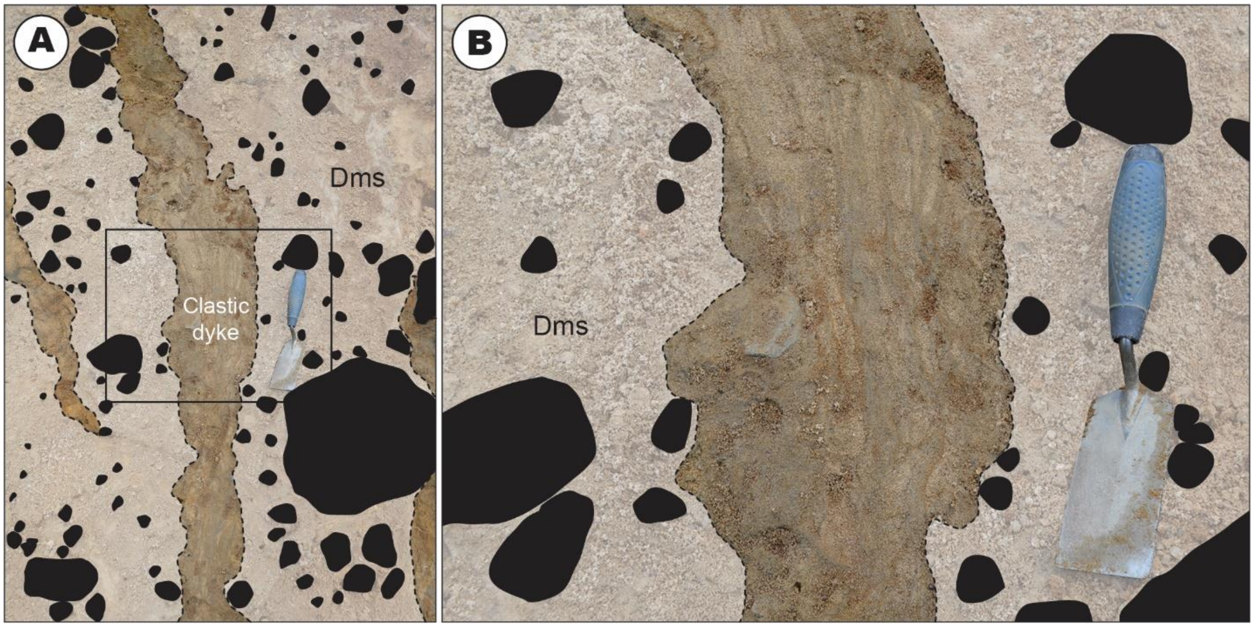


Fig. 6. A. Annotated field photograph of the largest clastic dyke within moraine BCL-07. The black frame shows the location of the photograph in B. For location, see Fig. 5B. B. Close-up photograph showing the sediments within the largest clastic dyke. Trowel for scale; the blue handle is 12 cm long.

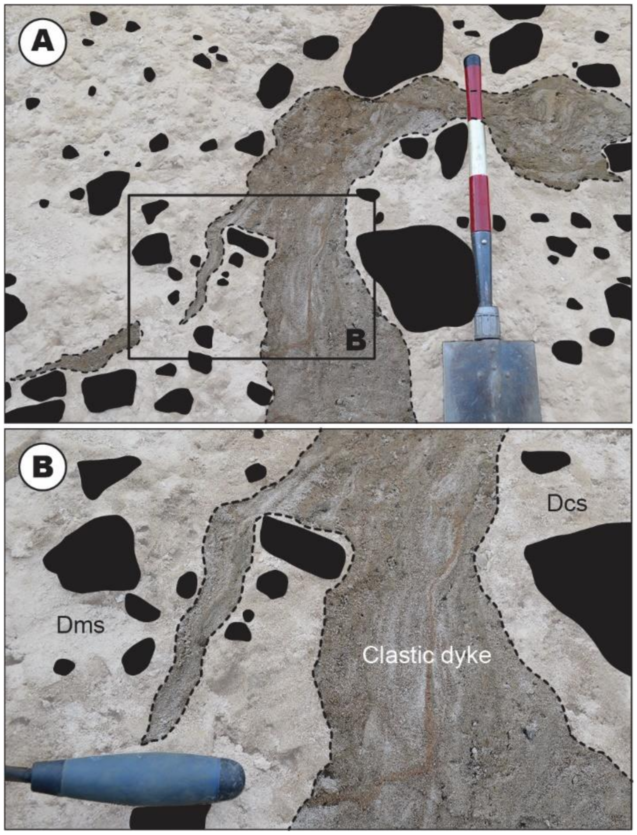


Fig. 7. A. Annotated field photograph of the clastic dyke within moraine BCL-04. The black frame shows the location of the photograph in (B). Trenching tool for scale; the painted red and white intervals are 10 cm long. For location, see Fig. 5C. B. Close-up photograph showing the sediments within the largest clastic dyke. Trowel for scale; the blue handle is 12 cm long.

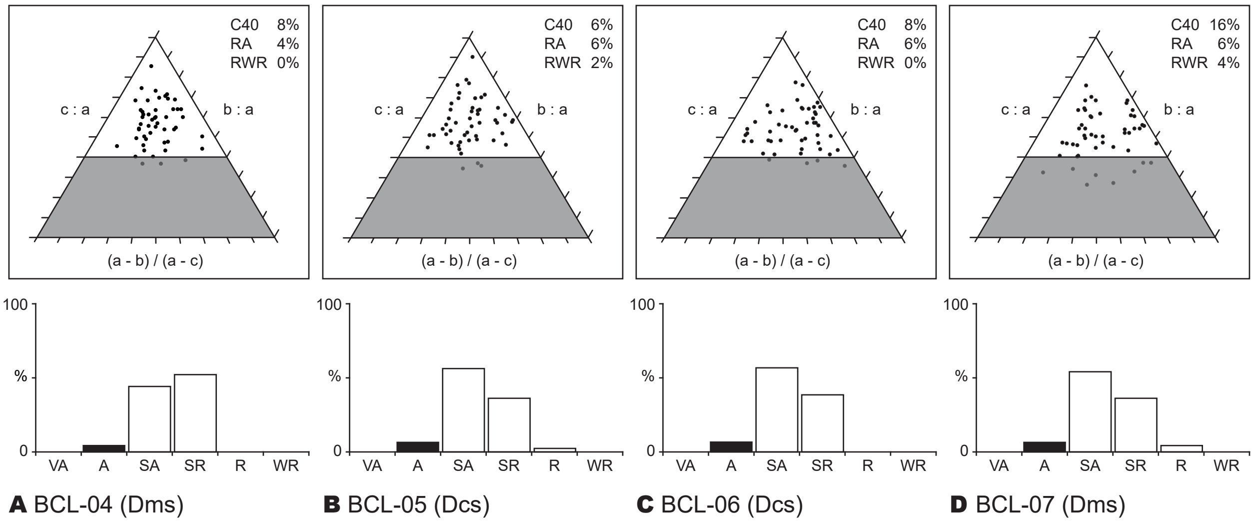


Fig. 8. Results of the moraine clast shape analyses conducted on samples obtained from the moraines described above. Ternary diagrams and indices were derived using a modified version of TriPlot (Graham & Midgley, 2000). Roundness classes for the frequency distribution plots follow the scheme of Benn & Ballantyne (1994). See text for description.

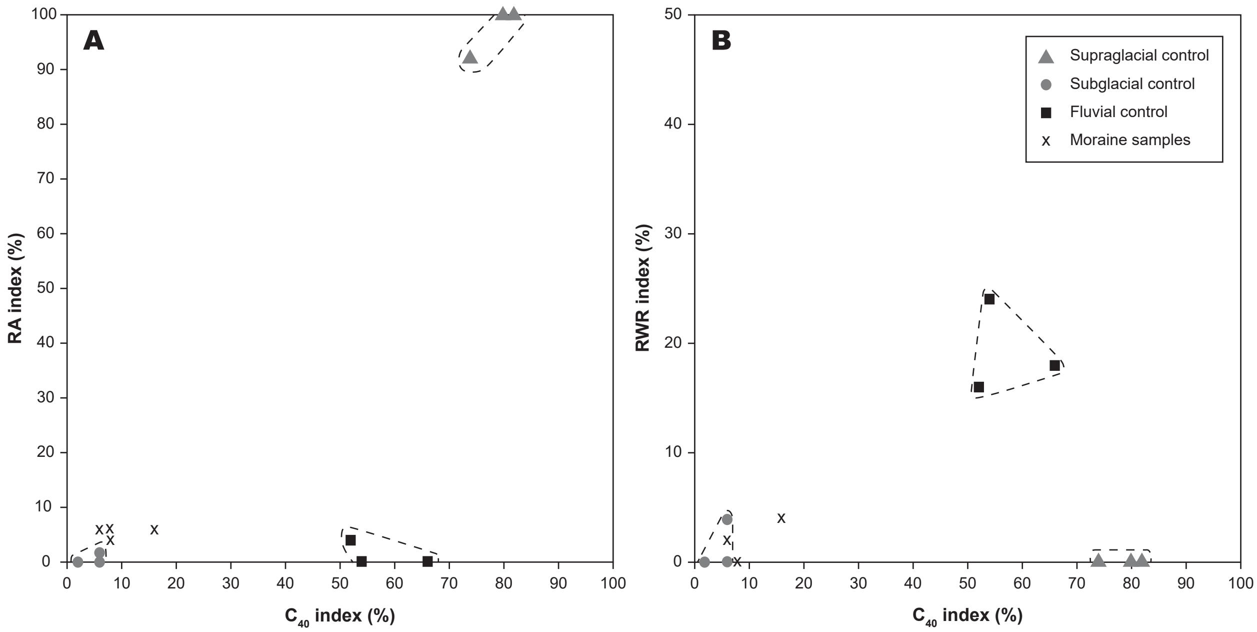


Fig. 9. Covariance plots displaying (A) the RA-index plotted against the C_{40}-index and (B) the RWR-index plotted against the C_{40}-index for the various control samples and moraines. Samples from the moraines suggest they contain subglacially-sourced material. See text for further details.

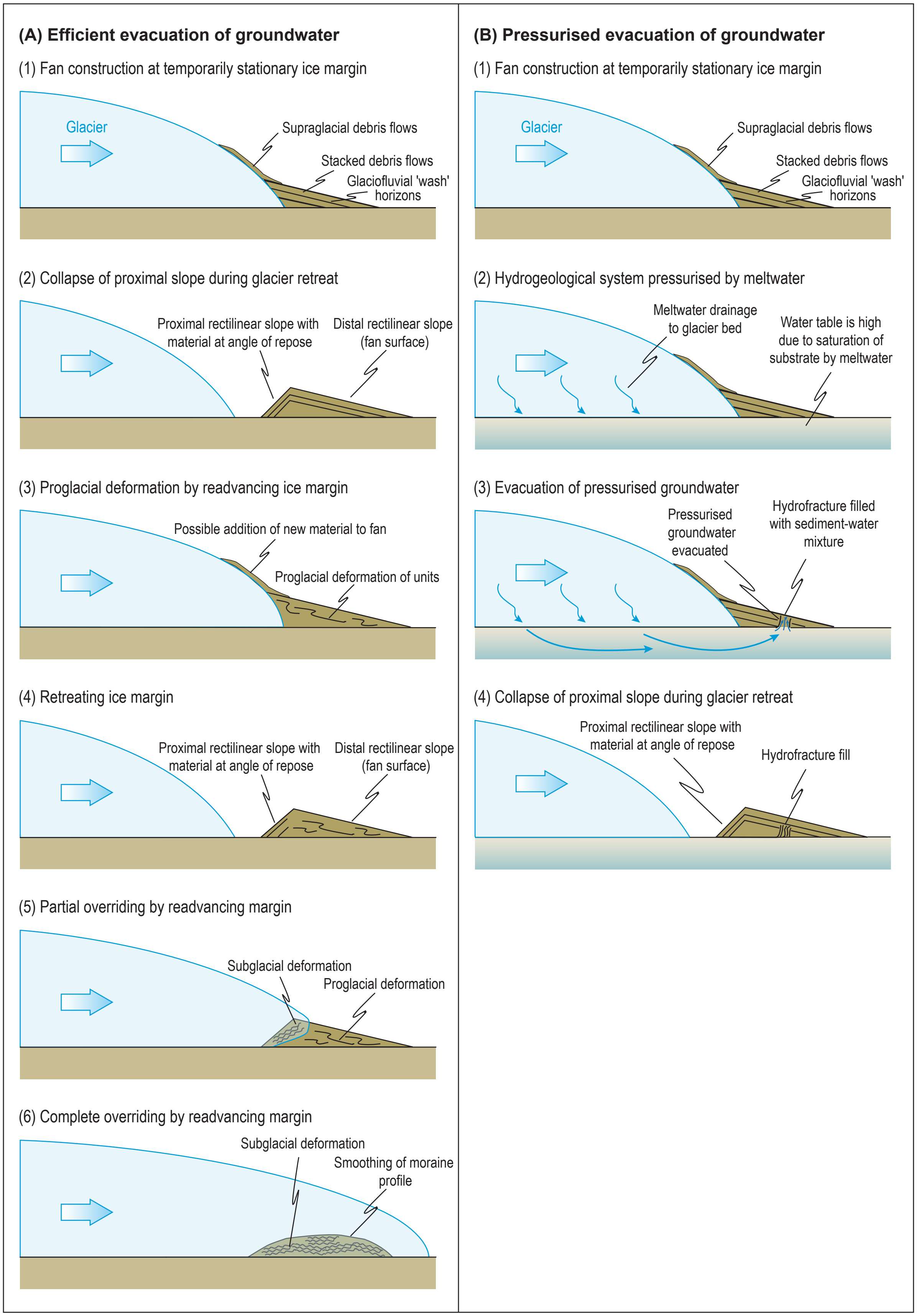

(A) Efficient evacuation of groundwater
(1) Fan construction at temporarily stationary ice margin
Glacier
Supraglacial debris flows
Stacked debris flows
Glaciofluvial 'wash' horizons
(2) Collapse of proximal slope during glacier retreat
Proximal rectilinear slope with material at angle of repose
Distal rectilinear slope (fan surface)
(3) Proglacial deformation by readvancing ice margin
Possible addition of new material to fan
Proglacial deformation of units
(4) Retreating ice margin
Proximal rectilinear slope with material at angle of repose
Distal rectilinear slope (fan surface)
(5) Partial overriding by readvancing margin
Subglacial deformation
Proglacial deformation
(6) Complete overriding by readvancing margin
Subglacial deformation
Smoothing of moraine profile
(B) Pressurised evacuation of groundwater
(1) Fan construction at temporarily stationary ice margin
Glacier
Supraglacial debris flows
Stacked debris flows
Glaciofluvial 'wash' horizons
(2) Hydrogeological system pressurised by meltwater
Meltwater drainage to glacier bed
Water table is high due to saturation of substrate by meltwater
(3) Evacuation of pressurised groundwater
Pressurised groundwater evacuated
Hydrofracture filled with sediment-water mixture
(4) Collapse of proximal slope during glacier retreat
Proximal rectilinear slope with material at angle of repose
Hydrofracture fill

Fig. 10. Schematic representation of the sequence of events involved in the formation of terrestrial ice-contact fans, modified from Lukas (2005). A. Terrestrial ice-contact fan formation where groundwater drainage is efficient: A1. Fan construction along a temporarily stationary ice margin by stacking of supraglacial debris flows and glaciofluvial sediments. A2. Formation of the rectilinear ice-contact face where material is at the angle of repose as a result of partial collapse following withdrawal of ice support. A3. Short-lived re-advance of the glacier margin causing widespread deformation within the fan and occasionally the addition of new material. A4. Formation of a new ice-contact face and abandonment of the fan. A5. Partial overriding of the proximal part of a moraine leading to partial glaciotectonisation. A6. Larger-scale overriding leading to smoothing and alteration of the original moraine asymmetry and complete glaciotectonisation. B. Terrestrial ice-contact fan formation in situations where the hydrogeological system becomes pressurised: B1. Fan formation, as in (A1). B2. The local hydrogeological system becomes pressurised after meltwater fluxes saturate the substrate. B3. Pressurised groundwater is evacuated into the fan while it is still in contact the glacier margin, resulting in a hydrofracture within the moraine. B4. Formation of the rectilinear ice-contact face, as in (A2). Note: Pressurisation of the groundwater system likely occurs only in specific situations (see text).