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## Glacially-moulded landslide runout debris in the Scottish Highlands

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## Glacially moulded landslide runout debris in the Scottish Highlands

ABSTRACT A tongue of hummocky terrain ~1 km long and ~400 m wide extends downslope from the source area of a rock-slope failure that formed the summit arête of Sgùrr nan Ceathreamhnan in the NW Highlands. The tongue descends from ~810 m to ~650 m, crosses a corrie obliquely and laps onto an opposing slope. Individual hummocks are circular to elongate, up to 6 m high and streamlined. A possible origin as recessional or ice-stagnation moraines is inconsistent with hummock morphology and the alignment of the hummock belt, and the streamlining of the hummocks is incompatible with the form of unmodified rock-avalanche runout hummocks. It is proposed that the tongue of hummocky terrain represents rock-slope failure during or after ice-sheet deglaciation, and subsequent modification of runout debris by subglacial erosion during the Loch Lomond Stade (~12.9–11.7 ka). This interpretation implies (i) that the debris was deposited by an excess-runout rock avalanche; (ii) that the glacier that subsequently occupied the corrie was warm-based; (iii) that Lateglacial landslide runout debris was not invariably evacuated by Loch Lomond Stadial glaciers, as previously suggested; and (iv) that some features interpreted as hummocky moraines elsewhere may have a similar origin.

KEY WORDS: glacial bedforms; hummocks; Lateglacial; Loch Lomond Stade; rock avalanche; rock-slope failure

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## Introduction

In this paper the term *landslide* refers to rock-slope failures (RSFs) in the form of rockslides, rock avalanches, major rockfalls, toppling failures, deep-seated rock-slope deformations and complex failures involving two or more types of movement. Landslides are a pervasive feature of mountainous terrain in the Scottish Highlands. Watters (1972) and Holmes (1984) showed that large postglacial landslides are widespread on metasedimentary rocks, particularly schists, and a compilation of documentary evidence (Ballantyne 1986) identified 564 RSFs in the Highlands and Hebrides. Jarman (2006, 2007) estimated that the Highlands alone contain over 550 RSFs, including 140 with areas exceeding 0.25 km<sup>2</sup>.

Cosmogenic nuclide exposure dating of the runout debris of catastrophic RSFs in Scotland and NW Ireland has demonstrated that almost all located outside of the limits of the Loch Lomond Readvance (the glaciers that culminated during the Loch Lomond Stade (LLS) of ~12.9–11.7 ka) occurred during the Lateglacial period, the interval between ice-sheet deglaciation (~17–15 ka, depending on location) and the end of the LLS at ~11.7 ka. Analysis of the timing of 20 Lateglacial RSFs suggests that landslide activity peaked within two millennia following ice-sheet deglaciation in response to (i) progressive weakening of rock slopes due to deglacial stress release and associated propagation of internal joint networks, and (ii) seismic activity associated with fault movements due to rapid glacio-isostatic uplift (Ballantyne et al. 2014a, 2014b). It follows that *inside* the limits of the Loch Lomond Readvance many large catastrophic RSFs must also have occurred during the Lateglacial period, but that the resultant runout debris has been removed by glacier ice. The sites of such ‘debris-free’ RSFs take the form of landslide scars on mountainside slopes, typically characterised by steep headscarps, planar or stepped failure planes, sidescarps, tension cracks above headscarps and, more rarely, detached landslide blocks near the crest of the failure plane (Ballantyne 2013; Cave & Ballantyne 2016).

The fate of landslide runout debris removed by Loch Lomond Readvance glaciers is poorly understood. At a few sites, landslides appear to have deposited debris directly on to the surfaces of these glaciers, which then transported it farther downvalley (Peacock 1975; Robinson 1977; Ballantyne & Stone 2013). Benn (1989) has shown that exceptionally large lateral moraines emanating from corries are linked to the presence of cliffed corrie sidewall source areas, suggesting that such moraines comprise mainly glacially-reworked rockfall and RSF debris. Similarly, a massive end moraine fronting Coire Fearchair in the Red Hills of

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3 Skye appears to represent the final destination of runout debris from one or more rockslides  
4 from the corrie headscarp (Ballantyne *et al.* 2016). It also seems likely that Lateglacial RSFs  
5 that occurred before or during the Loch Lomond Readvance contributed to the vast quantities  
6 of glacial sediment present in the recessional hummocky moraines that represent  
7 oscillatory retreat of Loch Lomond Readvance glaciers in many Highland glens (Ballantyne  
8 2013).

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13 A further possibility is that Loch Lomond Readvance glaciers over-ran and modified  
14 Lateglacial landslide debris at some sites. Glacial modification of very large landslide blocks  
15 is evident on the Trotternish Peninsula on Skye, where successive ice sheets have smoothed  
16 and moulded displaced masses of basaltic lavas east of the zone of postglacial slope failure  
17 (Godard 1965; Ballantyne 2007a, 2016). The Trotternish landslides, however, are exceptional  
18 in that they involved foundering, sliding and lateral displacement of exceptionally large  
19 blocks of basaltic lava up to 300 m thick that have resisted entrainment by glacier ice, and are  
20 both structurally and morphologically unrepresentative of RSFs elsewhere in Scotland. **In this**  
21 **paper** the evidence for glacial modification of Lateglacial landslide runout debris is described  
22 with reference to an apparently 'debris free' RSF site at Sgùrr nan Ceathreamhnan in the NW  
23 Highlands.  
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### 32 **Sgùrr nan Ceathreamhnan**

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34 Sgùrr nan Ceathreamhnan (NG 057228; 57°15'N, 05°14'W; Figure 1) is located on the main  
35 N–S watershed in the Kintail area of the NW Highlands. The highest parts of the mountain  
36 consist of twin summits, the East Top (1151 m) and West Top (1143 m). These are 500 m  
37 apart and linked by a narrow arête formed by a major landslide south of the summit ridge  
38 (Figure 2a). The mountain and adjacent low ground are underlain by pelitic and psammitic  
39 schists (May *et al.* 1993). South of the summit arête these are strongly foliated, fractured and  
40 dip steeply (65°) southwards, forming the backscarp of the landslide (Figure 2b).  
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46 During the Last Glacial Maximum of ~26–19 ka, the mountains of Kintail were completely  
47 buried under the last Scottish Ice Sheet; Hughes *et al.* (2014) calculated that the LGM ice  
48 divide over northern Scotland must have exceeded ~1400 m relative to present sea level. By  
49 ~16.0 ka summits in Wester Ross and adjacent areas had emerged from the ice (Fabel *et al.*,  
50 2012), and it is likely that all low ground in the area was deglaciated by, or shortly after, the  
51 onset of rapid warming that heralded the beginning of the Lateglacial Interstade of ~14.7–  
52 12.9 ka (Ballantyne & Small 2018). Glacier ice reoccupied the corries and valleys the Kintail  
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3 area during the ensuing Loch Lomond Stade (~12.9–11.7 ka). During this period glacier ice  
4 filled Coire Allt an Tuirc, south of Sgùrr nan Ceathreamhnan (Figure 1), and fed a large  
5 valley glacier that terminated 25 km to the east at the mouth of Glen Affric (Bennett &  
6 Boulton, 1993a, 1993b). During the Loch Lomond Readvance maximum the higher parts of  
7 Sgùrr nan Ceathreamhnan formed a nunatak, completely surrounded by glacier ice. On  
8 neighbouring Sgùrr Gaorsaic (839 m; NG 036219), 2 km to the SW, a well-defined trimline  
9 indicates a maximum Loch Lomond Readvance ice-surface altitude of ~700 m, and ice  
10 probably extended 100–200 m higher at the headwalls of the corries that flank Sgùrr nan  
11 Ceathreamhnan.  
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### 18 **The Sgùrr nan Ceathreamhnan landslide and hummock belt**

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20 The landslide source area on Sgùrr nan Ceathreamhnan is roughly concave in planform and  
21 extends ~700 m from the West Top to the crest of cliffs about 200 m SE of the East Top  
22 (Figures 1 and 2a). The cliffs that comprise the scar are 50–100 m high and largely defined  
23 by the dip of the foliation (~65°) and associated joints (Figures 2a and 2b). Tension cracks  
24 and down-dip displaced blocks occur near the crest of the scar. There is no evidence of ice-  
25 moulding or other form of glacial modification, indicating that the landslide occurred after  
26 downwastage of the last ice sheet. Conversely, the absence of bouldery runout debris or  
27 slipped masses of rock downslope from the landslide source indicate that failure must have  
28 occurred during the Lateglacial period, in the interval between ice sheet deglaciation (after  
29 ~16 ka) and the end of the Loch Lomond Stade. A much smaller landslide scar is represented  
30 by an arcuate cliff about 300 m south of the West Top; this also lacks runout debris.  
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39 Downslope from the main landslide scar a tongue of hummocky terrain ~1 km long and  
40 ~400 m wide extends obliquely across the floor of Coire Allt an Tuirc (Figures 1, 2c and 3).  
41 The hummock belt descends from about 810 m altitude directly below the landslide scar,  
42 crosses the main stream (Allt Beithe Garbh) then slightly ascends the far slope to 700–710 m  
43 to terminate east of Beinn an t-Socaich (Fig. 1). The margins of the hummock belt are well  
44 defined, **though terminal or lateral ridges are absent**; outside of the belt the slopes are covered  
45 by gently undulating glacial drift or hill peat. Hummocks are confined to the tongue  
46 apparently emanating from the main failure scar (Figures 1 and 3) and are absent from the  
47 western part of the corrie.  
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54 Most individual hummocks are 2–6 m high and 25–60 m long. They range from circular in  
55 plan to elliptical or elongate, appear to be randomly but fairly uniformly distributed and are  
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3 commonly separated by bogs or ponds (Figure 2d). All are gently domed, and most are  
4 streamlined in a southerly direction. Many support scattered glacially-deposited schist  
5 boulders up to 1.5 m long. Exposures in the hummock belt are limited to two shallow stream  
6 banks. These reveal interlocked angular clasts of varying size, some of which have apparently  
7 experienced *in situ* fracturing, with an infill of coarse granular material in the voids between  
8 clasts. By contrast, a streambank exposure downvalley from the hummock belt reveals clasts  
9 of various sizes embedded in a tough silty-sand matrix; some of the clasts exhibit the edge  
10 rounding and faceting characteristic of debris that has been in modified at the bed of a former  
11 glacier, indicating that this downvalley deposit is a subglacial till.  
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### 18 **Interpretation**

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20 Although from a distance the mounds superficially resemble hummocky recessional moraines  
21 formed during the oscillatory retreat of Loch Lomond Readvance glaciers (e.g. Benn 1992;  
22 Bennett & Boulton 1993b; Benn & Ballantyne 2005; Benn & Lukas 2006; Ballantyne  
23 2007b), but such hummocky moraines are generally steeper, often peaked and lack the  
24 streamlining of characteristic of the hummocks described above (Figure 2d). Moreover,  
25 hummocky recessional moraines link to form a nested sequence of concentric ridges or  
26 chains of mounds that descend downvalley, each ridge marking a former ice margin position  
27 during overall glacier retreat. The hummocks in Coire Allt an Tuirc, however, are randomly  
28 if fairly evenly distributed, and not aligned in this way. Interpretation of the hummocks as  
29 hummocky recessional moraines also fails to explain why the tongue of hummocky terrain  
30 crosses the corrie obliquely, rather than being focused around the corrie axis (Figures 1, 2c  
31 and 3). Formation of the hummocks as ice-stagnation hummocky moraines can also be ruled  
32 out, as though such moraines may be randomly distributed, they are typically steep-sided,  
33 often conical and lack the streamlining evident on the Coire Allt an Tuirc hummocks (Benn  
34 1992). Such streamlining (Figure 2d) strongly suggests that the hummocks represent  
35 subglacial bedforms that have been moulded to their present morphology by the Loch  
36 Lomond Readvance glacier that occupied the corrie, though they lack the consistent  
37 alignment typical of classical bedforms such as fluted moraines, drumlins or ribbed moraines  
38 (Benn & Evans 2010), and explanation of the hummocks simply as subglacial bedforms  
39 formed in corrie-floor drift deposits fails to explain the oblique alignment of the hummock  
40 belt across the corrie floor and its apparent relationship with the landslide scar on Sgùrr nan  
41 Ceathreamhnan.  
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3 This relationship suggests that the tongue of hummocky terrain represents the runout of a  
4 rockslide or rock avalanche sourced at the landslide scar that forms the south face of Sgùrr  
5 nan Ceathreamhnan. Hummocks are a common feature of the runout of large rock  
6 avalanches, particularly those associated with collapse of volcanic edifices (e.g. Siebe *et al.*  
7 1992; Yoshida *et al.* 2012), though opinions differ as to how they form. Dufresne & Davies  
8 (2009) envisaged that they represent the remnants of longitudinal flow ridges, formed where  
9 runout velocity perpendicular to flow approaches or equals flow velocity, but analogue  
10 models developed by Paguican *et al.* (2014) suggests that they evolve from large landslide  
11 blocks that break up during movement. Hummocks on the runout zones of large rock  
12 avalanches, however, tend to exceed (sometimes greatly) about 10 m in height. Rock  
13 avalanche hummocks beside the Dart River in New Zealand rise only 1–10 m above the  
14 floodplain, but as floodplain deposits have buried the base of these hummocks their true  
15 heights may be considerably greater (McColl & Davies 2011). It is notable, however, that the  
16 shallow streambank exposures at the base of two hummocks in Coire Allt an Tuirc closely  
17 resemble the clast-supported facies depicted in McColl & Davies (2011, Fig. 7). The  
18 principal morphological difference between documented rock avalanche hummocks and  
19 those investigated here is that the former are typically conical or elongate with steep sides,  
20 whereas the hummocks in Coire Allt an Tuirc are gently-domed, streamlined features.

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22 Explanation of the origin of the hummocky terrain in Coire Allt nan Tuirc must satisfy two  
23 criteria, namely (i) the apparent relationship between the major rockslide scar on Sgùrr nan  
24 Ceathreamhnan and the tongue of hummocky terrain and (ii) the smooth, subdued,  
25 streamlined nature of the hummocks. As argued above, no single process or origin appears to  
26 satisfy both criteria. The most plausible explanation of the hummocks is that they represent  
27 the outcome of two processes, namely: (i) catastrophic structurally-guided failure of the south  
28 face of Sgùrr nan Ceathreamhnan in the form of a rock avalanche, and consequent deposition  
29 of a tongue of hummocky runout debris analogous to those reported in the studies cited  
30 above; and (ii) subsequent (re)occupation of Coire an Tuirc by glacier ice that eroded and  
31 moulded the landslide runout hummocks into the subdued forms now present.

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33 In terms of this interpretation, there are two possible scenarios. First, it is possible that the  
34 rock avalanche occurred when a small residual glacier occupied Coire an Allt Tuirc during  
35 the final stages of ice-sheet glaciation (~15.0–14.5 ka), so that landslide debris was spread  
36 over the ice surface, forming hummocky stagnant ice topography as the ice downwasted. This  
37 scenario, however, requires the residual ice body to have been stagnant and immobile at the



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3 time of the rock avalanche, otherwise debris would have been redistributed downvalley by  
4 glacier movement. The second possibility is that the rock avalanche occurred during the  
5 Lateglacial Interstade (~14.7–12.9 ka), when the corrie was ice-free. As the tongue of  
6 hummocky terrain extends downslope for 1 km from ~810 m altitude to ~650 m where it  
7 crosses the main stream (Allt Beithe Garbh) and up the opposite slope to ~700–710 m, this  
8 scenario implies that the postulated rock avalanche exhibited excess runout, defined as runout  
9 distance that exceeds that which might be expected from frictional sliding alone. Many rock  
10 avalanches exhibit excess runout, including some in the British Isles, such as the Lateglacial  
11 Errigal and Muckish landslides in NW Ireland (Ballantyne *et al.* 2013) and the Beinn Alligin  
12 rock avalanche in Torridon, which involved debris runout of 1.25 km (Ballantyne & Stone  
13 2004). In his classic analysis of this phenomenon, Hsü (1975) suggested that excess runout  
14 distance ( $L_e$ ) could be approximated by:

$$L_e = (L - (H / \tan \phi)) \quad (1)$$

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25 where L and H are respectively the total horizontal and vertical distances from the crown of  
26 the slide scar to the toe of the runout debris (Corominas 1996), and  $\tan \phi$  is the coefficient of  
27 sliding friction. Hsü (1975) assumed  $\phi = 32^\circ$  so that  $\tan \phi = 0.625$ . In the present case  
28 L = 1600 m and H = 470 m, and assumption of  $\phi = 30^\circ$ ,  $32^\circ$  and  $35^\circ$  indicates excess runout  
29 of 785 m, 852 m and 928 m respectively; these values represent the runout distance of debris  
30 beyond that which might be expected from frictional sliding alone.  
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36 Although it has been widely accepted that excess runout represents movement by large-scale  
37 grainflow, most early explanations of this phenomenon involved particular topographic  
38 circumstances, runout over water-saturated or deforming substrates, or physical processes of  
39 questionable validity (Campbell, 1989; McSaveney & Davies 2007). A more plausible  
40 model, outlined by Campbell (1989) and elaborated by Cleary & Campbell (1993), explained  
41 excess runout in terms of development of a thin layer of highly-agitated particles that reduce  
42 friction at the base of the mobile debris. More recently, it has been proposed that excess  
43 runout (and the motion of large rockslides in general) can be explained by crushing of grains  
44 under large dynamic stresses, causing fluid-like behaviour that lowers the frictional resistance  
45 to flow (Davies & McSaveney 2002; Davies *et al.* 1999, 2010; McSaveney & Davies 2007).  
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52 Irrespective of the runout mechanism involved, it is proposed here that the landslide debris  
53 initially formed hummocky terrain that was subsequently modified by the glacier that  
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3 occupied Coire Allt an Tuirc during the Loch Lomond Stade. This interpretation implies that  
4 the corrie glacier was warm-based, and hence capable of sliding over its bed and eroding the  
5 landslide debris through a combination of abrasion, quarrying (plucking) of debris from the  
6 lee sides of hummocks and entrainment of loose debris that was frozen on to and  
7 incorporated within the base of the ice. The resultant streamlined mounds are therefore not  
8 moraines but the products of subglacial erosion, broadly similar in morphology to both  
9 whalebacks (ice-moulded bedrock forms) and small drumlins (ice-moulded drift features),  
10 though it is likely that their present planform (circular, elliptical or elongate) was dictated by  
11 that of the original landslide hummocks. A possible alternative explanation, also consistent  
12 with the available evidence, is that the runout debris was *not* hummocky but characterised by  
13 zones of variable resistance to subglacial erosion (e.g. large semi-intact landslide blocks) that  
14 were subsequently transformed by subglacial erosion into streamlined hummocks and  
15 intervening depressions.  
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## 24 Discussion

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27 Cook *et al.* (2013) have described the characteristics of rock-avalanche debris that was over-  
28 run by a minor (~400 m) readvance of the margin of Feegletscher (Switzerland), and  
29 remained buried under the glacier for 10–40 years. Subsequent retreat of this glacier has  
30 exposed the over-run debris, which exhibits very limited modification; over-run boulders  
31 have retained their angularity and brecciation, and form small (~1 m high) hummocks  
32 consisting of angular metre-scale boulders covered by a drape of diamicton. Lack of glacial  
33 modification of the over-run rock avalanche debris was attributed by Cook *et al.* (2013) to  
34 ‘armouring’ of the runout deposit by a surface cover of large boulders that resisted subglacial  
35 entrainment. Their study confirms that coarse rock avalanche debris may survive over-  
36 running by glacier ice, as postulated above, but is not strictly comparable to the situation at  
37 Sgùrr nan Ceathreamhnan. This is because they investigated over-running of coarse debris by  
38 a thin, low-gradient glacier over a period of less than 40 years, whereas the Loch Lomond  
39 Readvance glacier that occupied Coire an Tuirc must have been at least 100 m thick,  
40 probably had a moderate to steep surface gradient and persisted for at least 500–1000 years.  
41 As the shear stress generated at the base of glaciers scales directly with ice thickness and  
42 nonlinearly with ice surface gradient, the basal shear stress of the glacier that formerly  
43 occupied Coire an Tuirc must have been much greater than that at the base of Feegletscher,  
44 permitting progressive erosion of rock-avalanche runout debris over a much longer timescale.  
45 Conversely (but speculatively), it seems probable that the hummocks in Coire an Tuirc have  
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3 survived glacial erosion because of the *relative* brevity of the Loch Lomond Readvance; had  
4 ice continued to thicken to form an ice sheet (such as the last Scottish Ice Sheet, which  
5 persisted for ~15 ka), it seems likely that such hummocks would have been completely  
6 removed by subglacial erosion.  
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9 A number of studies have highlighted the problems associated with differentiating landslide  
10 deposits from moraines, or have demonstrated that the interaction of landslides with glacier  
11 ice produces landforms or landform associations that reflect the operation of both agents (e.g.  
12 Davies *et al.* 2013; Deline 2009; Deline & Kirkbride 2009; Hewitt 1999, 2009; Larsen *et al.*  
13 2005; Schulmeister *et al.* 2009; Shakesby & Matthews 1996; Tovar *et al.* 2008; Wilson &  
14 Jarman 2013). As noted by Davies *et al.* (2013), in formerly glaciated mountain areas there  
15 has been a tendency for uncritical attribution of landforms to glacial erosion or deposition.  
16 The evidence presented here provides a new perspective on the interaction of Lateglacial  
17 landslides and the Loch Lomond Readvance glaciers in Scotland. Previous studies have  
18 suggested that ‘debris-free’ Lateglacial landslide scars represent complete evacuation of  
19 runout debris by Loch Lomond Readvance glaciers, and its subsequent incorporation in  
20 moraines (Ballantyne 2013; Cave & Ballantyne 2016). The evidence presented here indicates  
21 that in some localities landslide runout debris survived (but was modified by) glaciation  
22 during the Loch Lomond Stade.  
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32 It remains to be established how widespread this phenomenon is in Scotland: it is possible  
33 that some areas previously mapped as hummocky moraines actually represent glacially-  
34 moulded landslide runout deposits such as that described here. One probable example occurs  
35 at the head of Coire na Cràlaig (NH 096161) below an apparent landslide scar on the east  
36 flank of Stob Coire na Cràlaig (1008 m; NH 091163), 7 km SSE of Sgùrr nan  
37 Ceathreamhnan. At this site a zone of subdued hummocks, ponds and disordered drainage  
38 similar to that in Coire nan Tuirc occurs at ~750–850 m on gently-sloping ground (Figure 4),  
39 though here some of the hummocks are aligned as broad transverse or oblique ridges.  
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47 A possibly analogous site has also been described in Cwm Cerrig-gleisaid, in the Brecon  
48 Beacons of South Wales. At this site the upper part of a kilometre-long flowslide or excess-  
49 runout rock avalanche deposit is crossed by a zone of low mounds and ridges that Shakesby  
50 and Matthews (1996) attributed to modification of runout debris by a small (~0.25 km<sup>2</sup>)  
51 corrie glacier that occupied the upper corrie during the Loch Lomond Stade. Within the  
52 inferred glacier limit, clasts exhibit generally greater edge-rounding and some are striated.  
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Streamlined forms such as those described in the present paper are absent, but given the very small size and probably limited lifespan of the inferred Cwm Cerrig-gleisaid palaeoglacier, the features described by Shakesby & Matthews (1996) probably represent an early stage of runout debris modification, whereas those in Coire an Tuirc represent a much more advanced stage.

## Conclusions

1. Downslope from a landslide scar on Sgùrr nan Ceathreamhnan a tongue of hummocky terrain ~1 km long and ~400 m wide extends obliquely across a corrie, descending from 810 m to ~650 m and ascending to 700–710 m up an opposing slope. Individual hummocks are randomly-spaced, circular to elongate, mound-shaped, streamlined and generally less than 6 m high.
2. The streamlined morphology of individual hummocks and their concentration in a tongue that crosses the corrie floor rules out their interpretation as hummocky recessional moraines or ice stagnation moraines. The low, streamlined nature of the hummocks excludes their interpretation as unmodified rock avalanche hummocks.
3. The hummock belt is here interpreted as a tongue of hummocky rock avalanche runout debris, initially deposited during or after downwastage of the last ice sheet and subsequently moulded into streamlined subglacial bedforms by the glacier that reoccupied the corrie during the Loch Lomond Stade of ~12.9–11.7 ka.
4. This interpretation implies that the rock avalanche experienced excess runout of ~800–900 m, and that the glacier that subsequently reoccupied the corrie was warm-based, permitting subglacial erosion of the rock avalanche tongue.
5. Wider implications of this interpretation are: (i) that Loch Lomond Readvance glaciers did not invariably evacuate debris from Lateglacial landslides, as previously supposed; in some cases, landslide debris survived (but was modified by) glacial erosion and entrainment; (ii) some areas previously mapped as hummocky (recessional or ice-stagnation) moraines may represent glacially-moulded landslide runout debris.

The findings of this study contribute to growing awareness of the importance of landslide-glacier interactions in the evolution of glaciated mountain landscapes. In Scotland, landslides and rockfall during interglacial and interstadial periods have contributed to trough widening, corrie extension and the formation of arêtes (Jarman 2009; Ballantyne 2013), and it has been shown that ancient landslide scars are persistent landforms that have survived the last ice-

sheet glaciation (Cave & Ballantyne 2016). This study suggests that even the runout debris of large landslides locally survived over-running by glacier ice, albeit in modified form.

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### Captions to Figures

**Figure 1.** Sgùrr nan Ceathreamhnan and Coire Allt an Tuirc, showing the location of landslide scars and the tongue of hummocky terrain south of the main landslide scar.

**Figure 2.** (a) The East Top (1151 m) of Sgùrr nan Ceathreamhnan from near the West Top, showing headscarp of the former landslide. (b) Steeply-dipping schists of the landslide failure zone. (c) The belt of hummocky terrain that crosses Coire Allt an Tuirc. (d) Typical hummocks and intervening depressions near the terminus of the hummock belt, showing the streamlining typical of glacial bedforms.

**Figure 3.** Oblique Google Earth™ aerial image of Coire Allt an Tuirc, showing the distribution of hummocky terrain below the twin summits of Sgùrr nan Ceathreamhnan.

**Figure 4.** Hummocky terrain below an apparent landslide scar in Coire na Cràlaig (NH 097161) west of Stob Coire na Cràlaig (1008 m) in Kintail.

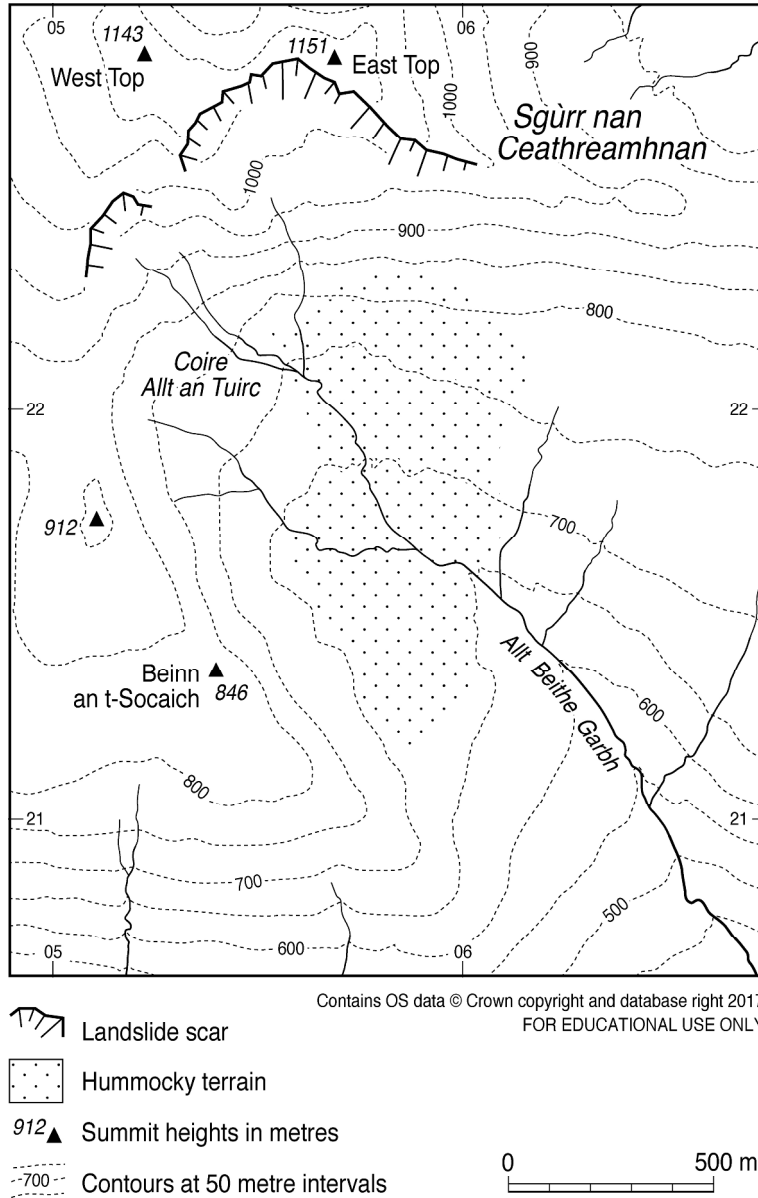


Figure 1. Sgùrr nan Ceathreamhnan and Coire Allt an Tuirc, showing the location of landslide scars and the tongue of hummocky terrain south of the main landslide scar.

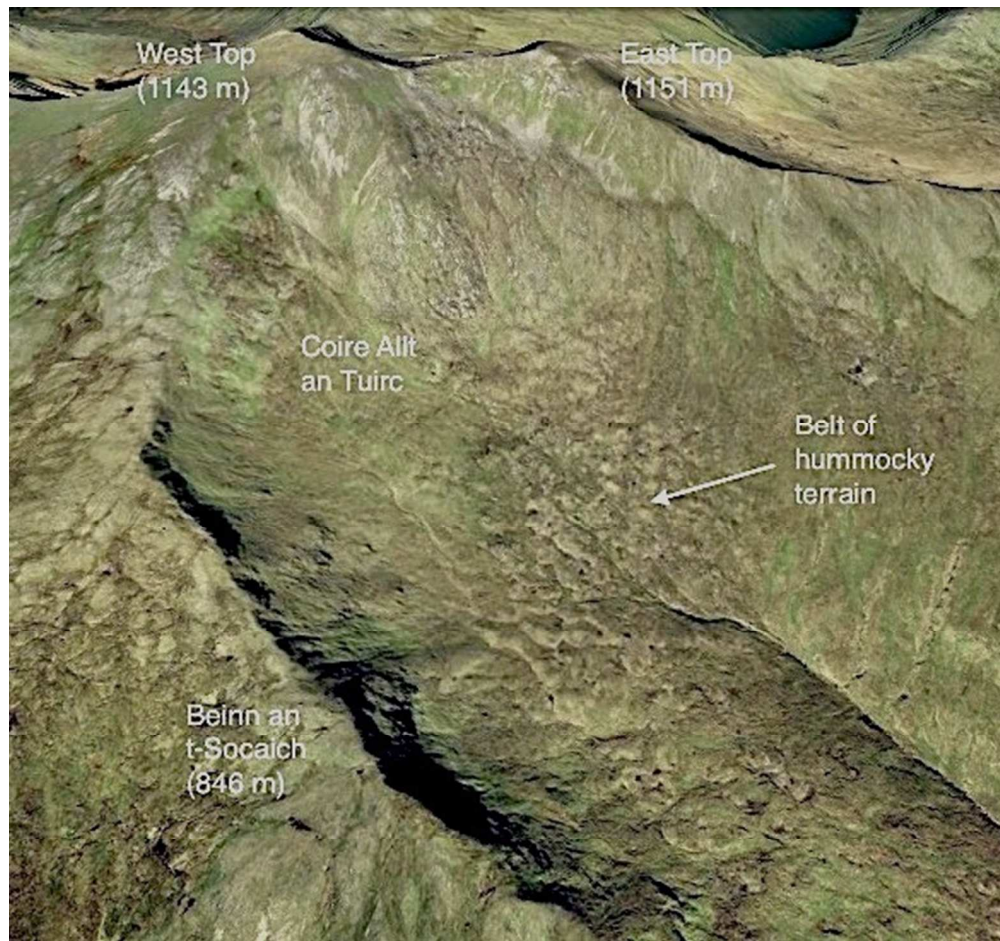
117x185mm (600 x 600 DPI)



Figure 2. (a) The East Top (1151 m) of Sgùrr nan Ceathreamhnan from near the West Top, showing headscarp of the former landslide. (b) Steeply-dipping schists of the landslide failure zone. (c) The belt of hummocky terrain that crosses Coire Allt an Tuirc. (d) Typical hummocks and intervening depressions near the terminus of the hummock belt, showing the streamlining typical of glacial bedforms.

128x97mm (300 x 300 DPI)





37 Figure 3. Oblique Google EarthTM aerial image of Coire Allt an Tuirc, showing the distribution of hummocky  
38 terrain below the twin summits of Sgùrr nan Ceathreamhnan.

39 206x193mm (72 x 72 DPI)



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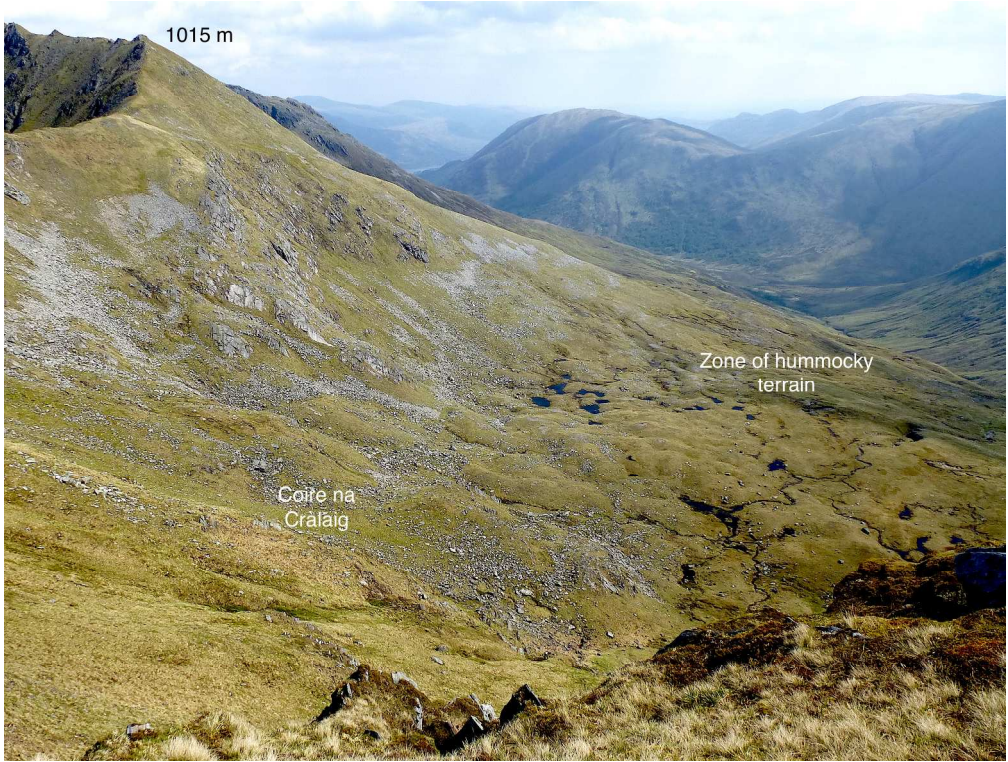


Figure 4. Hummocky terrain below an apparent landslide scar in Coire na Cràlaig (NH 097161) west of Stob Coire na Cràlaig (1008 m) in Kintail.

477x361mm (180 x 180 DPI)

View Only