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Kirkbride, Martin P.

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ABSTRACT Observations are presented of a newly-deposited snow-push ridge superimposed on a Holocene moraine in Coire an Lochain in the Cairngorm Mountains. The ridge formed when a sliding snow slab was thrust up the proximal slope of the moraine, entraining till gravel and redepositing it on the moraine crest. The process was a late-stage event during the complex wastage of a large snowfield resting on a rock slab, involving basal sliding, avalanching and melting. Snow-push landforms appear to be rare in Scotland. Nevertheless, these observations suggest that fresh material may be added to relict moraine crests in the present-day climate, with implications for exposure-age dating of moraines. However, in this case the addition of debris by snow push to a late-Holocene moraine crest does not affect the interpretation of moraine age.

Key words

Snow push
Moraine formation
Cairngorm Mountains

1. **Introduction**

Snow-push landforms are a form of pronival landform associated with the deformation and/or bulldozing of sediment by late-season snowpacks. Snow-push ridges are formed both by gravitational sliding of snowbeds (Shakesby 1997), or by glacier-push mechanisms (Birnie 1977). Gravitational snow sliding can erode rock slopes (Costin & Jennings 1964, Gomez & Diaz 2010) and rework sediment in the pronival zone. Reworking by snow-push creates ridges at the lower margin of steep snowbeds, where the downslope force exerted by the snow on unconsolidated sediment is sufficient to deform the sediment. Alternatively, the snow may slide across the sediment surface, bulldozing debris into a ridge (Shakesby 1997, Shakesby *et al*. 1999). The process requires snowpack conditions favourable for snow-glide (McClung *et al*. 1994), including low substrate roughness and presence of basal water.

Detailed analysis of active snow-push ridges in southern Norway (Shakesby *et al*. 1999) identifies diagnostic criteria to separate push ridges from other landforms, and demonstrates that subnival debris transport may occur. In Britain, nival ridge and rampart formation have been ascribed to either debris moving over the snow surface (Ballantyne & Kirkbride 1986, Anderson *et al*. 2001) or avalanche impact and runout processes (Ballantyne 1989. Luckman 1992). Studies are hampered by the lack of direct observations of these processes (Shakesby *et al*. 1997), with process largely being inferred from landform morphology and sedimentology. The apparent rarity of snow-push deposition in Britain (Ballantyne 2008) makes observations of active snow-push events noteworthy.

This short paper presents field observations of a newly-formed snow-push ridge in Coire an Lochain (Cairngorm Mountains, Scotland, 57°07'N 3°40'W), combined with before- and after-photographs of the site. A fuller site description is given by Kirkbride *et al*. (2014). The site is unusual because the snow-push ridge has been constructed on the crest of a larger, older moraine ridge which has been dated by cosmogenic ^{10}Be to the late Holocene. These observations show that snow-push is an active process under present-day climate in favourable localities. Its significance is discussed in terms of the facilitating site conditions, and of the superposition of recent debris to the crests of existing moraines, which could contaminate exposure-age dating of older moraines.

2. **Ridge characteristics and formation**

A small ridge of fresh debris was observed on 18 June 2014, located on proximal side of the crest of an existing larger moraine ridge (Figure 1), the right-lateral moraine of a 3.6 ha cirque glacier dated to the late Holocene by Kirkbride *et al*. (2014). The ridge had not been present on a visit 11 days earlier (Figure 2) nor when rock samples were collected for dating. The proximal moraine slope is a steep 4 m-high bank of freshly-exposed sandy gravel which is annually disturbed by snow creep, sliding and avalanching. Removal of material from the base of the bank maintains a high-angle, and erosion is progressively removing the toe of the late Holocene moraine (Kirkbride *et al*. 2014). Nival activity disperses debris downslope as splays rather than as ridge forms. No new ridge had previously been observed forming by nival action on the moraine crest.

The new superposed ridge extended for c. 12 m and was up to 0.8 m high, and marked by a distinct break of slope between it and the broader moraine crest (Figure 2). At the time of observation, the upcurved edge of a snow slab extended up the proximal moraine slope and over the crest of the superposed ridge (Figure 3). It comprised gravel with small boulders and blocks of vegetated turf, in a silty sand matrix dominated by medium and coarse sand (Table 1), chaotically dumped in a distinct ridge.The turf lumps were only on the distal side of the ridge: the proximal side consisted of fresh pink sandy gravel and was contiguous with the proximal flank of the moraine.The ridge exhibited a cross-sectional asymmetry, with a convex distal slope (cf. Shakesby *et al*. 1999). The snow slab itself was detached from the snowfield upslope by a crevasse several metres wide, and was itself breaking into smaller slabs along crevasses (Figure. 3A). Loose debris was trapped in the space created by melting of the base of the snow slab away from the ground.

Macroscale snowpack evolution has been reconstructed from online photographs (Sport Scotland 2014) to supplement field visits on 7 and 18 June. The snowfield covering the Great Slab of Coire an Lochain showed a large bergschrund on 14 February, and the toe of the snowfield had avalanched from the foot of the slab by 24 February. Evidence of accelerated sliding was apparent by mid-March as meltwater production increased with warming spring temperatures. In some years the whole central snowfield releases in a single avalanche to the cirque floor. However, in 2014 fragmentation of the snowfield created several discrete crevasse-bounded snow slabs which slid gradually down the rock slab. Some released as small avalanches during May, but others melted in situ. By June 7, a remnant transverse snow band extended across the Great Slab, held by lateral shear strength as snow above and below melted and avalanched away. When the snow band gave way soon after 7 June, smaller but substantial snow slabs were released as coherent block slides. One such slab (X in Figure 1) thrust obliquely up the proximal moraine face, dragging debris at its base which was pushed, rolled and slid upslope to accumulate where the snowpack separated from the ground at the ridge crest.

Melting of the snow slab away from the moraine slope meant that ridge deposition ceased before the visit on 18 June, so the timescale of formation of the snow-push ridge was a few days only. The small size of the ridge was not constrained by debris availability, but by the short period in which snow-thrusting was possible. This in turn is constrained by the timing of disintegration of the snowfield and the rapid decay of the sliding snow slabs. Ridge formation was therefore a discrete event rather than a continuous process at the seasonal timescale. A process is envisaged where the snow slab slipped rapidly across the wet bedrock slab at perhaps a few metres per second, enough to cause the dense, wet snow to ride up en masse obliquely across the proximal moraine slope, thereby bulldozing unconsolidated moraine debris into a push ridge. The distance moved is constrained by the widening of the upper bounding crevasse of the snow slab ("C" in Figure 1). It appears that the dense, wet snow slab only slipped 4-6 m to bulldoze the ridge, but this was sufficient to entrain enough debris to construct a small ridge. The density of isothermal late spring snowpacks in the Cairngorms Mountains is high, typically in the range of 0.45 – 0.60 t m^{-3} (Ward *et al*. 1985).

3. Discussion: implications for dating relict moraines

The snow-push event at Coire an Lochain has two implications, first for the magnitude, frequency and distribution of present-day nival modification of the mountain landscape, and second for the dating of snow-modified moraines.

The observations in this paper are site-specific, and the cirque is unusual in Scotland because of the juxtaposition of a moraine ridge and a smooth rock slab at high altitude, the product of late-Holocene glaciation (Kirkbride *et al*. 2014). Active snow push at this site suggests that the process may occur more widely in the Scottish Highlands, but with subtle and very localised landscape modification. The snow-push process requires the interplay of a very specific set of circumstances to be able to operate, not least the pre-existence of a moraine into which snow bulldozing can occur. In the few hundred winters since the Coire an Lochain moraine was formed, there is little evidence that snow push deposition has contributed significantly to moraine crest accretion. Indeed, in 2014 only about 12 m length of the moraine was affected. Incorporation of turf from the moraine into the disturbed debris indicates that disturbance events may be separated by decades. Further up the same moraine, a subtle small ridge (Figure 4) is evidence of an earlier similar event. This ridge bears a morphological resemblance to the 2014 ridge, but is more subdued. In neither case has the bulldozed debris extended more than 2 m distally from the top of the proximal slope. It seems that the great majority of years do not see snow push transport of debris to the moraine crest. More likely, snow slides erode the proximal slope without pushing upwards as far as the crest. There seems to be no possibility that the whole moraine could have formed by nival processes. Indeed, the long-term effect of snow motion on the Great Slab is probably net erosion of the moraine, as demonstrated by the downslope debris splays from the moraine toe (Kirkbride *et al*. 2014)

Nevertheless, even rare events introduce reworked debris to moraine crests, and could contaminate exposure-age determinations of moraine age with “young” boulders. The right-lateral moraine was dated by three cosmogenic^{10}Be samples to less than 1.6 ± 0.3, 2.8 ± 0.5 and 5.5 ± 0.5 k yr (Kirkbride *et al*. 2014). The corresponding left-lateral moraine yielded two further late-Holocene ages. These were interpreted to be maximum ages of a probable Little Ice Age moraine, given the likelihood that moraine debris comprises reworked Holocene detritus from the Great Slab. The Coire an Lochain ages cluster in the Late Holocene: comparison with statistical models of exposure-age distributions implies that this age pattern reflects maximum ages due to isotopic inheritance (Applegate et al. 2010). Age-distributions of boulders from single moraine ridges tend to skew towards the young end of the age distribution where inherited boulders have been added to an older moraine. Skew towards older age is associated with post-depositional exhumation, which models indicate occurs early in the post-depositional period. (Putkonen & Swanson 2003; Applegate *et al*. 2010). In Scotland, exhumation should produce a Lateglacial and early Holocene age cluster following moraine deposition during the Younger Dryas Stadial (12.9 – 11.7 k yr), a pattern which is not found at the study site. Rather, we envisage a geomorphological model of moraine formation whereby rock fall and frost-shattered debris accumulated on a partly vegetated Great Slab throughout the Holocene, later to be entrained by a late Holocene glacier and deposited as ice-marginal moraines. Thus, the moraines are relatively young, but are largely constructed of older debris (Kirkbride *et al*. 2014). The short life-span of the glacier would preclude large addition of contemporary rock fall to the moraine, but reworking of pre-existing debris with variable beryllium concentrations would explain why a recent glacier formed moraines of apparent greater age.

However, if Kirkbride et al. (2014) sampled boulders which had been reworked by snow-push from the body of the moraine and recycled to the moraine crest during the late Holocene, the exposure ages would represent maximum ages of the moraine and would not date it closely. This interpretation would require much or all of the ridge to be formed by nival processes because the dated boulders were dispersed along the upper distal slope. This scenario is highly unlikely, primarily because of the mid-slope location of the ridge. Break-of-slope locations are necessary for gravitational snow-push ridge formation, in order to create the necessary compression of the snowbed against the slope-foot sediment (Shakesby et al. 1999). Without a pre-existing ridge, there would be no adverse slope for the snow to push against, nor a source of debris for reworking into a snow-push landform. Furthermore, the dated boulders are larger than clasts observed to have been pushed by the snowbed in 2014. They are embedded in the moraine matrix and not associated with any superimposed minor ridge forms.

Observations of snow-push ridge formation in June 2014 therefore do not undermine the late Holocene interpretation of moraine age in Coire an Lochain, which remains a more likely scenario based on the field evidence than the alternatives. More generally, the study does demonstrate that nival modification in the Holocene of moraines elsewhere in the Scottish Highlands could have supplied younger debris to Younger Dryas-age moraine crests, and therefore sampling for exposure dating should consider the possibility of sample contamination.

4. Conclusions

1. A mechanism of snow-push ridge formation is identified, where sliding of dense snow blocks across a rock slab caused up-thrusting of the snow margin against a proximal moraine slope and upslope redistribution of debris.
2. Snow-push ridge formation is small-scale, and occurred as a discrete bulldozing event rather than as a more continuous deformational process.
3. Superimposed snow-push ridges can resemble minor moraines which could be interpreted as forming by small-scale ice-margin oscillation.
4. In this case, snow-push deposition has not affected the interpretation of the exposure ages of moraine boulders. More widely, the potential exists for younger snow-push debris to be mistaken for glacially-transported boulders, and such a possibility may in particular circumstances need to be acknowledged.

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Table 1. Grain size data (weight %) for the ≤ 2 mm fraction of the matrix of the snow-push ridge.

Sample	Sand				Silt	Clay	Silt:Clay
	Very coarse 1-2 mm	Coarse 500 - 1000 µm	Medium 250-500 µm	Fine 63-250 µm			
1	3	19	25	32	18	3	6:1
2	6	24	26	29	13	2	6.5:1
3	16	32	27	18	6	1	6.1
Mean	8	25	26	27	12	2	
Standard deviation	6	7	1	8	6	1	

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Figure 1A.

Photograph on 7 June of the snow slab (X) beginning to slide up the proximal moraine slope. Arrows mark zone of snow-push reworking of moraine debris. Note debris released onto the snow surface and into a crevasse (circled). Crevasse C was several metres wider on 18 June as the snow slab X separated and slid against the moraine (see Fig. 1B).

Figure 1B.

The moraine in CoireanLochain with the edge of the snow push ridge (arrowed) marked with a dotted line. X marks the same snow slab as in Fig. 1A. Large boulders sampled for cosmogenic^{10}Be dating (Kirkbride et al. 2014) lie beyond the affected crest location. Photograph taken on 18 June after the central snowfield remnant had avalanched.

Figure 2.

View of the fragmenting snowpack on the Great Slab on 7 June, eleven days before the snow-push ridge was observed. The site of the ridge is circled, but no such ridge exists on this photograph and the snow has not yet pushed up over the lateral moraine. Note how the central remnant of the snowfield bridges across the slab and is partly buttressed by its lateral extension.

Figure 3A.

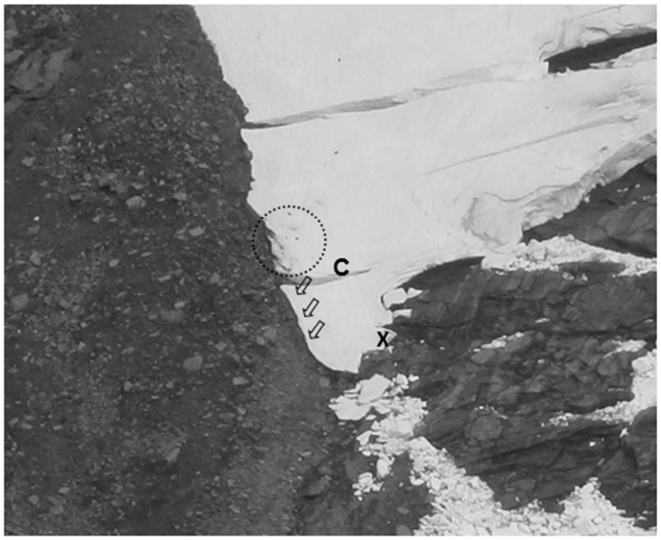
Upslope view of the upcurvedsnowbed over-riding the moraine ridge, with debris trapped between the base of the snow and the moraine. The proximal slope is freshly-eroded granite debris, the more gentle distal slope is vegetated.

Figure 3B.

The fresh, loosely-consolidated snow-push ridge superimposed on the crest of the late-Holocene moraine.Figure for scale.

Figure 4.

A possible snow push ridge located upslope from the June 2014 deposit. It resembles a superposed till deposit of a minor glacial readvance.



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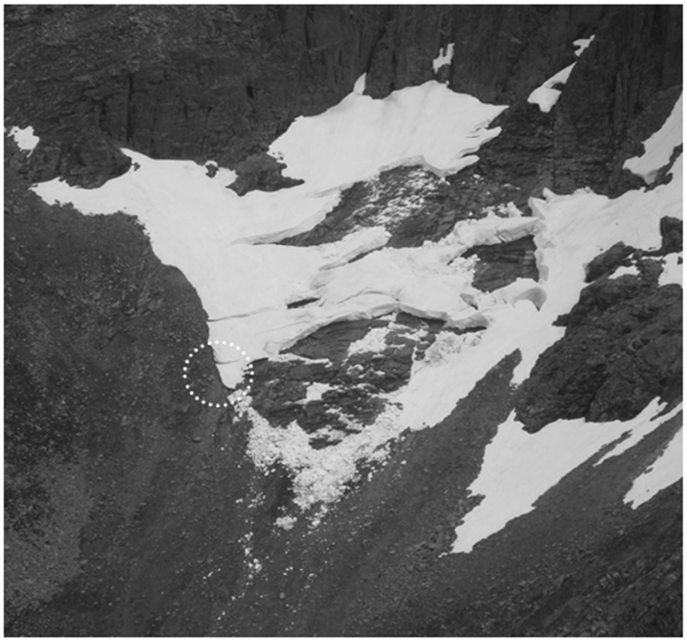

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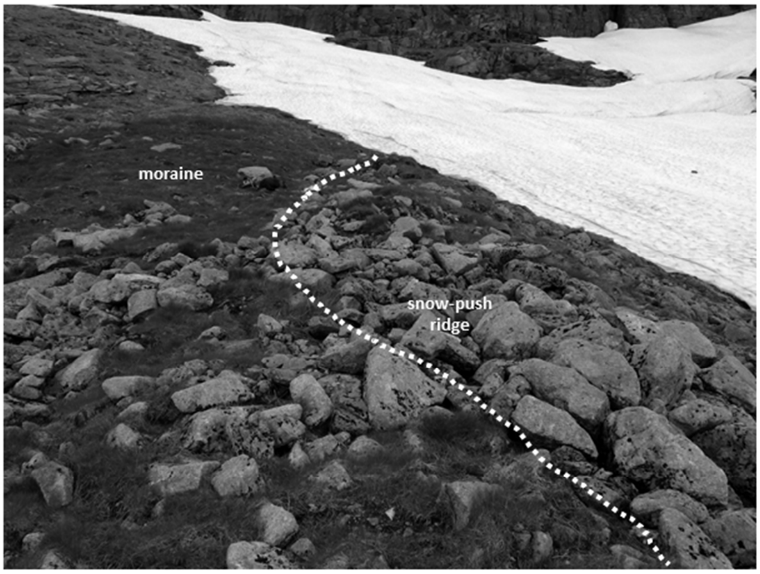

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