



Evidence of palaeo-cirque glaciers in the Ewes Valley, southern Scotland

Benjamin M. Boyes & Danni M. Pearce

To cite this article: Benjamin M. Boyes & Danni M. Pearce (2025) Evidence of palaeo-cirque glaciers in the Ewes Valley, southern Scotland, *Scottish Geographical Journal*, 141:1-2, 59-70, DOI: [10.1080/14702541.2024.2341936](https://doi.org/10.1080/14702541.2024.2341936)

To link to this article: <https://doi.org/10.1080/14702541.2024.2341936>



© 2024 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group



Published online: 29 Apr 2024.



Submit your article to this journal [↗](#)



Article views: 637



View related articles [↗](#)



View Crossmark data [↗](#)

Evidence of palaeo-cirque glaciers in the Ewes Valley, southern Scotland

Benjamin M. Boyes ^a and Danni M. Pearce ^b

^aDepartment of Geography, University of Sheffield, Sheffield, United Kingdom; ^bFaculty of Environmental Science and Natural Resource Management, Norwegian University of Life Sciences, Ås, Norway

ABSTRACT

While glaciation in the English Lake District and the Scottish Highlands was extensive after the retreat of the last British-Irish Ice Sheet, glaciers are thought to have been restricted to the highest uplands of southern Scotland. However, geomorphological features in the Ewes Valley indicate glacial activity in three amphitheater-shaped hollows after the retreat of the last British-Irish Ice Sheet. The geomorphological evidence of former glaciation is used to reconstruct the dimensions of three very small glaciers (totally $\sim 0.3 \text{ km}^2$) with equilibrium line altitudes (ELA) between 329 and 401 m asl. An assessment of the glacier dimensions and potential snowblow contribution area indicates that redistribution of snow via wind was essential for the development of these glaciers.

ARTICLE HISTORY

Received 23 January 2024

Accepted 5 April 2024

KEYWORDS

Palaeo-glaciation; Scotland; cirque; last glacial-interglacial transition

Introduction

At present, there is general agreement that cirque and plateau icefield glaciation in southern Scotland during the Last Glacial-Interglacial Transition (LGIT; *c.* 20–10 ka) was restricted to the highest upland surfaces of The Cheviot, the Moffat and Tweedsmuir Hills, and the Galloway Hills (Bickerdike et al., 2018; Golledge, 2010). It is also widely regarded that southern Scotland was a climatically dry and cold landscape that was unable to support widespread local glaciations and was instead subject to intense periglacial and paraglacial processes (Ballantyne, 1984; Bickerdike et al., 2018; Galloway, 1961; Golledge, 2010). However, previously undocumented glacial landforms in the Ewes Valley, southern Scotland (Figure 1), may demonstrate the last presence of former glacial ice outwith the normally considered locations of southern Scotland. This is important because evidence of more extensive palaeo-cirque glaciation across southern Scotland has significant implications for palaeo-climate reconstruction during the LGIT. For example, identification of small palaeo-ice masses shows that these features may have been more extensive during the LGIT than was previously thought. This is crucial for understanding landscape formation processes in marginal glacierised terrains (Barr & Spagnolo, 2015; Evans et al., 2012; Harrison et al., 1998, 2001, 2015). In addition,

CONTACT Benjamin M. Boyes  b.boyes@sheffield.ac.uk  Department of Geography, University of Sheffield, Sheffield S10 2TN, United Kingdom

© 2024 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group

This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License (<http://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited, and is not altered, transformed, or built upon in any way. The terms on which this article has been published allow the posting of the Accepted Manuscript in a repository by the author(s) or with their consent.

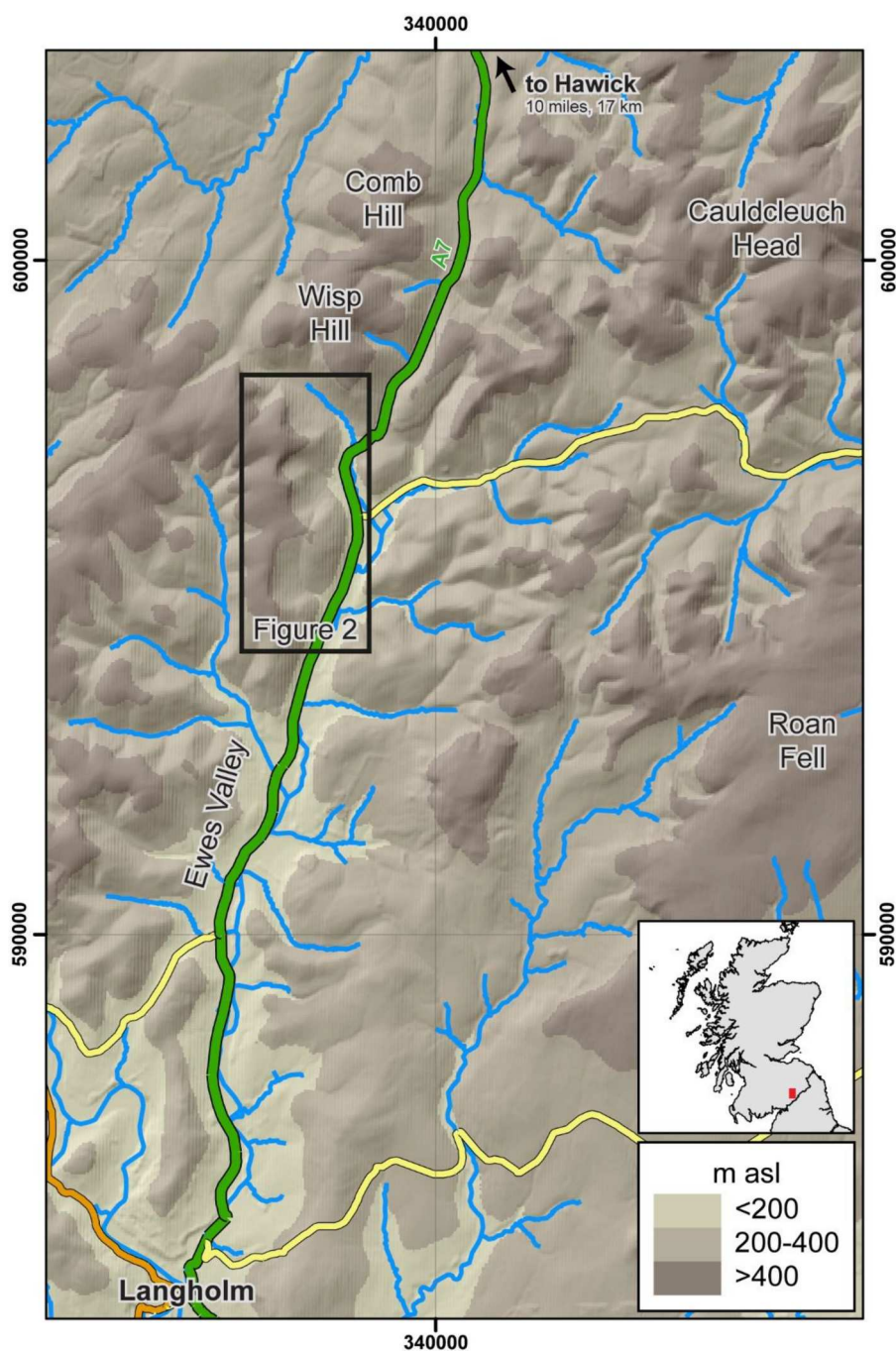


Figure 1. Location of the Ewes Valley study area, southern Scotland.

because of its high climatic sensitivity, the regional trend of the equilibrium line altitude (ELA) of palaeo-ice masses has been widely used as a climatic proxy for temperature and precipitation gradients (Barr et al., 2017; Barr & Spagnolo, 2015; Coleman et al., 2009). Thus, the addition of ELA data from newly reconstructed palaeo-ice masses will allow the

refinement of boundary conditions for numerical ice sheet models in areas previously considered extra-glacial.

Methods

The Ewes Valley is an approximately north-south aligned U-shaped valley located between the towns of Hawick and Langholm in southern Scotland (Figure 1). The valley has few visible outcrops of bedrock but is largely dominated by greywacke and interbedded silty mudstone (British Geological Survey, 2016). This study focuses on four hollowed depressions on the slopes of Frodaw Height, Dan's Hags, and Stibbiegill Head, which are located at the head of the Ewes Valley (Figure 1).

The glacial geomorphology in the Ewes Valley was established by detailed mapping of landforms in the four hollows and surrounding slopes, totalling an area of approximately 3 km² (Figure 1), following methods outlined by Chandler et al. (2018). Field mapping was carried out using enlarged base maps reproduced from the 1: 25,000 Ordnance Survey map. Landforms mapped include hollow headwalls, morainic deposits and ridges, relict channels, alluvial deposits, and rock slope failures.

The reconstruction of the surface area of former glaciers is based on the evidence of the geomorphological field mapping, following the procedures outlined by several authors to reconstruct palaeo-cirque glaciers in the British uplands (Cornish, 1981; Evans et al., 2012; Harrison et al., 1998, 2006; Johnson et al., 1990). The down-valley limit of glaciations is established from the outermost moraine deposits and ridges, and the upslope extent of the glaciers are extrapolated up to 30 m below the hollow headwalls. Where possible, the lateral margins of the glaciers are delineated by valley side moraines and meltwater channels. The 3-dimensional palaeo-glacier surface topographies are subsequently created from the reconstructed glacier outlines using GlaRe ArcGIS toolbox, a semi-automated method of glacier reconstruction (Pellitero et al., 2016), and automated ArcGIS toolboxes (Pellitero et al., 2015; Spagnolo et al., 2017) were used to analyse the glacier surfaces and topography. In these analyses, Ordnance Survey Terrain 5 Digital Terrain Model (DTM) data are used; these DTM data are not used in the geomorphological mapping stage as the landforms are more apparent in the field (OS Terrain 5 [XYZ geospatial data]).

From the 3-dimensional reconstructions, the equilibrium line altitude (ELA) for each glacier was estimated using the Area Altitude Balance Ratio (AABR) method (Furbish & Andrews, 1984; Oien et al., 2020; Pellitero et al., 2015; Rea, 2009) and a global median AABR value of 1.56 (Oien et al., 2022) is employed for palaeo-ELA calculation. To account for the contribution of snowblow and avalanching from the upland plateau in the Ewes Valley, a corrected snow contribution area ELA (scaELA) was also calculated (Benn et al., 2005; Kłapyta et al., 2022; Mitchell, 1996). The snow-blowing area for each glacier was defined as the terrain lying above the AABR 1.56 ELAs laterally continuous to the reconstructed glacier and sloping toward its surface (Coleman et al., 2009; Sissons & Sutherland, 1976). To include uphill snowblow toward the glaciers, a maximum slope angle of 10° away from the glacier was assumed as a boundary threshold for snowblow (Coleman et al., 2009). Potential avalanche areas were identified as the slopes surrounding the glaciers greater than 25° (McClung, 2013; Sissons & Sutherland, 1976). To further understand the influence of snowblow and avalanche contributions to palaeo-glacier mass balance, the avalanche factor (AF) and the snowblow factor (SBF)

were calculated. The AF was calculated as the ratio of the glacier area to the avalanche area (Coleman et al., 2009; Sissons & Sutherland, 1976) and the SBF was expressed as the glacier area to the square root of the snowblowing area (Mitchell, 1996).

Geomorphological results

Four amphitheater-shaped hollows with steep, arcuate headwalls are identified on the western side of Ewes Valley (Figure 2). Hollow 1 is a northeast facing (mean aspect

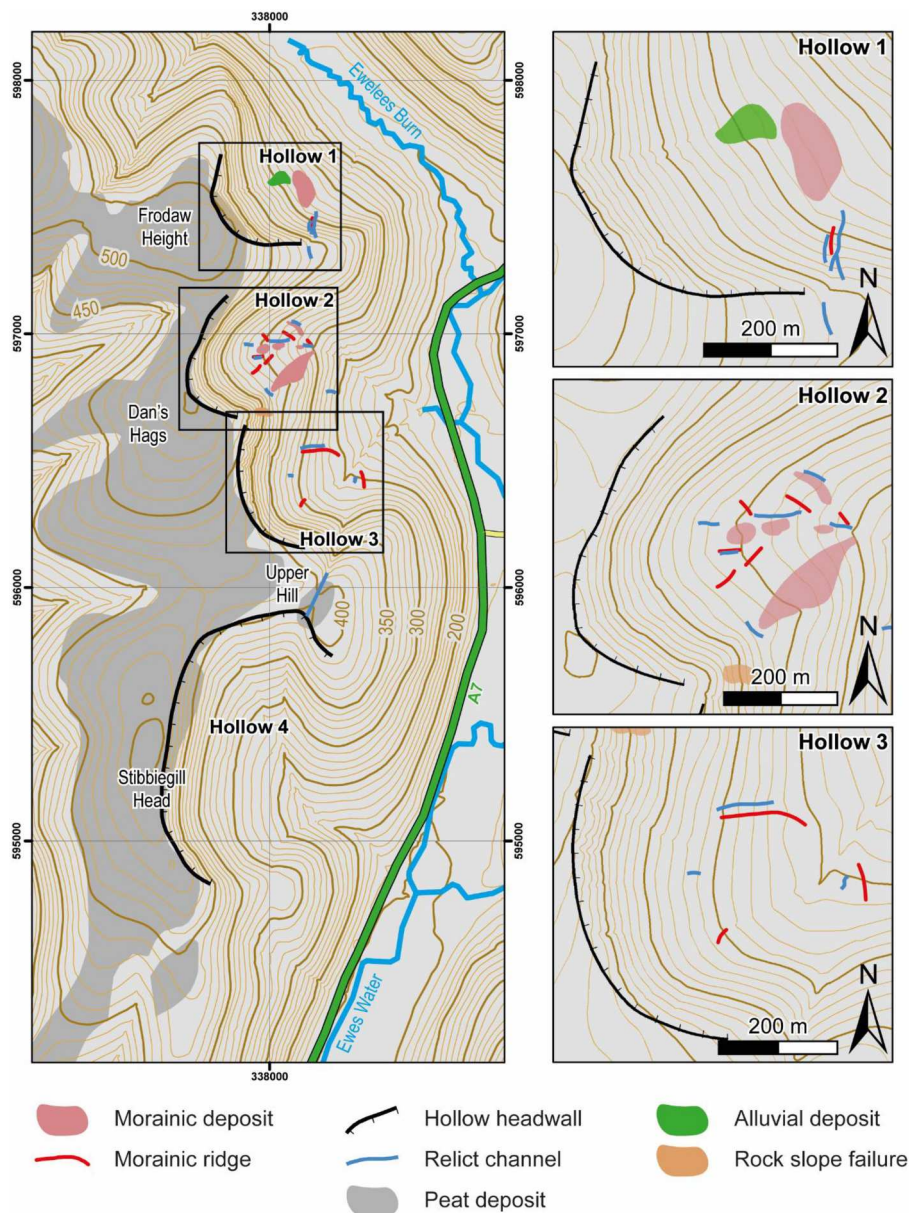


Figure 2. Glacial geomorphology of the study area. Four amphitheater-shaped hollows are identified, but glacial landforms are only identified in Hollows 1, 2, and 3.

57°) depression with a minimum altitude of 322 m asl and is characterised by a steep concave slope across the length of the hollow with an absence of lateral spurs. In contrast, the other hollows identified in the study area have an obvious change in slope angles down valley and distinct lateral spurs. Hollow 2 is east facing (mean aspect 77°) with a minimum altitude of 301 m asl, and Hollow 3 has an east-northeast aspect (mean aspect 62°) and a 239 m asl minimum altitude. Hollow 4 contrasts with the other amphitheater-shaped depressions in size, aspect, and elevation, and is characterised by a low minimum altitude (190 m asl) and southeast aspect (mean aspect 128°).

Morainic deposits and ridges are found in and around the valley floors and lower slopes of Hollows 1, 2, and 3, between 320 and 460 m downslope from the headwalls (Figures 2–4). Moraines are sporadic and range in morphology, including very subtle (~1 m in height) to large (<10 m in height) ridges that possess rounded crestlines and subdued hummocky deposits 20–50 m across. Field observations show that the moraines are arranged as oblique down-valley chains, often curving arcuately towards the valley centre line.

Numerous meltwater channels are identified across the study area. In Hollows 1, 2, and 3, relict channels with oblique down-slope profiles and often interspersed among moraines (Figure 2) are interpreted as lateral meltwater channels. Deep gullies on hollow headwalls are not mapped as they likely represent contemporary drainage networks; this is supported by an alluvial fan deposit in Hollow 1 (Figure 4(a)). However, deep (~7 m deep) relict channels aligned perpendicular to slope profiles on the spurs between Hollows 1–2 and Hollows 3–4 are unlikely to represent contemporary drainage networks (Figures 2 and

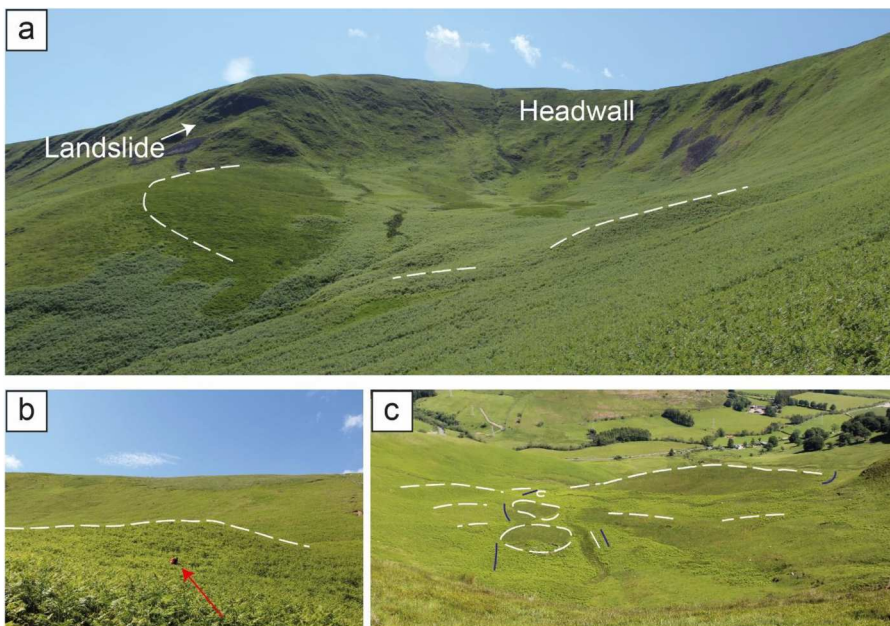


Figure 3. Glacial signatures of Hollow 2. (a) View southwest into Hollow 2, showing the amphitheater-shaped hollow, arcuate headwall, and frontal moraine rides (broken lines). A landslide scar and deposit on the southern lateral spur is indicated. (b) Prominent, <10 m high moraine ridge (broken line marking the crest) on the northern edge of Hollow 2. A person indicated by the red arrow stands in front of the moraine ridge for scale. (c) View northeast from the backwall of Hollow 2. Moraine ridges and hummocks indicated by broken lines and relict channels indicated by blue lines.

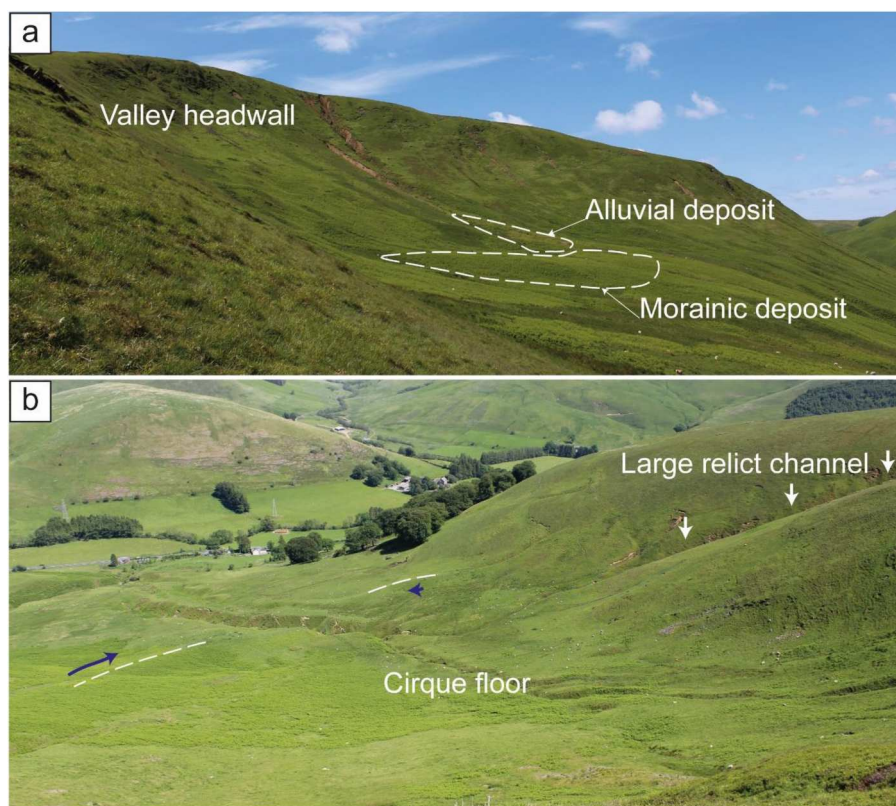


Figure 4. Glacial geomorphology of Hollows 1 and 3. (a) View northwest into Hollow 1, showing the arcuate headwall, moraine deposit, and alluvial deposit. (b) View east from the backwall of Hollow 3. Moraine ridges <2 m high indicated are broken lines and relict channels indicated by blue arrows. White arrows indicate the large, ~7 m deep relict channel located on the lateral spur between Hollows 3 and 4, which is interpreted as a meltwater channel associated with ice sheet-scale glaciation.

4). These two relict channels are therefore likely to be meltwater channels, but their morphostratigraphic position beside the valley headwalls suggests the relict channels are probably associated with ice sheet-scale glaciation rather than cirque glaciation.

Paraglacial features are also identified in the study area. A small rock slope failure complete with upslope scarring and a down-valley accumulation of loose angular clasts is evident on the subtle spur between Hollows 2 and 3. Extensive peat accumulations are present on the hill summits in the study area (Figure 2; British Geological Survey, 2016). However, field observations suggest that the peat accumulations do not obscure any geomorphology.

Glacial interpretations and reconstruction

From the geomorphological evidence identified in the study area, Hollows 1, 2, and 3 are interpreted as cirques (Table 1), with Hollow 2 being the most evident cirque the Ewes Valley. The morphology of Hollow 2 and the accompanying moraines and meltwater channels (Figures 2 and 3) qualifies it as a grade 3–4 cirque (Evans & Cox, 1995), and its aspect is conducive to cirque development. Although the aspect of Hollows 1 and 3

are also conducive to cirque development, less obvious glacial landforms and basin morphologies (Figures 2 and 4) only qualify Hollows 1 and 3 as marginal grade 4–5 cirques (Evans & Cox, 1995). Nevertheless, Hollows 1, 2, and 3 are indicative of the early stages of erosion by glaciers where wind-blown snow preferentially accumulates in pre-existing bedrock hollows or scarp slopes, especially on north or northeast facing hillsides in the northern hemisphere (Coleman et al., 2009; Evans, 1977; Evans & Cox, 1995; Harrison et al., 1998). Moreover, the distance of morainic deposits and ridges from the headwalls in Hollows 2 and 3 exceeds the *c.* 30–70 m limiting value for protalus rampart development (Ballantyne & Benn, 1994), indicating that the morainic sediments have been transported to their current position through ice movement. In Hollow 1, the downslope morainic deposit is located at the base of a steep concave slope that could be the remnants of a talus slope; thus, it is possible that this could represent the remnants of a protalus rampart. However, a lateral morainic ridge and relict channels in Hollow 1 suggest that glacial ice movement may have occurred in this hollow.

Three palaeo-cirque glaciers are therefore reconstructed in the study area (Figure 5; Table 2). All glaciers were similar in size (area of 0.09–0.11 km²), exceeding the minimum size threshold for differentiating snowpatches and glaciers, which is often defined as between 0.05 and 0.01 km² (Leigh et al., 2019; Lindh, 1984). This suggests that very small cirque glaciers glaciated Hollows 1–3 in the Ewes Valley. The AABR 1.56 ELAs for individual reconstructed glaciers in the Ewes Valley range between 329 and 401 m asl. However, Hollow 3 is an obvious outlier with an ELA >70 m lower than the other two hollows.

The total snow contribution area in the study area was between 2.4 and 6.1 times greater than the glacier surface area. For all reconstructed glaciers, the snowblow factor (SBF) was higher than 1.0 and the southwest vector represents at least 45% of the total snowblow area for each hollow, rising to 80% for Hollow 2. The inclusion of the snowblow contribution area in the ELA calculation gives a scaELA range between 419 and 461 m asl, which is at least 90 m higher than the AABR 1.56 ELA. This suggests that in the study area additional snowblow delivery had an important effect on glacier mass balance. In contrast, the avalanche factor (AF) for each of the hollows is <0.64 and the avalanche area represents from 9% to 24% of the total snow contribution area. This indicates that in the study area avalanching had a limited effect on glacier mass balance.

Age of glaciation and palaeo-glaciological significance

At present, the precise ages of the moraines in Hollows 1, 2, and 3 are unknown. However, the Ewes Valley is known to have been glaciated by the last British-Irish Ice Sheet, which is thought to have undergone deglaciation *c.* 17–15 ka (Clark et al., 2022). The moraines in Hollows 1, 2, and 3 could represent recessional moraines

Table 1. Landform signatures identified in the Ewes Valley compared with cirque diagnostic criteria (after Barr et al., 2017; Barr & Spagnolo, 2015; Coleman et al., 2009; Evans, 1977).

	Hollow 1	Hollow 2	Hollow 3	Hollow 4
Arcuate headwall	X	X	X	X
Obvious lateral spurs	–	X	X	X
Shallow, flat, or overdeepened floor	–	X	X	–
Reverse bed slope and threshold at downstream limit	–	–	–	–
End moraine(s)	X	X	X	–

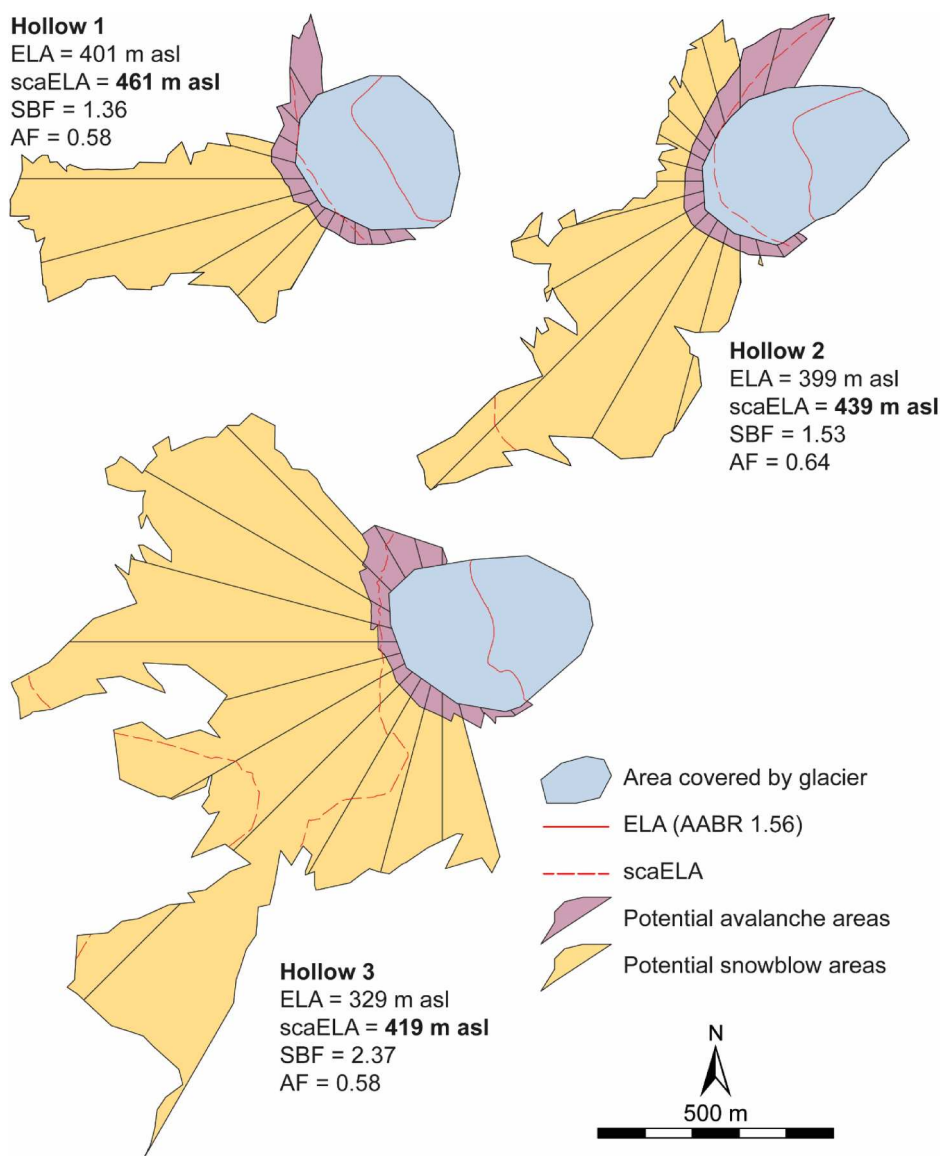


Figure 5. Distribution of potential snowblow areas and potential avalanche areas for the reconstructed glaciers in the Ewes Valley. The positions of the AABR 1.56 ELA and scaELA are marked as solid and broken red lines, respectively.

associated with the retreat of the ice sheet into an upland landscape, as is thought to have happened elsewhere in Britain (Clark et al., 2012). However, no other landforms associated with ice margin retreat are identified outwith the hollows in the Ewes Valley. Moreover, the relict channels on the spurs between Hollows 1–2 and Hollows 3–4 (Figure 2) may be indicative of ice sheet thinning in the Ewes Valley and ice sheet retreat down-valley (i.e. away from the hollows) during deglaciation. As such, the moraine ridges in Hollows 1, 2, and 3 appear to be the result of a single, separate glacial event after ice sheet deglaciation. Similar glacial re-inception is known to have occurred on The

Table 2. Table of glacier metrics and snowblow metrics for the reconstructed palaeo-glaciers in the Ewes Valley.

		Hollow 1	Hollow 2	Hollow 3
Glacier metrics	<i>Glacier area (km²)</i>	0.090	0.101	0.108
	<i>Glacier length (m)</i>	330	444	402
	<i>Aspect (°)</i>	57	77	62
	<i>Mean thickness (m)</i>	23	30	28
	<i>Z min (m asl)</i>	322	301	239
	<i>ELA (m asl)</i>	401	399	329
Snowblow metrics	<i>Snowblow area (km²)</i>	0.165	0.237	0.605
	<i>scaELA (m asl)</i>	461	439	419
	<i>SBF</i>	1.36	1.53	2.37
	<i>AF</i>	0.58	0.64	0.58

Cheviot, the Moffat and Tweedsmuir Hills, and the Galloway Hills in response to climatic cooling c. 12.8–11.7 ka (Bickerdike et al., 2018; Golledge, 2010). Thus, it is possible that cirque glaciation also occurred in the Ewes Valley during climatic cooling events of the LGIT, including the Younger Dryas stadial.

Compared to reconstructed ELAs for other known cirque glaciers and icefields in southern Scotland (Bickerdike et al., 2018; Cornish, 1981; Golledge, 2010; Harrison et al., 2006; Pearce, 2014), the reconstructed scaELAs in the study area appear anomalously low (up to 100 m lower). Coupled with the regionally dry and cold climate that is considered to have existed during the stadials of the LGIT (Bickerdike et al., 2018; Golledge, 2010; Pearce, 2014; Pennington, 1975), this might imply that glacial ice could not have formed in the Ewes Valley. However, the presence of a plateau above the hollows and high snowblow factor for each hollow suggests that the growth of glacial ice could have been considerably aided, and sustained, by the contribution of windblown snow. This is especially the case for Hollow 3: despite having the lowest reconstructed scaELA, Hollow 3 displays subtle evidence of glaciation that would have been supported by the largest snowblow contribution area in the study area (Table 2). Therefore, the redistribution of snow into the east and northeast facing hollows during the LGIT may have been sufficient to support the development of glacial ice. Similar snowblow dynamics are thought to have sustained marginal ice masses at the periphery of the West Highlands Glacier Complex during the Younger Dryas stadial (Chandler et al., 2019; Kirkbride et al., 2013; Standell, 2014). Nevertheless, this area of southern Scotland was probably extremely marginal to glaciation given the inland location of the Ewes Valley, the low altitude of the hollows, and the supposedly arid regional climate during the LGIT. The former presence of very small glaciers at relatively low altitudes in the Ewes Valley suggests that other amphitheater-shaped hollows in southern Scotland – such as Wisp Hill, Comb Hill, Roan Fell, and Cauldcleuch Head (Figure 1) – may have also supported glacial ice development during the LGIT. We therefore recommend that future studies re-evaluate other landforms on the uplands of southern Scotland in terms of a potential glacial legacy in the landscape.

Conclusion

Geomorphological investigations in the Ewes Valley have demonstrated the presence of three former cirque basin glaciers. The morphostratigraphic position of the hollows

suggest that they were occupied by glacial ice after ice sheet deglaciation, possibly as late as the Younger Dryas stadial. While relatively low ELA values for the study area would seem to preclude the development of glacier ice during the Late Glacial, the development of cirque glaciers in the study area may have been facilitated by accumulation of wind-blown snow from the adjacent plateau.

Acknowledgements

Rosie Boyes is thanked for her company in the field. The Authors would also like to thank the two anonymous reviewers for their thoughts on the manuscript.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Benjamin M. Boyes  <http://orcid.org/0000-0003-1309-2672>

Danni M. Pearce  <http://orcid.org/0000-0002-6889-224X>

References

- Ballantyne, C. K. (1984). The Late Devensian periglaciation of upland Scotland. *Quaternary Science Reviews*, 3(4), 311–343. [https://doi.org/10.1016/0277-3791\(84\)90011-8](https://doi.org/10.1016/0277-3791(84)90011-8)
- Ballantyne, C. K., & Benn, D. I. (1994). Glaciological constraints on proglacial rampart development. *Permafrost and Periglacial Processes*, 5(3), 145–153. <https://doi.org/10.1002/ppp.3430050304>
- Barr, I. D., Ely, J. C., Spagnolo, M., Clark, C. D., Evans, I. S., Pellicer, X. M., Pellitero, R., & Rea, B. R. (2017). Climate patterns during former periods of mountain glaciation in Britain and Ireland: Inferences from the cirque record. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 485, 466–475. <https://doi.org/10.1016/j.palaeo.2017.07.001>
- Barr, I. D., & Spagnolo, M. (2015). Glacial cirques as palaeoenvironmental indicators: Their potential and limitations. *Earth-Science Reviews*, 151, 48–78. <https://doi.org/10.1016/j.earscirev.2015.10.004>
- Benn, D. I., Owen, L. A., Osmaston, H. A., Seltzer, G. O., Porter, S. C., & Mark, B. (2005). Reconstruction of equilibrium-line altitudes for tropical and sub-tropical glaciers. *Quaternary International*, 138–139, 8–21. <https://doi.org/10.1016/j.quaint.2005.02.003>
- Bickerdike, H. L., Evans, D. J. A., Stokes, C. R., & Ó Cofaigh, C. (2018). The glacial geomorphology of the Loch Lomond (Younger Dryas) Stadial in Britain: a review. *Journal of Quaternary Science*, 33(1), 1–54. <https://doi.org/10.1002/jqs.3010>
- British Geological Survey (Cartographer). (2016). *DiGMapGB-50 [SHAPE geospatial data]*. <https://digimap.edina.ac.uk>
- Chandler, B. M. P., Boston, C. M., & Lukas, S. (2019). A spatially-restricted Younger Dryas plateau icefield in the Gaick, Scotland: Reconstruction and palaeoclimatic implications. *Quaternary Science Reviews*, 211, 107–135. <https://doi.org/10.1016/j.quascirev.2019.03.019>
- Chandler, B. M. P., Lovell, H., Boston, C. M., Lukas, S., Barr, I. D., Benediktsson, ÍÖ, 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. <https://doi.org/10.1016/j.earscirev.2018.07.015>
- Clark, C. D., Ely, J. C., Hindmarsh, R. C. A., Bradley, S., Ignéczi, A., Fabel, D., Ó Cofaigh, C., Chiverrell, R. C., Scourse, J., Benetti, S., Bradwell, T., Evans, D. J. A., Roberts, D. H., Burke,

- M., Callard, S. L., Medialdea, A., Saher, M., Small, D., Smedley, R. K., ... Wilson, P. (2022). Growth and retreat of the last British-Irish Ice Sheet, 31 000 to 15 000 years ago: The BRITICE-CHRONO reconstruction. *Boreas*, 51(4). <https://doi.org/10.1111/bor.12594>
- Clark, C. D., Hughes, A. L. C., Greenwood, S. L., Jordan, C. J., & Sejrup, H. P. (2012). Pattern and timing of retreat of the last British-Irish Ice Sheet. *Quaternary Science Reviews*, 44, 112–146. <https://doi.org/10.1016/j.quascirev.2010.07.019>
- Coleman, C. G., Carr, S. J., & Parker, A. G. (2009). Modelling topoclimatic controls on palaeoglaciers: Implications for inferring palaeoclimate from geomorphic evidence. *Quaternary Science Reviews*, 28(3), 249–259. <https://doi.org/10.1016/j.quascirev.2008.10.016>
- Cornish, R. (1981). Glaciers of the Loch Lomond Stadial in the western Southern Uplands of Scotland. *Proceedings of the Geologists' Association*, 92(2), 105–114. [https://doi.org/10.1016/S0016-7878\(81\)80011-9](https://doi.org/10.1016/S0016-7878(81)80011-9)
- Evans, D. J. A., Harrison, S., Vieli, A., & Anderson, E. (2012). The glaciation of Dartmoor: The southernmost independent Pleistocene ice cap in the British Isles. *Quaternary Science Reviews*, 45, 31–53. <https://doi.org/10.1016/j.quascirev.2012.04.019>
- Evans, I. S. (1977). World-wide variations in the direction and concentration of cirque and glacier aspects. *Geografiska Annaler. Series A, Physical Geography*, 59(3/4), 151–175. <https://doi.org/10.2307/520797>
- Evans, I. S., & Cox, N. J. (1995). The form of glacial cirques in the English Lake District, Cumbria. *Zeitschrift Fur Geomorphologie*, 39(2), 175–202. <https://doi.org/10.1127/zfg/39/1995/175>
- Furbish, D. J., & Andrews, J. T. (1984). The use of hypsometry to indicate long-term stability and response of valley glaciers to changes in mass transfer. *Journal of Glaciology*, 30(105), 199–211. <https://doi.org/10.3189/S0022143000005931>
- Galloway, R. W. (1961). Periglacial phenomena in Scotland. *Geografiska Annaler*, 43(3/4), 348–353. <https://doi.org/10.2307/520131>
- Golledge, N. R. (2010). Glaciation of Scotland during the Younger Dryas stadial: A review. *Journal of Quaternary Science*, 25(4), 550–566. <https://doi.org/10.1002/jqs.1319>
- Harrison, S., Anderson, E., & Passmore, D. G. (1998). A small glacial cirque basin on Exmoor, Somerset. *Proceedings of the Geologists Association*, 109(2), 149–158. [https://doi.org/10.1016/S0016-7878\(98\)80014-X](https://doi.org/10.1016/S0016-7878(98)80014-X)
- Harrison, S., Anderson, E., & Passmore, D. G. (2001). Further glacial tills on Exmoor, southwest England: Implications for small ice cap and valley glaciation. *Proceedings of the Geologists Association*, 112(1), 1–5. [https://doi.org/10.1016/S0016-7878\(01\)80043-2](https://doi.org/10.1016/S0016-7878(01)80043-2)
- Harrison, S., Anderson, E., & Patel, D. (2006). The eastern margin of glaciation in the British Isles during the Younger Dryas: The Bizzle cirque, southern Scotland. *Geografiska Annaler: Series A, Physical Geography*, 88(3), 199–207. <https://doi.org/10.1111/j.1468-0459.2006.00295.x>
- Harrison, S., Knight, J., & Rowan, A. V. (2015). The southernmost Quaternary niche glacier system in Great Britain. *Journal of Quaternary Science*, 30(4), 325–334. <https://doi.org/10.1002/jqs.2772>
- Johnson, R. H., Tallis, J. H., & Wilson, P. (1990). The Seal Edge Coombes, North Derbyshire - a study of their erosional and depositional history. *Journal of Quaternary Science*, 5(1), 83–94. <https://doi.org/10.1002/jqs.3390050108>
- Kirkbride, M. P., Everest, J., Benn, D. I., Gheorghiu, D. M., & Dawson, A. (2013). Late-Holocene and Younger Dryas glaciers in the northern Cairngorm Mountains, Scotland. *The Holocene*, 24(2), 141–148. <https://doi.org/10.1177/0959683613516171>
- Kłapyta, P., Bryndza, M., Zasadni, J., & Jasionek, M. (2022). The lowest elevation Pleistocene glaciers in the Carpathians - the geomorphological and sedimentological record of glaciation in the Polonyna Rivna and Borzhava massifs (Ukraine Carpathians). *Geomorphology*, 398, 108060. <https://doi.org/10.1016/j.geomorph.2021.108060>
- Leigh, J. R., Stokes, C. R., Carr, R. J., Evans, I. S., Andreassen, L. M., & Evans, D. J. A. (2019). Identifying and mapping very small (<0.5 km²) mountain glaciers on coarse to high-resolution imagery. *Journal of Glaciology*, 65(254), 873–888. <https://doi.org/10.1017/jog.2019.50>
- Lindh, L. (1984). Studies of transitional forms between snowpatch and glacier in the Abisko Mountains, Swedish Lapland. *Svensk Geografisk Arsbok*, 60, 145–156.

- McClung, D. M. (2013). Effects of triggering mechanism on snow avalanche slope angles and slab depths from field data. *Natural Hazards*, 69(3), 1721–1731. <https://doi.org/10.1007/s11069-013-0771-2>
- Mitchell, W. A. (1996). Significance of snowblow in the generation of Loch Lomond Stadial (Younger Dryas) glaciers in the western Pennines, northern England. *Journal of Quaternary Science*, 11(3), 233–248. [https://doi.org/10.1002/\(SICI\)1099-1417\(199605/06\)11:3<233::AID-JQS240>3.0.CO;2-Q](https://doi.org/10.1002/(SICI)1099-1417(199605/06)11:3<233::AID-JQS240>3.0.CO;2-Q)
- Oien, R. P., Rea, B. R., Spagnolo, M., Barr, I. D., & Bingham, R. G. (2022). Testing the area–altitude balance ratio (AABR) and accumulation–area ratio (AAR) methods of calculating glacier equilibrium-line altitudes. *Journal of Glaciology*, 68(268), 357–368. <https://doi.org/10.1017/jog.2021.100>
- Oien, R. P., Spagnolo, M., Rea, B. R., Barr, I. D., & Bingham, R. G. (2020). Climatic controls on the equilibrium-line altitudes of Scandinavian cirque glaciers. *Geomorphology*, 352, 106986. <https://doi.org/10.1016/j.geomorph.2019.106986>
- OS Terrain 5 [XYZ geospatial data]. Scale 1:10000, Tiles: ny39ne,ny39se, Updated: 6 June 2023, Ordnance Survey (GB), Using: EDINA Digimap Ordnance Survey Service, <https://digimap.edina.ac.uk>, Downloaded: September 2023
- Pearce, D. (2014). *Reconstruction of Younger Dryas glaciation in the Tweedsmuir Hills, Southern Uplands, Scotland: Style, dynamics and palaeo-climatic implications*. [Doctoral dissertation]. University of Worcester.
- Pellitero, R., Rea, B. R., Spagnolo, M., Bakke, J., Hughes, P., Ivy-Ochs, S., Lukas, S., & Ribolini, A. (2015). A GIS tool for automatic calculation of glacier equilibrium-line altitudes. *Computers & Geosciences*, 82, 55–62. <https://doi.org/10.1016/j.cageo.2015.05.005>
- Pellitero, R., Rea, B. R., Spagnolo, M., Bakke, J., Ivy-Ochs, S., Frew, C. R., Hughes, P., Ribolini, A., Lukas, S., & Renssen, H. (2016). GlaRe, a GIS tool to reconstruct the 3D surface of palaeoglaciers. *Computers & Geosciences*, 94, 77–85. <https://doi.org/10.1016/j.cageo.2016.06.008>
- Pennington, W. (1975). A chronostratigraphic comparison of Late-Weichselian and Late-Devensian subdivisions, illustrated by two radiocarbon-dated profiles from western Britain. *Boreas*, 4(3), 157–171. <https://doi.org/10.1111/j.1502-3885.1975.tb00687.x>
- Rea, B. R. (2009). Defining modern day Area-Altitude Balance Ratios (AABRs) and their use in glacier-climate reconstructions. *Quaternary Science Reviews*, 28(3), 237–248. <https://doi.org/10.1016/j.quascirev.2008.10.011>
- Sissons, J. B., & Sutherland, D. G. (1976). Climatic inferences from former glaciers in the south-east Grampian Highlands, Scotland. *Journal of Glaciology*, 17(76), 325–346. <https://doi.org/10.3189/S0022143000013617>
- Spagnolo, M., Pellitero, R., Barr, I. D., Ely, J. C., Pellicer, X. M., & Rea, B. R. (2017). Acme, a GIS tool for Automated Cirque Metric Extraction. *Geomorphology*, 278, 280–286. <https://doi.org/10.1016/j.geomorph.2016.11.018>
- Standell, M. R. (2014). *Lateglacial (Younger Dryas) glaciers and ice-sheet deglaciation in the Cairngorm Mountains, Scotland: glacier reconstructions and their palaeoclimatic implications* [Doctoral dissertation]. Loughborough University. <https://hdl.handle.net/2134/16159>