



1 **Ice buttressing-controlled rock slope failure on a cirque headwall,**

2 **English Lake District**

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17

18 **Key Points**

19 Geometry and mechanics of cirque rock slope failure defined from the local geology

20 Rock slope failed slowly due to ice buttressing the cirque headwall

21 Rock slope failure occurred during deglaciation

22



23 **Abstract**

24 Rock slope failures in the English Lake District have been associated with deglacial processes
25 after the Last Glacial Maximum, but controls and timing of failures remain poorly known. A
26 cirque headwall failure was investigated to determine failure mechanisms and timing. The
27 translated wedge of rock is thin and lies on a steep failure plane, yet the friable strata were
28 not disrupted by downslope movement. Fault lines and a failure surface, defining the
29 wedge, were used as input to a numerical model of rock wedge stability. Various failure
30 scenarios indicated that the slope would have failed catastrophically, if not supported by
31 glacial ice in the base of the cirque. The amount of ice required to buttress the slope is
32 insubstantial, indicating likely failure during thinning of the cirque glacier. We propose that,
33 as the ice thinned, the wedge was lowered slowly down the cirque headwall gradually
34 exposing the failure plane. A cosmogenic ^{10}Be surface exposure age of 18.0 ± 1.2 ka from
35 the outer surface of the wedge indicates Late Devensian de-icing of the back wall of the
36 cirque, with a second exposure age from the upper portion of the failure plane yielding 12.0
37 ± 0.8 ka. The 18.0 ± 1.2 ka date is consistent with a small buttressing ice mass being present
38 in the cirque at the time of regional deglaciation. The exposure age of 12.0 ± 0.8 ka
39 represents a minimum age, as the highly-fractured surface of the failure plane has
40 experienced post-failure mass-wasting. Considering the dates, it appears unlikely that the
41 cirque was re-occupied by a substantial ice mass during the Younger Dryas Stadial.

42

43 **Key words:**

44 rock slope failure, Pleistocene glacial cirque, cosmogenic exposure dating, deglaciation,
45 Younger Dryas, English Lake District.

46

47 **1 Introduction**

48 There are at least 70 known or suspected rock slope failures (RSFs) in the Lake District of NW
49 England that have been associated with the Late Devensian glaciation (Marine Isotope Stage
50 2: Wilson *et al.*, 2004; Jarman and Wilson, 2015a). Such RSFs often are termed ‘paraglacial’
51 as they “are part of, or influenced by, the transition from glacial conditions to non-glacial
52 conditions” (Ballantyne, 2002; McColl, 2012). However, the relationship between glaciation,
53 deglaciation, and the occurrence of RSFs remains far from resolved. This paper provides a
54 contribution to further understanding of the topic. Although a few highly modified



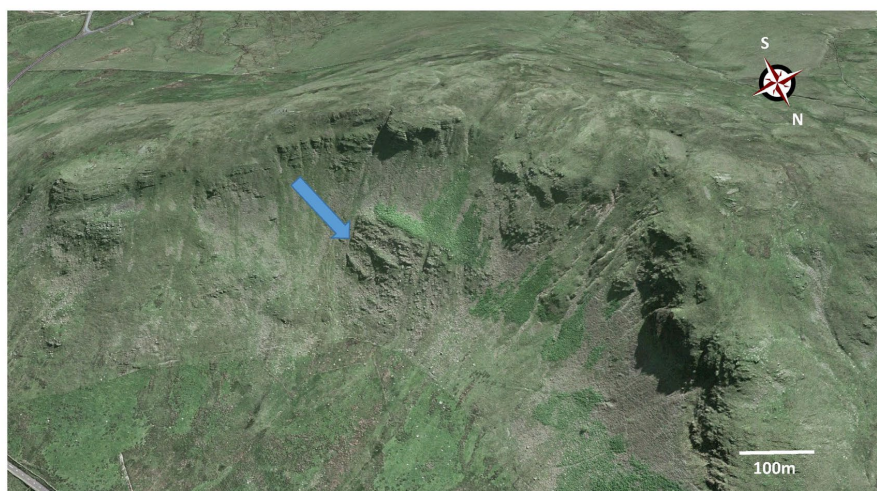
55 landforms have been identified tentatively as RSFs and related to time periods before the
56 Last Glacial Maximum (LGM; c., 26.5 ka BP to 19 ka BP, Clark et al., 2009) (Jarman and
57 Wilson, 2015b), the majority of Lake District RSFs have been associated with the end of the
58 Dimlington Stadial (see ‘Glacial Context’) and the final down-wasting of the Late Devensian
59 ice sheet within NW England. At that time, potential RSFs could have been fully supported
60 or partially supported by residual ice masses in topographic lows. Alternatively, some RSFs
61 could have occurred (Wilson, 2005) following the Scottish Readvance (c., 19.3 – 18.2 ka;
62 Chiverrell *et al.*, 2018) and the Younger Dryas Stadial (12.9 – 11.2 ka; Rasmussen *et al.*,
63 2006). However, only a few disintegrated RSFs have been dated. In contrast, those that
64 represent steep-slope deformation, or arrested slides, are of unknown age (Jarman and
65 Wilson, 2015b). An arrested hillslope failure occurs when the slipped mass is not evacuated
66 from the source area (Jarman, 2005), but is retained on the lower slope of the footwall. The
67 role of glacial ice in buttressing rock slopes, and thereby preventing failure (Whalley *et al.*,
68 1983; Holm *et al.*, 2004; Cossart *et al.*, 2008; Le Roux *et al.*, 2009; Allen *et al.*, 2010; Hilger *et al.*,
69 *et al.*, 2018), is largely speculative (Ballantyne, 2002; Jarman and Wilson, 2015b; Cody *et al.*,
70 2018; Hartmeyer *et al.*, 2020) and controversial (McColl *et al.*, 2010), as are the mechanics of
71 slope failure in situations where ice-support progressively diminishes (McColl and Davies,
72 2013; Klimeš *et al.*, 2021; Cave and Ballantyne, 2016). The latter two generic issues are the
73 primary focus of this paper.

74

75 Glacial erosion can steepen cirque headwalls to the extent that faulted and/or fractured-
76 rock slopes become unstable (Sass, 2005; Moore *et al.*, 2009), if not ice-supported. In
77 addition, the way slopes fail can provide insight to whether ice was present during the slope
78 failure. If ice-buttressed failures can be dated, then RSFs provide a source of information on
79 the timing of the final ice retreat. Here, an arrested (*sensu* Jarman, 2005) translational RSF is
80 described, dated, and the likely controls on the failure are defined and modelled. We test
81 the hypothesis that *a steep, faulted, and unstable rock slope has experienced buttressing by*
82 *glacial ice*. Our study area, which has not been previously identified as a RSF site, is within
83 Great Coum (54.3923° N, 2.6057° W), a small cirque within the southern Shap Fells to the
84 west of the Lune gorge (Fig. 1). A neighbouring cirque is named Little Coum. The Lune gorge
85 (south of Tebay; Fig. 2) separates the southerly extension of the Shap Fells to the west from
86 the Howgill Fells to the east. The site details and glacial context are described below.



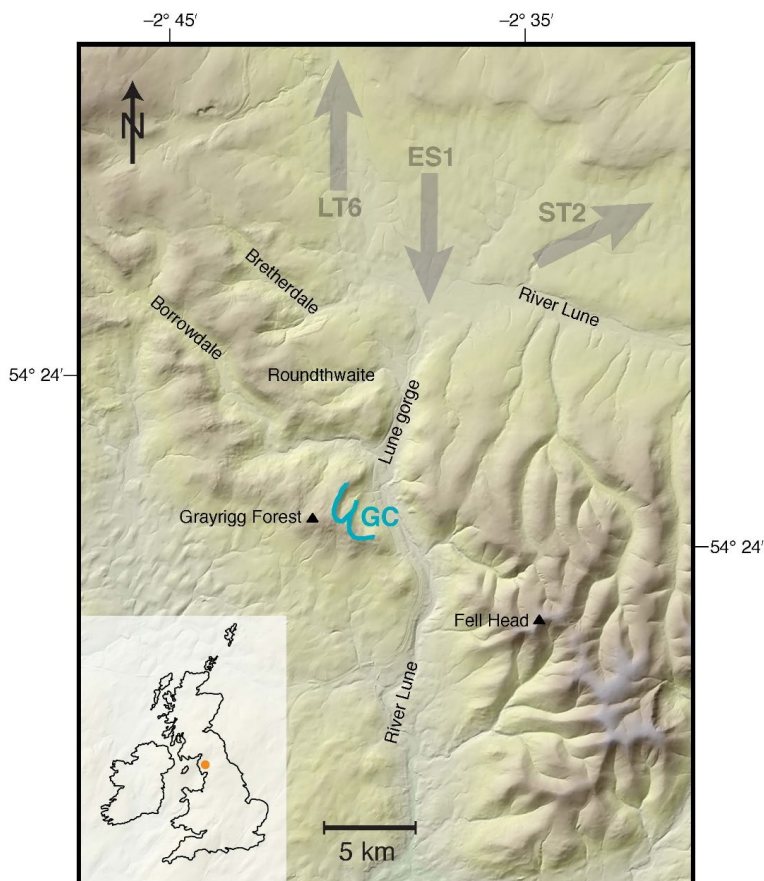
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88

89 Fig. 1: Oblique aerial view, looking southwestward, into Great Coum (Google Earth image).
90 The RSF is arrowed. The green grassy tread of the RSF (just above the arrow) is in sunlight
91 below the cliffed headwall (in shadow). The breadth of the RSF is between 125m and 180m.
92 Little Coum is just out of view to the right. Base image © Google Earth 2014. Scale bar
93 applies to the middle distance.

94



95

96

97 Figure 2: Regional map showing the location of Great Coum (GC) and Little Coum with
98 respect to generalized Dimlington (e.g., ES1) and (LT6) ice movements (after Livingstone *et*
99 *al.*, 2010; 2012). Locations referred to in the main text are also shown. Inset shows the
100 location of the study area in the context of the British Isles. Base NEXTMap digital elevation
101 topography has a 5 m resolution.

102

103 2 Glacial Context

104 The last period of extensive glaciation in northern Britain occurred during the Dimlington
105 Stadial of the Late Devensian substage of the Pleistocene (~28-15 ka; Rose, 1985; Scourse *et*
106 *al.*, 2009; Chiverrell and Thomas, 2010; Davies *et al.*, 2019), equivalent to Stadials 3 and 2 of
107 the North Greenland Ice Core Project (NGRIP) chronology (Lowe *et al.*, 2008) and the Marine
108 Isotope Stage 2 (Ehlers and Gibbard, 2013). During the LGM, the Lune gorge and surrounds
109 were covered by several hundred metres of ice. The Lune gorge is ice-sculpted, having a



110 parabolic bedrock cross-section with truncated valley-side spurs along both the west and the
111 east margins. Great Coum and Little Coum, on the western side of the gorge, are the only
112 recognized cirques in the Lune gorge. These two Lunedale cirques should not be confused
113 with two cirques with the same names in Dentdale (Barr *et al.*, 2017). The two conjoined
114 embayments were considered by Marr and Fearnside (1909) to be a single cirque, but
115 recently have been recorded as separate cirques (Barr *et al.*, 2017; Clark *et al.*, 2018).
116 Devensian till banks and moraine (entrenched by the River Lune) fill much of the Lune gorge
117 floor and till also occurs in most tributary valleys (Aveline *et al.*, 1888; Marr and Fearnside,
118 1909; BGS, undated; 2008 a and b).

119

120 **2.1 Complexity of Devensian glaciation around Great Coum**

121

122 The context in which the RSF occurred is relevant to the interpretation of the importance of
123 potential ice buttressing and is referred to within the Discussion. Here we provide the
124 setting. Little is known of the glacial history of the Lune gorge area (Carling *et al.*, 2023).
125 Nevertheless, prior findings, in the main, have been incorporated in the BRITICE maps of the
126 area (Stokes *et al.*, 2018). A complex interplay occurred in the vicinity of the Lune gorge
127 between several upland ice dispersal centres, primarily: the Scottish, Lake District and
128 Howgill ice masses, during the period of maximum ice cover ~ 26–22 ka. All three ice masses
129 interacted in the north whilst the latter two ice masses dominated to the south. After the
130 LGM, as the ice sheets down-wasted and ice flows became increasingly valley-confined, ice
131 emanating from the two cirques would have flowed northwards (Carling *et al.*, 2023).

132

133 The complexity of regional ice flow was simplified by Livingstone *et al.* (2010; 2012) by using
134 codes to refer to different ice streams (Fig. 2) that occurred in various locations and at
135 differing times; the relevant codes are as follows. In the ES1 phase, early LGM, northern ice
136 penetrated a short distance into the Lune gorge (Harkness, 1870; Goodchild, 1875; 1889;
137 Marr and Fearnside, 1909; Hollingworth, 1931; Moulson, 1966; Letzer, 1978) as far as
138 Carlingill and Great Coum (Fig. 2) but no further. However, Davies *et al.* (2019)
139 demonstrated that, close to the LGM, (ST2 phase; *sensu* Livingstone *et al.*, 2010) and during
140 the LT6 phase (Chiverrell *et al.*, 2018), ice flowed northwards from the Lune gorge (Fig. 2).
141 On the northern flank of the Howgill Fells, any ST2/LT6 ice flow would have been to the



142 north and east from the Howgill ice dome (Fig. 2) such that the higher summits of the
143 Howgill Fells were not overrun by ice from further north (Gunson, 1966; Stone *et al.*, 2010).
144 Rather, the Howgill Fells hosted its own local ice dispersal centre. Prior work failed to
145 determine whether northern ice entered the two Lunedale cirques. Consistent northerly
146 down-wasting ice-flow was established (Hollinsworth, 1931; Rose and Letzer, 1977) from 19
147 ka (Davies *et al.*, 2019) with surrounding areas north and south of the Lune gorge being ice
148 free by ~ 19.2 to 16.6 ka (see Carling *et al.*, 2023, for a review of regional dates). These dates
149 are broadly consistent with other dates for deglaciation of the central Lake District more
150 widely (Wilson and Lord, 2014) and are indicative of a general ~ 2–3 kyr window for the
151 timing of final Dimlington ice down-wasting within the Lune gorge when the back wall of the
152 Great Coum cirque could have become ice-free. We return to this point in sections 3 and
153 6.2.

154

155 Given that ice may have reoccupied upland terrain in Lake District during the Younger Dryas
156 (Brown *et al.*, 2013; Bickerdike *et al.*, 2018), in principle, an ice mass may also have occurred
157 in the general vicinity of the Lunedale cirques at this time. However, no evidence for
158 Younger Dryas ice in the Lune gorge has been reported.

159

160 **3 Geological Setting of the cirques**

161

162 The bedrock in the cirques comprises the marine Silurian Coniston Group (Soper, 1999;
163 Soper, 2006), which here consists of fine-grained, blue-grey, sandy siltstone (greywacke) in
164 beds from < 1 m to ~ 3 m thick. Most of the thicker beds crop-out within the headwalls of
165 the cirques. The thicker sandstone beds are more competent with fewer fractures, whilst
166 thinner fissile siltstone beds exhibit cleavage and are heavily fractured. Vertical joints are
167 frequent with spacings of a few metres, together with evidence of small-scale bedding
168 deformation and small-scale faulting. Moseley (1968; 1972) considered the considerable
169 complexity of the regional structure and noted folding, steep discontinuous local faulting,
170 joint patterns and the presence of slickenside surfaces in the southern Shap Fells. In the
171 Methods and the Results, this complexity is not considered, as the detail is not pertinent to
172 our study. None-the-less, reference is made to local steep faults, slickenside surfaces and
173 friability where these are relevant, as the rock structure in the vicinity of the RSF is critical in



174 assessment of slope stability (Bonilla-Sierra *et al.*, 2015; Stead and Wolter, 2015). The
175 apparent dips of the local beds range from 0° to 30°, SW into the headwall of Great Coum.
176 However, the apparent 8° plunge of the stratal sequence is towards the NW, such that the
177 true dip is to the WSW with a NW strike (BGS, 2008 a and b). Infrequent, but distinctive 10–
178 40 mm-thick pale bands of siltstone occur (*e.g.*, Taylor *et al.*, 1971, p. 26) in some of the
179 thicker beds, which extend discontinuously over distances of several decametres parallel to
180 the primary bedding. These siltstone bands are significant in that examples (here termed
181 marker horizons) occur in the headwall strata which correlate with similar siltstone bands in
182 the strata of the RSF.

183

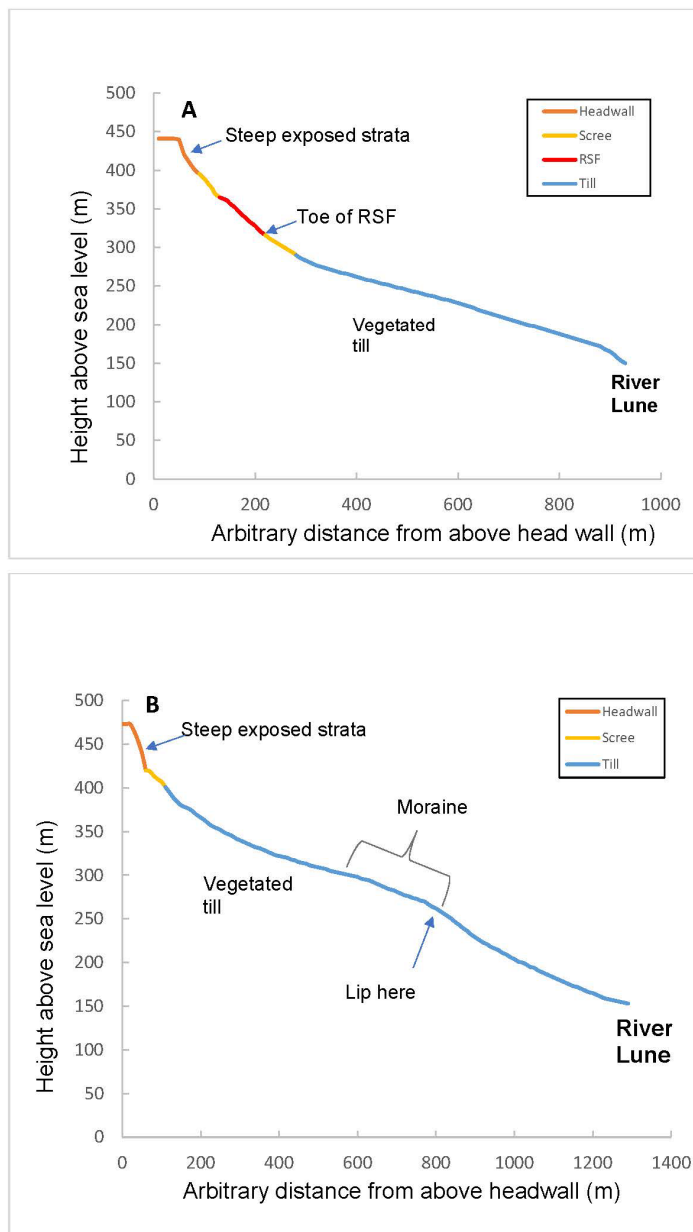
184 Great Coum is orientated NE, Little Coum is orientated NNE. The orientations of the cirques
185 are influenced by the strike of local paired anticlines (Marr and Fearnside, 1909; BGS,
186 2008a), and the low-insolation aspects of both sites would have encouraged Devensian snow
187 and ice accumulation and preservation. Great Coum exhibits no distinct lip (*i.e.*, no
188 overdeepening), the ground falls steadily from around 237 m (height above mean sea level,
189 m asl) to the River Lune below (Fig. 3A). Above 300 m the ground rises more steeply to
190 rocky head walls locally near 80° at 360–440 m, giving a height range of around 225 m. Little
191 Coum exhibits a slight lip at around 262 m altitude. Above 400 m the ground rises more
192 steeply to near 80° rocky head walls at 400–440 m, and the ridge crest at 480 m gives a
193 height range of around 220 m (Fig. 3B). First to second-order minor streamlets occupy the
194 lower parts of Great Coum, and Little Coum is drained by the third-order stream, Burnes Gill.

195

196

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198



199

200 Figure 3: Long profiles along centre of cirque: (A) Great Coum; transect from 54.389978 N;
201 2.606625 W to 54.396675 N; 2.598278 W; (B) Little Coum; transect from 54.393789 N;
202 2.615992 W to 54.400117 N; 2.602208 W. Exposed bedrock is indicated in the headwall and
203 in the RSF. Data extracted from Google Earth.
204



205 The British Geological Survey (BGS,2008b) map identifies till on the lower slopes of Great
206 Coum and the BGS borehole database contains the records of 24 shallow boreholes ranged
207 along the axis of the Lune gorge over 1.25 km immediately below Great Coum. These
208 borehole logs show that the slopes just below the cirque consist of a thin soil above a 2.5 m
209 thickness of Devensian diamicton, overlying the Silurian Coniston Grit. In Little Coum,
210 hummocky till infills the cirque below 400 m (BGS, 2008b); at lower altitudes, a flatter thin
211 diamicton drapes much of the basin, including a poorly defined curvilinear moraine that
212 terminates at the lip (Fig. 3B). It is not possible to calculate an equilibrium line altitude (ELA)
213 with any certainty based on the upper limit to highest lateral limits to the curvilinear
214 moraine (Porter, 2001), but 300 m asl is a reasonable estimate. Bedrock exposures along
215 Burnes Gill and augering during the current project indicate that this moraine is no more
216 than 6 m thick. The curvilinear moraine has a distinctive, sharp, outer margin along the
217 rocky rounded ridge that separates the two cirques. Within Little Coum, three faint
218 diamicton-covered (possibly ice-recessional) benches occur on the northern slope of the
219 cirque. Thus, although Great Coum lacks any preserved indication of ice retreat, such
220 indicators may exist within Little Coum.

221

222 All the deposits described above are significant. In the first instance, substantial till in the
223 Lune gorge below Great Coum has been related to northern ice penetrating the gorge
224 around the LGM (Carling, *et al.*, 2023). At that time, the whole region was covered by a thick
225 ice sheet (Merritt *et al.*, 2019). However, as down-wasting led to increasing topographic
226 control and valley glaciers predominated, there was likely to be ice flow out of the cirques
227 prior to the near-complete ice retreat that left the diamicton-covered benches. We envisage
228 that around the LGM, thick overriding ice in the vicinity of Great Coum was dictated by
229 regional ice gradients largely independent of the local topography (Carling *et al.*, 2023).
230 Post-LGM, ice-discharge from the cirque initially would have remained high but any
231 buttressing effect on the headwall would decline as the ice thinned.

232

233 The RSF occurred in Great Coum. The most southerly backwall section of the cirque consists
234 of a steep rocky headwall facing N, whilst to the west a further steep rocky headwall faces
235 NE; a steep grassy slope occurs between these two outcrops. The RSF caused headwall
236 retreat in the vicinity of the present grassy slope, leaving the intact steep rocky sections of



237 the backwall to either side, but the failure also extends below the north-facing headwall (Fig.
238 1). Indistinct, small RSFs also occur to the east and west, which are not considered further.
239 Little Coum also contains a steep rocky headwall, but with no evidence of slope failures. The
240 mass of the RSF in Great Coum appears to have descended as a translational near-intact
241 block. Although a near-vertical fracture occurs in the right-hand side of the slipped mass
242 (Fig. 4), in other respects the undisturbed strata within the block readily correlate with strata
243 in the headwall above.

244

245 **4 Materials and Methods**

246 **4.1 Mapping landscape features**

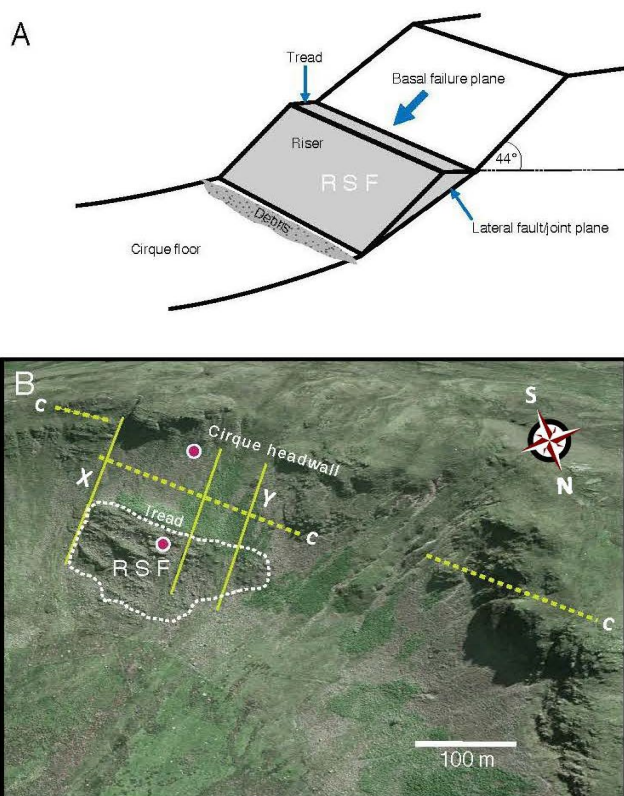
247 The British Geological Survey (BGS, 2008a) records several lineaments in the vicinity of
248 Great Coum that represent small faults or large block joints. Google Earth satellite images
249 (2004, 2009, 2011 and 2014) were used to visually identify these linear landscape features
250 as well as others of relevance (not recorded by the BGS). Lineaments trace topographic
251 discontinuities, stratigraphic offsets, vegetation differences and slickensides, and these
252 forms were checked in the field. Smaller-scale linear features consist of the silt banding
253 marker beds, and numerous minor joints (the latter not mapped). The various points of
254 interest were recorded as single point data in the field using a hand-held Garmin global
255 positioning system (GPS). The strikes of bedding and the direction of faults were recorded
256 as compass bearings whilst the dips of bedding and faults were recorded relative to a
257 horizontal plane using a digital clinometer.

258

259 Single point data are precise in planview whereas linear features, between two or more
260 well-determined points, provide the general trend of features such as gullies and faults.
261 GPS coordinates also were used to map the extent of the slumped block. Due to the
262 inaccuracy of hand-held GPS-derived altitudes, the planview GPS coordinates were used to
263 determine the altitude of each point from Google Earth, and these were taken as definitive
264 (error < 4%) after cross-checking with Ordnance Survey 1:50,000 maps (Harley, 1975).
265 Selected topographic profiles were also developed from Google Earth imagery by reading x,
266 y and z coordinates at 10m horizontal spacings along selected planview lines running from
267 the top of the headwall of each cirque, across the free face and the slope below. Finally, a
268 systematic search was made within both cirques for Shap granite or limestone erratics to



269 check whether northern ice had entered the cirques. Outcrops of both these lithologies
270 occur 10km to the north.



271
272 Figure 4: A) Schematic cartoon of a simple wedge failure to indicate the terminology used
273 within the main text. B) Annotated view of Great Coum (compare Fig. 1). The fault-aligned
274 rock slope failure plane (c), above and behind the RSF, is intersected by three major steep
275 fault lines, the outer two of which (X,Y) define the RSF model. The locations of samples (HW
276 and OSF) collected for exposure dating are shown by circled symbols. Base image © Google
277 Earth 2014. Scale bar applies to the middle distance.

278

279 We refer the reader to Figure 4A for an explanation of the RSF terminology used here,
280 although the failure planes bounding the wedge are omitted for clarity. The modern
281 headwall of the cirque locally constitutes the main exposed scarp of the failure plane behind
282 the translational wedge of the RSF. The outer face of the wedge is termed the 'riser' and the
283 near-horizontal head of the wedge is termed the 'tread'.



284

285 **4.2 Rock sampling for surface exposure dating**

286 Terrestrial cosmogenic radionuclides, such as ^{10}Be , are produced and accumulate in minerals
287 within a few metres of Earth's surface due to their exposure to secondary cosmic rays and
288 are lost via erosion and radionuclide decay (Lal, 1991). In our case, two free rock surfaces
289 are recognised (Fig. 4): the riser, being the outer surface of the RSF, and the tread, which
290 forms the top surface of the slipped mass. We set out to determine when the RSF riser was
291 first exposed to cosmic rays as ice receded from the cirque. For reasons of economy, we
292 collected one sample from the riser to compare the exposure age with the timing of
293 regional deglaciation. A ~15 kg intact block of bedrock (sample OSF) was collected from the
294 outer 10 cm-thick surface of the riser (Fig. 4B); a prominent thick undisrupted stratum close
295 to the top of the RSF mass. Our sampling strategy was restricted by the ease of access and
296 by the nature of the bedrock surfaces. The smooth bedrock surface of the riser we sampled
297 suggests minimal loss of rock mass due to surface fragmentation or spalling since the RSF
298 occurred. A second 15 kg bedrock block (sample HW) was collected from the failure plane
299 of the transverse fault line just below the cirque headwall (Fig. 4B) with an aim to
300 determine the timing of the failure. The sampled bedrock failure plane was observed to be
301 densely fractured, suggesting some loss of material from the surface since its exposure.
302 Surface erosion affects the abundance of cosmogenic nuclides and the estimated exposure
303 age; an issue we address in the Discussion (and Supplementary Materials). Samples were
304 cut from *in situ* bedrock surfaces using a powered rock saw, and their altitude, bearing, tilt,
305 and topographic shielding were recorded. Topographic shielding is significant for both
306 samples; details are given in Fig. S1 (Supplementary Materials).

307

308 Our approach entails three important assumptions about the last glaciation. First, we
309 assume that the cirque headwall experienced at least 2 m of bedrock glacial erosion, which
310 removed the nuclide inventory produced during preceding ice-free periods; and second, that
311 ice burial depth at the position of the OSF sample was at least 20 m and therefore sufficient
312 to effectively halt nuclide production and third, that this cover persisted until failure. These
313 assumptions mean that sample OSF began accumulating ^{10}Be only from the time that the
314 down-wasting ice exposed the surface to cosmic rays. In contrast, sample HW remained



315 deeply shielded (> 5 m) within the cirque headwall until the RSF exposed the failure plane
316 to cosmic rays.

317

318 4.3 Cosmogenic nuclide analysis

319 The two bedrock samples were prepared for cosmogenic ^{10}Be analysis at the Aarhus
320 University Cosmogenic Nuclide Laboratory, Aarhus, Denmark, following standard laboratory
321 procedures as described in Andersen *et al.* (2020). The $^{10}\text{Be}/^9\text{Be}$ ratios were analysed at the
322 accelerator mass spectrometer at AARAMS, Aarhus, Denmark. A summary of the
323 cosmogenic nuclide analyses is given in Table 1 and further details are found within
324 Supplementary Materials.

325

326 **Table 1.** Summary of the cosmogenic nuclide analyses. ^{10}Be concentrations in quartz
327 normalized to the “07KNSTD” standardization by Nishiizumi *et al.* (2007), and exposure ages
328 calculated using LSDn scaling (Lifton *et al.*, 2014) and global calibration dataset (Borchers *et al.*,
329 2016) via <http://hess.ess.washington.edu> v3.0.2. The analytical uncertainty includes AMS
330 error on measured ratios incl. standard uncertainty of 1.1. %, Be carrier concentration, and
331 processing blank propagation (<1.2 %). The total uncertainty also includes production scaling
332 and calibration uncertainties. Rock density was assumed as 2.7 g cm^3 .

333

Sample ID	Latitude	Longitude	Elevation (m.a.s.l.)	Topo shielding correction	Sample thickness (cm)	^{10}Be (at g^{-1})	Uncert (at g^{-1})	^{10}Be age (ka)	Analytic uncert (kyr)	Total uncert (kyr)
HW	54.3907	-2.6065	415	0.74	1	57499	1975	12.0	0.4	0.8
OSF	54.3917	-2.6064	348	0.58	1	63969	2017	18.0	0.6	1.2

334

335 4.4 Rock slope failure modelling

336 The RSF was modelled using *Swedge* version 6.0 (2018), a specialised rock-slope stability
337 software package, which can analyse a five-sided block (pentahedron) as a translational
338 wedge-failure—whereby a rock mass slides along a persistent basal plane of failure
339 bounded on each side by a fault or joint plane (Hoek and Bray, 1981; Rocscience Inc., 2018).
340 Either, or both, laterally bounding faults can act as additional slide planes, depending on
341 the geometry of the problem (Fig. 4A). In our case, two surfaces are not confined by
342 neighbouring bedrock: the outer surface of the RSF, the riser, and the top surface of the
343 slipped mass, the tread (Fig. 4). As well as varying the geometry of the failure and the



344 roughness of the failure planes, *Swedge* has options to consider the influence of: (i) a
345 tension crack at the back of the failure (not shown in Fig. 4A); (ii) water in the failure planes;
346 and (iii) the effect of any retaining normal stress that may counter the propensity to slide.
347 In engineering applications, restraining normal stress is conventionally realized using steel
348 rock bolts, or stone and concrete structures applied to the face of the riser, especially near
349 the toe. In contrast, here the issue is whether an ice mass in the cirque can buttress a slope
350 that is otherwise unstable, as is explored below. In glaciated mountain environments,
351 permafrost (and ice segregation) can penetrate bedrock to a depth of several metres
352 (Andersen *et al.*, 2015). Ice-filled fissures tend to be stable at temperatures below -2°C ,
353 which gives rise to the concept of 'ice-cemented' fractures (Ballantyne, 2018).
354 Consequently, the possibility that permafrost stabilized the RSF failure planes is considered
355 in section 5.3.

356
357 *Swedge* was implemented adopting the Mohr-Coulomb failure criterion (*e.g.*, Jaeger and
358 Cook, 1979) pertaining to the limit equilibrium stability of a three-dimensional rock mass
359 using field data (Table 2). Further details are provided in the Supplementary Materials and
360 within the Results. Stability is defined in terms of a factor of safety (F) where $F > 1$ indicates
361 a stable slope and $F < 1$, a failed slope. $F = 1$ represents a critical state. In general terms,
362 the factor of safety is defined as the ratio of the forces resisting motion to the driving forces.
363 Driving forces include the mass of the wedge accelerated through gravity and water
364 pressure; the latter applied normal to each wetted plane. Resisting forces arise from the
365 shear strength of the wedge sliding planes. Any ice load on the wedge is considered only as
366 a weight force contribution to the normal stress. Thus, active support due to the load of any
367 glacial ice (or firn) on the riser is included in the analysis as in Equation 1; where T_n is the
368 normal component and T_s is the shear component of the force applied to the riser. Active
369 support is assumed to act in such a manner as to decrease the driving force in the factor of
370 safety calculation:

371

$$372 \quad F = \frac{\text{resisting force} + T_n \tan \phi}{\text{driving force} - T_s} \quad (1)$$

373



374 Unless parameter values are known exactly, a single deterministic RSF model cannot be
 375 resolved using Equation 1. In view of the uncertainty, in our field case, related to the exact
 376 relationship between fault plane alignments and dips, a variety of potential failure
 377

Table 2. Parameter values for RSF as determined in the field and as explored within the three model scenarios.

	Riser Angle °	Tread Angle °	Riser length (m)	Riser Bearing °	Width of tread (m)	Breadth of RSF (m)	Failure Plane Dip °	Failure Plane Bearing	Failed volume (m ³)	Fault X Dip orientation °N	Fault Y Dip orientation °N	Fault X bearing °N	Fault Y bearing °N	Fault X Dip °	Fault Y Dip °	Tension crack
Field	53	1	70	24	15	179	44	11	Est: 68288	291	298	21	28	unknown	unknown	unknown
Model1	53	1	75	24	15	182	44	24	68333	201	208	21	28	80	72	none
Model2	53	1	75	24	15	182	44	24	67792	90	90	21	28	71	71	none
Model3	53	1	110	17	15	125	44	11-14	68739	111	62	21	28	90	62	present

378 scenarios must be considered. To narrow the number of models, we used preliminary trials
 379 of our field-derived parameter values as input, varying both strength and slope and
 380 geometry parameters. Then, consideration of a range of fault plane dips allowed us to
 381 exclude geometrically impossible configurations and those geometries that did not
 382 resemble the geometry of the RSF. In this manner, we devised three model scenarios that
 383 represent the RSF in terms of shape and mass. More than 10,000 simulations were
 384 performed for each scenario, varying parameter values systematically (typically ± 10%) to
 385 isolate the most probable model for each case. The uncertainty and probability analyses
 386 were conducted using the dedicated approaches built into the *Swedge* platform, selecting
 387 normal distributions to describe the possible range of parameter values; for example, ± 10°
 388 of dips measured in the field. Finally, the buttressing effect of any glacial ice against the
 389 potential RSF is considered by applying an external load evenly across the area of the riser
 390 to counter any propensity for failure.
 391

392

393 5.0 Results

394 5.1 The rock slope failure

395 The positions of the pale silt marker beds, located in the headwall and within the RSF,
 396 indicate the RSF has moved downslope by about 110 m (*H*) vertically and up to 192m (*L*)
 397 horizontally. The width of the tread is about 15 m; the breadth of the slide is between 125
 398 and 180 m and the vertical extent of the main slipped intact mass along the outer face (the
 399 riser) is about 70 m. Assuming the displaced block is a triangular wedge thinning towards



400 the toe (Fig. 4), the volume of the intact slip is $\sim 68,250 \text{ m}^3$. Below the main slip there is an
401 area of disintegrated rubble which could increase the length of the riser, potentially adding \sim
402 3 % ($\sim 2300 \text{ m}^3$) to our volume estimate (Table S1 Supplementary Materials). The value of
403 H/L is sometimes considered a mobility ratio, whereby large values of L for relatively small
404 vertical displacement (H) can indicate unimpeded rapid descent and a long runout. Given
405 the volume of the RSF, values of $H/L > 0.6$, as here, indicate no excessive runout (Whittall *et*
406 *al.*, 2017; Table S1 Supplementary Materials).

407

408 The slope of the riser of the RSF mass is currently $\sim 30^\circ$, that is, is similar to the static angle
409 of repose. This angle may suggest slow downslope movement rather than rapid failure,
410 which tends to produce slope angles much less than the angle of repose. In addition, there
411 was no evidence of hard-rock end-point control at the toe of the slumping block to impede
412 its descent although the toe has rotated outwards (Fig. 4A). The slope of the riser today is
413 less than the slope of the failure plane (44°), which suggests a portion of the intact wedge
414 may be lying above debris derived by over-running some of the disintegrated thin toe of the
415 wedge (Fig. 4A). It is significant that the stratigraphic layers within the main RSF wedge
416 remain intact, with no evident down-slope dilation and little deformation or fracture across
417 the face of the slipped mass. The apparent plunge of the strata (8 to 10° towards the north),
418 *i.e.*, across the face of the RSF, indicates that the western margin of the slip may have
419 descended slightly further downslope than the eastern margin, as the headwall strata plunge
420 6° to 8° in the same direction. The outer face (Fig. 4B) of the RSF has undergone no evident
421 modification.

422

423

424 As shown in Figure 4B, a distinct fault (BGS, 2008b), normal to the cliff face occurs to the
425 east of the RSF at location X, with undisturbed stratigraphy in the headwall either side.
426 Slickenside structures occur along the basal failure plane (c) that continues across the cliff to
427 the north-west. The fault X is aligned with the south-eastern margin of the RSF (as seen in
428 Fig. 4B), whilst a further fault is evident as a distinct fissure in the RSF, with another fault to
429 the north-west (Y). The easterly dip of these three faults could not be determined accurately
430 although they are steep, consistent with the findings of Moseley (1968; 1972) for the
431 Coniston group in the region (see section 5.3). The basal failure plane defined the back of



432 the RSF, whilst the lateral limits to the RSF model were defined by the two marginal fault
433 lines (X,Y).

434

435 **5.2 Estimation of original angle of the outer slope of the rock surface before failure**

436 To apply the *Swedge* model it is necessary to know the angle of the outer slope of the rock
437 face before failure. From the geometry of the residual RSF mass, with respect to the
438 observed failure plane (Fig. 4B), the RSF can be considered as a translational, plane failure of
439 a pentahedron wedge. Taking a side view, the geometry is triangular (Fig. 4B), so it is
440 possible to calculate the minimum slope of the outer rock face prior to slope failure by
441 repositioning the failed block further up the failure plane. The angle of the failure plane is
442 taken as equal to that of the minimum angle of the slickenside surfaces, 44° , with a bearing
443 of between 6 and 11° . The riser (outer face) of the RSF is 70 m in length and the tread width
444 is 15 m; both lengths could have been slightly larger before fracturing occurred along the
445 basal failure plane and at the toe of the RSF (Fig. 4A). Given the small degree of uncertainty
446 with regard to the configuration of the slope before failure, the length of the failure plane
447 (necessarily longer than the riser of the RSF) was varied systematically at the same time as
448 varying the length of the riser between the measured length of 70 m and 90 m; the latter
449 value includes the small area of disintegrated toe (Fig. 4A). The tread width also is varied
450 between the measured breadth of 15 m and a 'limit' of 20 m to allow for potential
451 disintegration along the failure plane at the back of the tread. Repositioning the RSF upslope
452 in this manner, the slope of the outer face could have been no lower than 53° and if the
453 angle of the failure plane is increased beyond $\sim 54^\circ$, the resulting lengths of the failure plane
454 and outer face become incompatible with field observations.

455

456 **5.3 The Swedge model of the rock slope failure without ice buttressing**

457 Initial application of the Swedge Model used the field data shown in Table 2. We did not
458 model the stability of the wedge in its present position because the basal friction properties
459 are unknown; whether the toe of the RSF rests on rubble derived from the failure plane, or a
460 bedrock surface cannot be determined. Given that the present angle of the riser is 30° and
461 the basal failure plane is at an angle of 44° it is assumed that the wedge is now stable ($F \gg 1$).

462



463 The slope of the riser utilized is that applicable to the rock mass before failure, as
464 determined in the preceding section. The width of the tread and the lateral extent (breadth)
465 of the failed mass are determined from the field data. The summit of the cirque is fairly flat
466 so an outward slope of 1° below horizontal is used for the tread; the model is not sensitive
467 to this parameter. The angle of the failure plane is the minimum value for the slickensides to
468 the south-east of the RSF (which were not disturbed by the slope failure). The model allows
469 for defining the additional effective roughness angle (r) on the failure planes by applying a
470 'waviness' parameter (w) that was determined from the range of recorded slickenside
471 values, following Miller (1988). Other parameters were defined from the field data. It was
472 noted above that the dip of the two lateral delimiting faults could not be determined in the
473 field. However, as local faults tend to be steep (Moseley, 1968; 1972) the model was
474 implemented with the values shown in Table 2 and then varied systematically as reported
475 below. Given the geometry of the problem only three modelling scenarios are necessary to
476 explore the uncertainty in a controlled setting:

477

478 *Model 1: the RSF slides over the basal plane and against Fault Y.* The model aligns
479 the compass orientation of the basal failure plane with the orientation of the riser
480 outer face, which assumes a simple downslope slide. The orientation of Faults X and
481 Y with respect to north are as determined from field data. The X and Y fault dips are
482 steep and both dip to the west. Dips and riser length were varied slightly to optimize
483 the failed volume of the RSF to match the field estimate. In this manner, the model is
484 not consistent with the eastern side of the slip having progressed less far down the
485 failure surface than the western side. Factor of Safety: 0.83.

486

487 *Model 2: the RSF slides along the basal plane and against Fault X.* The model aligns
488 the bearing of the failure plane with the bearing of the slickensides to the east of the
489 RSF, as these define the bearing of the basal failure plane that differs from the
490 bearing of the riser face by 13° . The bearings of Faults X and Y are as determined
491 from field data. The fault dips are steep and both dip to the east. Dips and riser
492 length were varied slightly to optimize the failed volume of the RSF to match the field
493 estimate. In this manner the model is consistent with the eastern side of the slip



494 having progressed less far down the failure surface than the western side. Factor of
495 Safety: 0.86.

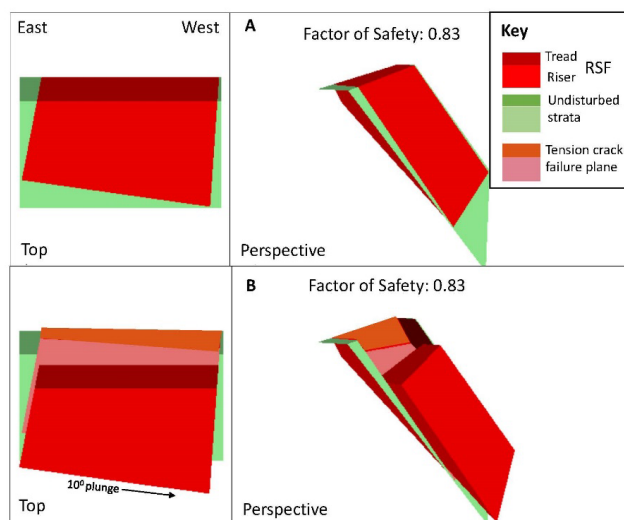
496

497 *Model 3: explores the addition of a tension crack to the back of the RSF.* It is not
498 known if a tension crack developed in the actual rock mass before failure, and the
499 properties of the tension crack are determined by the other model attribute values.
500 Including a tension crack, the western side of the RSF extends further down slope
501 than the eastern side, with the lower edge of the model block having a plunge of ~
502 10°, equal to the plunge of the RSF strata in the field. The bearing of the basal failure
503 plane is varied between 6° and 14°. Fault dips are steep, 90° and 62° to the east.
504 Dips and riser length were varied slightly to optimize the failed volume of the RSF to
505 match the field estimate. Given this scenario the RSF slides over the basal plane and
506 against Fault Y. Factor of Safety: 0.52 to 0.83 depending on basal plane bearing.

507

508 Given that there is unavoidable parameter uncertainty, none of the above models is an exact
509 representation of the RSF, although Model 3 is the closest match (Fig. 5). Yet, it is evident
510 that preserving the dip of the basal plane and solving to retain the mass of the failure, any
511 reasonable combination of data leads to a model of the failed block that resembles that seen
512 in nature and, in each case, the Factor of Safety is less than unity. A sensitivity analysis
513 showed that, for reasonable ranges of parameter values (typically $\pm 10^\circ$; outwith those listed
514 in Table 2), usually the geometry of the potential failure did not match that observed and so
515 could be dismissed. Specifically, in the 10,000 simulations of each model, model parameters
516 could be varied (*e.g.*, by $\pm 5^\circ$ in the case of angles), retaining a probability of slope failure of
517 96 %. In most cases the factor of safety was between 0.74 and 0.94. In a very few cases of
518 parameter combinations (4 %), a marginal factor of safety of between 1.07 and 1.22 is
519 achieved. In the latter cases, wetting between 20 and 30 % of the fault planes surface areas,
520 due to percolation of meltwater, caused the slope to fail.

521



522

523 Figure 5: Illustration of Swedge 6.0 Model 3: (A) before failure, and (B) during failure. The
524 basal failure plane orientation is 14° such that the base of the RSF is plunging 10° to the
525 north (right).

526

527 As a final consideration it should be noted that in deglaciating mountain regions, RSFs have
528 been related to permafrost degradation and consequent destabilization of ice-filled fractures
529 within the rock mass (Gruber *et al.*, 2004; Gruber and Haeberli, 2007). In the RSF failure
530 model described above, freezing of the failure planes can be considered by simply increasing
531 the friction factors, which can result in the block remaining intact despite the absence of
532 glacial ice buttressing. However, we expect that frozen failure planes did not persist long
533 after glacial down-wasting. Hydrostatic pressure in the failure planes would have high, and
534 percolation more generally lubricates failure planes (Hasler *et al.*, 2011). In addition,
535 permafrost support for the RSF does not explain the intact stratification of the RSF, as
536 permafrost degradation would have resulted in a rapid RSF. Consequently, permafrost was
537 not considered in any quantitative sense.

538

539 5.4 The Swedge model of the rock slope failure with ice buttressing

540 For the range of simulations reported in the previous section, $F < 1$ in all the 94 % of
541 physically plausible cases and wetting failure planes resulted in a 100 % failure in all 30,000
542 cases. Hence, the role of ice buttressing of the riser must be considered, as this is the most
543 likely explanation for slope stabilization. There is no information on the dynamic behaviour



544 of ice within the cirque. Consequently, selecting Model 3 above, three contrasting scenarios
545 can be envisaged that might stabilize the slope: (a) ice can be a static load variably
546 distributed around the centroid (Fig. 6A) of the riser; (b) ice can be dynamic, moving towards
547 the riser such that the stress is variably distributed around the centroid of the riser (Fig. 6B);
548 (c) ice can be dynamic, moving away from the riser such that a bergschrund opens between
549 the ice and the slope and the stress is distributed below the centroid of the riser. Broadly
550 consistent results also are found considering Models 1 and 2 (not reported herein).

551

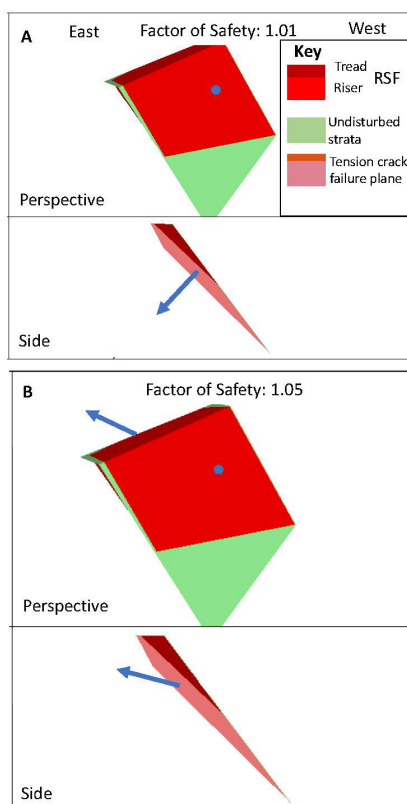
552 Firstly, considering scenario (a), the weight of an ice load is calculated, and the stress is
553 applied evenly across the area of the riser normal (*i.e.*, 90°) to the slope until it is stabilized
554 (for which condition: $F = 1.0065$; Fig. 6A). Subsequently, considering scenario (ii), the
555 analysis is repeated to ascertain the optimal direction to apply force that minimizes the ice
556 load. In scenario ii, the ice load can be reduced from that in (a) if the force is directed into
557 the slope and slightly upwards by 13° above the horizontal such that for $F = 1.0485$ (Fig. 6B).
558 In scenario (a), application of 40,659 tonnes of ice is required for a stable slope, which is
559 equivalent to $48,987 \text{ m}^3$, based on a debris-free low ice-density of 830 kg m^{-3} (Colgan and
560 Arenson, 2013). In scenario (b), application of 24,325 tonnes of ice ($29,307 \text{ m}^3$) is required
561 for a stable slope. For scenario (c), with a tension crack, the slope will remain stable as long
562 as the total stress applied to the slope is the same as for scenarios (a) or (b). In this study we
563 do not explore in detail how the ice mass and force direction might be distributed across the
564 riser to maintain slope stability as there are multiple permutations. Nonetheless, if the
565 cirque had been filled with ice to the top of the riser, around $166,000 \text{ m}^3$ of ice would be
566 required to fill the volume immediately adjacent to the potential RSF (Fig. 7), which is not
567 compatible with the small ice masses in scenarios (a) and (b) that are required to maintain
568 slope stability. Considering Fig. 7, it is important to recognize that, in any permutation of
569 potential RSF geometry (Table 2), the ice cover required to maintain slope stability is
570 typically less than 29 % (and possible as low as 17 %) of the volume to the top of the riser.
571 This result indicates that the slope would have remained stable as long as there was a
572 sufficiently small degree of ice buttressing due to ice in the cirque contributing a stress
573 normal to the face of the riser—which further implies failure occurred during final
574 deglaciation of the cirque. Note that, although the presence of sufficient ice on the riser
575 alone maintains rock mass stability, it is unlikely that this condition would pertain without



576 ice present immediately adjacent to the rock wedge. So, Figure 7 shows cirque ice beyond
577 the unstable slope, but only conceptually.

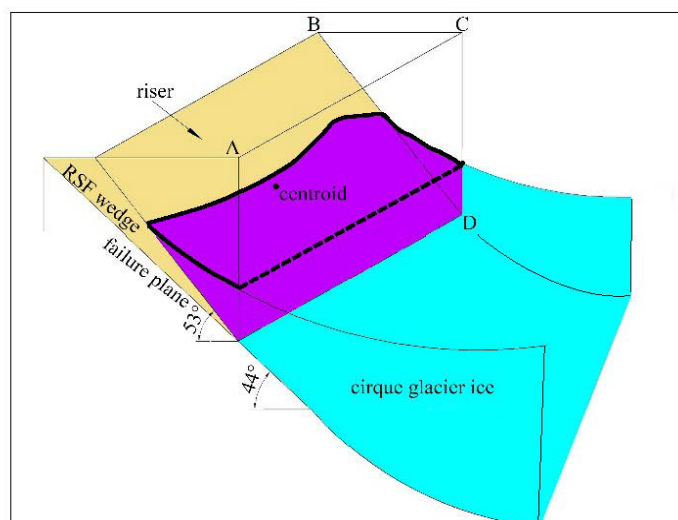
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579



580

581 Figure 6: Illustration of the force application required to stabilize the potential RSF: (A) With
582 the force (point and arrow) applied 90° to the slope, the ice load required to stabilize the
583 slope (i.e., $F = 1.0055$) is 40,967 tonnes; (B) With the force (point and arrow) applied at the
584 optimum angle (13° above horizontal) the ice load required to stabilize the slope (i.e., $F =$
585 1.0485) is 28,253 tonnes.



586

587 Figure 7: Cartoon depicting the concept of ice buttressing of the potential RSF. The RSF
588 wedge defines the unstable portion of the slope before the rock slope failure. Points A, B, C
589 and D define a pentahedral volume that, if filled by ice, would cover the complete face of
590 the riser. The pentahedral volume, with the upper ice surface outlined by a heavy black
591 line, shows that only a small percentage of the potential pentahedral ice volume is required
592 to be ice-filled to provide buttressing sufficient to prevent slope failure. Percentages were
593 obtained from the ice volumes required to buttress the slope. Additional ice might be
594 present in the cirque outside of the defined volume, but this ice does not contribute to the
595 stabilizing load directly applied to the riser.

596

597 5.5 Exposure ages from the rock slope failure

598 In both cirques, tills are composed of local lithologies exclusively, and a search for northern-
599 derived erratics confirmed their absence. The absence of erratic lithologies indicates that
600 the cirques were probably eroded by locally generated ice masses after the LGM. At the
601 time of the LGM, it is thought that the locations of the cirques were overridden by an ice
602 sheet from the north moving into the northern end of the Lune gorge (Carling *et al.*, 2023).
603 Under such thick ice conditions, the back wall of the cirque would have been stable as the
604 volume of ice was much greater than that required for slope stability—shown by either ice-
605 loading Model 3 scenario a or b. During active cirque erosion, after the LGM, the ice
606 volume in the cirque would decrease such that ice-loading also decreased such that the RSF
607 slowly descended as the loading fell below a critical F-value to sustain the slope. It is this
608 lowering of the RSF that we have attempted to date with cosmogenic nuclides.

609



610 The surface exposure age of 18.0 ± 1.2 ka (sample OSF) postdates the timing of maximum ice
611 cover and is consistent with the timing of deglaciation within the broader region (Carling *et*
612 *al.*, 2023) as is considered in the Discussion. As was noted in section 4.2, the outer face of
613 the RSF (the riser) constitutes a smooth surface of intact, undeformed strata, so
614 concordance of the surface exposure age and regional dates is to be expected. Exposure of
615 the RSF riser (sample OSF) predates significantly the exposure age of 12.0 ± 0.8 ka (sample
616 HW) calculated for the RSF basal plane, suggesting a relationship between debuttressing of
617 the riser face and the gradual downward slip of the RSF. The younger age for sample HW is
618 expected, due to the basal failure plane being progressively exposed after the upper portion
619 of the RSF (where sample OSF occurs) was clear of ice cover and the RSF began to move
620 downslope. Also of significance is the fact that the basal failure plane was disrupted by the
621 failure and is friable, as was noted in section 4.2. The loss of only one or two small blocks
622 from the location sampled at any time after failure should result in an age younger than that
623 of the outer face of the RSF (see Supplementary material). Results of the cosmogenic nuclide
624 analyses are summarised in Table 1.

625

626

627 **6.0 Discussion**

628 **6.1 Modelling the RSF dynamics**

629 The *Swedge* model was applied to the RSF assuming the original slope of the rock face was
630 53° , with a slide plane angle of 44° and no ice buttressing. The steeper slickenside surfaces
631 observed in the field directly above the RSF could indicate a steeper failure plane than that
632 used in the model, but these values were not used as they may represent strata disturbed by
633 the RSF. In any case, an increase in the failure plane angle, or the initial angle of the rock
634 face, both increase the propensity for failure. The waviness number calculated from field
635 data and applied in the model is low, which increases the propensity for failure. Preliminary
636 trials showed that to stabilize unstable model slopes would require the use of unrealistically
637 large waviness numbers (Miller, 1988) and so the waviness number was not varied in
638 sensitivity analyses. Thus, our results obtained with the *Swedge* model are conservative but
639 show that the rock face was consistently unstable before failure. The sensitivity analyses
640 accounted for parameter uncertainty and demonstrated that, in most cases, failure would
641 have occurred due to gravity alone. In those few cases where the slope was modelled as



642 marginally stable, moderate water lubrication of the failure surfaces (typically 30% of
643 surfaces) induced slope failure, but the addition of a modest amount of buttressing ice
644 ensured the slope remained stable. As there is no obstacle at the toe of the RSF to impede
645 descent, it is reasonable to assume that the slip occurred slowly as the ice decayed. The
646 need for buttressing of the slope to prevent rapid failure indicates that ice support was
647 important (Hilger *et al.*, 2018). Thus, our hypothesis '*a steep, faulted, and unstable rock*
648 *slope has experienced buttressing by glacial ice*' as proposed in the Introduction is
649 corroborated here.

650

651 As the amount of Model 3 scenario (a) ice (static load normal to the face) in the cirque
652 decreases, the level of the ice against the riser will fall towards the toe. Thus, the focal point
653 of the force applied to the slope by the ice cover migrates down the riser. As long as the
654 stabilizing load and the direction of the applied force remain sufficient as ice retreats, the
655 detached block will remain stable. However, the load within the cirque is unlikely to be
656 maintained as the ice elevation falls. The applied force also is variable through time and
657 across the riser as ice primarily deforms by internal flow (Hutter, 1983) such that, if any
658 additional pressure were exerted by residual ice adjacent within the Lune gorge, then the ice
659 mass within the cirque would respond accordingly. In particular, the uniaxial compressive
660 strength of ice is low and decreases as ice temperature increases, as will be the case during
661 deglaciation. Although in our model we do not consider the shear stresses associated with
662 the ice in a quantitative sense, brittle fracture of the thin, buttressing ice mass might
663 ultimately occur owing to the constant pressure associated with the mass of the RSF (Bovis,
664 1982; McColl and Davies, 2013). The presence of a tension crack will redistribute ice load
665 and induce ice segregation (frost-cracking) in the rock (Sanders *et al.*, 2012) close to the toe
666 of the rock mass, further reducing the competency. So as the factor of safety falls to close to
667 $F = 1$, the detached block will slowly move downwards. In the final stages of deglaciation,
668 low-density firn ($\sim 400\text{--}830 \text{ kg m}^{-3}$) will replace glacier ice ($\sim 830\text{--}917 \text{ kg m}^{-3}$) offering less
669 support to the RSF.

670

671 The RSF failure probably was controlled by distinct intersecting small-scale faults, as has
672 been modelled herein. Within the general area of Great Coum there appears to be two sets
673 of frequent lineaments, one trending to N to NW and the other NE, that intersect to define



674 bedrock blocks. Despite this propensity, the other steep headwalls in these two cirques
675 show no evidence of large-scale instability, although the basal fault plane of the RSF extends
676 (Fig. 4) behind the more western steep buttress in Great Coum, indicating that this slope is
677 also potentially unstable. One fault (BGS, 2008b) and several other lineaments occur roughly
678 normal to this alignment which, in conjunction, might delimit a potential wedge failure on
679 this western buttress. In the specific case modelled, slope failure is highly site-specific
680 depending, in the main, on fault alignments. Steepening of the cirque headwall via glacial
681 erosion may have altered the disposition of the rock mass load, increasing tensile stresses
682 along the fault planes, and promoting the RSF (Ballantyne, 2002). In this respect, the failed
683 slope was pre-conditioned (*sensu* McColl and Davies, 2013) to fail. However, the modelling
684 suggests that unloading likely played a role in controlling the timing of failure and the rate of
685 landslide displacement once initiated. Unloading may simply allow the unsupported
686 preconditioned block to fail, but the stress release accompanying unloading usually is
687 propagated along the fault network resulting in a reduction of internal locking stresses (*i.e.*,
688 the waviness number; Wyrwoll, 1977; Ballantyne, 2002). Other preparatory factors also
689 come into play as the ice load was removed, such as lubrication of the failure planes by
690 meltwater and weathering of the fault planes in general, moving the block closer to $F = 1$.

691

692 **6.2 Timing of the RSF**

693 Although there is only one terrestrial cosmogenic date for the riser of the RSF, the surface
694 exposure dating of 18ka is compatible with the RSF movement during final deglaciation
695 around 19.2 to 16.6 ka (see Carling *et al.*, 2023, for a review of regional dates). We interpret
696 the much younger exposure age (~ 12 ka) on the fault plane as the result of postglacial
697 weathering and erosion. Exposure dating necessarily only yields a minimum-limiting age of
698 exposure, except in cases where primary structures (*e.g.*, glacial striations or slickensides)
699 testify to negligible surface erosion. We observed some slickensides locally preserved on the
700 fault plane, but some degree of surface erosion is also indicated by a scattering of talus and
701 a shattered basal failure plane. We provide an estimate of the magnitude of surface erosion
702 assuming a range of plausible erosion rates in Fig. S2, Supplementary Materials wherein the
703 limitations of having only two cosmogenic samples is addressed.

704



705 We note that the locally derived till and absence of northern derived erratics in the cirques
706 suggests that northern ES1 ice did not enter the cirques, despite the presence of abundant
707 (northern) Shap granite erratics in Borrowdale, Roundthwaite valley and Bretherdale just to
708 the north (Carling *et al.*, 2023). Thus, buttressing of the slope by ice moving into the cirque
709 from the north can be ruled out. We suggest that the two cirques probably fed valley
710 glaciers associated with diminishing plateau icefields after the LGM (Carling *et al.*, 2023), and
711 their final form evolved during deglaciation. The Devensian termination is thought to be a
712 4–5 kyr period of ice decay just prior to the Last Glacial-Interglacial Transition at ~ 14.7–11.5
713 ka (Stone *et al.*, 2010). During deglaciation, there was unlikely to be sufficient ice in the
714 adjacent Lune gorge to bolster the cirque ice mass.

715

716 Regarding slope failures in cirques, Cave and Ballantyne (2016) and Klimeš *et al.* (2021)
717 noted that the role of glacial ice support in cirque back wall stability is conditioned by the
718 associated time scales considered. For example, Klimeš *et al.* (2021) reported high factors of
719 safety (> 1.95) for potential RSFs beneath glacial ice during the LGM, which is assumed to be
720 the case during full glacial conditions. Ballantyne *et al.* (2014) demonstrated that, following
721 the LGM, the timing of several dated RSFs is not consistent with the probable timing of
722 glacial debuttressing, reporting ages that correspond to deglaciation and well after. In
723 contrast, at Great Coum, the surface exposure age of 18.0 ± 1.2 ka is consistent with regional
724 estimates of the timing of deglaciation (see Carling *et al.*, 2023), as was noted above.
725 However, the apparent delay in final exposure of the fault plane, sometime before 12.0 ± 0.8
726 ka, indicates that a range of exposure ages might be associated with arrested RSFs; indeed,
727 some post-glacial dates may be associated with isostatic controls on slope failure (Ballantyne
728 *et al.*, 2014).

729

730 **6.3 An ice advance during the Younger Dryas?**

731 An important remaining issue is whether Great Coum could have supported a glacier during
732 the Younger Dryas Stadial. Although the Lake District was essentially ice-free by ~ 14.7 ka,
733 Younger Dryas cooling led to a subset of cirques in northern Britain refilling briefly (Evans,
734 1997). Sissons (1980) argued that many central Lake District cirques were re-occupied by ice
735 during the Younger Dryas, and subsequent studies (reviewed by Brown *et al.*, 2011) indicate
736 the presence of cirque glaciers in the central Lake District. However, the lowest Lake District



737 cirque floors are around 320 m asl (Temple, 1965), whereas the basal lip of Little Coum lies
738 at 262 m asl. In this context, Manley (1961) argued that cirques in the Howgill Fells lack
739 evidence for reoccupation during the Younger Dryas because they are too low. Norris and
740 Evans (2017) suggested the ELA in the western Pennines was 580 m asl during the Younger
741 Dryas with the lowest estimate placing the altitude at 445 m asl (Wilson and Clark, 1995).
742 Similarly, in the eastern Lake District, immediately to the north-west of Great Coum, the ELA
743 has been estimated at 400–600 m with 400 m being regarded as distinctly marginal (Wilson
744 and Clark, 1998). Glacial ice only descended to altitudes below 400 m asl where small outlet
745 glaciers were fed from plateau icefields (McDougall, 2013), the extents of which remain
746 controversial (Bickerdike *et al.*, 2018). In this respect, Harvey (1997) noted that there was
747 no evidence of ice readvance in the west facing Carlingill, neighbouring Great Coum.

748

749 As the top of the headwall of Great Coum is at 468 m asl, with no extensive plateau above, it
750 seems unlikely that snow supply was sufficient to maintain a Younger Dryas cirque glacier.
751 Others have also noted that Howgill cirques are too low to support Younger Dryas ice but
752 have suggested that the ‘fresh’ appearance of moraines in some Howgill and western
753 Pennine cirques indicate that Younger Dryas ice was maintained locally by extensive snow-
754 blow (Gunson, 1966; Gunson and Mitchell, 1991; Mitchell, 1996). If correct, this would
755 reduce the ELA locally to as low as 311 m asl (Mitchell, 1996). Mitchell’s estimate of ELA is
756 similar to the best estimate for Little Coum (300 m asl), and it is noted by several authorities
757 (Manley, 1961; Temple, 1965; Mitchell, 1996) that the dominant wind direction during the
758 Younger Dryas was from the W and SW, associated with cyclonic disturbances.

759 Nevertheless, we are not convinced by this argument. The extensive SW-facing slopes of
760 Grayrigg Forest and Grayrigg Pike are below the Younger Dryas ELA, so it is unlikely that
761 sufficient blown-snow could have been supplied to support glacial ice within the Great and
762 Little Coums. Our exposure age of 18.0 ± 1.2 ka (sample OSF) denoting ice-free conditions
763 on the outer face of the RSF suggests the cessation of glacial erosion at Great Coum.

764

765 **7.0 Conclusions**

766 We have demonstrated that a RSF in the headwall of a cirque in the Lune gorge occurred as
767 a slow downslope movement of an intact rock mass due to the presence of a supporting



768 glacial ice mass buttressing the failed slope. The estimated RSF timing corresponds with
769 regional deglaciation occurring by at least 18.0 ± 1.2 ka.

770

771 Although the case study reported herein supports the role of ice buttressing as a process
772 which may explain arrested RSFs, the vagaries of rock structure from one location to
773 another, coupled with the spatially variable role of isostatic uplift and local meltwater
774 climate (Cave and Ballantyne, 2016) provide strong site-specific controls on the nature and
775 timing of RSFs. Further modelling of RSFs should elucidate the range of conditions
776 associated with incipient failure whilst additional exposure ages for rock surfaces should
777 assist in constraining the timing during which processes such as glacial debuttressing
778 applied.

779

780 **Code availability**

781 *Swedge 6.0* is available from Rocscience Inc., Toronto (www.rocscience.com) for purchase or
782 as a licenced educational package upon application.

783 **Supplement Link**

784 *Note to reviewer: A supplement accompanies this manuscript*

785 **Author Contribution**

786 PAC devised the project and conducted the fieldwork and the *Swedge 6.0* simulations. TS
787 assisted in fieldwork. PAC and JDJ wrote the manuscript. JLA and MFK conducted the
788 cosmogenic nuclide analysis. All authors contributed to the final presentation.

789 **Competing interests**

790 The authors declare that they have no conflict of interest.

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797 contributed to the final presentation.

798 **Data Availability Statement**



799 The data required as input to *Swedge* version 6.0 (2018) are listed in Table 2. Use of *Swedge*
800 version 6.0 was licensed under an educational agreement with Rocscience Ltd., 2018:
801 www.rocscience.com. The ^{10}Be concentrations and underlying AMS data associated with the
802 ^{10}Be exposure ages are published on GitHub
803 https://github.com/CosmoAarhus/LakeDistrict_CosmoData.

804

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