Ice buttressing-controlled rock slope failure on a cirque headwall, English Lake District

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Figures S1, S2, Tables S1, S2. Here we present additional information regarding (1) the rock slope failure modelling and (2) the topographic shielding calculations for the cosmogenic nuclide data.

S1. Rock slope failure modelling

The simplest shear strength model applied to planar, clean discontinuities bounding a wedge of rock is the Mohr-Coulomb failure criterion:

$$\tau_f = c_p + \sigma_n' \tan(\emptyset_p + r) \qquad \text{(S1)}$$

where τ_f is the shear strength of a given failure plane; here three discontinuities are recognized: a basal plane of failure and two lateral bounding planes; c_p and $\emptyset_p$ are the cohesion and internal friction angle (*e.g.*, 31°; Zhang, 2017, p. 196) of the discontinuity, respectively; and σ_n' is the effective normal stress on the failure plane. The effective roughness angle *r* is due to asperities, such as slickensides, on the otherwise smooth discontinuities; this value is implemented within *Swedge* using a waviness number (*w* = 7.9) derived using the procedure of Miller (1988). The primes for c_p and $\emptyset_p$ have been omitted for brevity although they are for the effective stress conditions. In such a situation, c_p = 0 for a non-sliding plane (Zhang, 2017, p. 285) whilst a value of 0.025 MPa is selected where surfaces are in contact. The latter value has been found to yield good results where discontinuities are clean (*i.e.*, no fillings) and there are no intact rock bridges across discontinuities (Rocscience Ltd., 2018). Equations 1 (main text) and S1 underpin the limit-equilibrium rock-slope stability approaches adopted within the *Swedge* version 6.0 software (2018) which is used here to determine the key levels of normal stress associated with the RSF. In the absence of published technical data for the Coniston Group applicable to the rock slope stability of an unfailed headwall of the cirque in the late Quaternary, it considered that implementation of the *Swedge* model using field-derived data from the RSF will provide valuable guidance with respect to the probable environmental conditions that pertained at the time of failure.

The ratio of fall height (*H*) and horizontal runout distance (*L*) as a function of the RSF mass volume has been used widely to identify rapid or slow RSFs. In the current context the procedure of Whittall *et al*. (2017; their Eqs. 3 & 4) demonstrated that the RSF runout was commensurate with a weak rock, whether the toe of the main rock wedge was taken as the end of the runout, or if the additional rock debris below the wedge is taken as part of the runout (Table S1). Although the runout is as expected for a weak unsupported rock mass (Table S1), the lack of significant disruption of the strata within the thin wedge is surprising and might point to a slow descent of the wedge.

Table S1. RSF mobility data

	Wedge without debris extension at base		Wedge with debris extension at base		Mobility ratio	Wedge volume without debris[1]	Wedge volume with debris[2]
Parameter	*H* (m)	*L* (m)	*H* (m)	*L* (m)	*H*/*L* (-)	*V* (M m^3)	*V* (M m^3)
Observed values	110	192	130	242	0.54-0.57	0.06825	0.07055
Expected values: Whittall *et al*., 2017 — weak bedrock		182		228	0.57-0.60		
Expected values: Whittall *et al*., 2017 — strong bedrock		131		165	0.79-0.84		

[1] The volume of the main rock wedge was surveyed in the field.

[2] The volume of the additional rock debris was surveyed in the field (no correction for porosity).

S2. Limitations of the cosmogenic surface exposure dating

Although more rock samples for cosmogenic dating would have been preferable, preliminary trials showed that the lithology was laborious to prepare for dating such that an unrealistic resource would be required to date several rock samples. Because obtaining as precise a date as possible was critical, we paid especial attention to topographic shielding, calculating corrections for every 10° azimuth taking account of the inclination of the exposed surface, as is detailed in section 3 (Fig. S1). The outer surface of the RSF, the riser, was undisturbed and consequently replicate rock samples subject to the same sample preparation and dating procedures as sample OSF would likely provide a range of dates not dissimilar to that obtained: 18 ± 1.2ka.

Due to the friable nature of the bedrock, the RSF failure had resulted in disruption of the basal failure plane surface which meant that much of the exposed failure plane was unsuitable for sampling for cosmogenic dating. Sample HW was obtained from a relatively undisturbed exposure of the failure plane behind the RSF. By making reasonable assumptions about the rate of surface spalling of rock at the sampling site since the RSF occurred, the date of sample HW (12 ± 0.8ka) could be related to the original exposure date of the outer surface of the riser as is detailed in section 3 (Fig. S2).

S3. Cosmogenic surface exposure dating

Table S2. Topographic shielding field measurements. For samples OSF and HW, the shielding factor is calculated to be 0.580546, and 0.742680, respectively.

Sample OSF[1]		Sample HW[2]	
Azimuth (°)	*Inclination (°)*	*Azimuth (°)*	*Inclination (°)*
0	1.7	0	1.4
9	1.3	10	2.5
21	2.1	20	1.5
30	2.9	30	1.2
40	3.6	40	1.7
50	4.8	50	1.8
60	4.8	60	2.2
70	3	70	2.2
80	3	80	2.2
90	3	90	2.1
100	2.3	100	1.9
114	10.6	110	2.8
122	12.1	120	5
132	17.5	130	15.2
138	30.8	140	39.5
167	58	150	48
170	60.5	160	55.7
180	63	170	62.5
196	83	187	68
216	65.5	200	43.5
231	52.5	210	42.7
250	34.7	230	41
269	25.4	240	40.1
279	22.3	250	33.2
295	17.5	260	27.5

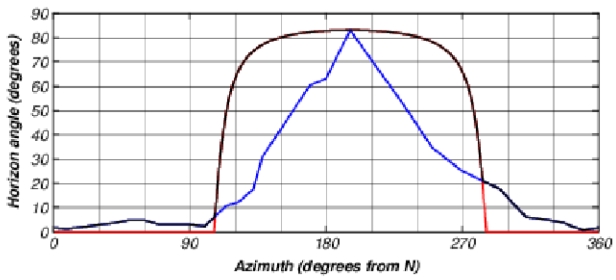
303	12	270	21.3
312	6.1	280	20.3
325	5.1	290	12.5
337	3.7	315	0
343	2.1	320	0.7
350	0.8	330	0.5
		340	0.4
		350	1.1

[1] sample surface dips 83°, strikes 286°

[2] sample surface dips 68°, strikes 277°.

Online topographic shielding calculator results for sample OSF (upper) and HW (lower)

Shielding factor:	0.580546



GMT Postscript

The blue line is the far-field horizon; red is the near-field horizon implied by the surface dip; black is the combined horizon. If you can't see any blue or red, it's under the black line.

Shielding factor:	0.742680

This plot is mainly just to check that you entered the data correctly.

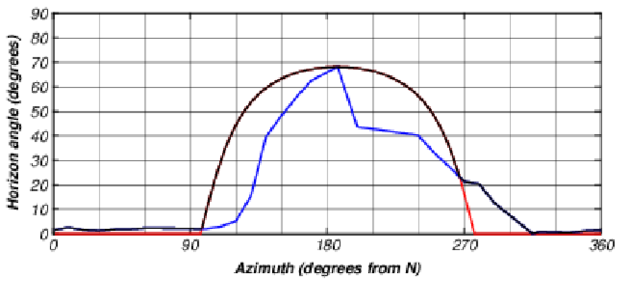


Figure S1. Topographic shielding calculated using the 'Topographic Shielding Calculator v.2' (http://stoneage.ice-d.org/math/skyline/skyline_in.html) based on field measurements for sample OSF (top panel) and HW (lower panel) given in Table S2. The diagrams show the portion of the skyline shielded by distal topography (blue) and resulting from the dip of the sampled surface itself (red), with total shielding shown in black. The resulting topographic shielding factors (numbers between 0 and 1) are multiplied with the calibrated site production rates to get the effective ^{10}Be production rate at our sites.

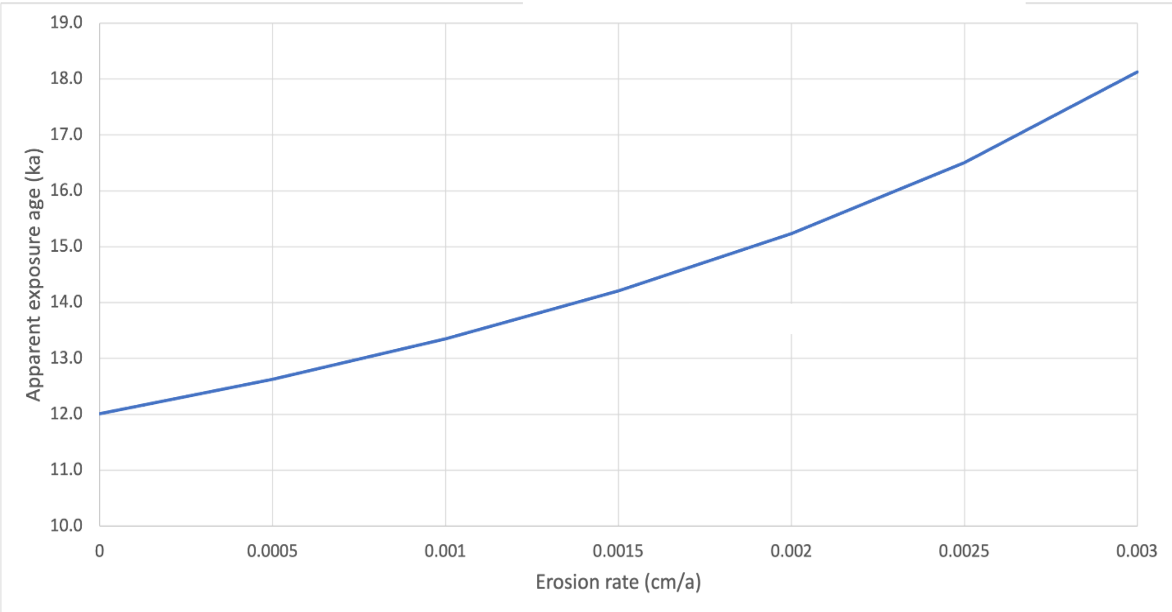


Figure S2. Combinations of apparent exposure ages and erosion rates consistent with the cosmogenic ^{10}Be inventory measured in sample HW. Surface erosion affects the abundance of cosmogenic nuclides and the estimated exposure age; we address this issue in the Discussion of the main text. We expect that the surface spalling led to loss of 10 to 20 cm thick blocks from the rock surface. This plot illustrates the case of an average erosion rate of 0.003 cm/yr at the HW sample site, which would be sufficient to allow samples HW and OSF to have the same exposure age (~18 ka).

Supplementary References

Zhang, L., 2017 Engineering Properties of Rocks (2nd Edition), Elsevier, 378pp.