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

Paul A. Carlinga, b, John D. Jansenc, Teng Sud, e, Jane L. Andersenf, Mads F. Knudsenf

a Geography & Environmental Science, University of Southampton, Southampton, SO17 1BJ, UK.

E-mail: P.A.Carling@soton.ac.uk

b Lancaster Environment Centre, Lancaster University, Bailrigg, Lancaster, LA1 4YW, UK.

c GFÚ Institute of Geophysics, Czech Academy of Sciences, Prague, Czechia

d University of Chinese Academy of Sciences, Beijing 100049, China.

e Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China.

f Department of Geoscience, Aarhus University, Aarhus, Denmark

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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:

(S1)

where is the shear strength of a given failure plane; here three discontinuities are recognized: a basal plane of failure and two lateral bounding planes; and are the cohesion and internal friction angle (*e.g*., 31o; Zhang, 2017, p. 196) of the discontinuity, respectively; and 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 and have been omitted for brevity although they are for the effective stress conditions. In such a situation, = 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 debris1 | Wedge volume with debris2 |
| *Parameter* | *H* (m) | *L* (m) | *H* (m) | *L* (m) | *H*/*L* (-) | *V* (M m3) | *V* (M m3) |
| *Observed values* | 110 | 192 | 130 | 242 | 0.54-0.57 | 0.06828 | 0.07055 |
| *Expected* *values*: Whittall *et al*., 2017 ─ weak bedrock |  | 182 |  | 228 | 0.57-0.60 |  | |
| *Expected value*s: 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

More rock samples for cosmogenic dating would have been preferable; however, preliminary trials showed that the lithology made it very difficult to extract and purify quartz for dating such that an unrealistic resource would be required to date several rock samples. Instead, we optimized the two dating measurements by paying close attention to topographic shielding, calculating corrections for every 10o azimuth and taking account of the inclination of the exposed surface, as is detailed in section 3 (Fig. S1).

Due to the friable nature of the bedrock, the RSF failure disrupted the basal failure plane surface, which meant that much of the exposed failure plane was unsuitable for exposure 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 OSF1 | | Sample HW2 | |
| *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)*



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 10Be production rate at our sites.

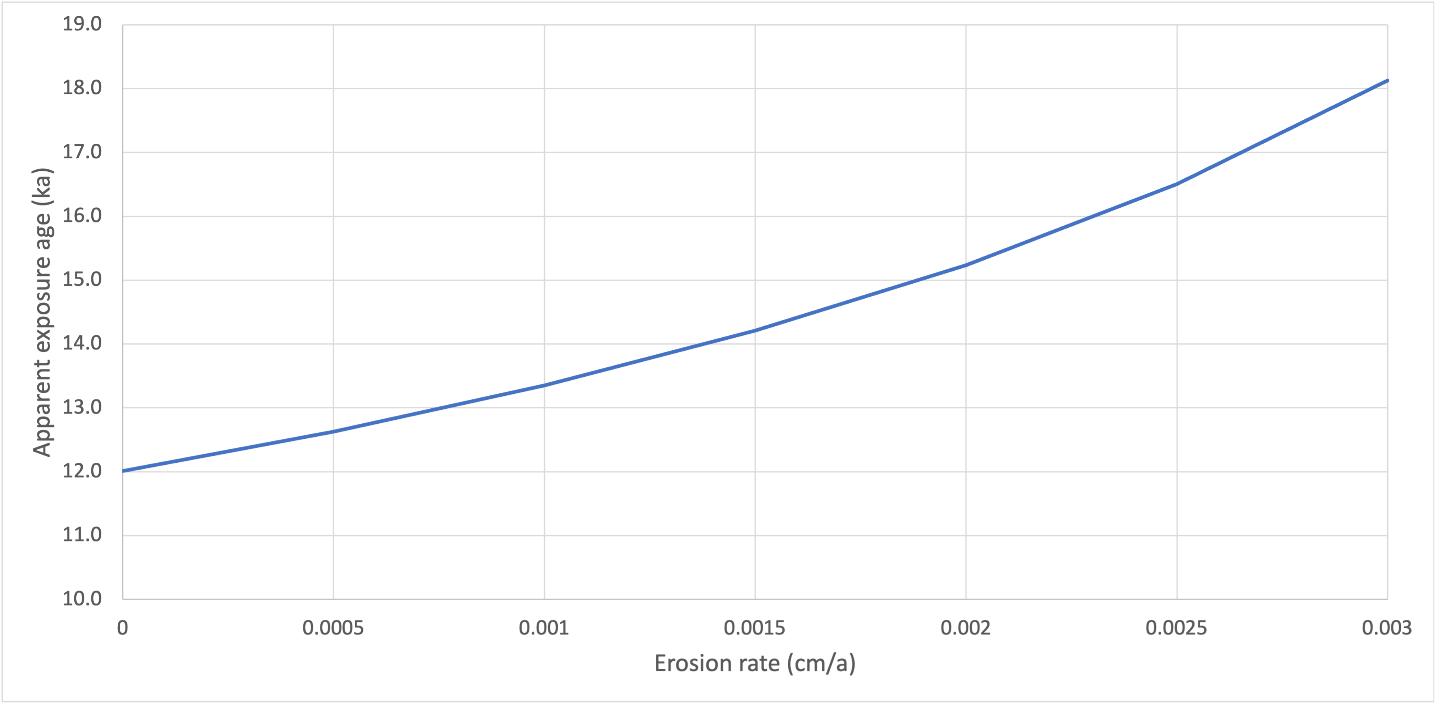


Figure S2. Combinations of apparent exposure ages and erosion rates consistent with the cosmogenic 10Be inventory measured in sample HW. Surface erosion affects the abundance of cosmogenic nuclides and the estimated exposure age; we address this issue in the Discussion of the main text. We expect that 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).



Figure S3. Cosmogenic samples. A) Block 45cm high (sample HW) *in situ* on the shattered failure plane; B) Block 50cm high (sample OSL) *in situ* on smooth but fractured and jointed surface of the riser of the RSF; C) same location as B after sample OSL has been removed. Note the smoothed surface to the right of the sample and the ice-rounded horizontal joint (arrowed).

Supplementary References

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