Review of Ms "Ice buttressing-controlled rock slope failure on a cirque headwall, English Lake District" by Carling et al.

Author responses to the reviewer's comments are given in blue text.

Ms # esurf-2023-14

Introduction This Ms proposes that a displaced but largely intact rock mass in Great Coum, Cumbria reached its present position by long-term, slow translation following failure, its motion being controlled by gradual debuttressing during post-LGM cirque glacier retreat. Two surface exposure dates, one (ca 18 ka) from the surface of the displaced mass and one (ca 12 ka) from the failure surface exposed by its motion, are claimed to constrain the timing of this event to ca 18 ka, which would be in line with established local deglaciation chronologies. The implication is that many of the undated intact RSF deposits in Britain are likely to have been retarded in their motion by gradual debuttressing by retreating ice.

We thank Prof. Tim Davies for this summary and the recommendation (at the end of the commentary) that we should submit a revised manuscript. However, we do not imply that the results of this specific investigation necessarily can be applied more widely as the reviewer avers. We do not claim that other UK RSFs were retarded by ice buttressing. Rather we present this study to illustrate the possibility that some RSFs were ice buttressed to spur further numerical investigation of RSFs.

This is a careful and detailed work that, irrespective of whether it is correct, would greatly benefit the community if published. The following comments suggest some further considerations that, in the opinion of the reviewer, would enhance the credibility of the work if addressed.

Thank you for noting that the work should be published to the benefit of the RSF community.

Review The critical evidence that supports the assumed gradual displacement of the rock mass is the fact that is substantially intact following a vertical displacement of ca 110 m on a slope of slightly greater than 30° (Fig. 4A, lines 644-5); however, there is stated to be an area of disintegrated rubble below the intact mass (lines 400-1) making up about 3% of the mass, so some degree of disintegration may well have occurred during emplacement.

If this slow displacement is accepted, then a cause can be provided in the form of downwasting of a cirque glacier assumed to have been present in Great Coum during the Last Glacial Maximum, so that the lateral support provided by the ice to the outer surface of the detached rock mass prevented it from displacing rapidly. This assumption is confirmed by detailed stability calculations for the in-situ rock mass, assumed to be detached from the parent mass by a planar failure surface in the form of a mapped fault; these show that the factor of safety F for the detached rock mass is in the region of 0.74-0.94 without ice support, whereas with ice support it is greater than 1.0.

The cosmogenic date of 18 ka for the outer surface of the displaced rock mass is asserted (lines 693-4) to be "compatible with the RSF movement during the final deglaciation around 19.2 to 16.6 ka". This is undoubtedly true; however, approximately the same date would have been found if the RSF had NOT moved at that time. There is no doubt that the rock mass moved – *but there is no direct evidence that it moved at ca 18 ka*. However, if ice buttressing is proven to have been necessary to explain proven slow RSF motion, then uncovering of the RSF surface would have occurred during deglaciation of the cirque as hypothesised.

It is of course true that the RSF could have occurred later than the first exposure of the outer face to cosmic rays but, adopting Occam's Razor, given there would be no support for the failure after the ice burden was removed, then associating the failure with 18 ka seems reasonable. We also demonstrate that the RSF would be unsupported without ice and therefore descent would occur approximately at the same time as the outer face was exposed (see response to **Slow displacement of the RSF** below) Note we report the uncertainty of this date as ± 1.2 ka. It is possible that the wedge of rock, that latterly constituted the RSF, was actually released from the headwall earlier than 18 ka and was supported by ice until the ice receded *c.*, 18 ka. However, this scenario is less likely as the thin wedge would probably have broken up within the ice body over time.

The hypothesis of the Ms therefore rests on (i) the assumption of slow displacement of the RSF, (ii) the interpretation of cosmogenic dating, and (iii) the stability analysis. These are now critically examined.

Slow displacement of the RSF In lines 404-406 Carling et al. indicate (correctly) that the H/L value for the event of 0.6 indicates no excessive runout, presumably to infer that this was a slow event; the largely intact nature of the RSF deposit leads to the same conclusion. But it is well-known that rapid blockslides can occur and remain intact at much lower values of H/L (e.g. Davies et al., 2006), meaning that *the fact that the deposit is intact is not a reliable indication that the movement was slow*. It is therefore quite possible that the RSF was emplaced rapidly (meaning at sliding speed commensurate with the marginal slope gradient – perhaps on the order of cm/sec to m/sec) and therefore it could have occurred after retreat of ice from its outer face – perhaps many thousands of years after.

The reviewer's statement is correct in principle. It cannot be known *post hoc* if the RSF descended rapidly or slowly. This issue can only be resolved using physical evidence and numerical modelling. We present two lines of physical evidence: 1) The short runout despite a steep failure plane, and 2) the remarkably undeformed fissile strata which are thinly bedded and <u>which constitute a thin wedge</u>. Undeformed strata might occur if the wedge had been very thick but that is not the case. Taken together we believe our case for slow descent is reasonable.

Cosmogenic dating As outlined in lines 614-6, the exposure date from the exposed headscarp (12 ka ± 0.8 ka) significantly postdates that from the outer face of the deposit (18.0 ± 1.2 ka). This requires that the upper headscarp became exposed about 6000 y after the disappearance of ice from the upper, outer face of the RSF. Carling et al. state (lines 614-620) that this is expected "… due the basal failure plane being progressively exposed after the upper portion of the RSF (where the sample OSF occurs) was clear of ice cover and the RSF began to move downslope" (note, however, that they later state (lines 695-7) "We interpret the much younger exposure age on the fault plane as the result of postglacial weathering and erosion.", suggesting some lack of confidence in this issue. The Supplementary Material indeed states that these factors have been considered in arriving at the quoted age). This means that the RSF had only displaced by about 20 – 30 m in the 6000 years following lowering of the cirque ice surface to expose the RSF outer surface. This requires extraordinarily slow downwasting of the cirque ice – is it compatible with what is known about post-LGM and pre-YD deglaciation rates? Line 732 states that "…the Lake District was essentially ice-free by 14.7 ka…", and Great Coum is very low at 262-468 masl, so expecting its cirque glacier to have continued to support the RSF until later than 12 ka seems to be stretching the point too far, especially given that the Younger Dryas stadial onset was 12.9 ka (line 62). From this perspective the younger cosmogenic age is difficult to reconcile with the Ms hypothesis.

The reviewer presents careful reasoning here, but their interpretation is incorrect, possibly because we did not make our points sufficiently explicit. We do not lack confidence in our interpretation, but we note in the manuscript that the fracturing and weathering on the failure plane would produce an exposure age on the failure plane likely younger than that of the outer face. We have revised the manuscript to make our interpretation of the dating clearer. Sample HW (from the failure plane, not the headwall) was 67 m above sample OSF (from the outer face of the RSF). However, sample HW is only 48 m above the tread of the RSF. Either way, the RSF has to descend only some 50 m or so to expose the failure plane which, given the uncertainty associated with the exposure age, would have been exposed at the same time as the RSF occurred, 18 ± 1.2ka. As noted in the text, the failure plane is fractured and weathered whereas the outer surface of the RSF is planar and in places smoothed (possibly by ice). We anticipate fracturing and weathering of the failure plane, hence a 2 m loss of material from the plane at the time of failure due to post-glacial processes is reasonable (see Supplementary Information). An exposure age much younger than 18 ka is to be expected, as post-glacial spalling of the bedrock surface is clearly an ongoing process at this site.

Slope stability analysis This appears to have been done with admirable attention to detail, and Carling et al. correctly emphasise the uncertainties involved (line 508). Nevertheless, in such work, particularly in the context of natural slopes where the subsurface composition is unknown and has to be inferred from surface exposures, it is necessary to include an error analysis to demonstrate the possible imprecision of the resulting factors of safety. For example, in section 5.3, F values are given to two decimal places with no indication of possible error. Further, in lines 518-9 reference is made to "marginal" F values of 1.07 to 1.22, suggesting that F = 1.22 is so close to 1.0 that it should be considered marginal. If this is the case (and it seems reasonable to me that there might be ~20% error in F values), then F = 0.78 should also be treated as marginal. In this perspective the factor of safety analysis becomes much less convincing in indicating that the RSF would have been unconditionally unstable in the absence of ice buttressing.

Thank you for noting the attention to the detail that we brought to this analysis. We had anticipated that without this level of attention our results might be called into question. We did not include a tabulated error analysis for the three cases precisely because of the inherent uncertainty that exists with this kind of modelling. Rather, we varied parameters typically by ± 10 % (sometimes greater) to explore the potential uncertainty across thousands of simulations, which we argue serves as a reasonably robust uncertainty analysis. We noted in the text that failure occurs in almost all cases unless ice buttressing is applied. Note that reported F values (*e.g.*, 0.78) for unsupported scenarios are the largest values possible for reasonable wedge configurations, so these values are not marginal (*i.e.*, the uncertainty does not approach 1). We have edited the manuscript to make this point clear. It is well known that the value of F is only a guideline to slope stability and that a slope that is modelled as stable or otherwise might be influenced by unknowable issues as well as by poor parameterization. We argue that moving from scenarios without ice buttressing (whereby F is always < 1) to an ice-buttressed scenario (where F is always > 1) is indicative of a shift in rock mass precarity towards stability.

Other inherent uncertainties in the stability analysis include

- The assumption that the rear boundary of the RSF is a (wavy) planar fault with specified cohesion and friction coefficient, with no asperities or rock bridges. Particularly at first failure it is quite likely that this was not the case, meaning that the estimated F values for the non-buttressed case could be too low.

As noted in the text at lines 641 to 645 'The waviness number calculated from field data and applied in the model is low, which increases the propensity for failure. Preliminary trials showed that to stabilize unstable model slopes would require the use of unrealistically large waviness numbers (Miller, 1988) and so the waviness number was not varied in sensitivity analyses.' For reasons of brevity, we did not expand our argument in the text. Local rock bridges can increase the stability of a rock mass (see Yu et al., 2013 Frontiers in Earth Science, DOI 10.3389/feart.2023.1209259) but the issue becomes complex and beyond the scope of simple models that currently can be applied to RSFs. Local enhanced bridging within the thinly-bedded thin wedge would have led to piecewise failure of the rock mass and progressive disintegration.

- Pore water pressure is treated rather offhandedly in the analysis, presumably because of lack of information. Assuming zero pwp would be the conservative assumption, given the stated fractured nature of the rock and the proximity of the failure surface to the exposed RSF face.

We argue that our consideration of pore water effects is not 'offhand'. We agree that it cannot be parameterized, so we considered the effects in those marginal cases whereby the stability of the rock mass might be influenced by pore water pressure and reported accordingly.

- It has been assumed that the ice surface of the cirque glacier is solid and horizontal throughout. This seems unlikely – my recollection of cirque ice is that it tends to slope very steeply up to a deep bergschrund where it contacts the rock. The presence of other crevasses is also likely to complicate the transmission of ice pressure to the RSF outer face.

We did not assume a horizontal ice mass and solidity is not an issue. Rather, we considered what ice loading force was required to stabilize the RSF and we present two cases. We calculate the load as the minimum required to maintain slope stability and note that the load can be applied variably across the outer face of the RSF. In this way we demonstrate that the amount of ice required to support this RSF is not large – this 'modest accomplishment' is all that we claim to demonstrate. We mention already in the text the issue of a bergschrund being present and note that the multiplicity of ways the load might be applied.

Thus, while the factors of safety appear to conclusively support the Ms hypothesis at first sight, the lack of information on likely imprecisions means that the outcome is unconvincing.

We regret that the reviewer does not find the outcome convincing. Perhaps the revised MS is convincing. Imprecision was dealt with by running thousands of simulations, the basic detail of which are summarized within the text, leading to most likely scenarios that trend from F<1 to F>1. We acknowledge that with additional field data (impossible to obtain) a different outcome might be achieved. However, given our field data and the model framework we believe that our interpretation of the values of F are defensible. We hope that our findings will stimulate further numerical modelling of RSFs to elucidate whether or not ice support occured in RSFs elsewhere.

Summary The above considerations cast some doubt on the certainty of the Ms hypothesis. For example, a plausible alternative hypothesis is that the RSF, having emerged from its ice cover at 18 ka, remained stable (with F > 1 but decreasing due to weathering) until it failed about 12 ka and translated while restrained only by basal and lateral friction, remaining largely intact as it did so.

We appreciate the reviewer's very careful consideration of our submission which we have found useful in preparing our revised MS. We agree that the scenario that the RSF might have occurred long after deglaciation must be considered, and we did consider that. However, we find implausible the fact that the thin-bedded thin wedge of rock did not break up when translated down a steep failure plane.

Recommendation

Revise Ms to address these comments (or rebut them) and resubmit.

Reference

Davies, T.R.H., McSaveney, M.J. and Beetham, R. D. (2006). Rapid block glides – slide-surface fragmentation in New Zealand's Waikaremoana landslide. Quarterly Journal of Engineering Geology and Hydrogeology, 39: 115–129.

Further comments (refer to annotated Ms)

To be addressed in a revised submission

- Abstract lines 29-31: Stability analysis considers only the situation up to failure – it tells us nothing about whether post-failure motion was "catastrophic" or not

  Text edited to correct

- Line 310: omit "and"

  deleted

- Line 404: the word "rapid" states that all events with low H/L are rapid, which is probably true; however the implied converse, that all events with high H/L are slow, only applies when "slow" is means of the order of cm/minute to cm/second. It does not imply "extremely slow" as is hypothesised for Great Coum

We agree with these statements, but the text referred to by the reviewer is only factual statements. No interpretation is made at this point that these ratios imply extremely slow decent of the RSF only that the runout is limited. Latterly we argue that the small runout is possibly indicative of a slow descent.

- Line 508: yes there is parameter uncertainty – it needs to be quantified.

We addressed this issue at lines 289 to 394 and at lines 450 to 459 where the uncertainty is quantified in terms of ranges. Altogether there were *c*., 30,000 model runs varying parameters, to explore the uncertainty. The main text has been revised to make it clear that the reported F values for the unsupported case are the maximum possible (see comments above for detail).

- Lines 556-8: Incorrect use of tonnes as unit of force

This is not the force applied by the ice, but the tonnage of ice required to supply the retaining force.

- Lines 600-605: Confusion in reference to "cirque erosion"

Text rewritten

- Lines 660-1: variation of ice strength with temperature is probably negligible in the context of the real precision of the present analysis

We agree with the reviewer's opinion. However, we felt that the issue of ice temperature might be in the mind of some readers and felt some comment was necessary. Note that temperature is not a parameter within the modelling.

- Lines 705-707: Not all glacial ice carries erratic

We agree, but within the context of the Great Coum within the Lune Gorge the absence of glacial erratics is indicative of northern ice not entering the cirque (see Carling et al., 2013 cited in the manuscript for context).