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Re-interpretation of the 'relict protalus rock glacier' at Grasmoor End, northwest Lake District

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Abstract
An accumulation of debris on the lower slopes of Grasmoor End, northwest Lake District, has previously been categorised as a relict protalus rock glacier. Detailed field examination of the feature and consideration of the character of the cliffed upper slope have led to the conclusion that rock-slope failure is a more likely explanation. A paraglacial origin rather than a periglacial origin is therefore proposed.

Keywords
Relict protalus rock glacier, discrete debris accumulation, rock-slope failure, paraglacial, Lake District

Introduction
Rock glaciers, in both active and relict states, have been reported from mountain regions around the world, including the British Isles. There is no single universally accepted definition for rock glaciers but they are usually considered to be accumulations of coarse rock debris with a lobate, tongue-shaped or spatulate plan form that rise above the immediately adjacent ground by up to a few tens of metres. Some active rock glaciers are known to have a core of glacier ice (Martin and Whalley, 1987) whereas others are supersaturated with interstitial ice and ice lenses (Barsch, 1996); as a consequence of the deformation of the contained or underlying ice the debris moves gradually downslope or downvalley. Characteristically an active rock glacier develops a surface pattern of arcuate ridges and furrows (flow structures) and a steep terminal slope at the angle of repose. These features are usually retained, if somewhat modified, when movement ceases and a relict status prevails.

The origin of the ice associated with active rock glaciers and those now in a relict condition, and the significance of their plan-form morphology, has long been, and continues to be, contested, and a variety of descriptive terminology has built up. For the so-called talus-derived, valley-wall, and protalus types of rock glacier, thought to have formed as a consequence of high rates of debris supply generated by rockfall from backing cliffs and the development of interstitial ice and ice lenses within the accumulating talus, Whalley and Martin (1992) re-introduced the term 'protalus lobe' in an attempt to '… avoid confusion and ambiguities …'. This non-genetic term summarises the location and form of a coarse debris accumulation. A similar non-genetic term favoured by Harrison *et al*. (2008) and Whalley (2009) is 'discrete debris accumulation'; this has been used to incorporate protalus lobes, rock glaciers, protalus ramparts and depositional landforms stemming from rock-slope failure. Such a term is valuable in that the process(es) responsible for debris deposition is/are neither implied nor inferred but may sometimes be determined from detailed investigation of the landform. In the case of relict landforms that morphologically resemble active rock glaciers it should be remembered that processes other than ice-related ones may have been involved. Nevertheless, usage of the term 'relict rock glacier' to encompass a range of forms, often with little secure evidence of formative process(es), has become firmly entrenched in the literature in spite of several attempts to dislodge it.

Relict rock glaciers in the Lake District
Sissons (1980) was the first to identify and describe relict rock glaciers (the valley-wall variety) from the Lake District of northwest England. He claimed that three such landforms

existed in valleys tributary to Wasdale and considered that they had formed during the Loch Lomond Stadial (LLS; 12.9–11.7 ka BP) in association with permafrost. He used them to infer that that mean annual temperature at ~300 m OD during the LLS was no higher than -1°C, and that mean annual sea-level temperature was no higher than 1°C.

Additional relict rock glaciers (protalus forms) were recognised by Oxford (1985, 1994) at Grasmoor End and Dead Crags respectively. Interpretation of the Grasmoor End feature has been challenged on at least three occasions: (1), Ballantyne and Harris (1994) considered it was a dubious example of a relict rock glacier, (2), Whalley (1997) thought the debris was more likely to be the result of a rockslide, and (3), Harrison *et al*. (2008) stated that it might possibly be a large gelifluction lobe.

A relict rock glacier (ice-cored variety) was described briefly by Whalley (1997) from Burtness Comb above Buttermere; this feature had previously been mapped as a lateral moraine by Sissons (1980). More recently Clark and Wilson (2004) argued that the debris is the product of a rock avalanche.

In their appraisal of relict rock glaciers and protalus lobes in the British Isles, Harrison *et al*. (2008) added another rock glacier (at Low Tarn) to the Wasdale cohort. From a detailed re-examination of all four of the Wasdale features Wilson (2011) established that designation as relict rock glaciers was no longer tenable for these landforms; alternative origins and descriptors were proposed, invalidating the palaeoclimatic inferences drawn by Sissons (1980).

Accordingly, the existence of any relict rock glaciers in the Lake District must now be in serious doubt. The feature at Grasmoor End has previously only been described by Oxford (1985) and depicted on a small-scale diagram. This paper provides a more detailed account of the feature, a larger-scale depiction, and a different interpretation to that offered by Oxford (1985).

Grasmoor End and its 'relict rock glacier'

Grasmoor End (NY 16 20, Fig. 1) is the western flank of Grasmoor (851 m OD), a mountain that rises above Crummock Water in the northwest of the Lake District. It takes the form of a triangular-shaped slope that falls from 730 m OD at the terminus of a tapering ridge, the apex of the slope, to the B5289 road (150 m OD), a distance of ~1.1 km at an average gradient of ~30°. The entire hillside is in the meta-sedimentary Kirkstile Formation (laminated mudstones and siltstones) of the Ordovician Skiddaw Group, with high-angle dips of ~30-50° to the south (British Geological Survey, 1999). The steeper upper half of the hillside is cliffed and riven by several prominent gullies eroded along faults and anticlinal axes. Talus sheets are present between ~350 m and ~200 m OD, as well as a large partly vegetated talus cone emanating from the base of one of the gullies. Vegetated slopes extend from the base of the talus to the road and it is from this area that Oxford (1985) described '… a series of gently arcuate bulges … flat topped and not separated from the talus by any form of depression. Their surfaces are strewn with angular boulders which have Schmidt hammer readings considerably lower than those of boulders on the talus.' This was used to infer that the boulder-strewn bulges were older than the talus and comprised a relict protalus rock glacier. From here on the Grasmoor End 'relict rock glacier' will be referred to as a discrete debris accumulation (DDA).

Field evidence

The DDA was mapped in the field using a hand-held GPS receiver with a resolution of <10 m. The information was transferred to a 1:10,000 scale Ordnance Survey map and to the Google™ Earth image shown in Figure 1. Three short profiles (A, B and C on Fig. 1) were surveyed, using Abney level and tape, across prominent breaks of slope in order to characterise the topographical changes evident in those places.

The DDA has maximum downslope length of ~150 m, a maximum across-slope width of ~670 m, and a surface area of ~0.072 km^2. It is divided into north and south components by a depression, ~125 m in length and ~30–50 m in width, with a peat-covered floor and a spring at its head (D on Fig. 1).

To the north of the depression the southern margin of the DDA is a 1–3 m high bank. At its western limit it turns to the north and trends across-slope for ~270 m and gradually grades into the adjacent hillside. The frontal slope rises, at a maximum gradient of 25°, between 1 m and 5 m above the ground immediately downslope (Fig. 2). The top surface of the bank rises more gradually (5–10°) for ~50–100 m to the foot of another bank that runs across the hillslope for ~125 m. This higher bank carries scattered boulders to 1.5 m in length, and at one place on the frontal slope there is a narrow (1 m wide) and short (15 m long) rock rib. Debris cast up by moles shows that, at least locally in the near-surface debris, the banks contain fine-grained material and gravel of local provenance.

The margin of the DDA on the south side of the depression (Figs 1 and 3) has a sinuous plan form and rises 2–7 m above the depression at gradients of up to 21° (profile

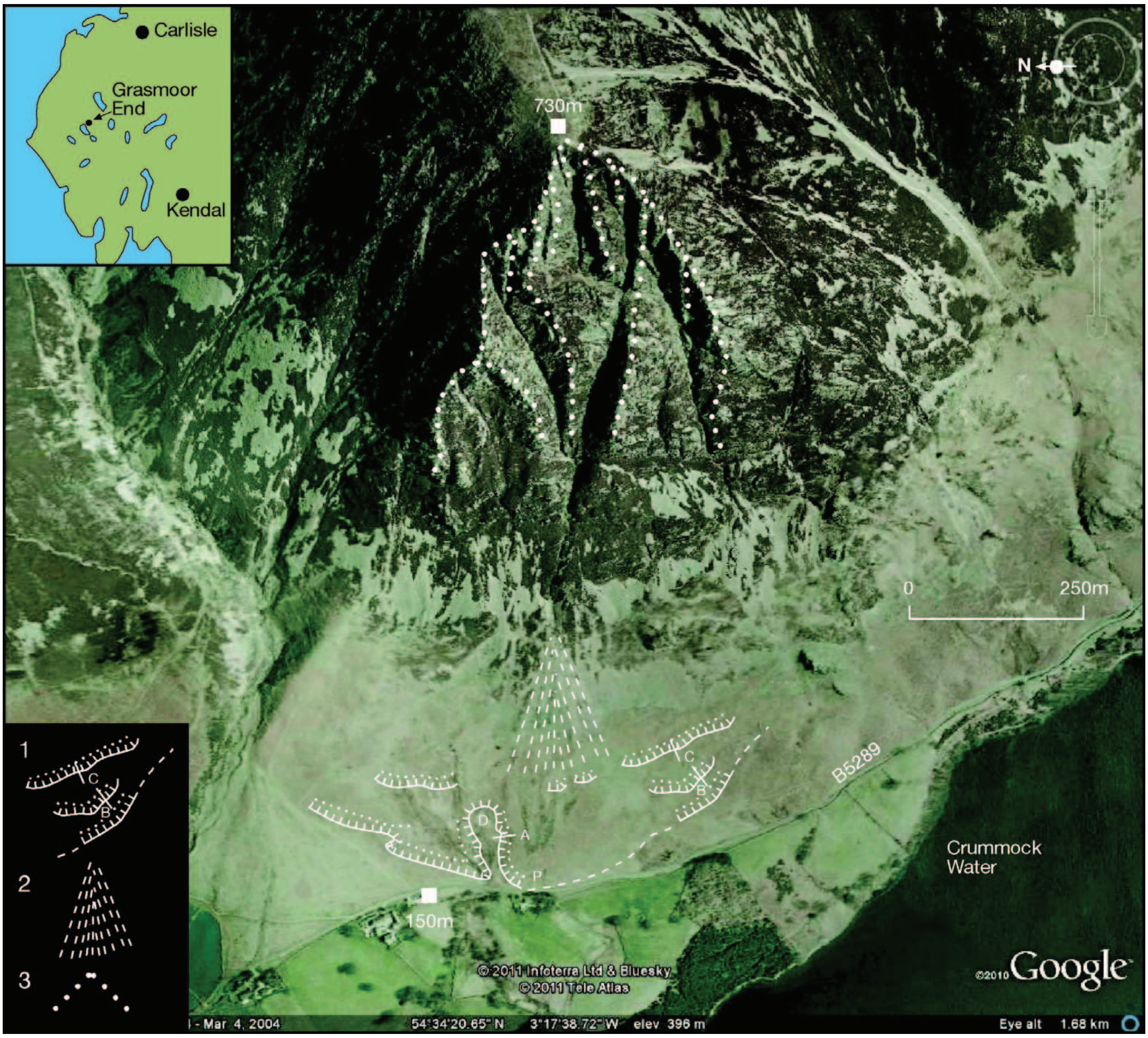

Figure 1: Google™ Earth image of Grasmoor End showing; 1. Outline of the DDA. 'Ticked' lines indicate basal breaks of slope, dashes indicate poorly defined margin, and dots indicate crest lines. Profile locations (A-C) are shown, D is the depression that divides the DDA into north and south components and P is the overgrown borrow pit. 2. Talus cone. 3. Failure scar margins on the cliffed slope.

A, Fig. 4). In contrast the west margin is poorly defined, being little more than a low (<1 m high) bank alongside the road. Towards the northern end of the west margin there is an overgrown borrow pit (~30 m x 10 m in maximum length and width respectively, and up to 1 m in depth; P on Fig. 1) from which material has been extracted and in which a few boulders are visible. The surrounding area is devoid of surface boulders. With increasing distance to the south the west margin of the DDA is poorly defined as it trends across-slope to the southeast; then for a short distance it becomes much more pronounced, rising 2 m above the immediate downslope area. Upslope from this part of the margin are two arcuate banks extending ~100–200 m across-slope. The westernmost of the two banks has a maximum frontal slope gradient of 25° and the slope crest stands 8 m above the ground below (profile B, Fig. 4). Exposed within the frontal slope is an area of ~200 m^2 of rock, although it is not clear if this is bedrock or part of a mass of displaced bedrock (a mega-boulder). Scattered boulders to ~1 m maximum dimension occur on this slope and at its base. The easternmost bank is aligned along the talus base and has similar maximum gradient and vertical height (profile C, Fig. 4) as the bank below it, but it extends for a greater distance across the hillside. Several areas of rock ~25–50 m^2 are exposed in the frontal slope of the bank. The top surface of the bank is horizontal in the north but dips to the west (outwards) and declines in elevation with increasing distance to the south. Talus laps onto the upper surface of

Figure 2: The frontal margin of the northern sector of the Grasmoor End DDA with extensive cover of Pteridium aquilinum (bracken). The basal break of slope is indicated by white dots.

Figure 3: The northern margin of the southern sector of the Grasmoor End DDA with extensive cover of Pteridium aquilinum (bracken). The basal break of slope is indicated by white dots.

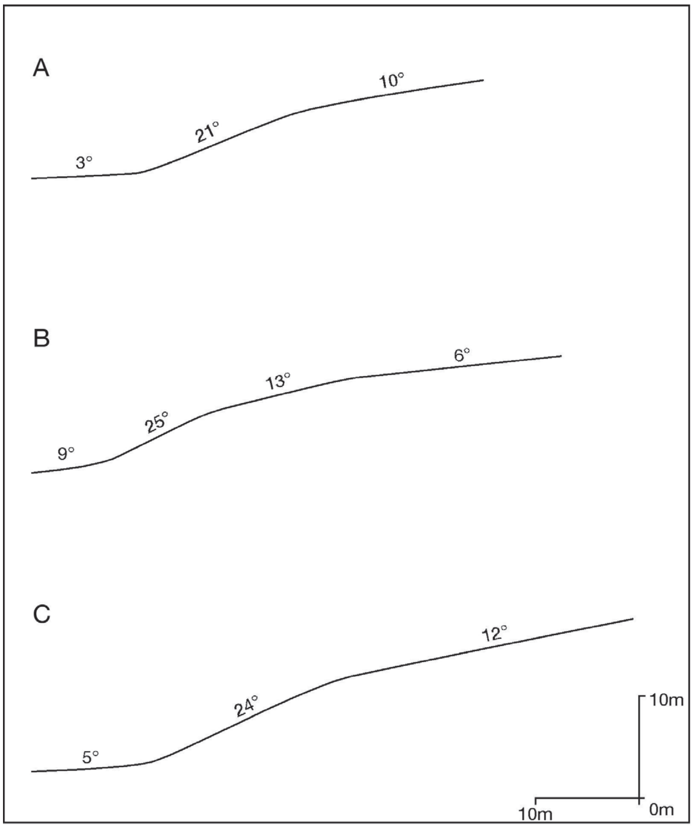

Figure 4: Profiles surveyed across parts of the Grasmoor End DDA. Profile locations are indicated in Figure 1.

the bank and there are many scattered boulders to 1.5 m in maximum dimension. Farther north at the talus base there are a few arcuate banks of coarse rock debris 3–5 m high. Only the local Skiddaw Group rock is represented in the coarse material and the areas of (? displaced) bedrock seen across the surface of the DDA.

Discussion

For several reasons a protalus rock glacier origin for the Grasmoor End DDA as proposed by Oxford (1985) can be challenged. First, there is no morphological evidence for extending and compressive movement in the form of transverse furrows and ridges. Such flow structure morphology is usually regarded as diagnostic of protalus rock glaciers as a consequence of the debris undergoing slow downslope transport due to the deformation of interstitial ice and ice lenses (Shakesby *et al.*, 1987; Barsch, 1996). Furthermore the DDA lacks steep lateral and frontal margins, features that are also considered to be critical defining characteristics (Harrison *et al.*, 2008). In the relict state such features may be less distinct than in the active state but normally they are still recognisable (Martin and Whalley, 1987). Second, if the large rock masses within the frontal slopes of some of the arcuate banks are mega-boulders they are more likely to be the products of large-scale rockfall or rock-slope failure and reached their present positions as a result of fall/failure, rather than having lodged higher on the slope and moved downslope as a result of rock glacier creep. Alternatively, if these rock bodies represent in situ bedrock then the arcuate banks of which they are a part are clearly unrelated to protalus rock glacier processes. Third, protalus rock glaciers normally consist of coarse rock debris with a marked absence of fine matrix particularly in the surface layers. Although there are no exposures in the DDA, material excavated by moles indicates that fine matrix is present. In addition, the abundance of *Pteridium aquilinum* (bracken) (Figs 2 and 3), which requires minimum soil depths of 20–30 cm for rhizome development (Ratcliffe, 1973), indicates that fine matrix is present across a much larger area of the DDA than revealed by the moles. The peat-floored depression that divides the DDA into north and south components (Fig. 1) also suggests an abundance of fines because if, as seems likely, the depression is a result of fluvial dissection, it is to be expected that such a feature would have been cut into predominantly fine material rather than coarse rock debris. Fourth, although the true thickness of the debris is unknown, the frontal slopes of the banks indicate a thickness that is not commensurate with rock glacier creep. Harrison *et al*. (2008) argue that in order to generate the necessary shear stress capable of causing downslope movement of a 35° talus with 25% interstitial ice requires a debris thickness of at least 23 m, which is considerably more than the estimated thickness of the arcuate banks that comprise the DDA. Thus there are no compelling reasons to consider the DDA as a relict protalus rock glacier.

An alternative origin, proposed by Harrison *et al*. (2008), is that the DDA is possibly a large gelifluction lobe. The plan form morphology and abundance of fine material lend support to this interpretation, but the large rock masses in the frontal slopes of some of the arcuate banks, irrespective of their status, argue against such an origin for at least those areas of the DDA.

Whalley (1997) thought that the DDA was more likely to be the product of a rockslide rather than a relict protalus rock glacier but did not provide any justification for this point of view. Nevertheless, concurrence with this interpretation is favoured here primarily because of the morphology of the steeper upper half of Grasmoor End. Figure 1 shows the outlines of contiguous rock-slope failure scars above ~400 m OD. Four large scars can be seen, within some of which minor rock ribs define subsidiary scar margins. It is inferred that the scars are the source areas for the DDA rather than having formed as a result of intermittent rockfalls. The cumulative basal width of the scars is ~400 m and they taper upslope as wedge-shaped features and occupy an area of ~0.12 km^2. Scar basal width is ~220 m less than the across-slope width of the DDA indicating that some lateral spreading of the debris occurred during downslope movement. This is particularly so with respect to the northern sector of the DDA. As noted above, the large rock masses in the frontal slopes of the arcuate banks may be mega-boulders produced by rock-slope failure. If so, then failure of the hillside resulted in grain sizes spanning several orders of magnitude, from mega-boulders to silt and clay size particles. Such a range is not unusual in slope debris deriving from meta-sediments, as are found at Grasmoor End.

Although favouring a rock-slope failure origin for the DDA there are still several unknowns that need to be resolved. It is not known, for example, if the DDA was created as a result of a single failure event or two or more events, with individual failure scars active at different times. The arcuate banks that occur upslope from the outer limit of the DDA may represent later events/additions. The age of the DDA also needs to be established, though it undoubtedly post-dates deglaciation of this part of the Crummock Water basin. No erratics of Borrowdale Volcanic Group lithologies or Ennerdale granite were seen on the DDA, though they do occur immediately to the north, west and south, with their source area being to the south.

Conclusions

The Grasmoor End DDA is considered to be a product of rock-slope failure rather than a relict protalus rock glacier as previously thought. This consideration is based largely on the character of the cliffed upper slope which displays a number of contiguous failure scars. Such scars are unlikely to be the consequence of intermittent rockfall activity, rather it is inferred that they represent larger-scale slope failure events.

Large-scale rock-slope failures have now been documented at over 50 sites in the Lake District (Wilson *et al*., 2004; Wilson, 2005; Wilson and Smith, 2006) and are regarded as paraglacial landforms, having been facilitated by the effects of former glacial ice cover. The Grasmoor End DDA should now be included within this category; a periglacial origin for the feature is no longer appropriate.

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