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The Kirkby Fell rock-slope failure, Malham, Yorkshire Dales

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Abstract

A two-phase development sequence of rock-slope failure on Kirkby Fell, Malham, is proposed based on field observations and Schmidt hammer data. The first phase was a rotational movement and the second was a rock slump-earthflow failure. An interval of unknown length separated these phases. Glacial/deglacial slope conditioning and seismic activity are considered to have been important triggering factors for the first phase of failure and seismic activity may have also played a role in the second phase. Rock-slope failures have been a neglected aspect of landscape studies in the Craven district and, as a consequence, their extent, variety, age and significance are largely unknown. Greater awareness and knowledge of these features is required in order to evaluate their contribution to landscape evolution.

Key words

Rock-slope failure, Schmidt hammer, glacial/deglacial slope conditioning, seismicity, Malham, Pennines.

Introduction

Rock-slope failure (RSF) is the downslope gravitational displacement of bedrock. It incorporates movements at all scales and sizes and results in the rock mass losing some or all of its structural characteristics. Rock-slope failures are usually classified by the nature of their movement and/or the morphology assumed by the displaced material. A more frequently used term is 'landslide' but not all RSFs are 'slides' in the true sense of that word. In addition to slides, RSF includes falls, topples, avalanches, sags, creep, stress-release fissuring and deformation. Distinctions between these categories are not always as clear-cut in the field as is often implied by the literature. In reality any failure is part of a continuum from incipient, with minimal loss of structure, to total disintegration of the rock mass (Jarman 2006). Furthermore, some RSFs may be compound (with two or more styles of movement being involved simultaneously or in succession) or complex (where a downslope change in rock behaviour has occurred).

Numerous RSFs are present in the uplands of Great Britain and many reports discuss their locational and morphological characteristics, their age and the underlying cause(s) of failure. The southern and western Pennines are well represented in this respect (Franks and Johnson 1964, Johnson 1965, 1980, 1987, Johnson and Walthall 1979, Muller 1979, Tallis and Johnson 1980, Johnson and Vaughan 1983, 1989, Redda *et al.* 1985, Redda and Hansom 1989, Skempton *et al.* 1989, Mitchell 1991a, b, c, 1996).

With good reason, landform studies in the Craven district of the Pennines have focused on the erosional and depositional effects of glaciation and on the extensive karstic features evident in areas of exposed limestone bedrock. In contrast, very little detail has been published concerning RSFs; there are brief details for the Settle area (Arthurton *et al.* 1988) and Whernside (Mitchell 1996) but with respect to the development of Craven scenery, the extent, variety and significance of RSFs is largely unknown (Wilson 2006).

One of the Craven RSFs mentioned by Arthurton *et al*. (1988) is on Kirkby Fell, near to the village of Malham. The glacial and karstic landforms of the Malham area are well documented (King 1960, Clayton 1966, 1981, Clark 1967) but the Kirkby Fell RSF has not previously been described in detail. In view of this and because the RSF represents another (different) facet of local landscape evolution it is considered here with emphasis placed on its morphological characteristics, its topographical and geological contexts, its age and the mechanism(s) that triggered failure.

Kirkby Fell

Kirkby Fell (546m OD; SD 875 635; Fig. 1) is about 3 km west-northwest of Malham, in the Yorkshire Dales National Park. It lies along the northern edge of a tract of moorland underlain by Namurian (Upper Carboniferous) rocks and bounded by Ribblesdale to the west and Airedale to the east. The summit 'plateau' (>500m OD) extends for about 1 km east-west and 0.3-0.5 km north-south. The southern slopes (Scosthrop Moor) fall at low to moderate gradients (4-12°) for a distance of about 2.5 km, south of which the moorland is dominated by northwest-southeast trending drumlins. The northern slopes fall for a distance of 300m at 5-8° to a broad col that links the fell to the Langcliffe Scar – Ewe Moor area that is underlain by Viséan (Lower Carboniferous) strata. The Middle Craven Fault trends east-west across the col (Fig. 1). The upper part of the fell above ~350-380m OD is in the outcrop of Grassington Grit and Pendle Grit; the Upper Bowland Shales occur below that elevation (British Geological Survey 1991). Access to the RSF from Malham is by walled lane to Burns Barn (SD 895 631) and Field Barns (SD 894 632) and then field paths by Butterlands Barn (SD 890 633) and Hoober Edge (SD 886 634). This path passes below Pikedaw Hill and rises to meet another path that runs from Settle to the minor road (SD 892 640) due west of Malham Cove and provides an alternative means of access.

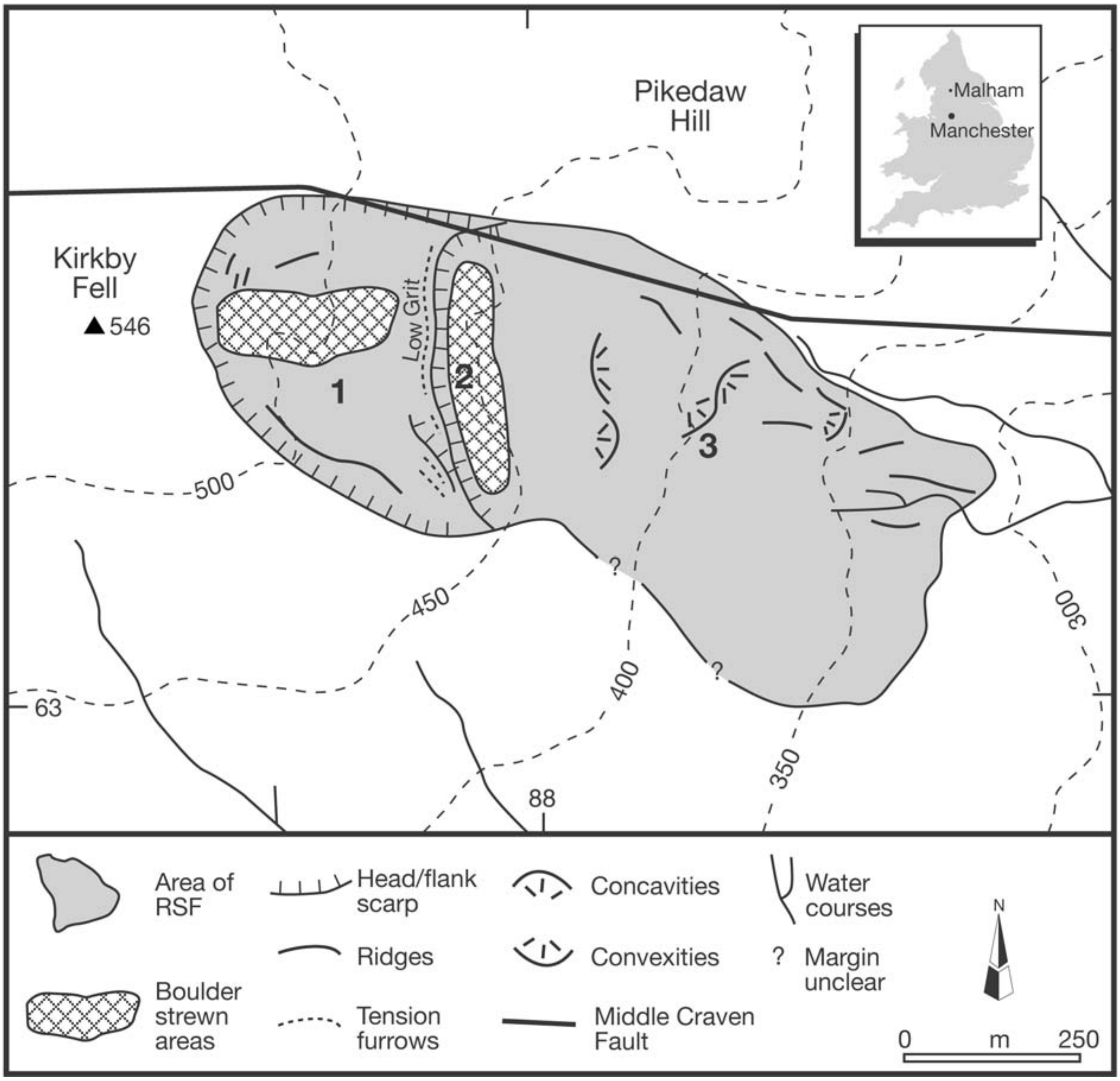

Figure 1: The Kirkby Fell rock-slope failure showing main morphological components / landform assemblage areas (1-3) and relationship to the Middle Craven Fault. Contours are in metres. Inset shows location of Malham in northwest England.(© Crown copyright Ordnance Survey. All rights reserved).

Methods

The margins and the main surface characteristics of the RSF were mapped in the field using a hand held GPS receiver with resolution of <10 m. The data were transferred to a 1:10,000 scale map, with 10m contour interval, to show the plan form of the component features. Details of surface characteristics and the surrounding terrain were also recorded. At two sites below the failure scarps, a Schmidt hammer (type N) was used to obtain data relating to the surface hardness of exposed boulders. Fifty boulders were selected at each site and on each one four hammer readings (R-values) were obtained from closely spaced points. These values were averaged to provide a single hardness value for each boulder.

Characteristics of the rock-slope failure

Figure 1 shows the outline and main morphological components of the Kirkby Fell RSF. The failure extends downslope (west-east), at an overall gradient of 11°, from 530m OD (crest) to 310m OD (toe), over a distance of 1.15 km. It has a maximum width of 0.45 km and an area of 0.43 km^2. On morphological grounds the failure has three distinct landform assemblage areas: (1) the area between the head scarp and the Low Grit Scarp, (2) the Low Grit scarp and its associated boulder strewn area, and (3) the area downslope of the lower limit of the Low Grit scarp boulders. There is evidence that parts of area 1 (and also between the head scarp and the summit of Kirkby Fell) have been worked for building stone. Small quarries, numerous shallow surface depressions with surrounding accumulations of similar sized blocks, and overgrown trackways testify to this former activity.

Area 1

A prominent arcuate head scarp and distinct flank scarps define the western, northern and southern margins of this area. The flank scarps increase in height from 1-3m at their eastern ends and are predominantly rectilinear slopes up to 30° with a cover of coarse grasses and scattered boulders. Several shallow embayments with gradients >35° notch the scarps. In contrast, the head scarp is 15-20m high, is stepped in profile and has bedrock outcrops and numerous boulders to 3m in length. Downslope of the head scarp are hummocks, benches and ridges of displaced material.

A boulder-strewn area occurs directly below the head scarp outcrops and extends east for 200m. Especially prominent are boulder covered mounds of displaced and back-tilted bedrock, with slopes of ~30° and amplitudes of 2-20m, and enclosed depressions. Some boulders are up to 5m in length. North and south of the boulder-strewn area failed materials are disposed as narrow vegetated ridges and benches. Some ridges are sinuous and bifurcate. A small peaty pool is present between the several short ridges directly below the head scarp and north of the boulder-strewn area. To the south of the boulders a narrow crested ridge 250m long parallels the head/flank scarp.

Area 2

The Low Grit scarp is a south-to-north aligned feature displaying marked curvature to the east at its northern end (Fig. 2a). At its southern end it rises steeply above a narrow linear depression that separates it from the eastern end of the low flank scarp of area 1. This southern part of the scarp is not a simple single feature. A subsidiary scarp 2-4m high with exposed beds of gritstone and boulders below occurs upslope of the main scarp and variations in ground surface levels and local dip gradients are indicative of differential movement having occurred (Fig. 2b). This area also has several prominent tension furrows and rifts. One such rift, behind the subsidiary scarp, is 50m long and a maximum of 5m deep and 2m wide at base. Another, behind the main scarp is 60m long and 4m deep. Along the central and northern parts of the scarp the area immediately upslope, for a distance of ~50m, has tension furrows aligned parallel and sub-parallel to the scarp. These features terminate where the scarp curves to the east.

Outcrops of gritstone 10m thick occur along parts of the scarp. Below the scarp crest is a morphologically complex zone of displaced and back-tilted bedrock masses and numerous large boulders (Fig. 2c). Rock masses form ridges and mounds, with amplitudes of up to 20m, between which are closed and semi-enclosed depressions. Some rock masses have lodged on the scarp, obscuring the bedrock, others have descended to the scarp foot. Angular boulders, up to 6m in length, cover much of this area.

At the northern end of the scarp, broken rock masses give way to vegetated slopes on which are lodged a few erratic limestone boulders. A scarp exposure in this area shows a limestone-rich diamict, with some striated clasts, overlying shales.

Area 3

This area occupies ~60% of the RSF and comprises a stabilised and vegetated debris tongue from 440-310m OD at an average gradient of 10.5° (Fig. 2a). The northern and eastern margins of the debris are clearly defined because they rise sharply as steep banks above the adjacent slopes, but the southern margin is less clear as the debris is spread more

Figure 2:

(*a*) *Part of the Kirkby Fell rock-slope failure as seen from the low ground to the east. The skyline scarp is the lower of the two gritstone scarps (Low Grit) indicated in Figure 1 (area 2) and the hummocky ground in the middle distance is vegetated failure debris (area 3). At the extreme right above the trees is the limestone slope of Hoober Edge, along the base of which runs the Middle Craven Fault.*

b

(b) *View along the southern part of the Low Grit scarp, towards the left-hand edge of the skyline shown in (a). The main scarp (left) and subsidiary scarp (centre-right background) are evident. Tension furrows and differences in ground surface levels are indicative of the area having undergone downslope movement.*

(c) *The boulder strewn Low Grit scarp as seen from near its southern limit.*

thinly, has a subdued surface topography, and merges with the surrounding ground. Across the northern sector of the tongue the debris is disposed as a series of smooth rounded ridges, up to 10m high, aligned parallel and sub-parallel to the margin. There are also some sinuous cross-slope banks that rise 15m above the ground immediately downslope. In places bank frontal slopes are convex, elsewhere they are concave with hummocky ground directly below suggesting that some debris moved away from the bank after it had formed. Gritstone boulders protrude from the banks and spoil from animal burrows shows much fragmented shale and fine-grained material. Waterlogged ground and springs are common across the area.

Schmidt hammer results

Schmidt hammer R-values from boulders in areas 1 and 2 are shown as a dispersion diagram in Figure 3. The Student's *t*-test and the Mann-Whitney *U*-test applied to these data indicate a high probability that readings from area 1 differ significantly ($p<0.01$) from those of area 2. From these results it may be inferred that the boulders in area 1 are more weathered than the boulders in area 2 and that this hardness contrast reflects the difference in the time that they have been exposed to subaerial weathering (cf. Ballantyne 1986, Anderson *et al*. 1998, Clark and Wilson 2004).

Style of failure

As indicated by Hansen (1984), Hutchinson (1988) and Dikau *et al*. (1996) there are numerous classifications and abundant terminology for RSFs and landslides. Most of the descriptors used in these classifications are based on the nature of the movement and/or the morphology assumed by the displaced material, and this practice is adopted here.

Area 1 displays the characteristics of an arrested deep-seated rotational RSF (also termed a rock slump). It has distinct head and flank scarps in gritstone below which are masses of failed material, some back-tilted, others fragmented, that extend for a maximum of 45m below and 200m from the crest of the head scarp.

Area 2 is also regarded as an arrested deep-seated rotational RSF for the same reasons as given above and is also in gritstone. Downslope from the toe of this failure, the debris tongue (area 3) is of markedly different lithological and morphological character. Field observations indicate gritstone boulders overlie an undetermined thickness of shale-dominated debris that has encouraged waterlogging. The prominent ridges in the northern sector of the tongue are probably levees associated with discrete movements of material and the sinuous cross-slope banks are interpreted

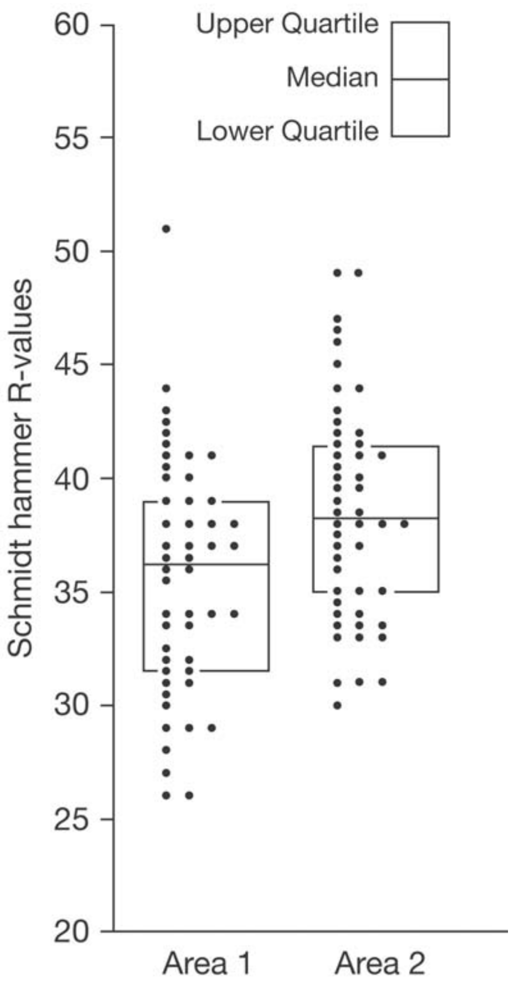

Figure 3: *Dispersion diagram of Schmidt hammer R-values for 50 boulders in each of areas 1 and 2. Each data point represents the mean of four R-values obtained from a single boulder.*

as the post-depositionally modified frontal margins of such movements. The evidence suggests that the debris tongue has characteristics similar to those of failures termed earthflows and mudflows. Therefore, taken together, the failures in areas 2 and 3 are regarded as a rock slump-earthflow, a compound type of RSF. Similar RSFs have been reported from elsewhere in the Pennines and in all cases occur in situations where stronger cap rocks (gritstone, sandstone) overlie less competent strata (shale, mudstone) (Johnson and Walthall 1979, Tallis and Johnson 1980, Johnson 1987, Skempton *et al*. 1989, Mitchell 1991b, c), as is also the case at Kirkby Fell. It seems likely that the "two distinct phases of movement" recognised at Kirkby Fell by Arthurton *et al*. (1988) correspond to the two failure types (rotational RSF and rock slump-earthflow) outlined above.

Chronology of failure

No absolute age dating for either the upper rotational failure or the lower rock slump-earthflow failure is available. That they formed following the removal of the last regional ice sheet ~16 cal. ka BP seems incontrovertible. Had they formed before the last glacial advance across the area, which was from northwest to southeast (Arthurton *et al*. 1988, British Geological Survey 1991) it is likely that the debris would display some evidence for marked modification by ice (ice moulding or streamlining) and many of the gritstone boulders below the scarps would have been incorporated into the ice and transported some distance away (cf. Ballantyne 1990; Bentley and Dugmore 1998). Furthermore, the exposure of limestone-rich diamict with striated clasts at the northern end of the Low Grit scarp is interpreted as a sub-glacial till and demonstrates that at that location the failure must post-date deglaciation.

Absolute age estimates for RSFs in other parts of the Pennines have been derived in several ways. On Swarth Fell (Mallerstang), moraine ridges that formed at the margins of a small local glacier that developed during the Loch Lomond Stade (LLS; 12.9-11.5 cal. ka BP) lie on top of RSF debris (Mitchell 1991a, 1996). The RSF clearly pre-dates the LLS. At other western Pennine sites morpho-stratigraphic relationships indicate RSFs have occurred since the loss of LLS glaciers (Mitchell 1996). In the southern Pennines, pollen analyses and ^{14}C dating of organic sediments that accumulated on failed materials have provided minimum ages for debris emplacement, and organic sediments buried by failed materials have provided maximum ages for RSF initiation. Together these techniques reveal that failure has been episodic from early in the Holocene until about 2,000 years ago (Franks and Johnson 1964, Johnson and Walthall 1979, Muller 1979; Tallis and Johnson 1980, Redda *et al.* 1985, Johnson and Vaughan 1989, Redda and Hansom 1989, Skempton *et al*. 1989). From several sites there is evidence for an area-wide concentration of RSF activity ~8.0-6.5 cal. ka BP.

Although absolute ages have not yet been obtained for the Kirkby Fell RSF, a two-phase RSF development sequence is proposed. Where RSFs undergo enlargement this may occur by retrogression or advancement. Retrogressive RSFs are those that progress upslope because the toe of the initial failure is removed by erosion and/or the original failure removes support from the scarp. In both instances further failures may occur upslope (Selby 1993, Dikau *et al*. 1996). However, this is unlikely to have been the case at Kirkby Fell. Rather, an advancing mode (downslope progression) of RSF development is envisaged and the proposed sequence of events is outlined in Figure 4.

Following removal of the last ice sheet a rotational RSF occurred on the upper slopes of Kirkby Fell creating a broad elongated depression within which the failed materials lodged (B, Fig. 4). This debris increased the stress on the slope segment immediately downhill (self-loading) and was a contributory factor in generation of the rock slump-earthflow RSF (C, Fig. 4). Thus, RSF advanced downslope but the second phase of failure need not have been an immediate response to slope loading. This two-phase development sequence separated by an interval of unknown length is supported by results obtained for boulder surface hardness using the Schmidt hammer (Fig. 3).

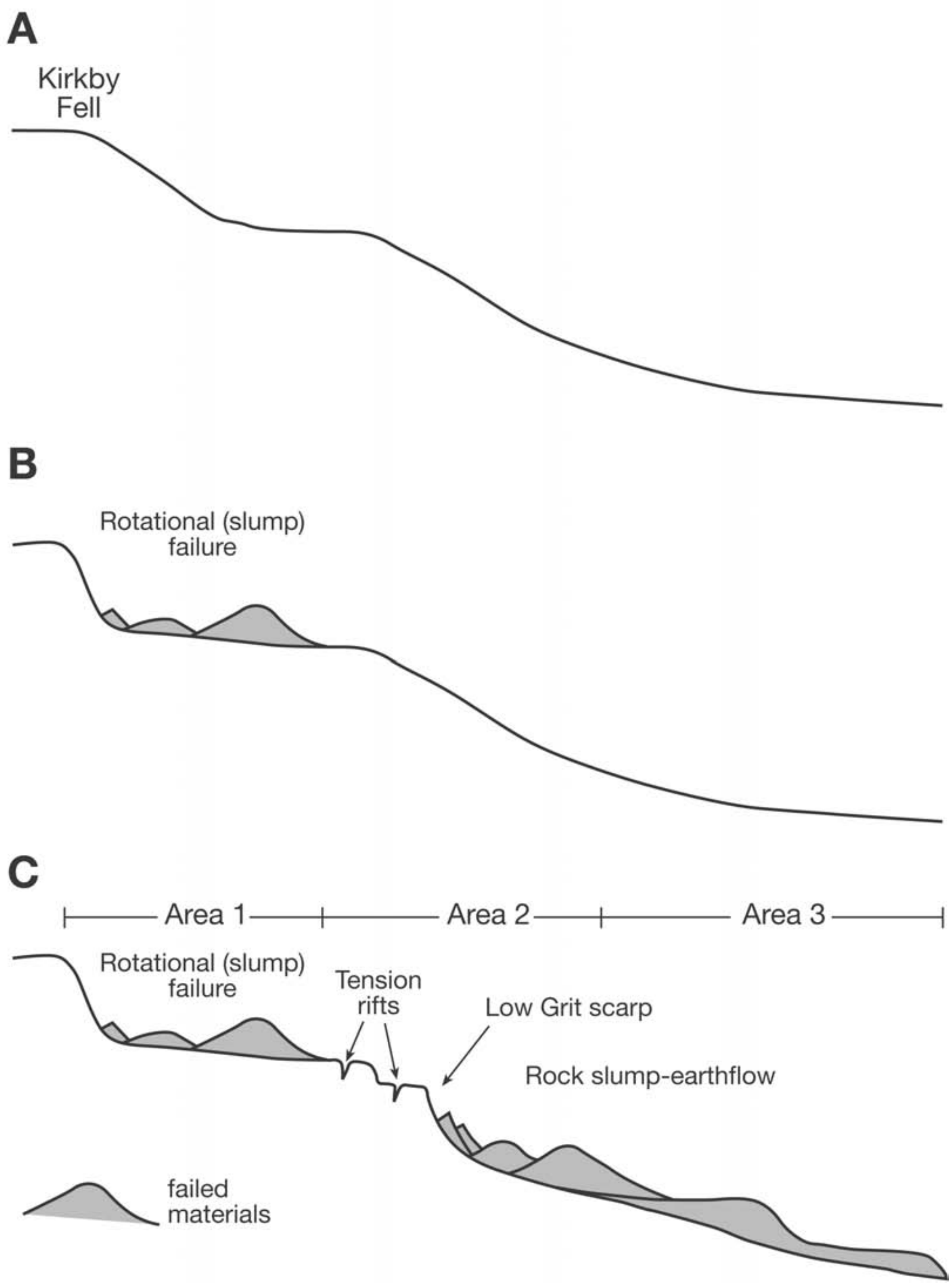

Figure 4: *Model of RSF development on Kirkby Fell (schematic).* ***A*** *represents the inferred pre-failure slope profile;* ***B*** *is the profile following the first phase of failure in which the upper scarp was formed as a result of rotational movement;* ***C*** *is the profile after the second phase of failure which created the Low Grit scarp and the rock slump-earthflow. Time intervals within and between phases* ***B*** *and* ***C*** *are not known and the figure is not to scale.*

Rock slump-earthflow failures have also been considered in terms of development stages. For example, the Bradwell Sitch slump-earthflow in the southern Pennines is considered by Tallis and Johnson (1980) to have undergone two phases of movement. The first phase affected the less competent mudstone/shale of the lower hillslope, which moved out from beneath the overlying strata and downslope. This movement was followed by slumping of the overlying cap rocks. Whether a comparable sequence of movements occurred at Kirkby Fell is not known but any pronounced movement of the less competent lower slope strata is likely to have been followed by an instantaneous response from the slope above. For this reason the rock slump-earthflow is regarded as a single failure event.

Underlying causes of the RSFs

As noted by Johnson (1987) there is an inherent difficulty in attempting to identify the underlying cause(s) of relict RSF in that the conditions that facilitated instability are usually no longer extant. Therefore it becomes a somewhat speculative exercise to discuss what might have happened to induce failure at Kirkby Fell. Nevertheless, evaluation of potential causes can often assist in transforming a list of 'possibles' to a shorter list of 'probables'.

Acceptance of the RSF development sequence outlined above means that it is particularly important to determine the trigger mechanisms for the rotational RSF at the head of the slope because the rock slump-earthflow of the mid-lower slope developed in response to slope loading by debris from the rotational failure. The trigger for the initial failure is likely to be one or both of two mechanisms.

First, the impacts of glaciation and deglaciation as causes of slope instability are widely accepted and RSFs on formerly glaciated slopes are generally regarded as paraglacial phenomena (Augustinus 1995, Ballantyne 2002, Holm *et al*. 2004, Wilson 2005). Glaciation and deglaciation can lead to changes in slope stress fields and can provide excess water that acts to increase pore water pressures such that during and following ice removal there may be immediate or delayed RSF. Similar reasoning has been used to explain RSF in the western Pennines (Mitchell 1991d) but many RSFs in the southern Pennines have occurred on slopes that lay beyond the margins of the last ice advance. In those cases periglacial processes are thought to have been instrumental in preparing slope materials for subsequent failure (Johnson and Walthall 1979, Johnson 1980, Johnson and Vaughan 1983, 1989, Skempton *et al*. 1989). Therefore recent glaciation is not a pre-requisite for RSF on Pennine hillslopes.

Second, seismic activity consequent on glacio-isostatic crustal readjustments and/or the reactivation of ancient faults is regarded as having generated RSFs both in the UK and elsewhere (Sissons and Cornish 1982, Eberhart-Phillips *et al*. 2003, Turnbull and Davies 2006). Details of seismic shock frequency and magnitude over most of the time since the deglaciation of Kirkby Fell are not known but a number of earthquakes with a magnitude exceeding $3M_L$ (Richter Local Magnitude) have occurred in the area during the last 350 years (Versey 1948, Melville 1986, Musson and Henni 2002). Of these, three were located near Skipton and ranged from 3.1-4.8 M_L and one was located near Settle and had a magnitude of 3 M_L. The Skipton earthquake of 1944 was in the area crossed by the Craven Faults (Versey 1948). The effect of more distant seismic activity has also been felt in the area (e.g. the 4.7 M_L Carlisle earthquake of December 1979). This event, as well as earlier ones in Cumbria, caused small-scale rockfalls from Lake District cliffs (Melville 1986, Wilson 2003). The implication of this is that higher magnitude earthquakes in the more distant past may have been sufficient to trigger quite large RSFs. Seismic activity along the Middle Craven Fault (Fig. 1) and adjacent structural discontinuities, either independently or in combination with glacial/deglacial conditioning of slopes, was probably a very significant factor in slope failure at Kirkby Fell.

Although the rock slump-earthflow is thought to be a product of slope loading, the Schmidt hammer data indicate a time lag between the two phases of failure. This indicates that the mid-lower hillslope did not exceed its stability threshold immediately loading occurred and that other factors were influential in promoting failure. Seismic action may again have been involved either directly or indirectly by, for example, expanding cap rock joints and enabling the underlying shales to receive greater quantities of water. Enhanced shale weathering, loss of cohesion and increased pore water pressures are likely to have occurred as a result (Johnson 1980). Fluvial under/downcutting has also been invoked as an important factor in south Pennine RSF (Johnson and Vaughan 1983, 1989). At present, surface water courses only occur in the lower reaches of the debris tongue and alongside the northern margin but prior to failure it is possible that a more developed stream network extended further upslope, was deeply incised into the shales and allowed for the relaxation of slope stresses and, ultimately, slope failure.

Conclusions

Field mapping and consideration of the Kirkby Fell RSF has resulted in a two-phase development sequence being proposed. The first phase involved rotational movement at the eastern edge of the summit plateau. Slope loading by the failed materials was a contributory factor in the second phase of movement on the mid-lower slopes where, after an interval of unknown length, a rock slump-earthflow occurred. Boulder hardness data obtained with a Schmidt hammer support this two-phase development sequence. It is considered that failure occurred following deglaciation and that the combined influences of glacial/deglacial slope conditioning and seismic activity may have been important factors with respect to the initial failure. Seismic activity may have also played a part in the second phase of failure. Recent low magnitude earthquakes in northwest England have been linked to small-scale rockfalls; higher magnitude tremors along the Craven faults may have been responsible for larger-scale RSF.

In contrast to the glacial and karstic landforms of Craven, very little detail is available concerning the location and characteristics of RSFs and with respect to development of Craven scenery the extent, variety, age and significance of these features is largely unknown. Preliminary observations indicate RSFs exist on the flanks of Penyghent and Ingleborough, and the eastern side of Whernside also carries a number of failures (Mitchell 1996). At these sites the RSFs are in gritstones and underlying shales and as yet no RSFs have been identified on limestone scars (Wilson 2006).

Rock-slope failures may be significant features in areas of former glaciation and indicate that the landscape continued in a dynamic state following the withdrawal of ice, but the contribution made by RSFs to landshaping is often not realised. Where failures occur on steep hillsides they contribute to the long-term evolution of those areas by helping to widen valleys and reduce plateau widths. They also provide abundant debris for onward transport in a subsequent glacial advance. Given that Craven has experienced several glacial episodes it is reasonable to infer that some of its hillslopes are products of repeated glacial erosion and RSF. When put in those terms the significance of RSF may be easier to appreciate.

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