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Rock-slope failure following Late Pleistocene deglaciation on tectonically stable mountainous terrain

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ABSTRACT

The ages of 31 postglacial rock-slope failures (RSFs) in Scotland and NW Ireland, derived from 89 cosmogenic isotope exposure ages, are employed to analyse the temporal pattern of failure and its relationship to the timing of deglaciation, rates of glacio-isostatic crustal uplift and periods of rapid climate change. RSF ages span almost the whole period since ice-sheet retreat, from 18.2 ± 1.2 ka to 1.7 ± 0.2 ka, or from 17.1 ± 1.0 ka to 1.5 ± 0.1 ka, depending on the production rate used in ^{10}Be age calculation, but catastrophic failure of rock slopes was ~4.6 times more frequent prior to ~11.7 ka than during the Holocene. 95% of dated RSFs at sites deglaciated during retreat of the last ice sheet occurred within ~5400 years after deglaciation, with peak RSF activity 1600–1700 years after deglaciation. This time lag is inferred to represent (1) stress release initiated by deglacial unloading, leading to (2) time-dependent rock mass strength degradation through progressive failure plane development, and ultimately (3) to either spontaneous kinematic release or failure triggered by some extrinsic mechanism. By contrast, 11 dated RSFs at sites reoccupied by glacier ice during the Younger Dryas Stade (YDS) of ~12.9–11.7 ka exhibit no clear temporal pattern, suggesting that glacial reoccupance during the YDS was ineffective in preconditioning a renewed cycle of enhanced RSF activity. Comparison of timing of individual RSFs with that of deglaciation and rapid warming events at ~14.7 ka and ~11.7 ka suggests that glacial debuttressing, enhanced joint water pressures during deglaciation and thaw of permafrost ice in rock joints could have triggered failure in only a small number of cases. Conversely, the timing of maximum RSF activity following ice-sheet deglaciation corresponds broadly with maximum rates of glacio-isostatic crustal uplift, suggesting that the two are linked by enhanced seismic activity. A seismic failure trigger is consistent with full-slope failure at all sites where failure planes are clearly defined. Our results indicate that numerous RSFs must have occurred in areas that were reoccupied by glacier ice during the YDS, but have not been identified because runout debris was removed by YDS glaciers. More generally, they provide the first reliably-dated body of evidence to support the view that retreat of the last ice sheets in tectonically-stable mountainous terrain initiated a period of enhanced rock slope failure due to deglacial unloading and probably Lateglacial seismic activity, implying that most undated RSFs in such areas are probably of Lateglacial or very early Holocene age. They also demonstrate, however, that a low frequency of RSF activity extended throughout the Holocene.

1. Introduction

Many formerly-glaciated mountain environments are characterized by a high spatial density of large-scale postglacial rock-slope failures (RSFs) in the form of major rockfalls, rockslides, rock avalanches or deep-seated gravitational slope deformations. Such RSFs are often described as *paraglacial*, implying that failure was conditioned by the preceding episode of glaciation and deglaciation (Ballantyne, 2002; Wilson, 2009; Kellerer-Pirklbauer et al., 2010; McColl, 2012). Several authors have inferred a causal connection between deglaciation of steep rockwalls and subsequent rock-slope failure, with regard to both recent retreat of mountain glaciers (e.g. Evans and Clague, 1994; Holm et al., 2004; Arsenault and Meigs, 2005; Allen et al., 2010) and shrinkage of Late Pleistocene ice sheets (e.g. Abele, 1997; Soldati et al., 2004; Blikra et al., 2006; Longva et al., 2009; Mercier et al., 2013; Cossart et al., 2013a). Proposed explanations for this association include stress-release fracturing, uplift and dilation of rock masses,

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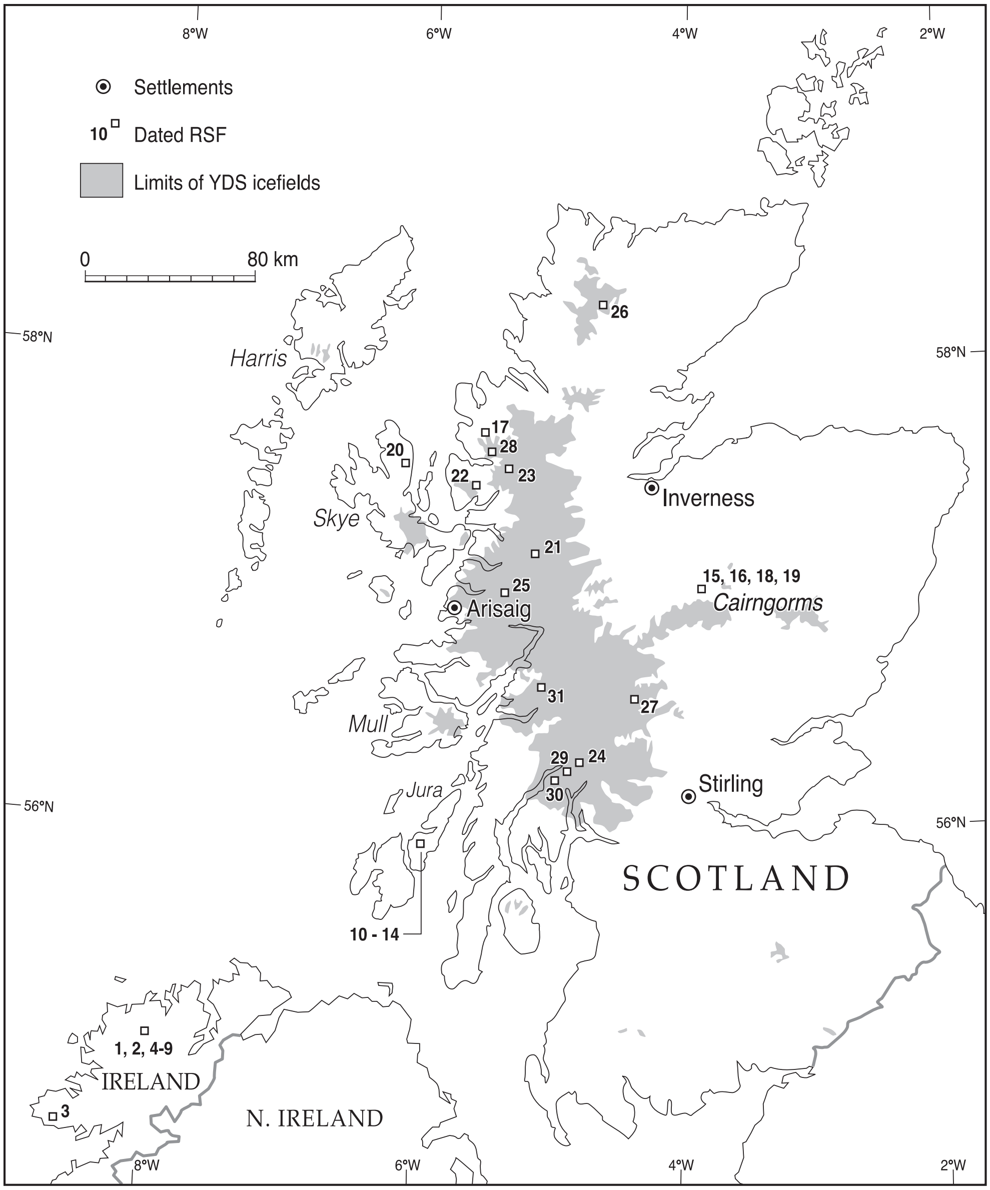

Fig. 1. Location of RSF sites (numbering as in Table 1), showing the extent of Younger Dryas icefields and other locations mentioned in the text.

debuttressing (removal of supporting glacier ice from unstable rockwalls), freeze-thaw activity, thaw of permafrost ice in ice-bonded joint networks, enhanced joint-water pressures during deglaciation and seismic activity (Prager et al., 2008; McColl, 2012).

In the case of RSFs following Late Pleistocene or early Holocene deglaciation, assessment of the manner in which deglaciation has affected rock-mass stability has been impeded by limited data on the timing of postglacial failures. Over the past two decades, however, surface exposure dating using cosmogenic isotopes (^{3}He, ^{10}Be, ^{21}Ne and ^{36}Cl) has been employed to establish the age of numerous individual postglacial RSFs, particularly in tectonically-active mountain belts such as the Alps (Bigot-Cormier et al., 2005; Van Husen et al., 2007; Hormes et al., 2008; El Bedoui et al., 2009; Hippolyte et al., 2009; Ivy-Ochs et al., 2009; Prager et al., 2009; Sanchez et al., 2010), Himalaya (Mitchell et al., 2007; Dortch et al., 2009), Andes (Hermanns et al., 2001, 2004; Fauqué et al., 2009; Welkner et al., 2010) and Karakoram (Seong et al., 2009; Shroder et al., 2011). Most of these studies, however, involve the dating of a single RSF or small number of RSFs, so the regional temporal pattern of RSF activity since deglaciation cannot be assessed. Moreover, almost all exposure-dated RSFs are located in tectonically-active mountain belts. In such areas earthquakes caused by postglacial fault movements due to tectonically-driven uplift or regional crustal stresses may trigger major RSFs, so that RSF ages may be largely independent of the timing of Late Pleistocene deglaciation (e.g. Hewitt et al., 2008, 2011; Antinao and Gosse, 2009; Sanchez et al., 2010; Stock and Uhrhammer, 2010; Hermanns and Niedermann, 2011; Penna et al., 2011).

Numerous postglacial RSFs are also present in mountainous parts of seismically-quiescent intraplate terrains, such as Scandinavia and much of the British Isles, that were completely buried under Late Pleistocene ice sheets. The Scottish Highlands, for example, are estimated to contain over 550 postglacial RSFs, including 140 with areas exceeding 0.25 km^2 (Jarman, 2006, 2007). For such areas, several authors have championed the idea that active faulting driven by glacio-isostatic rebound produced large magnitude ($M > 6.0$) earthquakes following ice-sheet shrinkage, with progressive reduction in seismic activity during the Holocene