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DEBRIS FLOW ACTIVITY IN THE SCOTTISH HIGHLANDS: TEMPORAL TRENDS AND WIDER IMPLICATIONS FOR DATING

Abstract. In the Scottish Highlands, debris flows are initiated on valley-side slopes > 30° or within bedrock gullies, but flow distribution is restricted to slopes that support a sediment cover of till, talus or regolith. Debris flows are most widespread on sediments with a coarse sandy matrix. Stratigraphic evidence and radiocarbon dating of debris flow deposits exposed in section shows that paraglacial debris flow activity was widespread during deglaciation and has occurred intermittently at flow-susceptible sites over the past 7,000 years. Radiocarbon dating of stacked debris flow sequences implies maximum recurrence intervals of 150–320 years for particular locations, and suggests that flow periodicity was non-uniform during the Holocene. Lichenometric dating of flow deposits and documentation of recent debris flow events suggests that recent recurrence intervals at flow-susceptible sites range from < 10 years to a few decades, similar to those recorded for alpine environments, though the volumes of individual debris flows in Scotland are significantly smaller. Geomorphic evidence implies an increase in debris flow activity in the Scottish Highlands over the past few centuries. Suggested causes include a reduction in slope stability due to progressive pedogenesis, destruction of a moisture-retaining bryophyte surface cover by burning, and/or changes in slope configuration triggered by exceptional rainstorm events during the "Little Ice Age". Wider implications are: (1) radiocarbon dating of debris flow units tends to overestimate the return period of debris flow events, as only a subsample of all flows are dated; (2) lichenometric dating of flow deposits is significantly biased towards younger ages by progressive burial of older deposits by younger flows; and (3) hillslope debris flow periodicity may be influenced by previous flow events that reduce the threshold for subsequent events by triggering a cycle of gully incision and vegetation stripping.

Key words: debris flow, radiocarbon dating, lichenometry, recurrence interval, Scottish Highlands

INTRODUCTION

The term *debris flow* describes the rapid downslope flow of poorly-sorted debris mixed with water. Two types of debris flow are widespread on steep mountain slopes in the Scottish Highlands: *hillslope flows,* which occur on open hillslopes, and *valley-confined flows*, which originate in bedrock gullies and are channelled for part of their length along gully floors. The two categories are transitional: many valley-confined flows debouch on to open ground, and hillslope flows often start in gullies cut in valley-side sediments (Photo 1).

Debris flow is the dominant agent of mass movement on steep slopes in many parts of the Scottish Highlands (Ballantyne 1991), though individual flows tend to be much smaller than those in alpine mountains (van Steijn 1996). A survey of the dimensions of hillslope flows in the Scottish Highlands by J. L. Innes (1985) suggests that 60% transported < 20 m^3 of sediment and 90% carried < 60 m^3 of sediment. Occasional valley-confined flows are much larger, however, transporting > 1000 m^3 of debris (Common 1954; Brazier and Ballantyne 1989).

Debris flows in the Scottish Highlands are generated in two main ways. On open hillslopes or gully sides, initial failure usually takes the form of shallow (0.3–3.0 m thick) translational landslides, often over bedrock. A transition from sliding to flow reflects loss of internal frictional strength, with consequent

Photo 1. Hillslope debris flow in the Lairig Ghru, Cairngorm Mountains. Earlier flows can be seen to the right of the main flow

liquifaction and remoulding of the mobile sediment (Jenkins et al. 1988). Within gullies, however, flood torrents may be transformed into debris flows by the addition of sediment from the gully floors and walls (Bovis and Dagg 1992), or by failure of debris dams (van Steijn et al. 1988). In all cases, debris flows are initiated when a build-up of porewater pressures in unconsolidated sediments causes a reduction in shearing resistance, leading to sediment failure and flow. All documented instances of recent debris flows in Scotland have occurred during prolonged rainstorms of exceptional intensity (Common 1954; Baird and Lewis 1957; Jenkins et al. 1988; Luckman 1992). Debris flow frequency cannot, however, be directly related to rainstorm intensity and duration, because of the effect of antecedent soil moisture conditions (Church and Miles 1987). Although there are recorded instances of major debris flow activity in Scotland triggered by rainfall intensities of 60–80 mm in 24 hours following periods of wet weather, much greater rainstorm intensities (up to 140 mm in 24 hours) have failed to generate extensive debris flow activity after a period of dry conditions (Acreman 1983).

Considerable debate has centred around the proposal that debris flow activity in Scotland has undergone a marked increase within the past two centuries, and, if so, the causes of such increased activity (Innes 1982, 1983a, 1989, 1997; Ballantyne 1991; Brazier and Ballantyne 1989; Curry 2000a). This paper reviews this proposition and attempts to establish (1) the factors that control the distribution of debris flow activity, (2) temporal trends in debris flow activity, (3) the duration of past and present recurrence intervals and (4) possible causes of an increased incidence of activity in the Scottish Highlands. It also assesses some wider implications of the use of radiocarbon dating and lichenometry to establish the timing and recurrence interval of debris flow events.

DISTRIBUTION OF DEBRIS FLOW ACTIVITY

Figure 1 is based on an airphoto search by J. L. Innes (1983a) for the presence of flow tracks within 100 km² grid squares, and indicates the main areas of debris flow activity in Scotland. Though Innes considered that his map under-represents the true distribution of debris flows as not all flows observed on the ground proved visible on the airphotos he used, the map nonetheless highlights a general correspondence between areas of endemic flow activity and high ground in the Scottish Highlands. Equally conspicuous, however, is the absence of recorded debris flow activity in some mountain areas, notably along the west coast and in the uplands of southern Scotland.

The primary determinant of the distribution of debris flows in the Scottish Highlands is relief. Surveyed hillslope flows have source areas on slopes of 30–46°, with most starting on gradients of 32–42° (Innes 1983b). Valley-confined

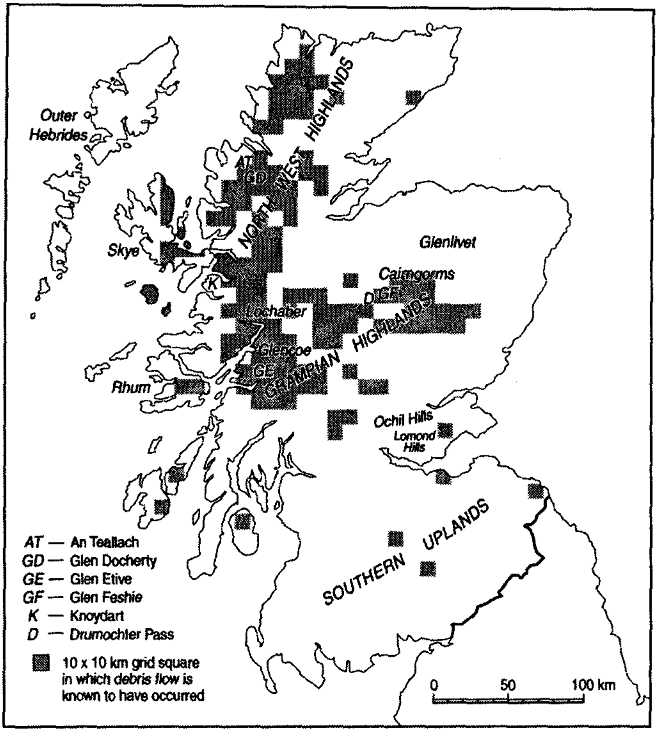

Fig. 1. Distribution of debris flow activity in Scotland based on an airphoto search for the presence of debris flow tracks within 10 × 10 km grid squares. Based on J. L. Innes (1983a) with additions

flows may be initiated on gully floors with lower gradients, but as such gullies are cut into rockwalls, all debris flows are restricted to areas of steep relief. Within such areas, debris flow distribution is largely determined by sediment availability. Three sources of sediment feed debris flows in Scotland, namely regolith derived from weathering of bedrock (Innes 1982, 1986; Reid 2001), till deposits mantling steep hillslopes (Baird and Lewis 1957; Brazier and Ballantyne 1989; Ballantyne and Benn 1996; Curry 2000a) and talus accumulations (Hinchliffe 1998, 1999; Hinchliffe et al. 1998). Debris flows, and particularly hillslope flows, are therefore rare or absent in areas of glacial scouring where regolith, till or talus cover is thin or absent on valley-side slopes, as is the case for many mountains along the western seaboard of Scotland.

A more subtle control on debris flow distribution is sediment texture. C. K. Ballantyne (1981) and J. L. Innes (1982, 1983b, 1986) have shown that the spatial density of debris flows in the Scottish Highlands is much greater on slopes mantled by sediment with a coarse-grained cohesionless sandy matrix. Hillslope flows are much more widespread on slopes underlain by sandstone and granite (which yield abundant coarse sand on weathering, and are often mantled by sandy till) than on slopes underlain by schists (which are mantled by till or regolith containing

Table 1

Spatial density of debris flow gullies on slopes underlain by granite and mica-schist (modified from Curry 1999a)

Site	Lithology	Gully density*
Glamaig, Skye	Granite	25 gullies per kilometre
Beinn Dearg, Skye	Granite	20 gullies per kilometre
Glen Einich, Cairngorms	Granite	13.7 gullies per kilometre
Glen Docherty, NW Highlands	Mica-schists	3 gullies per kilometre
Drumochter Pass, Eastern Grampians	Mixed schists	2.6 gullies per kilometre

* Gully density is number of gullies recorded across a 1 km wide section of slope

a much higher proportion of fine sand and silt). Figure 2 shows the contrast in flow density between Glen Einich in the Cairngorm Mountains, which is underlain by granite, and Glen Docherty in the NW Highlands, which is underlain by mica--schist. Though Glen Docherty supports a density of debris flows that is unusually high for terrain underlain by schists, the spatial density of flows here is less than one-third of that for Glen Einich (Table 1). The susceptibility of coarse-grained sediments to debris flow has been attributed to high infiltration rates, which permit a rapid rise in porewater pressures during rainstorms (Innes 1983b, 1986; Ballantyne 1981, 1986). The scarcity of hillslope debris flows on many mountains underlain by schistose rocks in the Highlands or shales in the uplands of Southern Scotland (Fig. 1) probably reflects the relatively fine-grained matrix of the regolith or drift mantling steep slopes in these areas.

TEMPORAL TRENDS

Four sets of data are relevant to identifying temporal trends in debris flow activity in the Scottish Highlands: (1) stratigraphic evidence, (2) radiocarbon dates on organic horizons underlying or overlying debris flow deposits exposed in section on hillslopes or debris cones, (3) lichenometric data relating to the frequency of debris flow activity over the past 500 years, and (4) documentation relating to debris flow events over the past 50 years.

STRATIGRAPHIC EVIDENCE

Stratigraphic evidence from several sites in the Scottish Highlands indicates that reworking of valley-side till by debris flows was widespread during and following ice-sheet deglaciation at ca 17–15 cal ka BP (Bennett 1999) and both during and immediately after glacier retreat at the end of the

Fig. 2. Distribution of debris flow landforms and deposits on terrain underlain by granite (Glen Einich, left) and mica-schists (Glen Docherty, right). Adapted from Curry (1999a)

Younger Dryas Stade, at ca 12–11 cal ka BP (Benn 1991, 1992; Dix and Duck 2000). Such widespread paraglacial debris flow activity reflects the instability of steep till-mantled slopes immediately after deglaciation, and probably lasted no more than a few centuries, though many relict debris cones were probably formed at this time (Brazier et al. 1988; Ballantyne and Benn 1994, 1996; Ballantyne 2002).

RADIOCARBON DATING OF DEBRIS FLOW DEPOSITS

Radiocarbon dating of debris flow deposits exposed in sections in sediment-mantled hillslopes and debris cones at nine sites (Fig. 3) reveals evidence for intermittent debris flow activity over much of the past 7,000 years, long after termination of the initial phase of paraglacial sediment reworking. Radiocarbon dating of organic sediments (buried peat layers and organic soils) immediately underlying debris flow deposits or related hyperconcentrated flows (cf. Matthews et al. 1999) yields a maximum age for the overlying deposit. The contact between the two is normally conformable, indicating that no erosion of the underlying peat or soil has occurred, so that the radiocarbon age provides a close estimate of the timing of the debris flow event. Radiocarbon ages

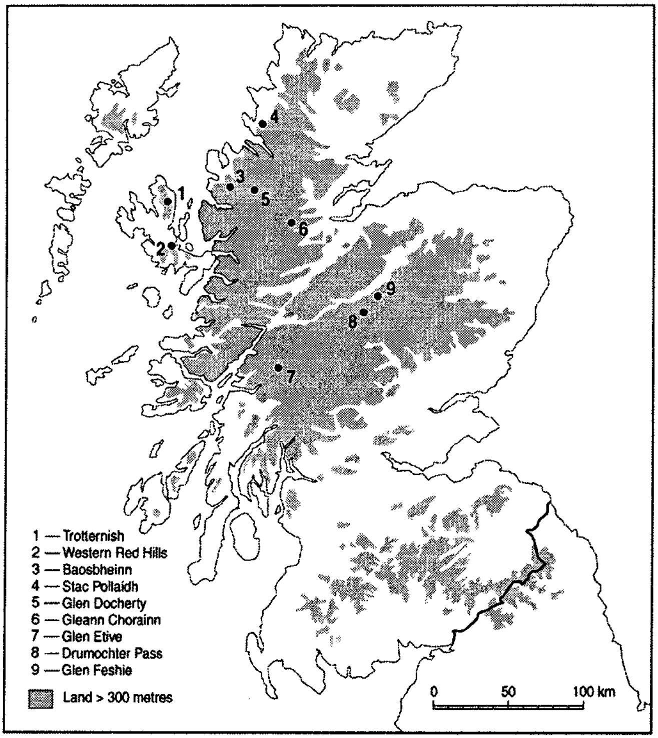

Fig. 3. Sites where radiocarbon ages have been obtained for organic layers underlying or overlying debris flow deposits exposed in section

obtained from the base of organic horizons overlying debris flow units provide a minimum age for individual flow units.

Figure 4 summarizes the radiocarbon dating evidence for the timing of debris flow activity in the Scottish Highlands over the past 7,000 years. Sampling and stratigraphic details are given in J. L. Innes (1983c), V. Brazier et al. (1988), V. Brazier and C. K. Ballantyne (1989), S. Hinchliffe (1998, 1999), A. M. Curry (1999a, 2000a, b) and E. Reid (2001). All dates have been calibrated using the CALIB 4.3 programme (Stuiver and Reimer 1993). The length of each horizontal bar in Figure 4 encompasses the 95% confidence limits for each calibrated age. Although the data indicate that debris flow activity occurred throughout most of the past 7,000 years, clustering of dates suggests that periods of enhanced debris flow activity occurred within the past 700 years, 1,700–2,700 years ago and possibly 3,400–3,800 and 5,900–6,400 years ago, with

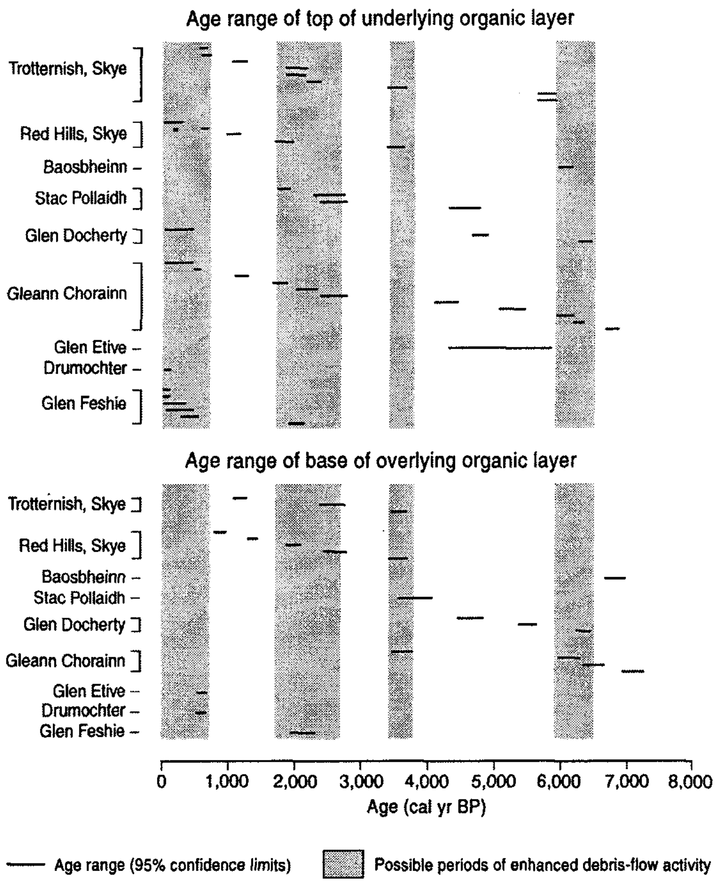

Fig. 4. Calibrated radiocarbon age ranges relating to debris flow deposits exposed in section, showing possible periods of enhanced activity. Horizontal bars encompass the 95% confidence limits for each calibrated age

intervening periods of reduced activity. Over a millennial timescale, such variations in the incidence of dated debris flow activity may be related to the frequency of extreme rainstorms.

For locations where debris flow units have been dated at several different exposures, it is possible to calculate an approximate recurrence interval for debris flow events by counting the number of discrete flow units above or between dated organic horizons. As only a subsample of flows have been dated, this approach yields only maximum recurrence intervals for particular areas. For five dated hillslope flow sites in Trotternish (Fig. 3; Hinchliffe 1999) the average recurrence interval per site ranges from ca 370 years to ca 900 years, and collectively the 5 sites indicate a maximum recurrence interval of ca 150 years for the area. Maximum recurrence intervals are ca 250 years for the Western Red Hills on Skye (Curry 2000a) and ca 320 years for Glen Docherty (Curry 2000b). However, these figures conceal changes in debris flow frequency through time (Fig. 4) and under-represent (possibly markedly) the true frequency of flow occurrence in individual areas. Radiocarbon dates obtained from organic horizons in debris cones where successive flows have spread over the cone surface are likely to be more representative than those obtained from a sample of hillslope flow deposits. Dates obtained for stacked debris flow units within debris cones in Glen Feshie (Fig. 3) suggest that the recurrence interval for debris flow activity over the past ca 150 years was ca 30–35 years (Brazier and Ballantyne 1989).

LICHENOMETRIC DATING OF DEBRIS FLOW DEPOSITS

J. L. Innes (1982, 1983a) attempted to reconstruct debris flow age and frequency in the Scottish Highlands by measuring *Rhizocarpon* lichens on flow lobes and levées, and calibrating the results using *Rhizocarpon* growth rates derived from dated tombstones in nearby graveyards. He employed this approach at 12 sites in three areas of the Highlands. His results (Fig. 5) suggest that virtually all debris flow activity at these sites occurred after AD 1700, with most occurring after 1850–1900. He proposed that these data indicate major destabilization of hillslope source areas within the past 200–300 years, and thus a major increase in both the extent and frequency of debris flows within this period. Lichenometric dating of debris flow deposits, however, suffers from a potential drawback, in that younger flows often bury older flow deposits, introducing a bias towards younger flow ages (Ballantyne 1991). The potential seriousness of this problem has been illustrated by B. H. Luckman (1992), who has shown that in the Lairig Ghru (Cairngorm Mountains), flows generated by a major rainstorm in 1978 largely obliterated a previous generation of flow lobes deposited in 1956 (Fig. 6).

The potential bias in lichenometric dating due to progressive burial of older flow deposits has been assessed by A. Finlayson (2000), who developed a model for the probability of survival of older debris flow deposits under the

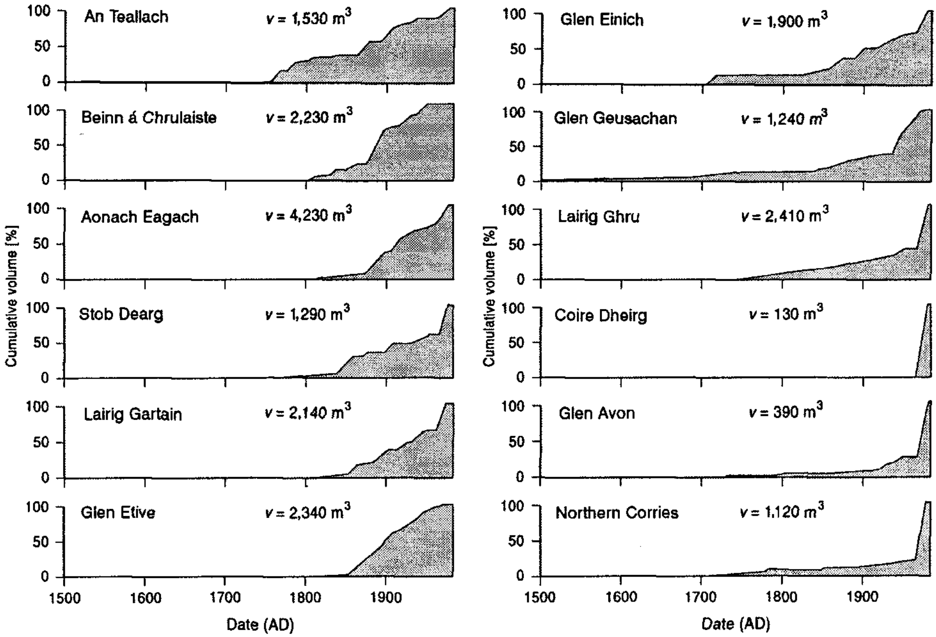

Fig. 5. Cumulative volume (v) of sediment transported by debris flows at 12 sites in the Scottish Highlands, AD 1500–1980. The data are derived from dating of debris flow deposits by lichenometry. The apparent increase in sediment transport within the past 200 years probably reflects sampling bias due to progressive burial of older debris flow deposits by later flows (see text). Adapted from J. L. Innes (1983a)

assumption that flow frequency is uniform through time. A. Finlayson tested this model by measuring the lichenometric age of debris flow deposits in Drumochter Pass (Fig. 3). He showed that the cumulative plot of lichenometric ages is not significantly different from the pattern that might be expected for a uniform debris flow periodicity of 1 flow per 1.5 years over the past 260 years, implying that the apparent increase in flow activity during this period (Fig. 7a) may be due entirely to the progressive burial of older debris flow deposits by younger flows. A. Finlayson (2000) also applied this analysis to J. L. Innes' (1983a) cumulative debris flow frequency distributions (Fig. 7b), and demonstrated that most of these could also be explained by burial of older debris deposits by younger flows. This analysis casts doubt on the validity of the pattern of debris flow accumulation presented by J. L. Innes (1983a), and suggests that the apparent increase in debris flow activity since AD 1700 (Fig. 5) may be due largely or entirely to the bias introduced into lichenometric dating of flow ages by progressive burial of older flow deposits. The lichenometric data of J. L. Innes (1983a) and A. Finlayson (2000) nonetheless demonstrate that debris flow activity at most sites occurred within most decades over the past 150–200 years (Innes 1997), implying a decadal or sub-decadal recurrence

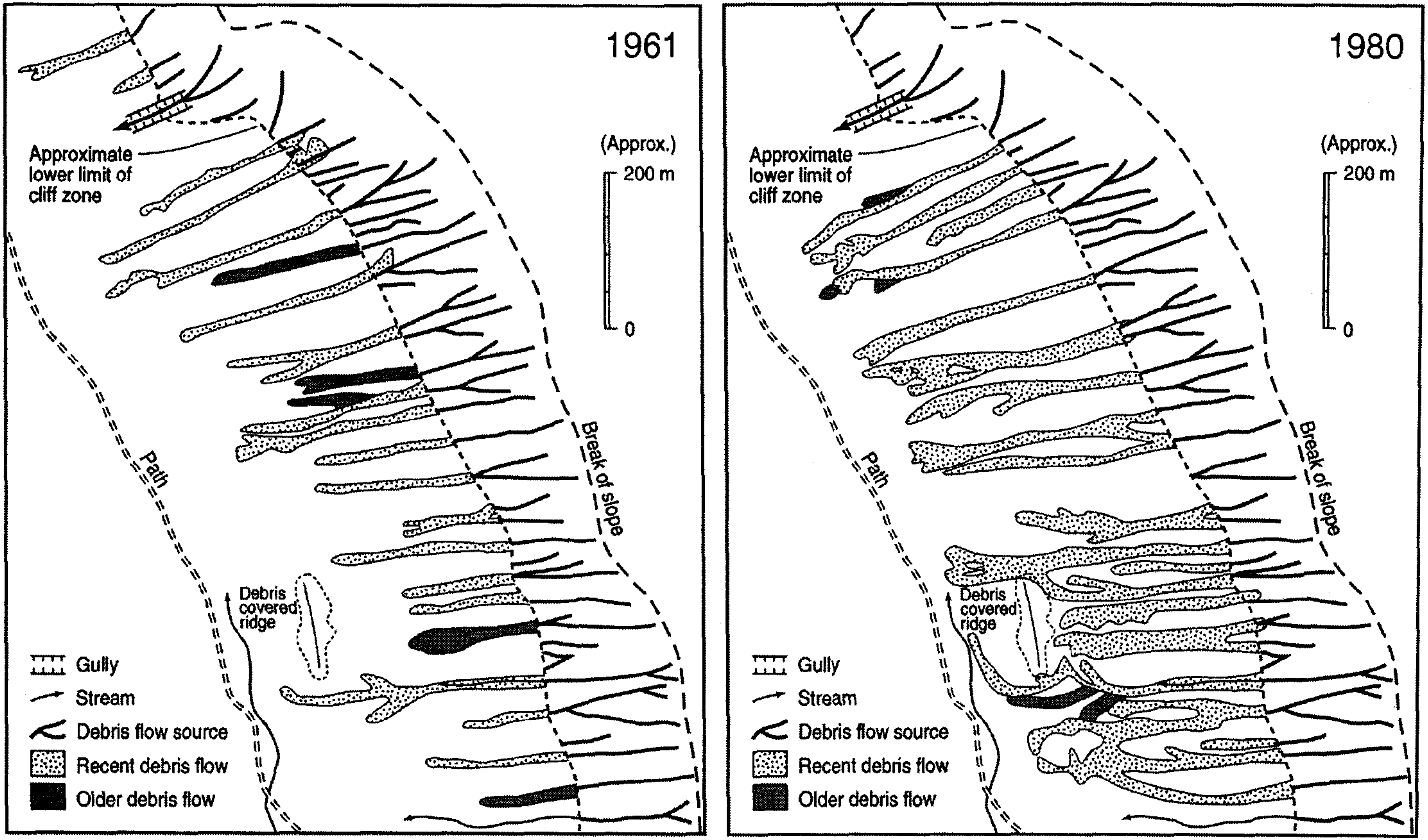

Fig. 6. Recent debris flows in part of the Lairig Ghru, Cairngorm Mountains, in 1961 and 1980, showing extensive burial of an earlier (1956) generation of debris flow deposits by later (1978) flows. Adapted from B. H. Luckman (1992)

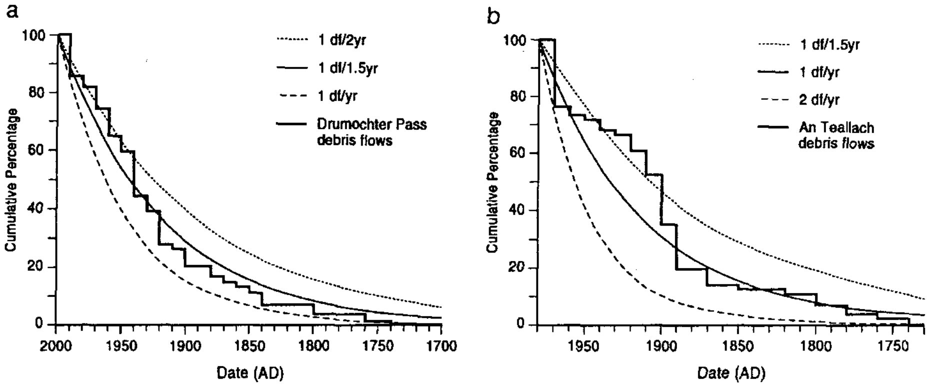

Fig. 7. Cumulative percentage frequency of lichenometrically-dated debris flow ages for Drumochter Pass (a) and An Teallach (b), compared with curves describing the expected cumulative frequency distribution under the assumption of uniform flow periodicity and progressive burial of older flow deposits by younger flows. The measured cumulative frequency age distributions are not significantly different from those that would be expected given a uniform frequency of 1 debris flow (df) per 1.5 years (10 debris flows per 15 years) at Drumochter Pass and 1 debris flow per year (10 debris flows per decade) at An Teallach. This result implies that the apparent increase in debris flow frequency can be explained entirely by progressive burial of older flows. Adapted from A. Finlayson (2000)

interval for debris flow events at flow-susceptible sites in the Scottish Highlands during this period.

RECENT DEBRIS-FLOW EVENTS

Though published documentation of recent debris-flow events in the Scottish Highlands is limited, amalgamation of such data with unpublished observations and airphoto data permit assessment of recent debris-flow recurrence intervals for a few locations. For the Lairig Ghru in the Cairngorm Mountains, for example, J. L. Innes (1982) observed fresh debris flow tracks on 1946 airphotos, implying a debris flow event within the preceding decade. Airphotos taken in 1961 show a new set of fresh tracks, probably produced by flows triggered by a major rainstorm in 1956 (Baird and Lewis 1957). In 1980, B. H. Luckman (1992) mapped a further extensive set of new tracks (Fig. 6). These probably represent flows activated by a storm in August 1978, though some may have occurred in response to intense rainstorms in 1976 or June 1978. At least 71 flows were mobilized in the Lairig Ghru between 1970 and 1978 (Innes 1983a), but none has occurred since. In sum, these data suggest that at least three major debris flow events occurred in the Lairig Ghru between ca 1935 and the present, implying a recurrence interval of ca 20 years or less (Table 2). Because of the brevity of the observation periods for recent debris flow activity at the sites identified in Table 2, however, the recurrence interval data should be regarded as indicative only. The data in Table 2 nevertheless suggest that, on terrain susceptible to debris flow activity, the recurrence interval

Table 2

Recent debris flow events in Scotland

Location	Recorded debris flow events	24 hour rainfall intensity	Maximum recurrence interval	Sources
Lairig Ghru, Cairngorms	1935–1946 August 1956 August 1978	> 86 mm > 80 mm	ca 20 yr	Baird, Lewis 1957 Innes 1982 Luckman 1992
Lochaber-Appin, W Grampians	May 1952 ca 1996	> 75 mm	ca 45 yr	Common 1954 Unpublished data
Glen Docherty, NW Highlands	1968 1990–1998		ca 25 yr	Unpublished data
Drumochter Pass E Grampians	1951 July 1978 ca 1990 1995–2000		10–15 yr	Innes 1982, 1983a Ballantyne 1981 Finlayson 2000 Unpublished data

of major debris flow generating events during the past 50 years has been at most a few decades, consistent with the findings of studies based on lichenometric dating.

DISCUSSION

In a review of Holocene geomorphic activity in the Scottish Highlands published a decade ago (Ballantyne 1991), the author argued that the evidence then available suggested that there were two periods of enhanced hillslope activity, namely during the period of paraglacial landscape adjustment immediately after deglaciation, and within the past few centuries, with limited evidence of intervening periods of hillslope reworking. Subsequent research has validated the notion of rapid paraglacial landscape adjustment during and immediately after deglaciation (Ballantyne 2002), but has also provided abundant evidence for the continued operation of a range of hillslope processes, including debris flow activity, throughout much of the Holocene (Hinchliffe 1998, 1999; Hinchliffe et al. 1998; Curry 2000a; Reid 2001; Fig. 4). Moreover, it is argued above that the lichenometric evidence for a marked increase in debris flow activity within the past 200 years is questionable, owing to the sampling bias introduced by burial of older flow deposits. Though both lichenometric and observational evidence suggests that during this period (and at present) the recurrence interval for major debris flow events in flow-susceptible terrain is of the order of a few decades at most, whereas the radiocarbon dating record for the Holocene suggests much longer (10^2–10^3 yr) recurrence intervals, the representativeness of the latter is questionable as only a subsample of flow deposits have been dated at particular sites. The dating evidence alone, therefore, does not provide conclusive support for the proposition that debris flow activity in the Scottish Highlands has undergone a marked increase within the past two centuries as proposed by J. L. Innes (1982, 1983a, 1989, 1997).

Geomorphic considerations nevertheless suggest that the recent decadal recurrence intervals implied by lichenometric and observational data cannot have been sustained throughout the Holocene. If sites of recent debris flow activity such as the Lairig Ghru, Glen Docherty and Glen Einich (Fig. 2 and 6) had experienced major debris flow events every few decades throughout the Holocene, upper slope sediments would have been completely removed within a few centuries or millennia (cf. Ballantyne and Benn 1994; Curry 1999b). Sediment sources on such slopes, however, are often largely intact but incised by fresh, active drift-cut gullies that have acted as the sources of recent flows (Photo 1). The implication is that many such gullies are of relatively recent origin, indicating enhanced erosion by debris flows over a timescale of no more than a few centuries. Similarly, though valley-confined flows often terminate in substantial debris cones that have accumulated over many millennia (Brazier et al. 1988; Brazier and Ballantyne 1989; Curry 2000b), the accumulated volume of flow deposits in the runout zone of hillslope flows is often very limited, and incompatible with frequent episodes of sediment discharge throughout the Holocene. J. L. Innes (1983a) also observed other evidence for a recent increase in activity, such as the burial by debris flows of abandoned cultivation systems. Thus although the dating evidence for a marked increase in activity in the past few centuries is questionable, geomorphic considerations nevertheless indicate an enhanced incidence and probably spatial extension of hillslope flow activity within the past few centuries. Whether valley-confined flows have also increased in frequency during this period is less certain.

CAUSATION

An increased frequency of hillslope debris flows within the past few centuries may reflect either a reduction in the shearing resistance of the hillslope sediment cover, or an increase in the frequency of extreme rainstorms of high intensity and prolonged duration. Modelling of the vulnerability of Scottish hillslopes to shallow sliding failure (Brooks et al. 1993, 1995) suggests that progressive pedogenesis (particularly the development of mature podzols) alters the hydraulic transmissivity of soils, rendering failure more likely during high-intensity rainstorms. This effect, however, is likely to lower the threshold of slope failure progressively over millennia rather than initiate a marked change in the incidence of failure and debris flow activity over a few centuries. Such a progressive reduction in shearing resistance may, however, have acted in concert with other shorter-term changes in initiating an increased frequency of hillslope flow activity. Other researchers have focused attention on anthropogenic causes. Palaeosols buried by debris flow deposits provide no evidence for woodland clearance (by burning or otherwise) as a trigger for increased debris flow activity (Brazier and Ballantyne 1989; Hinchliffe 1999; Curry 2000a). J. L. Innes (1982, 1983a), however, suggested that burning of heather to improve sheep grazing may have increased the susceptibility of slopes to initial failure and consequent debris flow activity, primarily by destroying the water-absorbing bryophyte cover and thus increasing the likelihood of soil saturation during extreme rainstorms. There is some local circumstantial evidence favouring this suggestion; in Drumochter Pass (Fig. 3), for example, hillslope flows were triggered in 1951 within few weeks of heather burning. Overgrazing by sheep was also considered by J. L. Innes (1983a) to be a possible contributory factor.

The possible influence of changing rainstorm frequency is difficult to assess because of the lack of records of storm intensity and duration. In this context, however, the stratigraphy of a debris cone in Glen Feshie (Fig. 3) is instructive. This exhibits a prolonged hiatus in debris flow accumulation between ca 2,000 cal yr BP and ca 300–500 cal yr BP, after which cone accumulation due to periodic debris flow deposition resumed. V. Brazier and C. K. Ballantyne (1989) noted that the gully sources of this cone are unlikely to have been influenced by anthropogenic activity, and suggested that renewal of debris flow activity at this site was triggered by an exceptionally high-magnitude rainstorm during the "Little Ice Age" of the 16th–19th centuries AD, a period characterized by an increase in the frequency and intensity of cyclonic storms tracking across Scotland (Lamb 1979, 1984; Whittington 1985). They suggested that such a storm may have stripped vegetation cover and incised gullies in till deposits in the source areas of the gully, lowering the threshold for subsequent debris flow events, and thus initiating a period of frequent debris flow activity that continues to the present. This model implies that destabilization of hillslopes throughout the Scottish Highlands may have been initiated by exceptional storms during the "Little Ice Age", and continued by rainstorms of lesser magnitude up to the present; if valid, this explanation could account for the geomorphic evidence for enhanced debris flow activity over the past few centuries throughout the Scottish Highlands.

Whatever the cause of more frequent debris flow activity in the Scottish Highlands in the past few centuries, recent and anticipated future climate changes seem likely to reduce the recurrence interval of major flow events. Annual precipitation totals for Scotland exhibit a general (though oscillatory) increase over the last century, with unprecedentedly high precipitation totals in the last two decades (Smith 1995). Recent increases have resulted in exceptionally high and increasing annual river discharges in Highland catchments (Smith and Bennett 1994), and imply a general increase in wetness that favours an increase in debris flow frequency. A recent increase in flood frequency (Black 1995) also suggests that extreme rainstorm events are now more common than formerly: no fewer than 7 major storms with intensities exceeding 60 mm in 24 hours occurred in the Cairngorm Mountains between 1955 and 1980 (Luckman 1992). Superimposed on a general increase in wetness (and thus an increased probability of high antecendent moisture conditions), any future increase in storm frequency is likely to generate more frequent debris flow events, at least on open hillslopes where sediment supply is abundant. The frequency of some valley-confined flows, however, may be "sediment-limited" rather than climatically-determined, as individual flows tend to flush out valley-floor sediments, so that subsequent flows are dependent on the renewed accumulation of sediment supplied from gully walls and tributaries.

SOME WIDER IMPLICATIONS

Several wider implications emerge from the above analysis. First, it highlights the problems of estimating recurrence intervals from radiocarbon dating of debris flow deposits. Because radiocarbon dating can usually be carried out for only a subsample of exposed flow deposits, only a maximum recurrence interval can be derived. It is notable that most studies that have employed this approach tend to yield very long recurrence intervals of 500–4,000 years (Corominas et al. 1996; table 7.3.3), suggesting that this problem is widespread. Second, though lichenometric dating has been widely employed to determine recurrence intervals and to identify past episodes of enhanced debris flow activity (e.g. André 1990; Rapp and Nyberg 1981), it has been shown that this approach may be undermined by sampling bias due to burial of older deposits by younger flows. This implies that apparent temporal trends in the incidence of debris flow activity identified on the basis of lichenometric dates must be treated with caution, particularly when these suggest a marked increase in recent activity.

A third implication of this survey is that though the size of debris flows in Scotland tends to be much smaller than those in alpine mountains (van Steijn 1996), the recurrence interval for recent flow events (< 10 years to a few decades) appears to be fairly similar. For the Bachelard valley in the French Alps, for example, Th. W. van Asch and H. van Steijn (1991) calculated a flow periodicity of 4–45 years, and for the Rocky Mountains in British Columbia, J. S. Gardner (1982) estimated a recurrence interval of 15–25 years. Recurrence intervals appear to be much longer in arctic and subarctic environments: M.-F. André (1990) estimated that the return period for major debris flow events on Spitsbergen in 80–500 years, and A. Rapp and R. Nyberg (1981) suggested that 50–400 years is typical for Swedish Lappland. Such contrasts probably reflect the greater frequency of extreme rainfall events in mid-latitude mountains.

Finally, this survey raises the question as to whether the present incidence of debris flow activity in the Scottish Highlands may reflect an initial destabilization of slopes by exteme rainstorm events in the past that lowered the threshold for debris flow initiation by triggering a cycle of gully incision, vegetation removal and sediment release that continues to the present day. This concept may have wider application in other mountain environments, particularly those in which debris flow activity is not sediment-limited but conditioned primarily by rainstorm intensity and duration.

CONCLUSIONS

1. In the Scottish Highlands, debris flow activity is limited to areas of steep relief with valley-side slopes >30° or deep bedrock gullies. Flows distribution in areas of steep relief is restricted to slopes that support a cover of unconsolidated sediment (till, talus or regolith), especially sediment with a coarse sandy matrix.

2. Debris flow activity was widespread during and immediately after deglaciation and has occurred intermittently at flow-susceptible sites over the past 7,000 years. Radiocarbon dating indicates maximum recurrence intervals of 150–320 years for particular locations, and suggests that flow frequency was not uniform throughout the Holocene.

3. Both lichenometric evidence and documentation of recent debris flow events suggest that the recent recurrence interval of flow events at flow-susceptible sites is <10 years to a few decades and thus similar to the return period of debris flows in alpine environments, though individual debris flows in the Scottish Highlands tend to be significantly smaller.

4. An increase in hillslope debris flow activity over the past few centuries is suggested by geomorphic considerations. Possible causes include reduction in the stability of sediment-mantled slopes through progressive pedogenesis, heather burning, and/or changes in slope configuration (gully incision, stripping of vegetation) associated with past extreme rainstorm events that lowered the threshold for subsequent debris flow initiation.

5. Major flow events have been triggered by rainfall intensities of 60–80 mm in 24 hours, though not all prolonged high-intensity rainstorms trigger widespread debris flow activity on flow-susceptible slopes; antecedent moisture conditions are critical.

6. Wider implications of this study are: (1) radiocarbon dating of debris flow units tends to overestimate the return period of debris flow events, as only a subsample of flow deposits are dated; (2) lichenometric dating of flow deposits must be treated with caution, as burial of older flow deposits by later flows introduces a significant bias in favour of younger ages; and (3) hillslope debris flow periodicity may be influenced by antecedent events that lower the threshold for subsequent debris flow generation, so that recurrence intervals are not independent of the recent history of events on a particular slope.

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REFERENCES

Acreman M. C., 1983. *The significance of the flood of September 1981 on the Ardessie Burn, Wester Ross.* Scottish Geographical Magazine 99, 150–160.

André M.-F., 1990. *Frequency of debris flows and slush avalanches in Spitsbergen: a tentative evaluation from lichenometry.* Polish Polar Research 11, 345–363.

van Asch Th. W. J., van Steijn H., 1991. *Temporal patterns of mass movements in the French Alps.* Catena 18, 517–527.

Baird P. D. and Lewis W. V., 1957. *The Cairngorm floods: summer solifluction and distributary formation.* Scottish Geographical Magazine 73, 91–100.

Ballantyne C. K., 1981. *Periglacial landforms and environments in the Northern Highlands of Scotland.* Unpublished PhD Thesis, University of Edinburgh, 593 pp.

Ballantyne C. K., 1986. *Landslides and slope failures in Scotland: a review.* Scottish Geographical Magazine 102, 134–150.

Ballantyne C. K., 1991. *Holocene geomorphic activity on the mountains of the Scottish Highlands.* Scottish Geographical Magazine 107, 84–98.

Ballantyne C. K., 2002. *Paraglacial geomorphology.* Quaternary Science Reviews, in press.

Ballantyne C. K., Benn D. I., 1994. *Paraglacial slope adjustment and resedimentation following recent glacier retreat, Fåbergstølsdalen, Norway.* Arctic and Alpine Research 26, 255–269.

Ballantyne C. K., Benn D. I., 1996. *Paraglacial slope adjustment during recent deglaciation and its implications for slope evolution in formerly glaciated environments,* [in:] *Advances in Hillslope Processes,* eds. S. M. Brooks, M. G. Anderson, Chichester, Wiley, 1173–1195.

Benn D. I., 1991. *Glacial landforms and sediments on Skye,* [in:] *The Quaternary of the Isle of Skye: Field Guide,* eds. C. K. Ballantyne, D. I. Benn, J. J. Lowe, M. J. C. Walker, Cambridge, Quaternary Research Association, 35–67.

Benn D. I., 1992. *The genesis and significance of "hummocky moraine": evidence from the Isle of Skye, Scotland.* Quaternary Science Reviews 11, 781–799.

Bennett M. R., 1999. *Paraglacial and periglacial slope adjustment of a degraded lateral moraine in Glen Torridon.* Scottish Journal of Geology 35, 79–83.

Black A. R., 1995. *Flood seasonality and physical controls in flood risk estimation.* Scottish Geographical Magazine 111, 187–190.

Bovis M. J., Dagg B. R., 1992. *Debris flow triggering by impulsive loading: mechanical modelling and case studies.* Canadian Geotechnical Journal 29, 345–352.

Brazier V., Ballantyne C. K., 1989. *Late Holocene debris cone evolution in Glen Feshie, western Cairngorm Mountains, Scotland.* Transactions of the Royal Society of Edinburgh, Earth Sciences 80, 17–24.

Brazier V., Whittington G., Ballantyne C. K., 1988. *Holocene debris cone evolution in Glen Etive, Western Grampian Highlands, Scotland.* Earth Surface Processes and Landforms 13, 525–531.

Brooks S. M., Richards K. S., Anderson M. G., 1993. *Shallow failure mechanisms during the Holocene: utilisation of a coupled slope hydrology — slope stability model,* [in:] *Landscape Sensitivity,* eds. D.S.G. Thomas, R. J. Allison, Chichester, Wiley, 149–175.

Brooks S. M., Anderson M. G., Collinson A. J. C., 1995. *Modelling the role of climate, vegetation and pedogenesis in shallow translational hillslope failure.* Earth Surface Processes and Landforms 20, 231–242.

Church M., Miles M. J., 1987. *Meteorological antecedents to debris flow in southwestern British Columbia: some case studies.* Geological Society of America, Reviews in Engineering Geology 7, 63–79.

Common R., 1954. *A report on the Lochaber, Appin and Benderloch floods, May, 1953.* Scottish Geographical Magazine 70, 6–20.

Corominas J., Remond J., Farias P., Estevao M., Zézere J., Díaz de Terán R., Dikau R., Schrott L., Moya J., Gonzále z A., 1996. *Debris flow,* [in:] *Landslide Recognition, Identification, Movement and Causes,* eds. R. Dikau, D. Brunsden, L. Schrott, M.-L. Ibsen, Chichester, Wiley, 161–180.

Curry A. M., 1999a. *Paraglacial modification of drift-mantled hillslopes.* Unpublished PhD Thesis, University of St Andrews, 350 pp.

Curry A. M., 1999b. *Paraglacial modification of slope form.* Earth Surface Processes and Landforms 24, 1213–1228.

Curry A. M., 2000a. *Holocene reworking of drift-mantled hillslopes in the Scottish Highlands.* Journal of Quaternary Science 15, 529–541.

Curry A. M., 2000b. *Holocene reworking of drift-mantled hillslopes in Glen Docherty, Northwest Highlands, Scotland.* The Holocene 10, 509–518.

Dix J. K., Duck R. W., 2000. *A high-resolution seismic stratigraphy from a Scottish sea loch and its implications for Loch Lomond Stadial deglaciation.* Journal of Quaternary Science 15, 645–656.

Finlayson A., 2000. *Using lichenometric dating to establish Late Holocene debris flow activity at the Pass of Drumochter, Eastern Grampian Highlands.* Unpublished BSc Honours Dissertation, University of St Andrews.

Gardner J. S. 1982. *Alpine mass-wasting in contemporary time: some examples from the Canadian Rocky Mountains,* [in:] *Space and Time in Geomorphology,* ed. C. E. Thorn, London, George Allen and Unwin, 171–192.

Hinchliffe S., 1998. *The structure and evolution of relict talus accumulations in the Scottish Highlands.* Unpublished PhD Thesis, University of St Andrews, 309 pp.

Hinchliffe S., 1999. *Timing and significance of talus slope reworking, Trotternish, Isle of Skye, Scotland.* The Holocene 9, 483–494.

Hinchliffe S., Ballantyne C. K., Walden J., 1998. *The structure and sedimentology of relict talus, Trotternish, northern Skye, Scotland.* Earth Surface Processes and Landforms 23, 545–560.

Innes J. L., 1982. *Debris Flow Activity in the Scottish Highlands.* Unpublished PhD Thesis, University of Cambridge, 638 pp.

Innes J. L., 1983a. *Lichenometric dating of debris-flow deposits in the Scottish Highlands.* Earth Surface Processes and Landforms 8, 579–588.

Innes J. L., 1983b. *Debris flows.* Progress in Physical Geography 7, 469–501.

Innes J. L., 1983c. *Stratigraphic evidence of episodic talus accumulation on the Isle of Skye, Scotland.* Earth Surface Processes and Landforms 8, 399–403.

Innes J. L., 1985. *Magnitude-frequency relations of debris flows in northwest Europe.* Geografiska Annaler 67A, 23–32.

Innes J. L., 1986. *Textural properties of regoliths on vegetated steep slopes in upland regions, Scotland.* Transactions of the Royal Society of Edinburgh, Earth Sciences 77, 241–250.

Innes J. L., 1989. *Rapid mass movements in upland Britain: a review with particular reference to debris flows.* Studia Geomorphologica Carpatho-Balcanica 23, 53–67.

Innes J. L., 1997. *Historical debris-flow activity and climate in Scotland.* Paläoklimaforschung 19, 233–240.

Jenkins A., Ashworth P. J., Ferguson R. I., Grieve I. C., Rowling P., Stott T. A., 1988. *Slope failures in the Ochil Hills, Scotland, November 1984.* Earth Surface Processes and Landforms 13, 69–76.

Lamb H. H., 1979. *Climatic variation and changes in the wind and ocean circulation: the Little Ice Age in the northeast Atlantic.* Quaternary Research 11, 1–20.

Lamb H. H., 1984. *Some studies of the Little Ice Age of recent centuries and its great storms,* [in:] *Climate Change on a Yearly to Millennial Basis,* eds. N.-A. Mörner, W. Karlén, Dordrecht, Reidel, 121–143.

Luckman B. H., 1992. *Debris flows and snow avalanche landforms in the Lairig Ghru, Cairngorm Mountains, Scotland.* Geografiska Annaler 74A, 109–121.

Matthews J. A., Shakesby R. A., Mc Ewen L. J., Berrisford M. S., Owen G., Bevan P., 1999. *Alpine debris flows in Leirdalen, Norway, with particular reference to distal fans, intermediate-type deposits and flow types.* Arctic, Antarctic and Alpine Research 31, 421–435.

Rapp A., Nyberg R., 1981. *Alpine debris flows in Scandinavia — morphology and dating by lichenometry.* Geografiska Annaler 63A, 183–196.

Reid E., 2001. *Holocene landscape evolution and climate change in mountain areas of the Northern Highlands, Scotland.* Unpublished PhD thesis, University of Stirling.

Smith K., 1995. *Precipitation over Scotland, 1757–1992: some aspects of temporal variability.* International Journal of Climatology 15, 543–556.

Smith K., Bennett A. M., 1994. *Recently increased river discharge in Scotland: effects on flow hydrology and some implications for water management.* Applied Geography 14, 123–133.

van Steijn H., 1996. *Debris-flow magnitude-frequency relationships for mountainous regions of Central and Northwest Europe.* Geomorphology 15, 259–273.

van Steijn H., de Ruig J., Hoozemans F., 1988. *Morphological and mechanical aspects of debris flows in parts of the French Alps.* Zeitschrift für Geomorphologie 32, 143–161.

Stuiver M., Reimer P. J., 1993. *Extended ^{14}C database and revised CALIB radiocarbon calibration programme.* Radiocarbon 35, 215–230.

Whittington G. W., 1985. *The Little Ice Age and Scotland's weather.* Scottish Geographical Magazine 101, 174–178.

STRESZCZENIE

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SPŁYWY GRUZOWE W GÓRACH SZKOCJI, TRENDY PRZESTRZENNE I CZASOWE I ICH ZNACZENIE DLA DATOWANIA ZDARZEŃ

Spływy gruzowe w Szkocji są inicjowane na stokach o nachyleniach przekraczających 30° lub w żlebach skalnych, lecz ich występowanie ogranicza się do stoków, które są okryte utworami morenowymi lub zwietrzelinowymi. Spływy gruzowe są szeroko rozpowszechnione w osadach zawierających matrix bogaty w piaski gruboziarniste. Argumenty stratygraficzne i datowania radiowęglowe osadów budujących spływy pokazują, że główna faza aktywności tych procesów wystąpiła

w warunkach paraglacjalnych podczas deglacjacji i miała wtedy szerokie rozprzestrzenienie. Natomiast podczas ostatnich 7 tys. lat spływy powstawały sporadycznie. Na podstawie datowań radiowęglowych ustalono, że powtarzalność ich występowania na różnych obszarach wynosi 150–320 lat, chociaż okresy występowania tych zdarzeń w holocenie nie były jednolite. Datowania lichenometryczne oraz dokumentacja formowania współczesnych spływów gruzowych pokazują, że współczesne okresy powtarzalności występowania spływów wahają się w przedziale < 10 lat do kilkudziesięcioleci, podobnie jak to ma miejsce w środowiskach alpejskich, chociaż objętości mas gruzowych przemieszczanych w Szkocji są znacznie mniejsze. Istnieją dowody geomorfologiczne wskazujące na wzrost aktywności spływów gruzowych w czasie ostatnich stuleci. Przyczyn tego zjawiska upatruje się w osłabionej stabilności stoków spowodowanej postępującą pedogenezą, rozluźnieniem pokryw stokowych spowodowanym wypalaniem oraz zmianami rzeźby stoków wywołanymi wyjątkowymi opadami podczas małej epoki lodowej. Szersze implikacje tych zjawisk są następujące:

(1) datowania radiowęglowe utworów tworzących spływy zdają się świadczyć, że długości okresów pomiędzy zdarzeniami są przeceniane, ponieważ tylko część osadów jest datowana,

(2) lichenometryczne datowania osadów spływów gruzowych zaniżają ich wiek, gdy następuje grzebanie starszych osadów przez młodsze spływy,

(3) okresowość występowania stokowych spływów gruzowych jest uwarunkowana wcześniejszymi spływami. Starsze spływy powodowały obniżenie wartości progowych opadów niezbędnych do powstania późniejszych zdarzeń. Starsze spływy, które prowadziły do rozcinania żlebów i usuwania roślinności, predysponowały formowanie młodszych przy obniżonych wartościach progowych.