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Some Key Topographic and Material Controls on Debris Flows in Scotland

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Abstract

Debris flow phenomena were investigated at six study sites across upland Scotland using a combination of laboratory and field based analyses. In agreement with previous research, higher spatial frequencies of debris-flow paths were measured in areas underlain by coarse-grained intrusive igneous and arenaceous sedimentary bedrocks compared to metamorphic and extrusive igneous geologies. A strong relationship between critical state friction angle of sampled initiation zone soils and spatial frequency of debris-flow paths suggests this trend is attributable to generally lower shear strengths in sandier hillslope material generated from coarser grained bedrocks. Topographic controls on debris flow susceptibility are demonstrated by higher numbers of debris-flow paths at sites with persistently steep upper slopes (≥30°) and a higher occurrence of potential initiation zones. Strong correlation between debris flow magnitude and slope length show that longer mass movements tend to produce higher volumes of material and terminal deposits which travel further at the slope foot. In the cases studied here this reflects greater opportunity for accumulation of fresh material during the transport phase, particularly in the case of long channelised flows. The highest levels of hazard are likely to occur where these topographic and material characteristics conducive to heightened susceptibility and magnitude coincide.

KEY WORDS: landslides, debris flow, geohazards, hillslope geomorphology

1. Introduction

Debris flows are a type of landslide characterised by the rapid downslope movement of partially saturated, well graded, hillslope material (Ballantyne, 2004a). In the Scottish context reported here they are generally initiated as shallow translational landslides which quickly make the transition from sliding to flow mass movements (Iverson, 1997; Ballantyne, 2004a; Hungr, 2005; Iverson et al., 2010). Debris flows are categorised by the physical setting in which they occur, either on open hillsides (known as *hillslope debris flows* or *debris avalanches*) or within bedrock gullies or stream channels (referred to as *channelised debris flows*) (Ballantyne, 2004a; Hungr, 2005). However, these classifications are sometimes hard to distinguish as hillslope flows frequently propagate into stream channels and debris flows generated in channels often spread onto unconfined areas of open ground. Furthermore, where successive hillslope flows follow the same route, they tend to gradually erode gullies into the underlying slope material (Ballantyne 2004a).

Debris flows occur frequently in areas of high relief where an adequate topographic gradient and a covering of loose or weak hillslope material exists (Innes, 1983a; Ballantyne, 1986, 2004a; Iverson, 1997). Thus, these landslides are common in upland areas around the world, often presenting as a serious geological hazard which has caused the loss of numerous lives (e.g. Lopez et al., 2003; Fernandes et al., 2004; Chen & Petley, 2005; Petley et al., 2007; Wooten et al., 2008; Hilker et al., 2009; Yune et al., 2013). In Scotland, the magnitude of individual debris flows is usually significantly smaller than those in mountainous areas of higher relief (Innes, 1985). For example, whilst a channelised debris flow at Glen Ogle in 2004 encompassing approximately 8500 m^3 of material was considered an exceptionally large event in a Scottish context (Milne et al., 2009), debris flows with volumes of several 100,000 m^3 have been known to occur in the Swiss Alps (Rickenmann & Zimmerman, 1993). Nevertheless, several Scottish events in recent years have resulted in considerable socio-economic impact caused by damage to infrastructure and disruption to the road and rail networks (Ballantyne, 2004a; Nettleton et al., 2005; Winter et al., 2006; Milne et al., 2009; Milne et al., 2010; BGS, 2015a).

Debris flows are typically triggered by a rapid input of water into the slope material during rainstorms. This causes the phreatic surface to rise leading to an increase in pore-water pressures, a reduction in effective stress and consequential slope instability (Ballantyne, 1986). In some cases, failure can also be triggered by loss of soil suction resulting from the downward migration of a rain induced wetting front (Fourie, 1996; Springman et al., 2003). The characteristics of preceding rainfall and the associated influence on antecedent soil moisture content also exerts a fundamental control on debris flow initiation (Church and Miles 1987; Ballantyne 2004a). Accordingly, the optimal conditions for the generation of debris flows occur when high magnitude rainfall follows a period of wet weather (Winter et al., 2005). However, although individual flows are generally triggered by a meteorologically-induced infiltration of water into the slope material, the susceptibility of any given hillslope is determined by a complex and variable suite of factors. In particular, material properties such as particle size distribution, permeability and shear strength, and geometric properties such as slope gradient can be considered as key and universal controls on debris flow susceptibility. For example, it is widely acknowledged that slope gradients in excess of 20° are normally a prerequisite for debris flow occurrence (Hungr, 2005) and observations in Scotland have shown that slopes with coarse-grained granite and clastic sedimentary lithologies (which are thus overlain by sandier, more permeable, non-cohesive soils) generally display the highest spatial frequencies of debris flow landslides (Ballantyne, 1981, 1986, 2004a; Innes, 1983a).

The socio-economic impacts and risk of serious injury and fatalities from debris flows demonstrate the need for optimal understanding of the contributory factors to landslide susceptibility/magnitude to inform effective geohazard management. In this paper the material and topographic controls on debris flow activity are investigated through examining debris flow phenomena at six study sites in Scotland using a combination of laboratory and field based analysis. It is acknowledged that debris flow is a complex phenomenon that has site specific and regional controls on initiation and magnitude. Rather than considering detailed scenarios, this paper highlights more general controlling parameters that can be used to assess susceptibility to similar hazardous debris flow events. Accordingly, it is intended that the research will improve understanding of the debris flow process and assist the management of the debris flow geohazard both in Scotland and in similar mountainous regions.

2. Study Sites

Six study sites with differing lithologies were chosen for investigation of the topographic and material controls on debris flow activity. The study sites were selected where debris flow activity has been recorded in the past and are situated across upland Scotland to avoid bias towards areas with higher average annual precipitation in the west of the country (Fig. 1). The physical characteristics of each site including citations for previous debris flow events are summarised in Table 1. Further details, including geomorphological maps showing the distribution of debris flows at each site, have been presented by Milne, 2008. It has been suggested that the underlying lithology exerts a critical control on the particle size distribution of the hillslope material at each site (Ballantyne, 2004a). This is because mountain soils are either formed directly by weathering of the underlying bedrock or, in the case of glacial drift and niveo-aeolian deposits, from the erosion of nearby bedrock and the reworking of pre-existing deposits of local provenance (Trenter, 1999; Ballantyne and Morrocco, 2006). The sites have been ranked from 1 to 6 on the basis of particle size distribution or how coarse (in terms of sand content) the sampled hillslope material is (see section 4) with An Teallach (1) having the highest sand content and Glen Ogle (6) having the least sand content. The sites are tabulated in this order for the rest of the paper.

The most northerly study site is located in the An Teallach mountain massif on the north-facing slopes of a peak known as Glas Mheall Mor (1). It is underlain entirely by Torridonian Sandstone (Table 1) with slopes mantled by talus and sandy niveo-aeolian deposits derived from adjacent mountain plateaux which are also underlain by Torridonian Sandstone (Ballantyne and Eckford, 1984; Ballantyne and Whittington, 1987; Ballantyne, 1993; Ballantyne and Morrocco, 2006).

The Lairig Ghru (2) is a steep sided glacial breach valley incised through the coarse-grained granite of the Cairngorm Mountains between the summits of Braeriach (1296 mAOD) and Ben MacDui (1309 mAOD) (Luckman, 1992). The study site comprises a 1 kilometre stretch of the west facing slope of the pass. At this location the slopes are largely covered by exposed talus and sandy regolith which has been reworked by debris flow activity and snow avalanching (Luckman, 1992; Ballantyne, 2004a).

The Pass of Drumochter (3) is a 500 m wide mountain pass and an important transport route as highlighted by the presence of a major trunk road and a railway line. The underlying bedrock predominantly consists of psammitic schist whilst the slopes are predominantly mantled with talus and sandy glacial till (Lukas, 2002; Ballantyne, 2004b).

The lithology at Glamaig (4), a steep sided mountain in the Western Red Hills on the Isle of Skye, comprises both granite (4a), which underlies debris flow initiation zones on the eastern side of the mountain, and basalt (4b) underlying the slopes to the west (Bell and Williamson, 2002). Consequently, debris flow activity in soils developed over both fine-grained basalt and coarse-grained granite can be investigated in close proximity at the site.

Mill Glen (5) is situated in the Ochil hills, an upland area comprised of comparatively resistant Devonian extrusive lavas within the generally low-lying Midland Valley geological province of Scotland. The study site is located in the upper reaches of the glen and is completely underlain by andesitic lavas (Francis et al. 1970; Jenkins et al., 1988). The drift geology comprises of glacial till ubiquitously overlain by Holocene brown forest soils (Jenkins et al. 1988).

Glen Ogle (6) is dominantly underlain by Upper Dalradian metamorphic rocks, particularly schistose semipelites (BGS, 2015b). The valley walls are steep, frequently exhibiting rocky crags and rising to altitudes of 707 m and 719 m AOD on the west and east side of the glen respectively. The soil on the slopes is characterised by glacial till with an almost ubiquitous upper horizon of blanket peat. The debris flows investigated at Glen Ogle were all initiated by a rainstorm with a peak intensity of *c*.20mm hr^{-1} on the 18th of August 2004, generating more than thirty debris flows at the site. Two of these crossed the A85 trunk road during the event, leading to a helicopter airlift rescue of 57 occupants from 20 trapped vehicles (Winter et al., 2006; Milne et al., 2009).

3. Methodology

3.1 Site characterisation

At each study site walkovers were carried out to investigate the dominant geomorphological characteristics with particular emphasis on the nature and distribution of debris flows. A measure of relative susceptibility to debris flow activity at each site was established by dividing the number of observed debris-flow paths by the cross-slope distance along the contour closest to the initiation zones to give a *spatial frequency of debris-flow paths per kilometre* (Fig. 2) (after Curry, 1998; Ballantyne, 2004a; MacNaughton, 2004). The studied cross-slope distance was restricted to hillsides of topographic similarity delimited by geomorphic constraints such as rock slopes, stream channels and mountain passes. For example, the studied hillslope in Fig. 2 (the Lairig Ghru) is a rectilinear slope constrained between a cliff to the north and a stream to the south. A *debris-flow path* encompasses the initiation, transport and deposition zones of the mass movement (Hungr, 2005) and can be identified in the field by the presence of associated landforms such as source landslide scars, debris tracks and flow deposits. Successive flows can follow the same debris-flow path often burying evidence of earlier events (Luckman, 1992; Ballantyne, 2004a). It is important to acknowledge that the measure of debris-flow path spatial frequency used in this research does not separately count individual stacked debris flow events which have occurred along the same debris-flow path or consider the recurrence interval, or temporal frequency, of flow activity. Thus, the true propensity to debris flow activity will be underestimated at sites where there is a higher recurrence of successive flows following the same route downslope. Nevertheless, in the absence of an array of stratigraphic, radiocarbon, dendrochronological and historical data to permit accurate calculation of temporal debris flow frequency (Jakob, 2005) by quantifying the incidence of landforms associated with flow activity this approach provides a useful assessment of comparative susceptibility at each study site .

Along with field characterisation the sites had also to be considered in terms of varying rainfall regimes characterised by the strong rainfall gradient in Scotland which results in higher rainfall totals in the western highlands compared to uplands in the east of the country (Table 1). The influence of rainfall was considered by normalising the spatial frequency of debris flows per km at each study site with 1961-1990 average annual rainfall extrapolated from the Flood Estimation Handbook (Institute of Hydrology, 1999). Although the 30-year mean does not necessarily represent the frequency of high magnitude rainfall events which can trigger debris flow, it was considered appropriate for normalisation due to the critical importance of antecedent rainfall as a prerequisite for optimal debris flow generation (Church and Miles 1987; Ballantyne 2004a; Winter, 2005).

3.2 Sampling and Geometric Characterisation

A total of 9 debris-flow paths were chosen for detailed measurement of geometric parameters of which 7 had soil sampled from their initiation zones for investigation of geotechnical properties in the laboratory. Geometric characteristics were measured using a 30 m measuring tape and an Abney Level to determine slope profile gradients. The width, length and depth of slope-foot deposits were measured to allow calculation of the volume of debris involved in each flow. In contrast to the determination of spatial frequency (Table 2) effort was made to measure the most recent deposits and initiation slides so that only the geometric properties of individual debris flow events were characterised. These were differentiated by the extent of vegetation recolonisation and lichen cover relative to older deposits and scars as well as by excavation through debris fans to assess depositional history. Geometric parameters investigated in this research are defined in Fig. 3.

Slope material was sampled from exposed profiles at the main scarp of translational landslides which had initiated debris flows. Sampling was restricted to initiating landslides on open hillslopes or at gully heads which were identified as having occurred due to hydro-meteorological induced changes in pore water pressure rather than on gully walls where fluvial erosion at the toe of the slope may have triggered failure (Innes, 1983a). It was also ensured that the sampled initiating landslides had physical characteristics (e.g. stratigraphy, gradient, depth of failure plane) generally typical of debris flow generating slope failures at each site. Before sampling, the main scarp was cleared back for approximately 100 mm using a spade to avoid taking material from the surface which may have been subject to removal of smaller particles by wind and run-off. The depth of the soil profile was recorded and mineral soil corresponding as closely as possible with the position of the failure plane was sampled. The *in situ* density of slope material at debris flow initiation zones, required for preparation of test specimens in the lab, was determined directly in the field at the time of sampling. This involved cutting a horizontal bench into the exposed soil profile and removing a sample from the resulting flat surface using a trowel. To allow accurate determination of moisture content at the time of sampling, the soil specimen was immediately placed in a sealed, air-tight container for measurement on return to the laboratory (Head, 1982). A thin plastic film was then placed in the resultant void into which a measured quantity of water was decanted to determine the volume of the sample. The *in situ* density of the soil was subsequently calculated by dividing the mass of the sample by its volume. This approach was used as an alternative to the sand replacement method of measuring density (BSI, 1990) due to the remoteness and steepness of sampling areas and the need to minimise the amount and weight of field equipment (Milne et al., 2009).

3.3 Laboratory Analyses

Sampled soils were analysed in the laboratory to determine effective stress parameters and permeability; characteristics which are essential in determining the susceptibility of a slope to debris flow (Selby, 1993). All the sampled soils were observed to be matrix-dominated (whereby coarser clastic material larger than 2 mm is entirely supported within finer grained particles). Accordingly, as the shear strength and permeability are determined by the supporting matrix in such soils, all the tests in the laboratory investigation were carried out on the < 2mm fraction (Fannin et al., 2005).

The constant-head permeability test (BSI, 1990) was used to determine the permeability of the hillslope material in the laboratory. These tests were carried out on 51 mm diameter by 40 mm high soil specimens using a small permeameter cell with dimensions sufficient to allow for accurate determination of permeability as stipulated in BS 1377-4 (BSI, 1990). Shear strength parameters (apparent cohesion (c') and critical state friction angle (φ')) were measured from 25mm by 60mm^2 specimens in a direct shear box following the procedures detailed in BS 1377 (BSI, 1990). Shear box tests were carried out under drained conditions and under normal loads representing the range of low effective stresses encountered at the sample sites (between 2 and 13 kPa). Shear box and permeability tests were carried out on disturbed soil specimens which included the organic faction. For testing, these were reconstituted to match the water content and density initially encountered *in situ* at the sample sites. To achieve this, the samples were air dried and then re-wetted before being directly hand tamped into the shear box and permeameter apparatus to match the density measured at the sampled main scarp. This approach may not represent potential *in situ* structural controls on strength and permeability such as roots, soil pipes or predisposal to failure along existing failure planes. However, it does allow the soils to be classified and compared and generates parameters that give insights to key material controls. For instance, generating effective stress parameters allows exploration of the position of the water table, existing or predisposed failure planes and soil suctions in a rudimentary manner through slope stability analysis. In addition, detailed investigation of sampled profiles was carried out in the field so that the influence of such controls on initiation could be considered further if present.

Classification of the organic content of soil matrices was also carried out using the loss on ignition technique (BSI, 1990), and particle size distribution analysed using a Coulter LS250 laser granulometer following removal of the organic faction by treatment with hydrogen peroxide.

4. Results

The measured spatial frequency of debris-flow paths per cross-slope kilometre at each study site is summarised in Table 2. This demonstrates that the highest number of debris-flow paths was observed on the granitic slopes of Glamaig (4a) and the Lairig Ghru (2) whilst the lowest were measured at Glen Ogle (6) and Mill Glen (5). After normalisation for the effect of varying rainfall the study sites at An Teallach (1), Glamaig (4a, 4b) and the Lairig Ghru (2) experience greater reductions in frequency of debris-flow paths due to higher average annual rainfall totals at these locations (Table 3). In spite of this, a generic trend in which slopes underlain by coarse grained lithologies are seen to yield a greater number of debris-flow paths than slopes underlain by finer grained lithologies endures in the data after normalisation.

Observations in the field have also demonstrated that higher numbers of debris-flow paths tend to occur at sites where the topography is characterised by persistently steep (≥30°), rectilinear upper slopes with a high incidence of potential debris flow initiation zones in the form of depressions, gullies and passages through crags. This topography is particularly apparent at the Lairig Ghru (2) and on both the basaltic and granitic slopes of Glamaig (4a, 4b) (Fig. 4). At these sites, the hillslopes are extensively scarred by mass movement with almost every identifiable potential initiation zone having yielded a debris flow. It can therefore be inferred that these study sites have likely reached a maximum spatial frequency of debris-flow paths. By comparison the Drumochter (3) and An Teallach (1) study sites have persistently steep, rectilinear slopes but with fewer potential initiation zones whereas the Glen Ogle (6) and Mill Glen (5) study sites are marked by more undulating topography and a comparatively restricted distribution of steep slopes.

Measurements related to the geometric properties of the sampled debris flows are summarised in Table 3. Of the sampled debris flows seven can be categorized as hillslope flows and two as channelised flows. Further details of the geomorphological characteristics of the sampled debris-flow paths are provided using the attributes outlined by Corominas (1996) in which symbols are assigned to commonly observed features associated with debris flows (Table 3). Several of the sampled debris flows have undergone what Corominas (1996) refers to as *channelling* (assigned the symbol "h") in which "debris streaming and confinement" has occurred within a topographic conduit during the transport phase. In the case of several of the sampled hillslope debris flows (1a, 1b, 2, 5) this took place in shallow gullies eroded into the hillside by successive flows following the same path (Fig. 5), whereas in the two sample channelised debris flows (6a, 6b) this occurred within bedrock-incised stream channels. Of the four hillslope flows which conduit through gullies eroded into hillside, two pass through *active*, comparatively freshly-eroded gullies (1a, 2) whereas the other two are characterised by relict (stabilised) gullies which have become extensively vegetated due to inactivity (1b, 5) (Table 3). *Bends* (b) in the transport zone formed by topographic obstacles such as rock outcrops and sinuations in gullies which lead to changes in flow direction of less than 60˚ were encountered in several sampled flows (1a, 1b, 3, 6a, 6b) and *deflection* (d) where obstacles lead changes in flow direction greater than 60˚ was encountered in one of the channelised debris flows (6a). Conversely, two sampled hillslope flows (4a, 4b) travel down slope *unobstructed* (u) by any topographic obstacles and three hillslope flows (2, 4a, 4b) travel over talus and colluvium referred to as *scree* (s) using Corominas' (1996) terminology. In the deposition zone, several of the sampled flows (1a, 1b, 2, 3, 4a) displayed evidence of *toe thickening* (t) with the "piling up" of successive, viscous debris fronts towards the distal end of the debris-flow path. Debris flow deposits were *free spreading* (e) with unhindered lateral and downward expansion in the deposition zone at the remainder of the flows (4b, 5, 6a, 6b) (Table 3).

Slope material properties from sampled soils corresponding with the failure plane at 7 debris flow initiation zones are summarised in Table 4. The debris flows sampled in the field were triggered as shallow translational landslides in thin mountain soils (0.3 - 0.6 m). Soil profiles at the main scarps revealed that at Glen Ogle 1 (6a), Mill Glen (5), the Lairig Ghru (2) and Drumochter (3) the failure plane exists at depth within the superficial soil cover just above the interface with underlying bedrock. This suggests that despite the proximity of the failures to the bedrock, the properties of the soil are the primary material control on landslide initiation rather lower shear strength between dissimilar materials at the soil-rock interface. The position of these failure planes is also indicative of landslide initiation by a rising phreatic surface leading to failure close to the soil-rock interface (Brooks & Richards, 1994), a mechanism which would be facilitated by the interface acting as an aquatard and a flow path for groundwater. Alternatively, in the initiation zone of the An Teallach 1(1a) debris flow, the failure plane was observed closer to the surface at a depth of 300 mm within an 800 mm thick mantle of niveo-aeolian sand deposits. Similarly, failure planes in the sampled debris flow initiation zones at Glamaig (4a, 4b) exist close to the surface at or just above the interface between the soil and the underlying, free draining, relict talus (the roughness of the talus surface ensuring that failure occurred within the overlying soil). An exposed section through the talus down to the underlying bedrock in a gully wall observed on the granite side of Glamaig (4a) indicates that the thickness of the talus at the site is approximately 1 to 1.5 metres thick above the underlying bedrock. Therefore, the close proximity of the slip plane to the surface at these sites (1a, 4a, 4b) suggests failure in unsaturated soils where the downward migration of a wetting front results in loss of suction and failure at a shallow depth in the soil profile (Fourie, 1996; Springman *et al*. 2003).

Loss on ignition tests indicate that soil sampled from the initiation zones on both the basalt and granite parts of Glamaig (4a, 4b) and the Pass of Drumochter (3) have high organic content, the material at Mill Glen (5) and at the Lairig Ghru (2) has medium organic content, and that from An Teallach (1a) and Glen Ogle (6a) has low organic content (BSI, 1999). The most permeable soils were those at An Teallach (1a) and the Lairig Ghru (2) whilst the Mill Glen soil (5) was found to be the least permeable. All of the permeability coefficients are typical of those expected for coarse sands, except for Mill Glen (5) which has a permeability comparable with a fine sand (Selby, 1993). The critical state friction angles (φ') of the tested soils ranged between 29.1º for the Pass of Drumochter (3) to 47.5º for Mill Glen (5) (Table 4). Particle size analysis showed that all of the sampled matrices were found to be dominated by sand-sized particles with each soil comprising upwards of 79.5% sand. However, samples collected from soils yielded from schistose and extrusive igneous bedrocks generally displayed a greater component of silt-sized particles than those developed over granite and Torridonian sandstone (Table 5; Fig. 6).

5. Discussion

In agreement with observations from previous research (Ballantyne, 1981, 1986, 2004a), higher numbers of debris-flow paths were observed on hillslopes underlain by sandstone (1) and granitic bedrocks (2, 4a) compared to those with schist (6) and extrusive lava lithologies (5, 4b) (Table 2). This trend largely persists when the data are normalised for site-specific average annual rainfall totals despite the fact that the study site locations underlain by granite and sandstone have higher average annual rainfall totals and can accordingly be considered meteorologically more predisposed to debris flow activity. However, it was found that the normalised debris flow density at Drumochter (3), a site with a schistose lithology, is slightly greater than An Teallach (1) which is underlain by Torridonian sandstone. This is most likely the consequence of the relatively coarse nature of soil yielded from the psammitic schist at Drumochter (Innes, 1986) leading to lower critical state friction angles (Milne et al. 2012; Table 4).

Observations have also demonstrated the importance of slope geometry and morphology in determining debris flow susceptibility. Sites with persistently steep (≥30°), rectilinear upper slopes are subject to greater shear stresses whilst depressions, gullies and passages through rocky crags facilitate concentration of hillslope runoff and subsurface drainage leading to localised soil saturation, reduced effective stress and instability (Reneau and Dietrich, 1987; Luckman, 1992; Fannin and Rollerson, 1993; Palacios et al. 2003; Fernandes et al. 2004; Heald and Parsons, 2005; Tarolli et al. 2008). Accordingly, a combination of these characteristics will increase the likelihood of debris flow activity. For example, at the Glamaig study site (4) the occurrence of such topography results in a markedly higher spatial frequency of debris-flow paths on the basalt side of the mountain (4b) than that experienced at the other study sites with fine-grained extrusive igneous or schistose lithologies (Table 2; Fig. 4).

To gain further understanding of the importance of topographic and material controls on debris flow susceptibility the relationships between the primary material controls on landslide initiation (permeability and frictional strength), measured debris flow geometric parameters and normalised spatial frequency of debris-flow paths were analysed. It was found that there is a strong relationship between the normalised spatial frequency of debris flows and the critical state friction angle at sampled initiation zones. This is shown in Fig. 7 where the normalised spatial frequency of debris flows is plotted against the factor of safety for a dry infinite slope which is essentially the critical state friction angle (φ') of the sample source area divided by the slope angle at the source (topographic control β_i) (e.g. Atkinson, 2007) for an infinite slope:

$$\text{Factor of safety, } F = \frac{\tan\phi'}{\tan\beta_i}\left[1 - \frac{\gamma_w}{\gamma}\right] \quad (1)$$

where γ_w is the unit weight of water and γ is the unit weight of the soil. For a dry infinite slope equation 1 reduces to:

Factor of safety, $F = \frac{\tan \phi'}{\tan \beta_i}$ (2)

The analysis shows that if the slopes are assumed to be dry, many of the source area failures have factors of safety that exceed 1, the minimum value that indicates slope stability. Indeed several have factors of safety exceeding 1.1 to 1.2, values that are often considered adequate for the design of engineered slopes. However, if a worst case scenario is assumed where the slope is completely waterlogged with steady state seepage parallel to the slope, the effect is that the stability of all the initiation zones drops significantly below a factor of safety of 1. This emphasizes that the stability of the slopes is significantly influenced by the site specific groundwater regime and effective stress profile. The data also demonstrates that the steep initiation zones at several of the study sites - Glamaig (granite, 4a), Lairig Ghru (2) and Pass of Drumochter (5) - are inherently unstable with safety factors less than 1 irrespective of metrological preconditioning and the height of the phreatic surface. This suggests that factors other than critical state friction angle may be providing a stabilising effect on these hillslopes, such as soil suctions generated by negative pressures in the smaller pore spaces of high organic content soils at Glamaig (granite, 4a) and the Pass of Drumochter (3), and an observed presence of roots through the soil profile at the Lairig Ghru (2).

It may also be expected that the results shown in Fig. 7 could be influenced by other factors such as the position of the failure plane relative to contrasting materials such as bedrock. However, in the cases where failures occur in the superficial material just above the bedrock interface – the Lairig Ghru (2), the Pass of Drumochter (3) Mill Glen (5), and Glen Ogle (6a) - there is no apparent influence on the spatial frequency of debris-flow paths with both Mill Glen and Glen Ogle displaying the lowest spatial frequency whilst the Lairig Ghru and the Pass of Drumochter have high spatial frequencies. Table 4 shows typical values of basic friction angle for the corresponding rock type (Barton & Choubey, 1977; Ziogos et al., 2015). If the factor of safety is again calculated using these values, no direct correlation is found with the spatial frequency of debris flows, although it is acknowledged that where the basic rock friction angle is significantly lower than the soil friction angle (e.g. the Pass of Drumochter (3) and Glen Ogle (6a)) this may represent a potential contributing factor for other debris flows at these sites. The general lack of correlation is consistent with field observations where failure was observed just above the bedrock layer in the superficial material suggesting soil-soil shear strength predominates. This is consistent with the findings of others who showed that it is the relative roughness of the two materials that dictates if failure will occur at the interface or in the soil (Jardine et al., 1993). Therefore, the strong relationship in Fig. 7 suggests that the simple assessment of landslide susceptibility based upon slope gradient and critical state friction angle offers a useful first evaluation of debris flow potential without the need for analysis of complex groundwater regimes which may not be a practical proposition in assessing the debris flow geohazard over an extended area (e.g. the risk to the road network through areas of high relief). The analysis also helps to highlight other factors that are important in determining site-specific slope stability such as those discussed above.

In contrast, the relationship between the frequency of debris-flow paths and the permeability of the sampled soils was found to be poor. Consequently, if the material parameters at sampled initiation zones are typical of soil mantling upper slopes at the study sites, the data suggests that soil strength coupled with initiation zone topography exerts a more important control than permeability on debris flow susceptibility. Thus, the trend observed in this and previous research (Ballantyne, 1981, 1986, 2004a) in which slopes underlain by coarse grained granite and sandstone lithologies generally present a higher frequency of debris-flow paths, may be attributed to the sandier sediments generated from these lithologies having fewer inter-particle contact points (a lower coordination number) and a lower critical state friction angle than more poorly sorted matrixes generated from extrusive igneous and schistose lithologies (cf. Milne et al., 2012). However, in interpreting the relationship between debris-flow path frequency and permeability evident in the above data-set, it is important to recognise that the high organic contents of some of the sampled soils (Table 4) will reduce the permeability. Infiltration into the slope material will also be impeded in stratified soil profiles where organic or peaty horizons overlie the mineral layer in which failure planes develop (Warburton et al. 2004). Such anisotropic conditions were encountered at Glen Ogle (6a) (peat overlying a layer of till), The Pass of Drumochter (3) (peaty horizon overlying organic rich mineral soil) and at Mill Glen (5) (Brown Forest Soil overlying till). At sites where the soils have low to medium organic content and are characterised by isotropic stratigraphies (such as at An Teallach (1) and the Lairig Ghru (2)), permeability and infiltration rates determined by the matrix particle size distribution are likely to exert a critical control on hillslope susceptibility to debris flow (Ballantyne, 1986). However, although organic soils have relatively low densities, they can potentially maintain relatively high soil moisture content. Therefore, although the lower permeability of overlying organic soil horizons may reduce a slope's sensitivity to intense rainstorms by acting as a barrier to rapid inundation, their capacity for moisture retention can also reduce slope stability by increasing the downslope component of loading.

The relationships between the volume of the debris flow events and *slope length* (L_{it}), is strongly correlated with debris-flow paths where the slope above the deposition zone (encompassing the initiation and transport zones) is longer tending to yield higher volumes of debris deposits (Fig. 8). As well as influencing the deposit volume, longer debris flows also tend to produce deposits which travel further at the slope foot (*deposit length*, L_d) as demonstrated by the strong correlation between these geometric characteristics (Fig. 9). This data varies from the more commonly adopted vertical drop (H) and travel distance (L) (Corominas, 1996) which encompasses a measure of the entire debris-flow path from the main scarp to the terminus of the deposition zone (Fig. 10). By adopting analysis based purely upon the geometry of initiation and transport zones (i.e. ignoring the deposition zone) it is possible to predict the likely volume and runout of material based upon geometry above the slope-foot where infrastructure at risk is typically situated. This then lends itself to automated hazard identification using Geographic Information Systems (GIS) in which slope dimensions can easily be defined.

It is important to recognise that the number of debris flows in the data-set could be supplemented in future research to provide further confidence in the relationships presented. Nevertheless, strong correlations between debris flow geometry and magnitude have been identified elsewhere in the world (Corominas, 1996; Legros, 2002; Rickenmann, 2005) underlining the universal importance of geometric parameters in understanding the debris flow geohazard. Longer debris flows provide greater opportunity for the accumulation of fresh material particularly in the case of long channelised flows, such as those sampled at Glen Ogle (6a, 6b). In such debris flows the volume of the mass movement is augmented during the transport phase by sediment entrained from the channel floor and incorporated from channel wall failures during the event (Hungr et al. 1984; Wieczorek et al. 2000; D'Agostino and Marchi, 2003; Jakob et al. 2005; Milne et al. 2010; Iverson et al. 2011). This accumulation (also known as bulking) is demonstrated in Table 3 where marked increases in volume were recorded in the Glen Ogle channelised debris flow events (6a, 6b). However, where hillslope flows are characterised by debris-flow paths with active, comparatively freshly-eroded gullies (such as at the Lairig Ghru (2) and An Teallach 1(1a)) a potential source of, loose, mobilisable sediment exists in the transport zone (Ballantyne 2004b). This also presents an opportunity for the occurrence of accumulative debris flow events as is apparent in the 400% and 354% bulking from the Lairig Ghru (2) and An Teallach 1 (1a) debris flows respectively (Table 3; Fig. 5). However, it is important to acknowledge that in these cases this is likely to represent an upper limit for bulking as, due to difficulty in differentiating the freshest debris deposits at these sites, the measured volume of material in the deposition zone may have been the product of more than one debris flow event. Alternatively, those hillslope flows which are unobstructed (4a,4b), don't experience channelling (3) or pass through relict, stabilised gullies (1b, 5) have accumulated much less material from the transport phase of the mass movement, in one case (3) losing volume during propagation downslope (Table 3) .

It is notable that the relationship between H/L and volume of slope foot deposits is similar to that found by Corominas (1996) (Fig. 10). However, three events (4a, 2 and 6a) appear to produce significantly more material than predicted by Corominas (1996). For example, for the debris flow sampled on the granitic slopes of Glamaig (4a) it would appear that the H/L relationship fails to adequately capture the characteristics of the flow as it has a particularly high angle of reach, α (tan α = H/L) and a relatively long slope length, (L_{it}) of 194 m. In contrast, the Mill Glen flow (5) has a very similar angle of reach to the Glamaig (granite, 4a) flow but only has a slope length of 64 m. This is also the case for the Lairig Ghru (2) and Glen Ogle 1 (6a) debris flows when they are compared to flows of the same typology with similar angles of reach. This suggests that in debris flows of the magnitude studied in this paper, the transport zone length has greater influence in terms of accumulation of material and that using the debris flow slope length above the deposition zone (L_{it}) to predict debris flow volume (as shown in Fig. 8) appears to be more appropriate than using H/L in such cases. It should be noted that the potential for higher reach angle events to create greater volumes of debris shown here (2, 4a, 6a) than predicted by Corominas (1996) is likely to be a function of the differences in data sets where Corominas (1996) was fitting a larger number of landslide events incorporating flows typically an order of magnitude greater than Scottish debris flows.

The geometric and material controls on the debris flow process observed in this research have several implications for the management of the debris flow geohazard. Accurate identification of areas where slope foot infrastructure is most likely to be affected by debris flow is a crucial to inform mitigation measures that can lessen the severity of the hazard (Winter et al. 2006). The observations in this research have highlighted that areas characterised by persistently steep upper slopes (≥ 30°) in conjunction with a high frequency of potential initiation zones (denoted by features such as hillslope concavities, gully heads and rockslope conduits which facilitate a localised accumulation of water) are more likely to yield a higher frequency of debris-flow paths. Longer debris flow slopes (L_{it}) tend to deposit larger volumes (V) of material with longer deposit travel distances (L_d) (Fig. 8, and 8). Accordingly, higher hazard rankings should be attributed to areas of high relief where long, accumulative transport pathways, particularly bedrock incised stream channels (Winter et al., 2006; Milne et al., 2009), provide a connection between upper slope initiation zones and slope foot infrastructure. Alongside these topographic controls on flow susceptibility, this research has underlined the greater tendency to slope failure in areas mantled by the sandier hillslope material which tends to develop over coarse grained intrusive igneous and arenaceous sedimentary lithologies (Ballantyne, 1981, 1986, 2004a) (Table 4). The highest levels of hazard are likely to occur in areas where these material and topographic precursors to optimal flow susceptibility and magnitude coincide. Geohazard mitigation measures, frequently constrained by budgetary constraints, should accordingly be prioritised where at risk infrastructure exists in such locations.

6. Conclusion

Analysis of a series of debris flows sampled from 6 study sites across upland Scotland provides insights into key topographic and material controls on debris flow activity with implications for effective management of the associated geohazard both locally and in similar areas of high relief across the world. In agreement with earlier research on debris flow processes (Ballantyne, 1981, 1986, 2004a; Innes, 1983a) this investigation has shown a greater spatial frequency of slope failure in upland study sites underlain by coarse grained intrusive igneous and arenaceous sedimentary bedrocks, which tend to develop sandier superficial hillslope deposits, compared to those with metamorphic and extrusive igneous geologies, which typically produce sediments with higher silt contents. It was found that there is a strong relationship between critical state friction angle of soils sampled from debris flow initiation zones and the frequency of debris-flow paths. Accordingly, this demonstrates that the observed trend in which granite and sandstone slopes appear to have a greater tendency to debris flow, is likely to be attributable to the sandier sediments generated from these rock types having lower critical state friction angle than more poorly sorted sediment matrixes generated from extrusive igneous and schistose lithologies.

Alongside these material controls on debris flow susceptibility, slope geometry and morphology are shown to have a critical control on debris flow susceptibility. This is apparent from observations of higher debris flow densities tending to occur at sites with persistently steep upper slopes (≥ 30°) and a high frequency of potential debris flow initiation zones in the form of hillslope concavities, gullies and passages through rocky crags which facilitate localised accumulation of hillslope hydrology. The relationship between the volume of these debris flows and the length of the debris-flow path above the deposition zone (*slope length*, L_{it}), is strongly correlated with those mass movements occurring on longer slopes tending to yield a higher volume of debris deposits due to increased potential for bulking as the landslide travels downslope. Furthermore, debris-flow paths where the slope above the deposition zone is longer tend to produce terminal deposits which travel farther at the slope foot. This is particularly the case in long channelised debris flows where the mass movement is augmented by material accumulated from the channel during the transport phase of the flow. Similar strong correlations between flow geometry and magnitude have been identified in flow mass movements elsewhere in the world (Corominas, 1996; Legros, 2002; Rickenmann, 2005) demonstrating the importance of geometric controls on debris flow geohazard potency. The highest levels of hazard are likely to occur in areas where the topographic and material characteristics conducive to heightened susceptibility and magnitude highlighted in this study coincide. Geohazard mitigation measures, frequently constrained by budgetary constraints, should accordingly be prioritised where at risk infrastructure exists in such locations.

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Tables

Table 1. Summary of physical characteristics of study sites and previous research on debris flow activity at each site.

ID	Study Site	Location	Dominant Lithology	Dominant Drift	Maximum Altitude (mAOD)	Mean annual rainfall (m, 1961 -1990)	Literature on site-specific debris flow activity
1	An Teallach	57º49'N, 5º15'W	Torridonian Sandstone	Glacial till, talus, niveo-aeolian deposits, frost shattered detritus	979	2.489	Ballantyne & Eckford, 1984; Ballantyne, 1993
2	Lairig Ghru	57º06'N, W3º42'	Granite	Glacial till, talus, frost shattered detritus.	1083	2.038	Baird & Lewis, 1957; Luckman, 1992; Ballantyne 2004a
3	Drumochter Pass	56º51'N, 4º15'W	Psammitic Schist	Glacial till, niveo-aeolian deposits, talus.	739	1.797	Curry, 2000; Ballantyne, 1981, 2004a, 2004b
4	Glamaig	57º17'N, 6º6'W	Granite and Basalt	Glacial till, talus, frost shattered detritus.	775	* 2.888	Curry, 2000; MacNaughton, 2004
5	Mill Glen	56º10'N, 3º44''W	Andesite	Glacial till	525	1.648	Jenkins *et al*. 1988
6	Glen Ogle	56º24'N, 4º18'W	Mica Schist	Glacial till, blanket peat	719	1.978	Winter *et al*. 2005, 2006; Milne, 2009.

* proxy data from Sgurr Na Coinnich, 25 km ESE of Glamaig

Table 2: Spatial frequency of debris flows at each study site.

ID	Study site	Dominant Lithology	Cross-slope distance (km)	Number of debris-flow paths (n)	Debris flow spatial frequency km^{-1} (n/km)	Debris flow spatial frequency normalised for mean annual rainfall
1	An Teallach	Torridonian sandstone	1.4	34	24.3	9.8
2	Lairig Ghru	Granite	0.9	27	30	14.7
3	Drumochter Pass	Psammitic schist	1.7	31	18.2	10.1
4a	Glamaig	Granite	1	32	32	11.1
4b	Glamaig	Basalt	1	24	24	8.3
5	Mill Glen	Andesite	1.1	6	5.5	3.3
6	Glen Ogle	Schistose semipelites	5	29	5.8	2.9

Table 3. Measured geometric characteristics of sampled Scottish debris flows.

ID	Sampled debris Flow	Debris flow typology	Debris-flow path attributes*	Slope length, L_{it} (m)	Slope height, H_{it} (m)	Deposit length, L_d (m)	Total flow length, $L_{it} + L_d$ (m)	Travel distance, L (m)	Vertical drop, H (m)	Average initiation gradient, β_i, (°)	Average transport gradient, β_t, (°)	Average deposition gradient, β_d, (°)	Initiation volume (m^3)	Approx. deposit volume, V (m^3)	Accumulation (%)
1a	An Teallach 1	Hillslope (active gully)	b,h,t	80	41	23	103	90	50	36	32	21	13	59	354
1b	An Teallach 2	Hillslope (relict gully)	b,h,t	88	50	47	135	117	66	37	34	20	63	90	43
2	Lairig Ghru	Hillslope (active gully)	h,s,t	310	160	75	385	338	177	36	31	14	306	1530	400
3	Drumochter	Hillslope	b,t	403	195	26	429	373	204	30	30	11	604	391	-35
4a	Glamaig (granite)	Hillslope	u,s,t	194	89	37	231	193	126	36	34	29	546	731	34
4b	Glamaig (basalt)	Hillslope	u,s,e	137	66	21	158	139	74	31	29	21	181	183	1
5	Mill Glen	Hillslope (relict gully)	h,e	64	35	9	73	60	40	31	34	29	20	20	0
6a	Glen Ogle 1	Channelised (stream channel)	h,b,d,e	902	417	225	1127	1010	452	21	27	9	280	8500	2936
6b	Glen Ogle 2	Channelised (stream channel)	h,b,e	817	336	142	959	880	357	22	26	6	285	3200	1023

*Definitions after Corominas (1996)

Table 4: Material properties of soils corresponding with the failure plane in sampled debris flow initiation zones.

ID	Debris Flow Initiation Zone	Sampled soil type (corresponding with failure plane)	Main scarp height (m)	Organic content (%)	Moisture content at time of sampling (%)	Dry Density (Mg m^{-3})	Coefficient of Permeability (k, m s^{-1})	Critical state friction angle (φ', °)	Bedrock basic friction angle, (°)
1a	An Teallach 1	Slightly silty SAND	0.3	1	9.4	1.5	6.1×10^{-3}	38	25-35
2	Lairig Ghru	Silty SAND	0.4	6.1	14.1	0.9	4.3×10^{-3}	30.3	29-35
3	Drumochter Pass	Silty SAND	0.5	23.6	42.9	0.6	1.3×10^{-3}	29.1	23-29
4a	Glamaig (granite)	Silty SAND	0.3	25.1	36.9	0.8	1.2×10^{-4}	32.1	31-35
4b	Glamaig (basalt)	Very silty SAND	0.3	21.7	34.4	1	2.1×10^{-4}	39.2	31-38
5	Mill Glen	Very silty SAND	0.4	14	39.4	1	6.8×10^{-6}	47.5	33
6a	Glen Ogle 1	Very silty SAND	0.6	1.7	28.3	1.3	1.2×10^{-3}	42.7	23-29

*Basic rock friction angles from Barton& Choubey (1977) and Ziogos et al (2015).

Table 5. Particle size distribution of soil matrices corresponding with the failure plane in the initiation zones of sampled debris flows (particle size ≤ 2.0 mm).

ID	Sampled debris flow	% Clay (<0.002 mm)	% Silt (0.002 -0.06 mm)	% Sand (0.06 - 2 mm)
1a	An Teallach 1	0.2	2.2	97.6
2	Lairig Ghru	0.3	8.7	91
3	Drumochter Pass	0.7	10.5	88.8
4a	Glamaig (granite)	0.3	11.8	87.8
4b	Glamaig (basalt)	0.3	18.4	81.3
5	Mill Glen	0.3	18.5	81.2
6a	Glen Ogle 1	0.1	20.4	79.5

List of Figures

Fig. 1: Location of study sites across Scotland.

Fig. 2: Plan of the Lairig Ghru study site defining the cross-slope distance for measuring *spatial frequency of debris-flow paths per kilometre*.

Fig. 3: Schematic representation of debris flow anatomy with definitions of geometric components.

Fig. 4: Persistently steep upper slopes and a high incidence of potential debris flow initiation zones in the form of depressions, gullies and passages through rocky crags leading to high debris flow spatial frequencies at the Glamaig (A) and the Lairig Ghru (B) study sites.

Fig. 5: The sampled hillslope flow at the Lairig Ghru (2). Successive flows following the same debris-flow path have eroded a gully into the hillside.

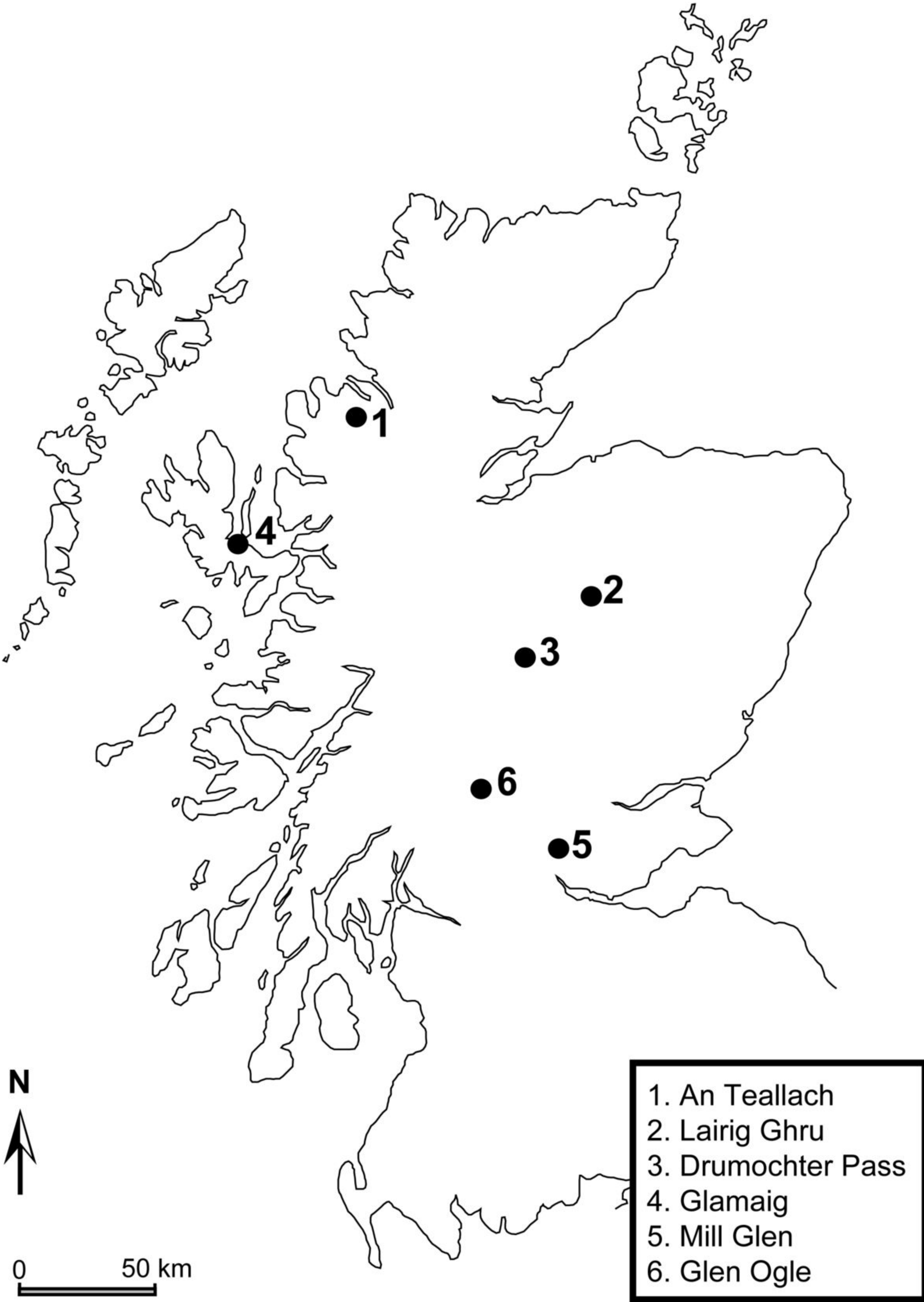
Fig. 6: Particle size distribution curves for sampled soil matrixes (particle size ≤ 2.0 mm) at debris flow initiation zones.

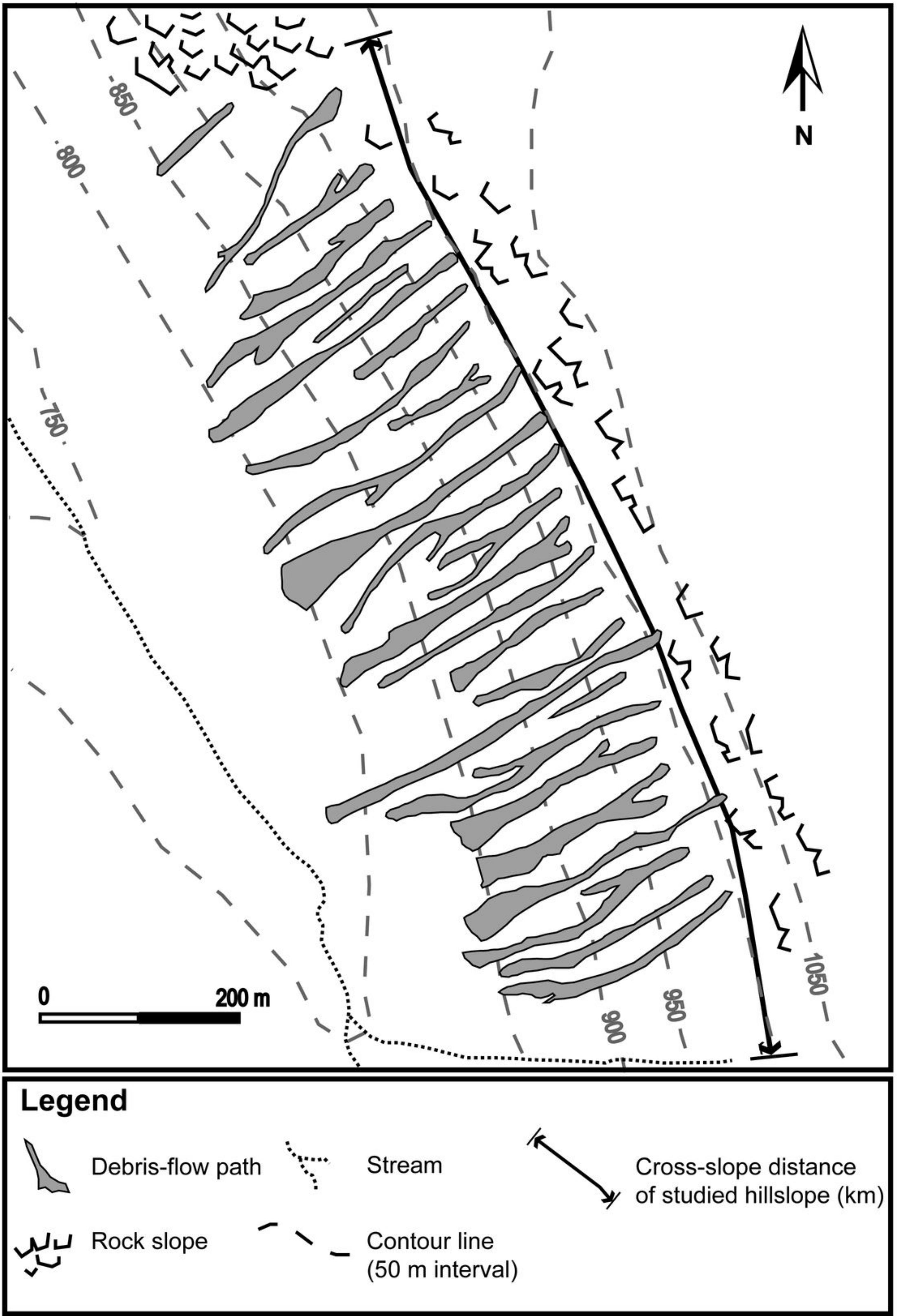
Fig. 7. Normalised debris flow frequency as a factor of both material and topographic controls shown as factor of safety for a dry infinite slope.

Fig. 8. Relationship between slope length and volume of slope foot deposits.

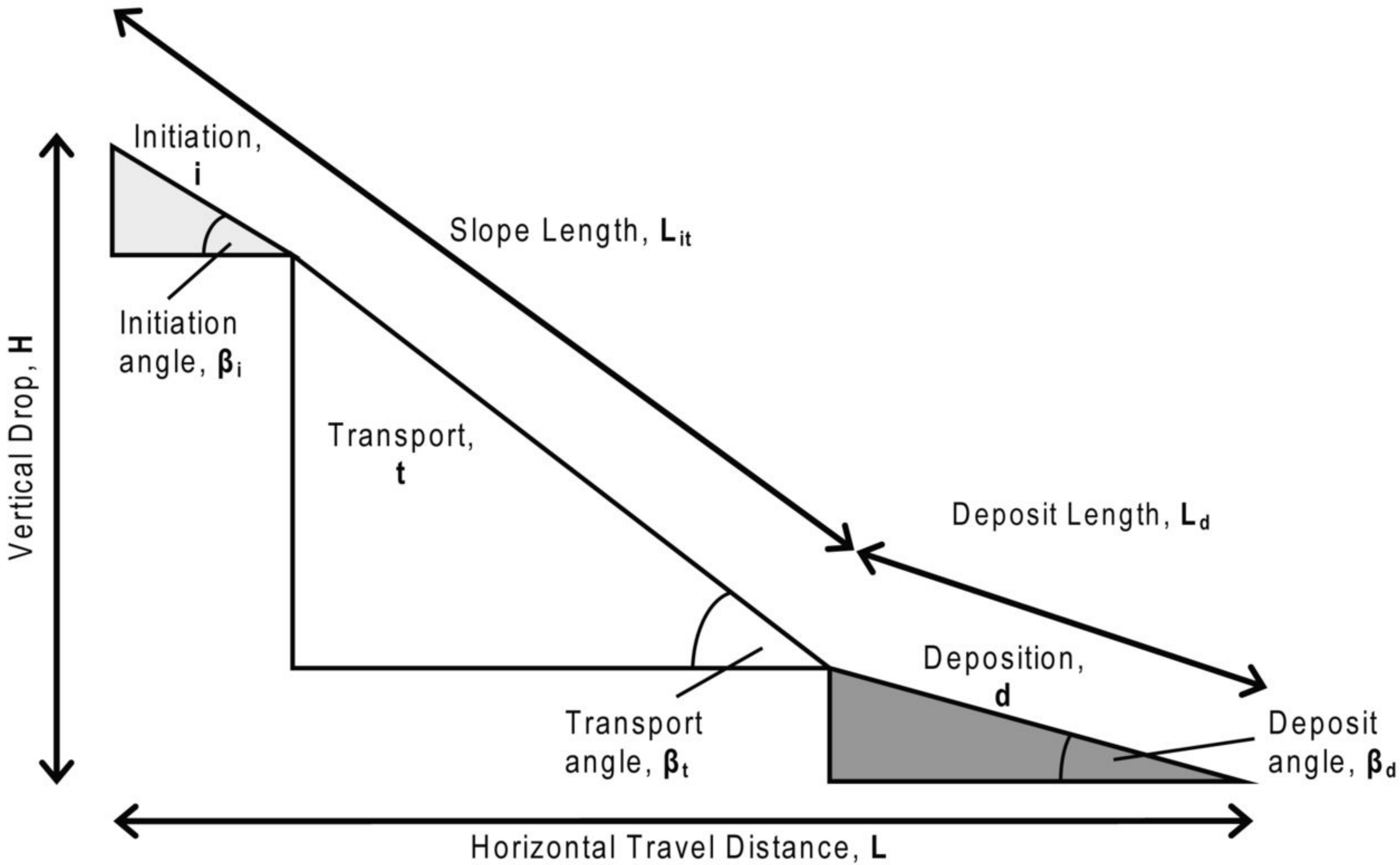
Fig. 9. Relationship between slope length and the runout of debris flow deposits (L_d).

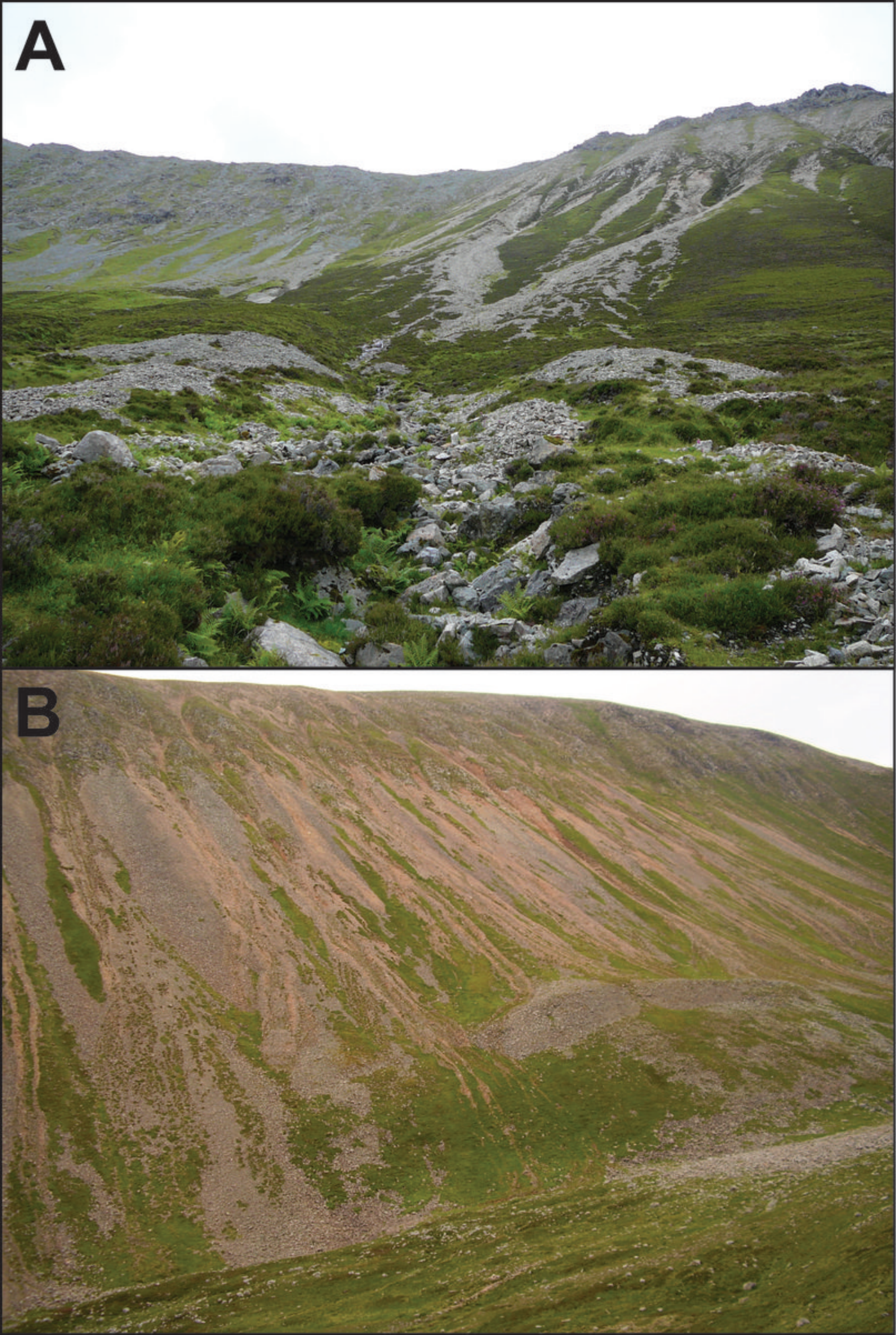
Fig. 10. Relationship between H/L and volume of slope foot deposits for the studied debris flows. Relationships for unobstructed and channelised debris flows found by Corominas (1996) are included for comparison.


1
2
3
4
5
6
N
0
50 km
1. An Teallach
2. Lairig Ghru
3. Drumochter Pass
4. Glamaig
5. Mill Glen
6. Glen Ogle

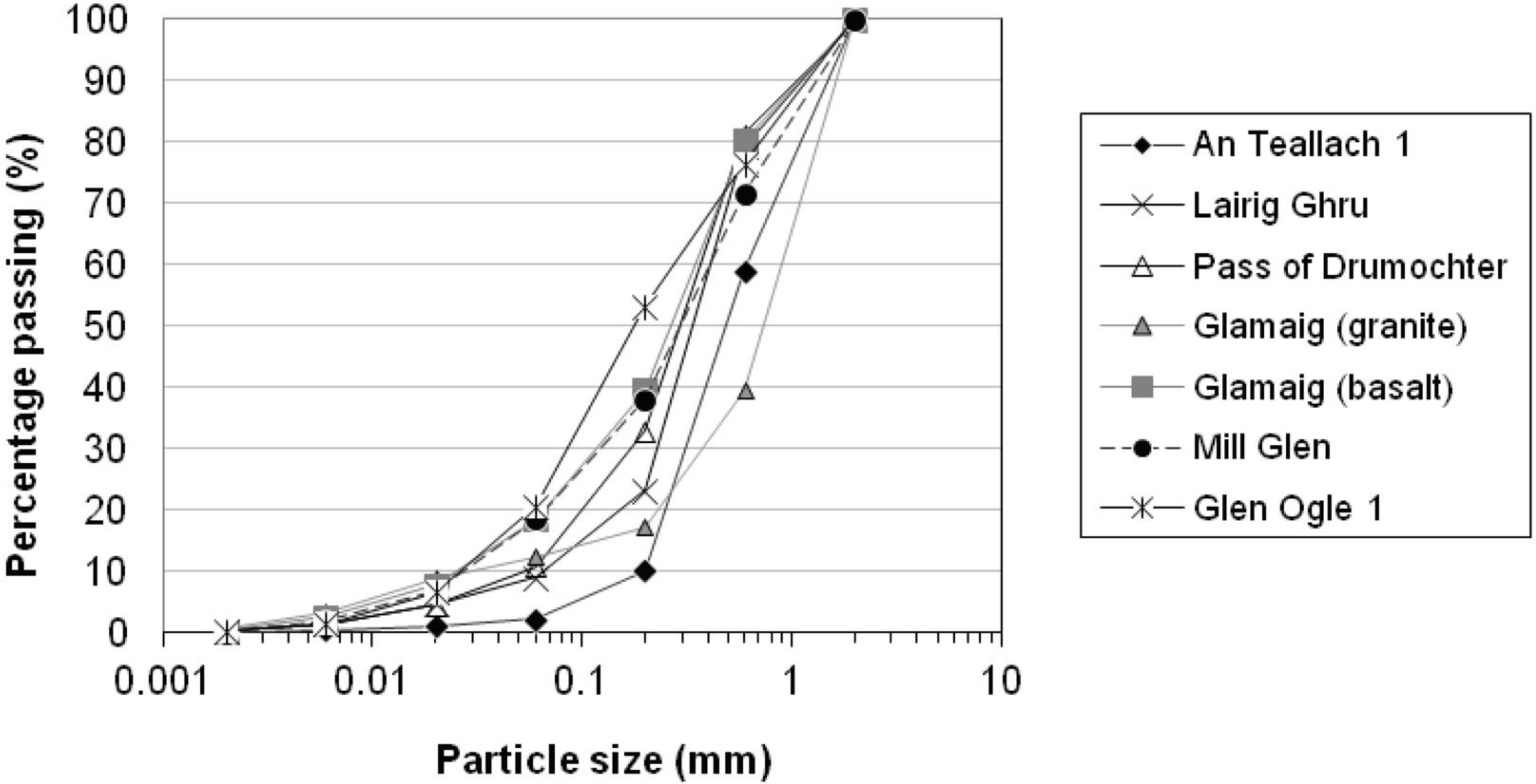


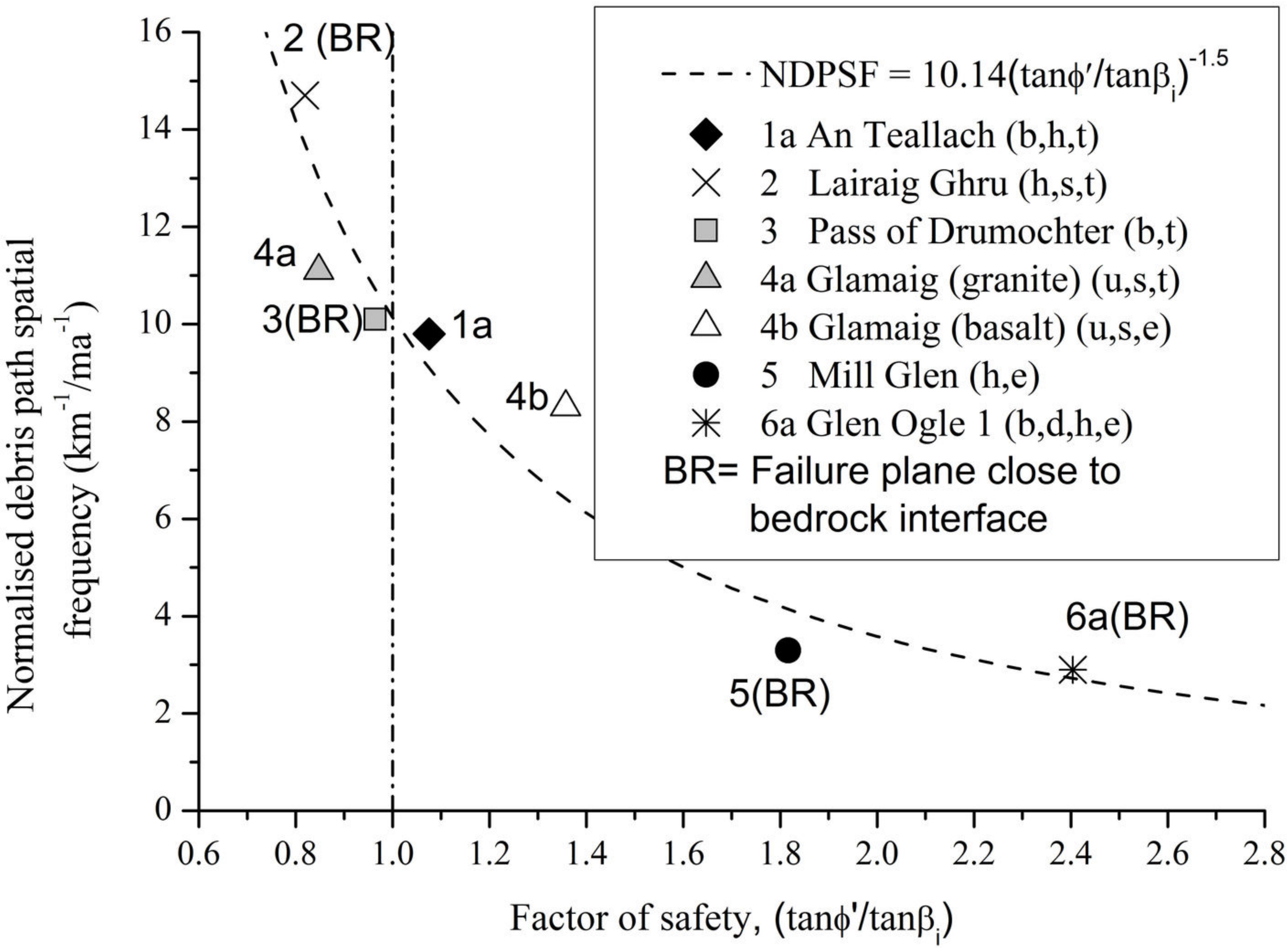
850
800
750
900
950
1050
N
0
200 m
Legend
Debris-flow path
Stream
Cross-slope distance of studied hillslope (km)
Rock slope
Contour line (50 m interval)


Initiation,
i
Slope Length, L_{it}
Initiation
angle, β_i
Vertical Drop, H
Transport,
t
Deposit Length, L_d
Deposition,
d
Transport
angle, β_t
Deposit
angle, β_d
Horizontal Travel Distance, L

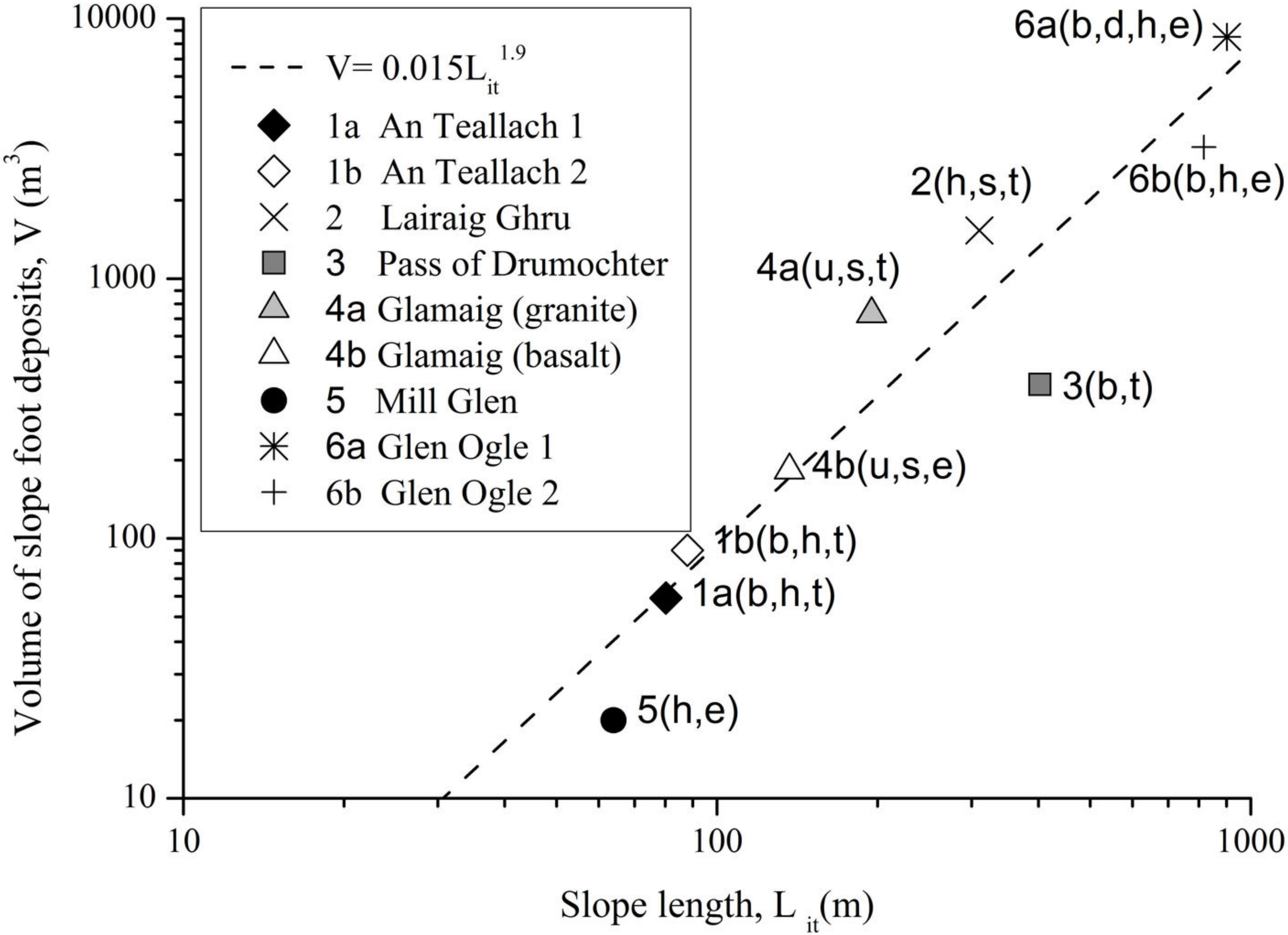

A
B


Initiation Zone
Gully
Deposition

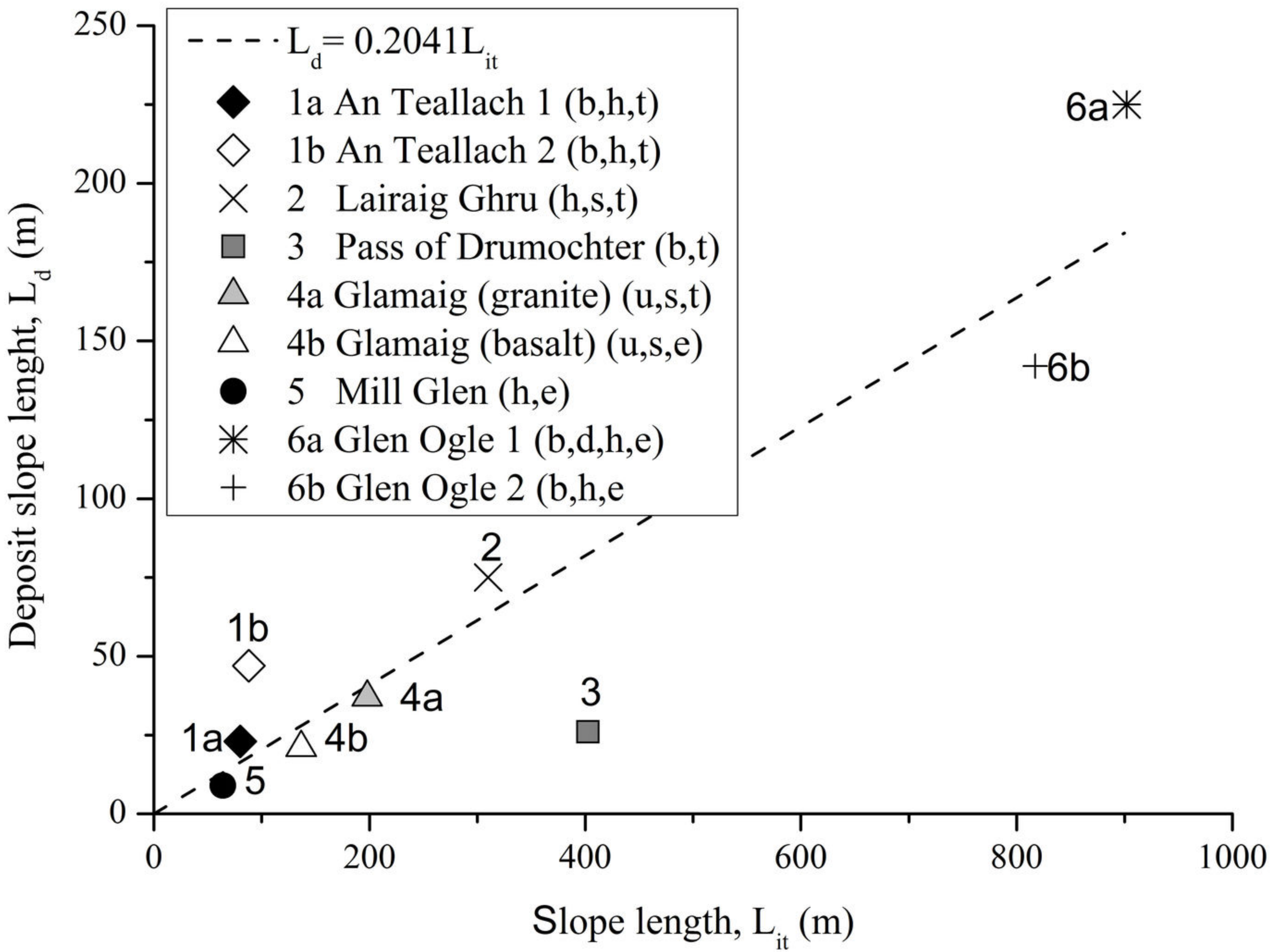

Percentage passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.001
0.01
0.1
1
10
Particle size (mm)
An Teallach 1
Lairig Ghru
Pass of Drumochter
Glamaig (granite)
Glamaig (basalt)
Mill Glen
Glen Ogle 1



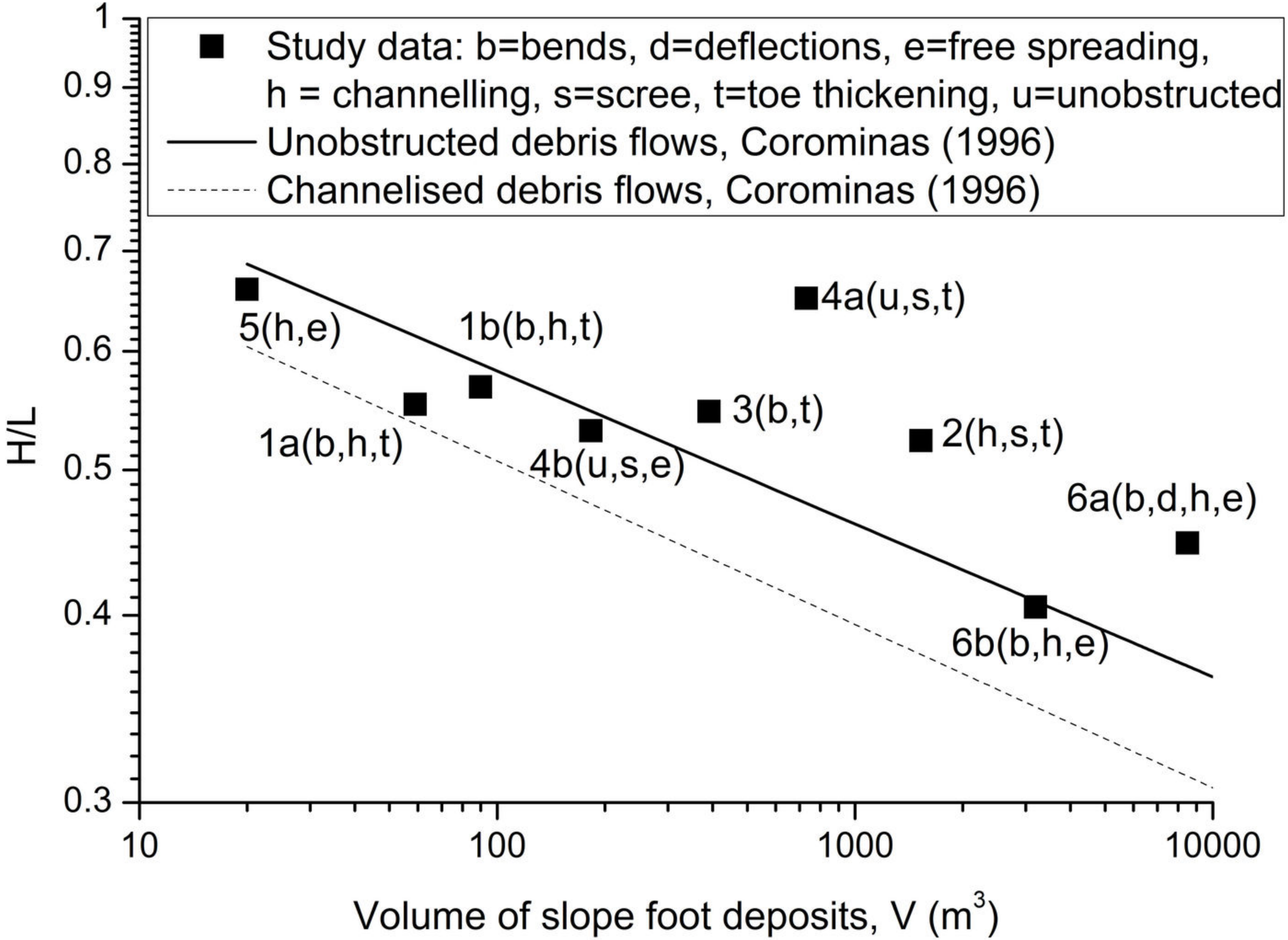
NDPSF = 10.14(tanφ′/tanβ$_i$)$^{-1.5}$
1a An Teallach (b,h,t)
2 Lairaig Ghru (h,s,t)
3 Pass of Drumochter (b,t)
4a Glamaig (granite) (u,s,t)
4b Glamaig (basalt) (u,s,e)
5 Mill Glen (h,e)
6a Glen Ogle 1 (b,d,h,e)
BR= Failure plane close to bedrock interface
2 (BR)
4a
3(BR)
1a
4b
5(BR)
6a(BR)
Normalised debris path spatial frequency (km^{-1}/ma^{-1})
Factor of safety, (tanφ'/tanβ$_i$)
0
2
4
6
8
10
12
14
16
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8



Volume of slope foot deposits, V (m³)
Slope length, L it (m)
10000
1000
100
10
10
100
1000
V= 0.015L it 1.9
1a An Teallach 1
1b An Teallach 2
2 Lairaig Ghru
3 Pass of Drumochter
4a Glamaig (granite)
4b Glamaig (basalt)
5 Mill Glen
6a Glen Ogle 1
6b Glen Ogle 2
6a(b,d,h,e)
6b(b,h,e)
2(h,s,t)
4a(u,s,t)
3(b,t)
4b(u,s,e)
1b(b,h,t)
1a(b,h,t)
5(h,e)



Deposit slope lenght, L_d (m)
Slope length, L_{it} (m)
0
50
100
150
200
250
0
200
400
600
800
1000
$L_d = 0.2041L_{it}$
1a An Teallach 1 (b,h,t)
1b An Teallach 2 (b,h,t)
2 Lairaig Ghru (h,s,t)
3 Pass of Drumochter (b,t)
4a Glamaig (granite) (u,s,t)
4b Glamaig (basalt) (u,s,e)
5 Mill Glen (h,e)
6a Glen Ogle 1 (b,d,h,e)
6b Glen Ogle 2 (b,h,e
6a
6b
2
1b
4a
3
1a
4b
5



Study data: b=bends, d=deflections, e=free spreading,
h = channelling, s=scree, t=toe thickening, u=unobstructed
Unobstructed debris flows, Corominas (1996)
Channelised debris flows, Corominas (1996)
5(h,e)
1b(b,h,t)
4a(u,s,t)
1a(b,h,t)
3(b,t)
2(h,s,t)
4b(u,s,e)
6a(b,d,h,e)
6b(b,h,e)
H/L
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
10
100
1000
10000
Volume of slope foot deposits, V (m3)