THE STRUCTURE AND EVOLUTION OF RELICT TALUS ACCUMULATIONS IN THE SCOTTISH HIGHLANDS

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THE STRUCTURE AND EVOLUTION OF RELICT TALUS ACCUMULATIONS IN THE SCOTTISH HIGHLANDS

by

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Date: ...6TH Feb 1998...

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Abstract

The aim of this thesis is to establish the evolutionary history of relict talus accumulations in the Scottish Highlands through study of their distribution, morphology, structure and sedimentology, and through dating and pollen analysis of buried soil horizons. Analyses of talus morphology demonstrates that though the investigated slopes comprise a basal concavity and upper straight slope, features hitherto interpreted as characteristic of unmodified rockfall accumulations, there is considerable variability in upper slope gradient. Surface relief indicates widespread reworking by slope failure, gullying and debris flows. Sections through gully-side exposures exhibit up to 3.5 m of stacked debris flow deposits, wash layers and buried soils overlying rockfall deposits, indicating a complex history of sediment reworking. Sedimentological analyses indicate that 27-30% of the talus sediments at one site (Trotternish) comprise fine (< 2 mm) particles representing granular weathering of the rockwall and syndepositional accumulation of both fine and coarse debris. The volume of talus on Trotternish implies an average rockwall retreat rate of *c.* 0.3 mm yr^{-1} since deglaciation, of which 0.08-0.09 mm yr^{-1} reflects granular weathering rather than rockfall. Failure and reworking of talus is inferred to reflect reduced infiltration rates (and high porewater pressures during rainstorms) caused by progressive accumulation of fines. Radiocarbon dating of buried soils indicates that reworking commenced prior to *c.* 6 cal ka BP, and has been intermittently active during the Holocene. Pollen analyses and charcoal concentration counts provide no evidence for accelerated reworking as a result of anthropogenic interference with vegetation cover, but the timing of reworking events provides support for enhanced activity associated with climatic deterioration after *c.* 2.7-2.3 cal ka BP. The characteristics of the investigated slopes show that models that treat talus as a free-draining accumulation of rockfall debris have limited applicability, and an alternative model that incorporates progressive reworking by other processes is proposed.

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Table of contents

Chapter 5 Internal structure

Chapter 6 Talus sediments

Chapter 7 The history and possible causes of talus reworking

List of figures

Chapter 5 Internal structure

List of tables

Chapter 1

Introduction

1.1 Aims and definitions

Talus slopes are steep accumulations of rockfall debris at the foot of cliffs. The term *talus* has been used to describe both the slope form and its constituent sediments. *Scree* is considered by some authors to be synonymous, though in practice this term refers to any slope cover of predominantly coarse debris, irrespective of location and origin.

Over the past 25 years a considerable volume of research has been published on the characteristics of talus slopes. In general, these studies have focused on two main concerns: first, the nature of processes operating on talus slopes; and second, the relationship between such processes and talus slope form and sedimentology. In particular, debate on the nature of talus development has become polarised between those researchers who have interpreted the form and surface sedimentary characteristics of talus slopes as primarily a reflection of the input energy of clasts falling from a rockwall (e.g. Statham, 1973a, 1976a, Kirkby and Statham, 1975; Statham and Francis, 1986), and those who have interpreted the form of talus slopes as predominantly the result of surficial sediment redistribution by other processes (e.g. Howarth and Bones, 1972; Carson, 1977; Church *et al.*, 1979; Whitehouse and McSaveney, 1983; Francou and Manté, 1990; Francou, 1991).

One interesting feature of this debate is that the evidence employed to test the validity of competing models of talus development has hitherto been restricted to the surface characteristics of talus slopes, notably slope form and the sorting (or otherwise) of surface clasts, occasionally backed up by observations of rockfall or sediment reworking by such processes as translational failure, debris flow, snow avalanches or creep. Little attention has been paid to internal structure of such slopes, or what this structure implies for talus slope evolution and behaviour. Yet there is evidence from a number of studies that talus slopes are not simply accumulations of coarse rockfall debris, but comprise a thin cover of rockfall boulders overlying a clast-supported or matrix-supported diamicton containing abundant fine sediment (Wasson, 1979; Church *et al.,* 1979; Åkerman, 1984; Selby, 1993; Salt and Ballantyne, 1997). Little research has been devoted to elucidating the origin and significance of the subsurface diamicton, despite its implications for the mechanical behaviour of talus accumulations.

The aim of the research reported in this thesis is to establish the nature of talus evolution through analysis of slope surface morphology, internal structure and sediments. Three particular aspects of talus form and history are considered. The first comprises an examination of the progressive modification of talus surface relief and internal structure by processes other than rockfall, using the results of analyses of talus surface morphology and sediment facies exposed in gully-side sections. The second involves sedimentological analysis of subsurface talus diamictons, to determine the character and provenance of both the fine and the coarse fractions, and thus establish the possible implications for the behaviour of talus and source rockwalls upslope. The third aspect of the research undertaken in this project involves an investigation of the possible links between environmental change and episodes of talus accumulation, reworking and erosion.

1.2 Field sites

Five field sites were investigated in the course of this study. The Trotternish Escarpment on the Isle of Skye was selected as the main field site due to the abundance of mature, relict talus slopes, and because this area supports evidence for a long history of accumulation and reworking of rockfall debris. Moreover, the numerous deep gullies that cut through the Trotternish talus slopes permit close inspection of the internal structure of the talus deposits, and frequently reveal buried organic horizons that provide sources of evidence concerning the timing and possible causes of talus reworking. Initial fieldwork on Trotternish highlighted inadequacies of existing models of talus development and led to the formulation of new ideas concerning the behaviour and evolution of talus slopes. To establish the wider applicability of these findings, fieldwork was subsequently extended to four further field sites on the Scottish mainland, namely Quinag in Assynt, Stac Pollaidh in Coigach, Baosbheinn in Wester Ross and upper Glen Feshie in the western Cairngorms. These areas were selected on the basis of airphoto reconnaissance, which showed that they support mature relict taluses that, like the Trotternish sites, exhibit evidence for reworking of rockfall debris. A further advantage of this range of sites is that it offers scope for investigating talus evolution on three contrasting lithologies, namely basalt (Trotternish), Torridon Sandstone (Quinag, Stac Pollaidh and Baosbheinn) and schist (Glen Feshie). Moreover, four of the five sites share a similar environmental history: all were covered by the last (Late Devensian) ice sheet but escaped glaciation during the Loch Lomond Stade of *c.* 11-10 ka BP (*c.* 12.9-11.5 cal ka BP), and were thus exposed to severe periglacial conditions during the Late Devensian Lateglacial. Only the slopes of Baosbheinn were reoccupied by ice during the Loch Lomond Stade, implying that the taluses at this site reflect rockfall accumulation only after final deglaciation. Further details concerning all field sites are given in chapter 3.

1.3 Structure of the thesis

The main body of this thesis falls into three parts. The first of these comprises chapters 2 and 3, which outline the context of the research. Chapter 2 reviews the literature concerning the characteristics, formation, age and reworking of rockfall talus accumulations. Emphasis is given to those studies that report the results of investigations of talus accumulations in upland Britain. Two competing models of talus slope evolution, namely, the 'discrete particle rockfall model' (Statham, 1973a, 1976a; Kirkby and Statham, 1975) and the 'two facet model' (Francou and Manté, 1990; Francou, 1991) are described in detail. Areas of contention and gaps in current knowledge are highlighted, and those issues requiring clarification or additional research are indicated. Further necessary background to this project is provided in chapter 3, which describes the relevant geological, geomorphological and ecological characteristics of all five study locations.

The second major section of this thesis comprises chapters 4 to 6, which report the results of analyses of the physical characteristics of relict talus slopes at the study sites. Chapter 4 is devoted to an investigation of the slope form and the distribution and surface relief of the relict talus slopes. The extent to which the surface configuration of taluses at all five study sites is consistent with existing theories of talus development is assessed, anomalies are highlighted and some possible implications for talus evolution are suggested. Chapter 5 considers the sub-surface structure of relict talus deposits and its implications for formative processes. The textural characteristics of relict talus alluded to in chapter 5 are considered in depth in chapter 6, which is devoted to the characteristics and provenance of subsurface sediments in talus accumulations. Thus chapters 4, 5 and 6 consider respectively the surface relief, internal architecture and sedimentology of relict talus accumulations investigated in the Scottish Highlands.

The final section of the thesis considers the evolutionary history of the relict talus accumulations at four of the study sites. The results of radiocarbon dating of samples from buried soil horizons underlying talus, and analysis of associated pollen assemblages and particulate charcoal content are reported in chapter 7. These data are used to reconstruct a possible chronology of reworking of relict talus debris, and to suggest possible causes of such activity. The inferences drawn from earlier chapters are carried forward into chapter 8, in which a general schematic model of the evolution of relict talus by secondary reworking is presented. The final chapter summarises the most important conclusions of the research, and suggests possible directions for further work on talus slope evolution.

Chapter 2

Talus slopes

2.1 Introduction

Talus slopes are accumulations of rockfall debris at the foot of cliffs. The term *talus* is used to describe both the slope form and its constituent material. Talus slopes are ubiquitous in upland areas that have experienced a periglacial climate. The operation of macrogelivation processes on oversteepened slopes is often the reason for this relationship. Taluses are not, however, restricted to active or former periglacial environments, but occur in all areas where the products of rock weathering have accumulated at the foot of a rock face (Ballantyne and Harris, 1994, p.219). This chapter will first outline the characteristics of unmodified rockfall talus as described in the literature on the topic, before going on to describe the processes considered responsible for these characteristics. Proposed models of rockfall talus will be discussed with some reference to their limitations. This chapter then considers the nature of secondary processes that operate to modify talus and their consequences. Finally, the existing literature regarding talus slopes in Britain will be examined. For convenience of comparison, conventional radiocarbon dates reported in the following sections, and in subsequent chapters, are transformed to calendar years using the CALIB 3.0 conversion programme of Stuiver and Reimer (1993) and the calibration data of Stuiver and Becker (1993). The calibrated age range is given at the 2σ level.

2.2 Unmodified rockfall talus slopes

Unmodified rockfall talus can be classified as either a talus sheet, a talus cone, or as an assemblage of coalescing talus cones (Rapp, 1960a; Rapp and Fairbridge, 1968; Church *et al.*, 1979; Ballantyne and Harris, 1994, p.219). This classification is somewhat arbitrary, however, as talus forms are transitional, with different types grading into each other. Unmodified rockfall taluses are therefore classified on the basis of their principal morphological characteristics when viewed in planform (Figure 2.1). Talus sheets accumulate at the foot of steep cliffs which have a fairly uniform debris supply along their length. In contrast, talus cones accumulate below steep gullies or rock chutes that concentrate clast delivery at the foot of the cliff. Individual cones may coalesce at sites where parent gullies are sufficiently closely spaced. The dominance of one form over another is thus largely a reflection of the irregularity of the source rockwall. Talus accumulations may appear to be very thick, but the inclination of the underlying rock is often similar to that of the talus surface. Where this is the case, talus often develops as a thin mantle of rockfall detritus over bedrock with thicknesses rarely exceeding 5 m (French, 1976). Greater thicknesses of *c.* 25 m (Fromme, 1955), or *c.* 35 m (Rapp, 1960b) may, however, develop under larger cones.

Transects up unmodified rockfall talus has been shown to comprise two units: a near-rectilinear upper slope and a basal concavity (e.g. Caine, 1969, 1974; Howarth and Bones, 1972; Young, 1972; Chandler, 1973; Statham, 1973a, 1975, 1976a; Kotarba, 1976; Francou and Manté, 1990; Francou, 1991). Where talus remains unmodified and basal erosion is inoperative, the upper rectilinear slope generally stands at an angle of 35-36° (Young, 1972; Chandler, 1973), although Rapp (1960b) argued that talus can attain angles of 40°. Differences in lithology may account for variation in the gradient of the rectilinear slope. 'Blocky' clasts when stacked together are better able to resist impact-induced movement than 'platy' debris, and can therefore support steeper gradients (Statham, 1973a, 1976a). Talus maturity may also exert an influence over the gradient of the rectilinear slope. Statham (1976a) argued that immature forms often display a relatively low-angled rectilinear facet, whilst mature taluses possess a steeper, more extensive rectilinear upper slope.

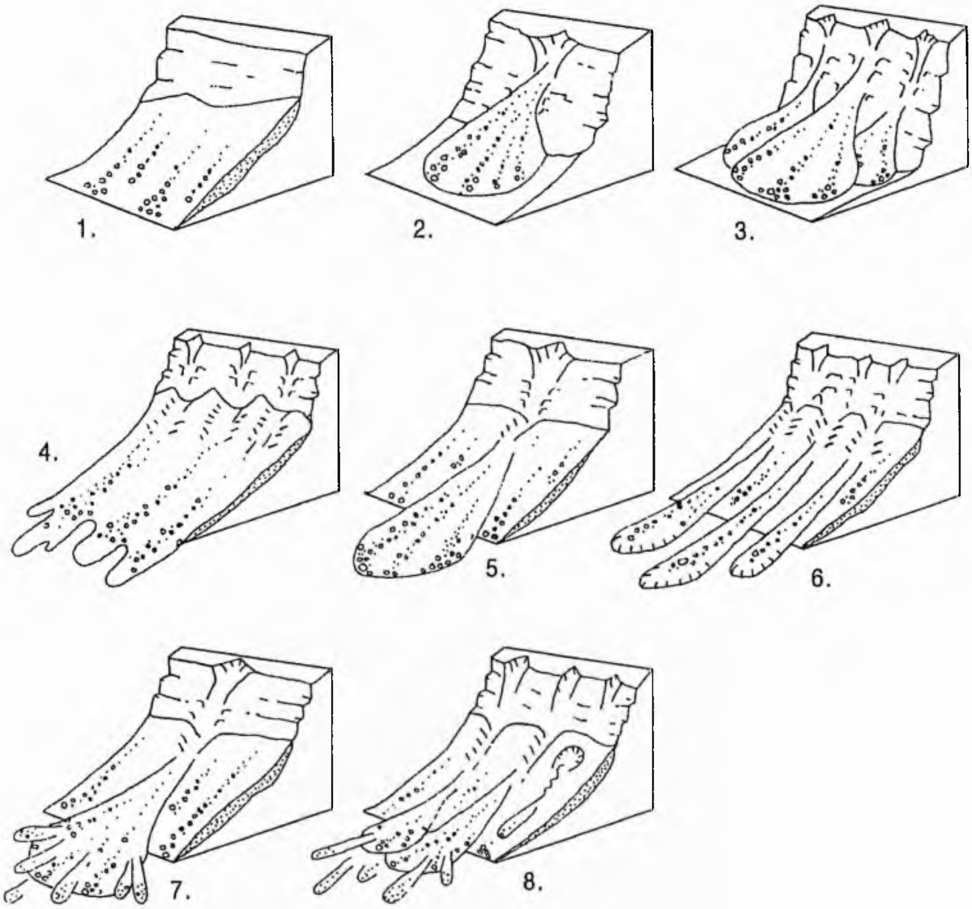


Figure 2.1. Types of talus slope and related landforms. 1, talus sheet; 2, talus cone; 3, coalescing talus cones; 4, avalanche modified talus; 5, avalanche cone; 6, avalanche boulder tongues; 7, debris cone; 8, hillslope debris flows (After Ballantyne and Harris, 1994, p. 220).

At the surface, size-sorting of material may be poor, but many rockfall dominated talus slopes exhibit a general increase in clast size downslope (e.g. Tinkler, 1966; Gardner, 1968; Bones, 1973; Statham, 1973a, 1976a; Kirkby and Statham, 1975; Carson, 1977; Shaw, 1977). Lateral sorting can also occur and may be controlled by cone surface relief (Pérez, 1986), or changes in the joint density of the rockwall source (Wilson, 1990). Sorting is, however, characteristic of only a shallow surface veneer of clasts, and surficial debris is often underlain by a poorly-sorted diamicton, sometimes clast supported, with interstitial fines (Wasson, 1979; Church *et al.*, 1979; Åkerman, 1984; Selby, 1993; Salt and Ballantyne, 1997).

2.3 Rockfall processes

Rockfall delivery to a talus slope takes several forms. It may be catastrophic as in the case of major rockslides or rock avalanches, or of low magnitude as with discrete rockfalls of individual particles. Frost shattering of cliffs under a periglacial climate may represent a significant component of rockfall accumulation, but is not the sole mechanism inducing particle falls form a rockwall. Weathered rock debris can be released from a free face by various modes of rock mass failure, including sliding failure, flexural toppling, creep, exfoliation, slab failure and wedge failure. Such displacements need not be triggered by macrogelivation, and therefore are not confined to periglacial climates. Rockfall may also be triggered by transient stresses associated with tectonic displacements, or stress release acting on glacially-oversteepened slopes. In terms of the latter, high levels of rockfall activity on cliffs recently exposed by glacier retreat may represent a paraglacial response (Ballantyne and Harris, 1994. p. 225; Luckman and Fiske, 1997; *cf.* Gardner *et al.*, 1983; Johnson, 1984; André, 1985, 1986, 1993; O'Conner *et al.*, 1993). Progressive failure associated with reduction of internal friction angles can also result in rockfall, especially when combined with a short term trigger like high cleft water pressure (Wyroll, 1977; Selby, 1993). It has been argued that the role of freeze-thaw processes in rock release are trivial when compared to intrinsic controls of rock mass stability (Whalley, 1984). This argument is supported by the work of Gardner (1983a) who recorded no seasonal variation in rockfall activity in an alpine environment. However, the freezing of water in cracks may be important in spring and autumn, when rock faces experience a maximum frequency of freeze thaw cycles (Rapp 1960a, 1986; Luckman, 1976; Church *et al.*, 1979; Francou, 1983). Irrespective of the precise mode of debris release, rates of rockfall accumulation appear to be strongly conditioned by the density of joints and fractures in parent rockwalls upslope, and also by microcracks in otherwise intact rock (Douglas *et al.*, 1991). Olyphant (1983), for example, reported that fracture density represents the primary influence on talus maturity in the Sangre de Cristo Mountains of southern Colorado. This finding was supported by André (1985, 1986, 1993) whose work on rock faces in Spitzbergen illustrated that heavily jointed rockwalls developed in quartzite and mica-schist yield much more debris than massive lithologies (sandstones and conglomerates).

Little attention has been paid to the importance of granular weathering of rockwalls. Carson and Kirkby (1972) suggested that granular disintegration may result from solution of chemical bonds between grains, differential absorption of heat by different mineral grains, raindrop impacts and microgelivation. The granular weathering of sandstones was modelled experimentally by Schumm and Chorley (1966). They exposed rock samples to a variety of simulated weather conditions and concluded that rates of granular weathering exhibit a strong positive relationship with the frequency of freeze-thaw cycles.

2.4 Models of talus development

Three models have been proposed to explain rockfall talus morphology and the downslope sorting of surface clasts, these are: (1) the angle of repose model, (2) the discrete particle rockfall model (Kirkby and Statham, 1975; Statham, 1976a), and more recently, (3) the two-facet model proposed by Francou and Manté (1990).

2.4.1 The angle of repose model

Coarse grained sediments exhibit two critical angles of rest with respect to mass movement activity. These two angles have been shown to be related to the onset and cessation of movement by shallow translational sliding failures, with the steeper angle representing the critical gradient for clast mobilisation, and the lower angle being the gradient at which material comes to rest. Allen (1969) introduced the terms 'angle of initial yield' and 'angle of residual shear' for the upper and lower angles respectively. The lower angle is synonymous with Burkalow's (1945) 'angle of repose' and has been employed to explain the significance of the rectilinear slope facet on unmodified talus slopes (e.g. Marr, 1900; Hobbs, 1931; Wood, 1942; King, 1942; Rapp, 1960a). Given the observed downslope movement of clasts over talus surfaces, Ward (1945) suggested that the maximum angle of the upper rectilinear facet may be taken as an approximate indication of the angle of shearing resistance of the talus material. In this model, debris accumulating near the top of the talus periodically attains an unstable angle and is subsequently redistributed downslope. Movement takes the form of shallow translational slides of coarse unconsolidated material or 'dry avalanches'. The importance of dry avalanches as a transport process was emphasised by Whitehouse and McSaveney (1983), whose study of New Zealand taluses led them to suggest that talus develops through a progressive build up of clasts at the slope crest, which are then periodically displaced downslope by dry avalanches.

The angle of repose model implies that as a talus slope is supplied with more material, it increases in height, but retains its original angle of inclination (the angle of repose). In this way the rectilinear slope enlarges with talus maturity, but talus form remains constant. Rockwall retreat associated with talus growth ultimately leads to cliff burial and the formation of a long, straight debris slope underlain by a rock substratum of similar declivity (Rapp, 1960b). In this model, talus will develop as a straight slope in response to the angle of repose of its constituent material. Any departure from this idealised profile may be explained by the operation of secondary processes on the talus, for example basal erosion by rivers or the sea, or gullying (Howarth and Bones, 1972).

Chandler (1973) challenged the angle of repose model and the assumption that the rectilinear slope facet represents the angle of residual shearing resistance of the talus. He demonstrated that talus slope gradients of 35-36° are less than the angle of shearing resistance for angular debris in a loose state of packing, which commonly exceeds 39°. This fundamental flaw in the repose angle model was attributed to error in one or both of the two starting premises:

$$i = \phi_{rep} < \phi'_{cv} \quad \text{or} \quad i < \phi_{rep} = \phi'_{cv}$$

where i = gradient of talus the slope, ϕ_{rep} = angle of repose of granular material, ϕ'_{cv} = angle of shearing resistance of angular debris. Carson (1977) argued that because $i < \phi'_{cv}$, the angle of the talus may be unrelated to the rockfall process; however, as an alternative hypothesis, he suggested that although $\phi_{rep} < \phi'_{cv}$ nonetheless $i = \phi_{rep}$ and in this sense, could be directly related to the rockfall process.

The upper rectilinear talus slope gradient of *c.* 35° reported by many workers (e.g. Andrews, 1961; Chandler, 1973; Statham, 1973a), lies below the repose angle for rockfall material of 39-40° (e.g. Leps, 1970; Blight, 1971; Chandler, 1973; Statham, 1973a). Statham (1975) argued that this inadequacy within traditional models of talus evolution, had arisen through the inappropriate application of angle of repose paradigm to some hillslope systems, misinterpretation of talus slope processes and overemphasis of the mechanisms of dry avalanching, or from acceptance of the angle of repose as a material constant. Clearly, any talus at the angle of repose throughout its entire length must be straight, and any departure from this idealised form indicates the operation of other processes on the slope. It is difficult therefore, to see how this theory of talus development could account for the basal concavity observed on many natural talus slopes. Marr (1900) suggested that the basal concavity may be due to some control other than the internal frictional properties of talus debris, but his explanation of concavity in terms of slow spreading of the rockfall deposit under its own weight is unlikely given the mechanical behaviour of dry cohesionless aggregates.

Acceptance of the angle of repose as a material constant was a further cause of problems. Allen (1969) observed considerable variation in the angle of initial yield of coarse grained material, which Statham (1975) attributed to differences in material packing characteristics. These observations suggested that any hillsides characterised by a slope failure angle cannot be represented by a single gradient, since only small changes in sediment characteristics are required to cause significant variation in the maximum stable angle. In addition, Statham (1975) showed that if the talus material possesses some cohesion, modelling rockfall accumulation slopes in terms of a single angle becomes unrealistic.

To summarise, Statham (1975, 1976a) argued that the angle of repose model is inadequate because most talus slopes possess a straight upper slope and a concave lower slope. Furthermore, he argued that the upper rectilinear facet is commonly about 5° less than the angle of repose, which suggests that other processes must be operative on talus. Statham (1975, 1976a) went on to argue that traditional ideas about talus evolution were also unable to explain fall sorting, previously described by many workers (e.g. Rapp, 1960a, 1960b; Andrews, 1961;

Gardner, 1968; Bones, 1973; Statham, 1973a, 1973b); nor could existing models account for the alignment of clasts in a downslope direction noted by Statham (1973a) and McSavenney (1972).

2.4.2 The discrete particle rockfall model

Jeffreys (1932) was perhaps the first to suggest that talus slope form may be related to the input energy of rockfall particles, rather than the mechanical properties of talus deposits. He argued that talus accumulations are in dynamic equilibrium with clast supply and the amount of kinetic energy of falling particles. Jeffreys's (1932) ideas were adopted by Statham (1973a, 1975, 1976a; also Kirkby and Statham, 1975) who proposed a model based on rockfall travel distances and the movement of surficial clasts triggered by rockfall impacts. They argued that clasts impacting on to a talus surface have a given amount of kinetic energy and are therefore capable of movement (mainly by bouncing) down slopes with gradients lower than the repose angle for that material. The energy of rockfall impacts can be equated with work done on the talus. This energy is dissipated through transporting the particle, and by displacing pre-existing particles on the slope and by frictional losses. The balance between energy losses and the form of the talus are related in a positive feedback system, whereby changes in energy balance bring about alterations to form and *vice versa* (Statham, 1976a).

According to Statham (1976a), immature taluses are characterised by large rockwalls and relatively small accumulations of rockfall debris. In this situation, clasts may fall from various heights on the rockwall and thus have variable amounts of kinetic energy. Falling particles may possess very large amounts of kinetic energy and are thus subject to relatively high impact velocities. The high kinetic energy of clasts in motion allows particles to travel over slopes with surface gradients less than the angle of repose for that material. Kirkby and Statham (1975) showed that the distribution of particle travel distances from a source rockwall is exponential, and argued that this form of rockfall input distribution accounts for the basal concavity observed on many talus slopes. In this way, the concave lower slope forms during the early phases of talus development, when rockfall clasts possess large amounts of kinetic energy.

As the rockwall is buried, the range of rockfall velocities is reduced and this effect, combined with the increasing length of the talus, results in a greater proportion of deposition higher up the slope. Thus the upper rectilinear slope becomes increasingly dominant with talus maturation. When the rockwall is completely buried and the height of rockfall is zero, particles will posses no impact velocity and the angle of the rectilinear segment will tend to $\phi'_{\mu d}$ (dynamic angle of friction of an individual particle on a granular surface). Carson (1977) observed that the mechanisms of talus growth in this context are founded in the physics of frictional properties of falling particles, rather than the shearing resistance of the bulk material of the talus slope.

Particle size was invoked by Statham (1973a, 1976a) to explain the presence of fall sorting observed on many taluses. Statham argued that moving clasts become lodged in surface depressions if they are smaller than the scale of topographic variation on the talus. Thus the upper surface of a talus apparently acts like a sieve, with the smaller clasts becoming lodged within the talus fabric at an early stage in their journey down the slope. Conversely, a larger clast is less likely to be affected by any surface irregularities and is capable of travelling greater distances downslope. In this case $\phi'_{\mu d}$ for the large particle will be equal to the true angle of plane friction for the material. However, for smaller particles $\phi'_{\mu d}$ will contain an element of material interlocking and is therefore size dependent.

Rapp (1960b), Gardner (1968) and Bones (1973) suggested that given a constant height of fall, larger clasts will travel farther down the talus slope because of the kinetic energy increment which accompanies increase in clast size. However, Statham (1976a) argued that kinetic energy is not strictly relevant since particle mass does not influence the sliding movement of a clast on the talus surface. He concedes that kinetic energy may have some role in the ability of larger particles to overcome obstacles in their path more easily than those of a smaller size, but the size-dependent effect is considered more important. However, a possible objection to Statham's analysis is that individual clasts tend to bounce rather than slide down a talus surface.

The theoretical relationships regarding downslope travel distances of individual particles offered by Statham (1973a, 1976a) and Kirkby and Statham (1975) were challenged by Carson (1977), who found that the discrete particle rockfall model could only offer a partial explanation of talus morphology. He questioned the degree to which laboratory findings could be generalised to field situations, particularly when no data existed to compare ϕ_r (angle of rest after avalanching in a rotating drum or tilting box) to ϕ_{rep} as determined by observations of cone-building on gravel stockpiles. Moreover, since laboratory experiments in cone-building tests must inevitably utilise much reduced heights of rockfall compared with those in the field, it is questionable whether laboratory tests produce angles of repose that are meaningful in a field context. Given the differences between ϕ_r and ϕ_{rep}, and the variation between laboratory test and field observation, Carson (1977) questioned whether the argument that talus slopes existing at $i = \phi_{rep}$, is, in reality, very close to being tautological.

The applicability of the discrete particle rockfall model to actual talus slopes can be questioned not only on the basis of how it defines the angle of repose, but also how it tests internal friction angles in talus deposits. Carson (1977) argued that

Chandler's (1973) estimate of ϕ'_{cv} for Spitsbergen talus, based on 120 cm^3 shear box tests containing grains with a maximum diameter of 6 mm, were unrealistic as these particles were too large for the experimental apparatus. The walls of shear box samples may also exert a frictional resistance to deformation during avalanching tests, comparable with 'boundary resistance' in fluid flow, and referred to as a 'wall effect'. Carson (1977) claimed that such effects can alter ϕ_r values obtained under experimental conditions. A point later disputed by Statham (1977) and Statham and Francis (1986).

Statham's (1976a) suggestion that large-scale mass avalanching of the talus surface is relatively infrequent, was also challenged when Carson (1977), Church *et al.* (1979) and Whitehouse and McSaveney (1983) reaffirmed the importance of dry avalanching on talus surfaces. Furthermore, investigations of gravel stockpiles showed that ϕ_{rep} angles of 35-36° are remarkably consistent, which suggested that taluses do stand at a characteristic gradient close to the angle of repose (Carson, 1977). The validity of these arguments is, however, dependent on the assertion that gravel stockpiles behave in the same way as rockfall taluses, a point disputed by Statham (1977) and Statham and Francis (1986). They argued that the stockpiles studied by Carson (1977) differ from natural taluses in terms of the nature of the input zone, the rate of input, grain size characteristics and the ratio of fall height to talus height.

2.4.3 The two facet model

Francou and Manté (1990) and Francou (1991) have forwarded a very different model of talus evolution. Studies in the French Alps led them to suggest that talus should be viewed not as a single system, but as an assemblage of slope facets which combine different dynamics and develop at different rates.

They suggested that in the early stages of talus evolution, owing to the height of the source rockwall, rockfall particles possess large amounts of kinetic energy and deposition occurs throughout the profile. It was assumed, however, that the majority of falling particles are deposited at the upper slope immediately below the rockwall, and are periodically redistributed downslope by dry avalanches, high energy rockfall impacts and creep. They further suggested that mass transport on talus slopes with massive rockwalls leads to the formation of a consistent break of slope 'ψ' of 33-34°. This break they explained in terms of the transition from a transport-dominated system on the upper slope (rectilinear facet) to an accumulation-dominated system on the concave lower slope (Figure 2.2). The straight upper slope is apparently kept at a constant angle by the combined influence of rockfall accumulation and downslope removal of debris, whilst the lower concavity reflects deposition alone.

The second stage of evolution occurs as the source rockwall tends to disappear and the height of fall declines. Francou and Manté (1990) suggested that a reduction in rockfall impact velocity leads to increased deposition near the rockwall, and an over-steepening of the upper slope. Continued downslope redistribution of talus debris may be accompanied by the formation of a second break of slope 'ψ_p' on the talus profile (Figure 2.2). They claimed that the angle of this second point of inflection rests between 34-37°, and that after its formation, the principal break of slope migrates downslope and assumes a gentler angle. Francou and Manté (1990) envisaged that in the final stages of rockwall retreat, talus slopes will develop a multi-segmented profile. They suggested that the components of this profile will be a straight upper section of 35° approaching the angle of repose, a middle section with a gentle concavity of approximately 30°, and a nearly stabilised basal concavity marked by low accumulation rates. In sum, the 'two facet model' predicts that slope concavity increases and the mid-slope gradient declines with talus maturation.

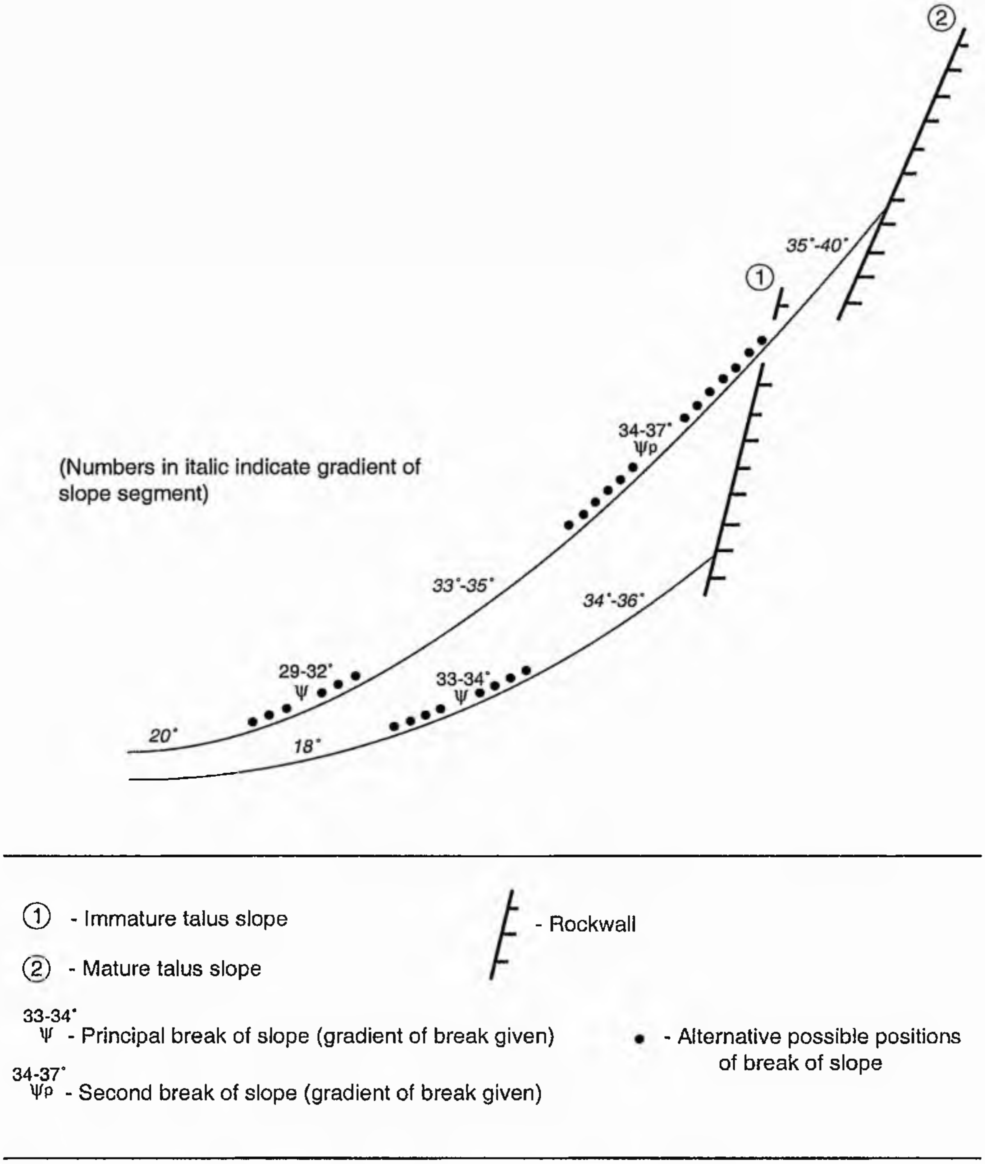


Figure 2.2. Characteristic talus slope profiles and breaks of slope envisaged by the 'two facet model' of rockfall accumulation. (After Francou and Manté, 1990).

Francou and Manté's (1990) approach to talus evolution represents a departure from Statham's (1973a, 1976a; Kirkby and Statham, 1975) model by its recognition of mass-transport processes as a significant control on talus morphology. Furthermore, the two facet model proposed that taluses tend towards an extensive concavity over time, whereas the discrete particle rockfall model predicts the formation of a steep, rectilinear upper slope with maturity. Both models do, however, suggest, either explicitly or implicitly, that the upper slopes of mature talus exist close to repose conditions. In the discrete particle rockfall model near repose conditions develop in response to a steepening of the upper talus slope when rockfall impact velocities are relatively low, whilst the two facet model implies that repose conditions are the product of the interaction of rockfall accumulation and downslope mass transfer.

2.4.4 Summary

The three models outlined above attempt to explain the morphology of unmodified rockfall talus either in terms of repose angles of rockfall debris, the kinetic energy of clasts impacting the talus surface (Statham's model), or by emphasising the relationship between rockfall and mass transport processes.

In an attempt to reconcile traditional angle of repose theories to the discrete particle rockfall model, Statham and Francis (1986) suggested that although the gradient of the rockfall accumulation slope is primarily controlled by the impact energy of falling particles, internal weathering of talus accumulations may lead to infilling of interstitial cavities and impeded drainage during rainstorms, thus facilitating high positive porewater pressures and subsequent failure and mass transport. This model of talus evolution implies that the kinetic energy of falling clasts is the main control on slope form during the early stages of talus development, but that redistributive processes including dry avalanching become increasingly important as taluses approach maturity. The importance accorded to transport processes by Statham and Francis (1986) would seem to lend support to Francou and Manté's (1990) two facet model.

One potential weakness in all three models of unmodified rockfall talus is the absence of any direct reference to the fine fraction of talus deposits. The presence of abundant fine-grained sediment in the interstices between clasts affects the mechanical behaviour of talus, particularly when considering internal shearing resistance. However, none of the three models of talus development makes explicit reference to this factor, nor do they consider the origins of fine debris in talus accumulations or the possible implications for rockwall retreat by granular weathering. Statham and Francis (1986), however, went some way to correcting these shortcomings by suggesting that fine material within a talus deposit may originate from internal weathering. Francis (1984) identified particle size, particle shape, surface frictional properties, void ratio, particle strength and normal stress during shearing as the factors important in influencing ϕ'_{cv} of a weathered sediment. Statham and Francis (1986) argued that changes in these geotechnical properties may alter the mechanical behaviour of a talus deposit, particularly if macropores become infilled by the fine-grained products of internal weathering thus impeding internal drainage. They suggested that this factor is of particular importance at the upper rectilinear slope where the products of granular weathering of the rockwall are most likely to accumulate. Their study does not, however, consider what proportion of a rockfall deposit may consist of fine material, nor how much fine sediment is required to effect a significant change in the mechanical behaviour of a talus.

2.5 Modified talus slopes

Talus becomes modified when secondary processes change the surface morphology, internal structure and sedimentology of a rockfall-dominated debris slope. In the absence of basal erosion (*cf.* Howarth and Bones, 1972), the main processes which modify talus include translational shearing, debris flow, gullying, avalanche activity and creep. These secondary processes redistribute rockfall fragments downslope, and in doing so bring about changes to talus form (Figure 2.1). Some models of rockfall talus evolution also recognise the importance of mass transport, for example, dry avalanching. In this context, however, downslope movement of talus debris is considered to have a formative role within the talus slope system and is not held responsible for any significant modification of rockfall-dominated talus slopes.

2.5.1 Talus shift

The term *talus shift* has been used to describe the downslope movement of clasts over a talus surface, irrespective of the specific mechanism involved. Talus shift so defined encompasses the processes of talus creep outlined by Rapp (1960a). The displacement of clasts downslope is often erratic, and particles on the same lateral transect can experience markedly different rates of movement. Gardner (1979) found that the downslope rates of movement of individual clasts on a single transect varied from 13 cm yr^{-1} to 88 cm yr^{-1}. Caine (1986), in a study spanning fourteen years, found that some clasts on a transect had moved more than 40 cm, but others remained immobile. Variation in rates of movement can often be attributed to differences in clast size. Pérez (1985, 1988, 1993) found that over a ten year period, bouldery debris on an Andean talus slope moved at an average rate of 3.7 cm yr^{-1}, whilst sands and gravel moved at a mean rate of 22.5 cm yr^{-1}. These variations are explained by the efficacy of different processes in transporting material of varying texture. The studies described above seem to suggest that in the short term talus shift is both episodic and localised in nature (e.g. Carniel and Scheidegger, 1976; Luckman, 1978, 1988), with relatively rapid displacements of material affecting only small areas of the total talus surface (Rapp, 1960a; Gardner, 1969).

It seems likely that talus shift operating on actively accumulating debris slopes is caused mainly by rockfall impact, snow avalanches, debris flows and simple shear. In addition, mature taluses with a greater proportion of fine sediment may also experience lower magnitude processes, which may include needle ice creep and surface wash (Pérez, 1993).

2.5.2 Translational sliding

Although Ballantyne and Eckford (1984) reported a rotational sliding failure supported on talus below the scarp of the Lomond Hills in Fife, shallow translational failures are more widespread on talus than rotational slides. This is due to the shallowness of the rock debris mantle which inhibits the development of deep-seated shear planes. When material begins to slide downslope it often leaves behind a depression surrounded by rounded scarps (release scar). These often merge with debris flows downslope (Nyberg, 1989). Slides are triggered by a rise in positive pore water pressures, and a consequent reduction in effective normal stress at the grain contacts. The nature of shearing on talus is influenced by the sedimentary characteristics of the slope and the depth of the deposit. Clast size, shape, surface roughness and packing characteristics all influence the degree to which interlocking and therefore shear strength resist failure (Church and Miles, 1987; Selby, 1993). The amount and distribution of fine sediment in the talus is often crucial. An uneven vertical distribution of fine material within talus slope sediments may lead to the formation of discontinuities and potential failure surfaces. Mapping of sediment transfers on a talus may also reveal the links between shearing resistance and the distribution of fine sediment. Statham and Francis (1986) suggested that the relatively high amount of fine material underlying the upper rectilinear slope, may explain the likely occurrence of translational failures in this zone.

2.5.3 Debris flows

Debris flows or 'sediment gravity flows' are defined as the rapid downslope flowage of poorly-sorted rock debris and soil, mixed with a significant amount of water and air (Varnes, 1978; Brunsden, 1979; Innes, 1983a; White, 1981; Costa, 1984). Brunsden (1979) classified debris flows on the basis of scale and by the nature of the source areas into catastrophic, hillslope and valley-confined flows. Catastrophic flows are of such a high magnitude that they are of little importance in the context of talus modification; hillslope and valley-confined flows are, however, active agents of sediment redistribution on taluses. Hillslope flows are those that flow down an open hillside and are not constrained by topography. Valley confined flows are those that are restricted for much of their length to a pre-existing valley or gully. In practice the two are often transitional and many valley-confined flows discharge on to open hillsides in their lower courses, and hillslope flows may follow pre-existing courses cut in drift, talus or regolith, by earlier erosional events. Neither type is confined to talus slopes, and as mechanisms of sediment transport they are often responsible for the reworking of large volumes of glacigenic deposits in recently deglaciated valleys (Jackson *et al.*, 1989; Zimmerman and Haeberli, 1992; Ballantyne and Benn, 1994, 1996). The importance of debris flow activity has been recognised in many environments, for example arid and semi-arid regions (e.g. Blackwelder, 1928; Hooke, 1967; Beaty, 1974; Johnson and Rodine, 1984); in humid temperate regions (e.g. Johnson and Rahn, 1970; Selby, 1974; Statham, 1976b; Pierson, 1977, 1980); in mid-latitude mountains (e.g. Kotarba and Strömquist, 1984; van Steijn *et al.*, 1988) and in arctic regions (e.g. Winder, 1965; Broscoe and Thompson, 1969; Jahn, 1976; Rapp and Nyberg, 1981; Lawson, 1982; Larsson, 1982; Nyberg, 1989).

2.5.4 Debris flow initiation

Flows are often generated by slumps, topples or translational slides that disaggregate during failure (Pierson 1980; Caine, 1974, 1980; Rapp and Nyberg, 1981; Innes, 1983a; Johnson and Rodine, 1984; Nyberg, 1985; Zimmerman and Haeberli, 1992). The transition from slide to flow can take place in seconds at varying distances downslope (Johnson and Rahn, 1970; Costa, 1984). This change is incompletely understood, but the important mechanism seems to be one of progressive liquefaction and internal deformation of the sliding mass (Campbell, 1974; Rodine and Johnson, 1976; Johnson and Rodine, 1984; Takahashi, 1991). High pore water pressures and diminished shear strength can cause particles to lose cohesion and to rework the talus mass thoroughly enough to promote internal deformation. This may cause the debris to change by spontaneous liquefaction from a rigid slab into a viscous fluid, and flow. These conditions are dependent on an increase in pore water pressure within the moving mass, and this is likely to occur when the rate of deep percolation is slower than the rate of surface infiltration (Terzaghi and Peck, 1967; Youd, 1973; Costa, 1984). However, not all debris flows are initiated by simple shearing under conditions of high pore water pressure. Van Steijn *et al.*, (1988) observed that translational sliding had a limited role in triggering debris flows in the French Alps, and invoked failure of debris dams in rock gullies as the principal cause of flow initiation.

The prerequisite conditions for most debris flows include an abundant source of unconsolidated rock and soil debris, steep slopes, a large but intermittent source of moisture, and sparse vegetation cover (Costa, 1984). The role of water in debris flow initiation is crucial and activity often follows heavy rain. The links between precipitation and debris flow activity are supported by several studies (Caine, 1980). For example, Prior *et al.* (1970) observed that debris flows in North Antrim followed heavy rain of 37 mm and 58 mm day^{-1}. Rapp and Nyberg (1981) also invoked heavy precipitation as a cause of hillslope flows in Nissunvagge, northern Scandinavia; and Kotarba (1989) suggested that hillslope flows in the Tatra mountains of Poland were triggered by summer rain storms with precipitation rates greater than 25 mm hr^{-1}.

Sediment liquefaction in the presence of excessive moisture may also be initiated by the rapid melting of snow (e.g. Sharp and Nobles, 1953; Morton and Campbell, 1974; Owens, 1974; Lindh *et al.*, 1988; Harris and Gustafson, 1993; Ballantyne and Benn, 1994), or segregated ground ice (Lewkowicz, 1987a, 1987b; Burn and Friele, 1989). Combinations of triggers are possible and snow melt may often combine with heavy rain to initiate failures of talus sediments (Broscoe and Thompson, 1969; Rapp and Strömquist, 1976). Moisture may also be delivered to talus materials by the bursting of water from behind sediment dams within a gully (Takahashi, 1981, 1991). Water transferred to a talus from gullies on a rockwall may also have an important role in triggering debris flows at specific locations (Johnson and Rodine, 1984). Gardner (1982) suggested that flood discharges in steep gullies in the Rocky Mountains may develop into debris flows by the addition of material from the channel walls and bed, and Bovis and Dagg (1992) have shown how impulsive loading of bed sediments in such locations may trigger debris flow. Other modes of initial failure are possible; for example, Ballantyne (1981) argued that flowage of talus sediments may also be initiated by undrained loading resulting from the impact of falling particles. Okuda *et al.* (1980) and Suwa and Okuda (1980), have argued that the vibrations caused by existing flows are able to fluidise debris deposits, and thus initiate further failures. Winder (1965) has even suggested that the vibrations caused from thunderstorms may trigger debris flows.

Caine (1980) attempted to define a rainfall intensity threshold for catastrophic slope failures of the debris flow type, in which the initial failure is frequently a shallow planar slide which rapidly disintegrates to become a flow. A threshold for shallow instability in terms of rainfall intensity and duration was plotted as a limiting curve which has the form:

$$I = 14.82\ D^{-0.39}$$

in which I = rainfall intensity (mm hr^{-1}), and D = the duration of the rainfall (hr). This threshold can, however, only be taken as an approximate indicator of failure conditions, as other variables including antecedent soil moisture conditions, hydraulic gradient, talus structure and depth, debris texture, and slope angle, influence the propensity for failure. Statham (1976b) for example, in his study on the Black Mountain, showed that although heavy rain of 54 mm day^{-1} was the most likely trigger of debris flows in 1971, on 15 other days that year 30 mm of rain fell, and on 3 days 60 mm fell, with no associated debris flow activity. The problems with Caine's (1980) threshold are further illustrated by reference to Watanabe (1985), who estimated that debris flows in Japan tend to occur only when precipitation exceeds 120 mm in 24 hours, but debris flow activity occurred in Spitsbergen after only 31 mm of rain in 12 hours (Larsson, 1982). This difference may be attributable to the presence of permafrost at shallow depth in the Spitsbergen taluses. The importance of antecedent moisture conditions was illustrated in the Polish Tatra Mountains by Kotarba *et al.* (1987), who showed debris flows during wet periods may be triggered by rainfall intensities of 20 mm hr^{-1}, whereas 40 mm hr^{-1} may fail to mobilise flows when the ground is initially dry. Thus local factors may have a significant influence on the propensity of hillslope drift to failure during rainstorms.

2.5.5 Debris flow motion

The nature of debris flow itself is disputed. Large concentrations of sediment alter the fluid characteristics of flowing water, and the resulting debris flows conform to rheologic, not hydrodynamic principles. Bagnold (1954, 1956) argued that any flow with a sediment concentration exceeding 9% no longer behaves as a Newtonian fluid, and this is apparent for debris flows. The Coulomb-Viscous Model advocated by Johnson (1970) and Johnson and Rodine (1984), implies that debris flows behave as a plastico-viscous Bingham fluid, in which a plug of debris is enveloped by highly viscous sediments and transported downslope. Within the rigid plug shear stress is less than shear strength, so no internal deformation takes place (Johnson, 1970). This raft of undisturbed sediment is believed to move at uniform velocity, bounded by a zone of laminar flow, in which the velocity varies parabolically from a maximum at the boundary with the plug to zero at the walls of the channel (Johnson and Rodine, 1984). Takahashi (1981, 1991) disputed the belief that debris flows behave as plastico-viscous fluids and using Bagnold's (1954) concept of dispersive pressure, suggested that flows behave as a dilatant fluid in which motion occurs due to the forces generated by particle collisions within the flowing material. The Bingham model attributes the movement of larger clasts to a buoyancy effect and the strength of the surge phase, but in the light of the available evidence Takahashi (1981, 1991) suggested that particle collisions due to internal shearing are the most important process moving larger clasts. Dispersive pressures caused by grain interactions can therefore be invoked to explain the movement of boulders to the top and edges of a flow, giving rise to the formation of inverse grading, marginal levées and bouldery terminal lobes (Pierson, 1980; Takahashi, 1981, 1991; Nieuwenhuijzen and van Steijn, 1990). The concentration of clay particles within the debris flows appears to be an important determinant of flow behaviour. Innes (1983a) suggested that debris flow diamictons containing little or no clay lack internal cohesion and act as dilatant fluids; those with high clay contents are more likely to behave as a Bingham fluid. Cohesionless flow may therefore be important in debris flows with a low clay content, a model relevant to mass transport on coarse-textured talus slopes.

Flow patterns are often characterised by a series of waves or surges, interspersed by periods of reduced activity (e.g. Sharp and Nobles, 1953; Johnson, 1970; Pierson, 1980; Okuda *et al.*, 1980). Surges are periods of increased discharge that transport the coarsest debris, and are followed by a more fluid phase with high suspended sediment concentrations, but fewer boulders. Costa (1984) suggested that surges originate from the creation of temporary dams in gullies, and their subsequent breaching. The nature of flow not only changes over time, but also with travel distances downslope. Okuda *et al.* (1980) observed that debris flows in Japan are characterised by an upper zone of accelerating flow velocity, with motion sometimes exceeding 10 ms^{-1}; a middle segment moving at constant velocity and a terminal portion characterised by deceleration of flow and velocities rarely exceeding 5 ms^{-1}. The exact mechanism by which debris stops flowing is uncertain. Rodine and Johnson (1976) argued that lateral spreading may permit the thickness of flows to decrease below that required to sustain motion. In contrast, Takahashi (1991) has suggested that debris flows come to rest when escaping pore-fluid (water, clay and fine silts) causes an increase in internal friction.

The flows themselves are highly variable in size, and reported volumes of deposits range from 1 m^3 (Larsson, 1982), to 3,420,000 m^3 (Niyazov and Degovets, 1975). Even within a single area the volume of sediment transported by individual flows can be very different. Nyberg (1985), for example, observed flows in Swedish Lappland ranging in volume from a few cubic metres to 10,000 m^3. The total volume of sediment transported down gullies is strongly related to the return intervals of debris flows, but these vary between regions. Return intervals of 80-500 years and 50-400 years have been reported for high magnitude debris flows in Spitsbergen (André, 1990) and Swedish Lappland (Rapp and Nyberg, 1981) respectively, whilst Nieuwenhuijzen and van Steijn (1990) calculated an 10-40 year interval between major events in the French Alps. It is difficult to extrapolate these findings to the smaller scale, valley-confined and hillslope debris flows that are commonly responsible for reworking talus slopes. Kotarba (1992) suggested that current activity in the Polish Tatra Mountains is of low magnitude and high frequency, and that redistribution of talus sediments at the present time is by such events, and not by high magnitude flows. Lichenometric studies of hillslope and valley-confined debris flows in Scotland and Norway by Innes (1985a) revealed that the frequency of debris flows declines with magnitude in what may be an exponential fashion. In addition, this study indicated no apparent difference between the magnitude-frequency distributions of hillslope and valley-confined flows, despite the morphological differences between the two. Grove (1972) argued that slope failures in Norway were more frequent during the 'Little Ice Age' (late sixteenth-early nineteenth centuries AD), than at present, a pattern repeated in the Polish Tatra Mountains (Jonasson *et al.*, 1991; Kotarba, 1992). Lichenometric dating of debris flow deposits has also revealed periods of increased activity in Norway between 1670-1720 AD and 1790-1860 AD (Innes, 1985b), and in the Scottish Highlands during the nineteenth and twentieth centuries AD (Innes, 1983b). It is difficult to draw general conclusions about the magnitude and frequency relationships of debris flows when the lichenometric record spans only the last 500 years Innes (1985a).

2.5.6 Debris flow morphology

At the large scale, the effect of debris flow activity on mature talus slopes is to erode sediment from the upper slope and to deposit it near the talus foot, thus reducing the overall gradient of the slope and creating a long, sweeping basal concavity (Statham, 1976b, Ballantyne and Harris, 1994, p.230). On debris slopes in Norway, Ballantyne and Benn (1994) have shown that recent debris flow activity has reduced overall mean slope gradients from 27-29° to 24-26°, and those of the upper rectilinear slopes from 34-36° to 29-32°. Similar modifications of slope morphology on the Black Mountain in Carmarthenshire were observed by Statham

(1976b), who noted how gullying of a relatively steep talus slope had resulted in the formation of a lower-angled, continuously concave profile along gully axes. Redistribution of sediment within gullies may also disrupt fall sorting, often through the deposition of smaller clasts and fine sediment at, or beyond the base of the talus (Ballantyne and Harris, 1994, p.229).

Talus surfaces may also be radically altered by gully incision and debris cone formation. Gullies containing confined debris flows often comprise an upper erosional zone characterised by release scars and steep gully incision, a middle transport section defined by parallel levées, and a basal depositional area (Ballantyne and Harris, 1994, p.229). The channels of larger confined debris flows may bifurcate and form dendritic patterns on the talus surface (Rapp and Nyberg, 1981). Such patterns were observed by van Steijn *et al.* (1988) and Nieuwenhuijzen and van Steijn (1990) in the French Alps. These workers described flow tracks that are composed of a debris source area, often in the form of a ravine, with a narrowing or dam in its lower part. They observed that this upper area is continued downslope by a transitional zone where the ravine may be accompanied by intermittent levées. They then described a middle transport zone characterised by a meandering flow track and continuous levées of debris. They believed that the dimensions of the levées (which diminish downslope), are influenced by both the properties of sediment flow and channel morphology. Finally, a terminal zone is evident, in which the levées may merge to form a series of frontal lobes, often arranged across and beside each other. This general pattern of debris flow morphology has also been recognised by Kotarba (1989, 1992, 1997) in the Tatra Mountains of Poland. Here, the largest flow tracks begin within the source rockwall and flow on to 'debris-mantled slopes' to form a ribbon-like pattern of lateral levées that coalesce in a terminal lobe at the base of the slope.

The dimensions and gradients of flow tracks are highly variable, being related to changes in the volume of the flow, the abundance and nature of the debris, the presence of rock outcrops on the slope and the length of the runout zone. Observations by Nyberg (1989) of debris flows in Nissunvagge, in Swedish Lappland, showed release scars to vary in size from a few metres to approximately 20 m in width and 0.5-2 m in depth. He also described flow tracks several hundreds of metres long, 0.5-5 m in depth and 2-10 m wide. In the Alps, van Steijn *et al.* (1988) observed flow track lengths of 240-570 m, with widths ranging between 3-30 m and levées that occasionally exceeded 1.5 m in height. Harris and Gustafson (1993) working in the St. Elias Range, in Yukon Territory, have shown how flow track gradients may change from 56° in the source area to 8° at the foot of an individual flow. Downslope change in the gradient of alpine debris flow courses were also illustrated by van Steijn *et al.* (1988), who observed a decline from a mean slope angle of 32° in the uppermost section, to 17° at the foot of the flow. The dimensions of debris flow courses may also change over time. For example, Okuda *et al.* (1980) recorded seasonal changes in flow track cross sections in Japan; these changes may be a response to variations in the nature of sediment periodically transported down gullies. Thus the morphological characteristics of individual debris flow tracks are highly variable.

2.5.7 Debris flow deposits

Debris flows deposit sediment in marginal levées and terminal lobes. Levées are characteristic of hillslope flows, but may also be present on fans at the foot of valley confined flows. Levées often consist wholly of coarse material and boulders, although fine sediment may have been removed by postdepositional processes (Innes, 1983a). Debris flow levées located on talus in the French Alps have been shown to consist of coarse openwork material, with a weak alignment of particles parallel to the direction of flow (Nieuwenhuijzen and van Steijn, 1990; Bertran and

Texier, 1994). Levée sediments near the flow track may, however, be characterised by matrix-supported diamicts, and display a higher degree of particle orientation in the flow direction (Nieuwenhuijzen and van Steijn, 1990). Van Steijn *et al.* (1988) suggested that the levées in the French Alps coarsen in zones of accelerating flow velocity where the flow track is steepest. Levée deposition has been explained in terms of the buoyancy of large clasts in the grain mixture (Rodine and Johnson, 1976), and dispersive pressures within the flowing mass (Takahashi, 1991), resulting in displacement of sediment to the margins of the flow where competence is low.

Blair and Mcpherson (1992) argued that the distinctive processes responsible for the construction of debris fans, coupled with the reworking of their deposits, yield unique facies assemblages that permit interpretation of fan sequences. Sections through sediment gravity flow deposits often reveal considerable variety depending on local conditions and geomorphic history. They may comprise clast- or matrix-supported diamictons, and texture may be variable within an individual unit. The clasts themselves can vary in size, shape and surface roughness depending on the nature of the sediment source and transport history. Individual flows can, however, be recognised by fabric analysis or through the presence of shear planes within the diamicton, and stratigraphic sequences may be present. Observations of the diamict facies of the Bow Valley in the Canadian Rockies, by Eyles *et al.* (1988), revealed sediment gravity flow deposits to be massive, ungraded, matrix-supported, and showing a wide variation in clast size, texture, concentration and orientation. Some crude stratification was observed as a result of the superimposition of multiple beds of massive diamicts, or through the presence of clast-rich horizons within individual flow deposits. Poorly defined upper and lower contacts were sometimes identified by thin (<10 cm) interbeds of silty-sand, and Eyles *et al.* (1988) believed these to represent conformable bedding within fans. Crudely-bedded facies were also identified in sections of the Cinquefoil

Creek fan, British Columbia, by Eyles and Kocsis (1988) but individual beds were poorly defined and could not be traced laterally for more than a few metres. The Cinquefoil Creek fan was also shown to posses eddy structures, inverse grading, and massive beds that grade laterally into weakly graded facies. A preferred orientation of clasts was also noted in the Cinquefoil Creek fan, and despite considerable variability within the data set, particles were shown to be aligned parallel to the local slope, in the direction of flow.

These deposits, however, are characteristic of catastrophic debris flow activity and are not commonly responsible for the reworking talus deposits. Most studies concerned with debris flow deposits (e.g. Eyles *et al*., 1988; Eyles and Kocsis, 1988; Derbyshire and Owen, 1990; Owen, 1991) involve investigation of massive deposits, and the sedimentological characteristics of small-scale debris flows are less well established. Some workers have, however, attempted to characterise the nature of hillslope and valley confined flow deposits. Wasson (1979), for example, described stratified matrix-supported debris flow diamictons underlying talus in the Hindu Kush of Pakistan. Similarly, Bertran and Texier (1994) described stratified debris flow facies of reworked talus debris in the French Alps, and noted that coarse openwork proximal facies grade into lenses of diamicton downslope. Suwa and Okuda (1980), described inverse grading in debris flow lobes in the Japanese Alps, a pattern repeated in Scandinavian deposits studied by Rapp and Nyberg (1981). Localised inverse grading and lenticular structures were observed by Nieuwenhuijzen and van Steijn (1990) in debris flow sections in the French Alps, which led them to suggest that such structures could be used to reconstruct the stratigraphic sequence in small-scale flow deposits. The contacts between individual flow units may also be defined by buried organic layers and palaeosols (Brazier *et al.*, 1988; Brazier and Ballantyne, 1989; Ballantyne and Benn, 1994; Bertran and Texier, 1994). These horizons suggest periods of stability prior to renewed flow activity, and have implications for long term landscape and talus evolution.

2.5.8 Gullying

Talus form and sedimentology can be modified by gully formation either in response to debris flow activity or concentrated surface runoff. Debris flow and surface runoff, however, are transitional and any distinction between them is arbitrary. Surface movement of water down a talus can lead to the development of steep sided, gullies down which sediment may be redistributed. Water movement may occur within the tracks of pre-existing hillslope or valley-confined debris flows, a hypothesis supported by observations of fluvial facies and intercalated debris flow diamictons underlying talus foot debris cones (Derbyshire and Owen, 1990). Wash deposits are often finer than debris flow units, and crude sorting may be present. In sections through Canadian debris cones and fans, Eyles and Kocsis (1988) and Eyles *et al.* (1988) observed layers of massive and crudely bedded sands and gravels. In some cases, these facies were interpreted as the tops of massive debris flows, reworked by fluvial or aeolian processes. A small, discrete debris cone in Glen Etive in the Scottish Highlands, described by Brazier and Ballantyne (1989) and Brazier *et al.* (1988), was also shown to comprise fluvially-reworked deposits overlying debris flow facies.

2.5.9 Snow avalanches

Snow avalanches may also transport debris downslope, thus modifying talus form and internal structure. They also have a secondary role in delivering material to a talus via erosion of the rockwall upslope (Luckman, 1977) but input rates by snow avalanching are generally less than those by pure rockfall processes (Luckman, 1988). The size and frequency of avalanches is controlled by climate and topography (Gardner, 1970; Butler and Walsh, 1990; Butler *et al.*, 1992). Avalanches can occur in response to either the loading of a pre-existing snow pack by fresh snowfall, the propagation of structural discontinuities within a snowpack, or loss of cohesion within snow, often as a result of melting during periods of thaw. However, for avalanches to be effective geomorphological agents, they must have access to an abundance of loose, entrainable debris that is unprotected by overlying snow cover or vegetation (Gardner, 1970; Ackroyd, 1986). Full depth avalanches on active rockfall talus slopes are therefore particularly effective in redistributing material downslope. Processes of avalanche erosion and deposition are, however, poorly understood. The effects of an individual avalanche are highly specific and cannot be readily generalised (Gardner, 1983b). There is no simple relationship between avalanche magnitude, frequency, velocity, and geomorphological effectiveness. According to Gardner (1983b), debris may be entrained by 'snowballing' of wet, cohesive snow, whilst less cohesive snow is thought to erode by scouring its bed. If shearing occurs within the snow pack then the potential of an avalanche to transport debris is low.

2.5.10 Avalanche modified talus

Effective avalanche activity may reduce the overall gradient of talus slopes, especially in upper sections which can be lowered well below the 35-36° characteristic of unmodified forms, and also enhance the basal concavity (Rapp, 1959; Caine, 1969; Luckman, 1971, 1977, 1978, 1992; Huber, 1982). Fall sorting is often disturbed by the passage of avalanches which redistribute poorly-sorted debris at the slope-foot, and specific avalanche-related landforms may be superimposed on taluses. Erosional features include long ridges of debris extending downslope in the lee of large boulders, and formed by erosion of the surrounding, unprotected talus (Gardner, 1970; Luckman, 1971, 1977, 1978; Gray, 1973). Other erosional features include 'avalanche impact pits', which are depressions of variable size, often water-filled and normally confined to the foot of a talus where the gradient becomes less steep. Some are found in association with a low ridge on their distal side, comprising debris excavated from the depression by impacting avalanches (Davis, 1962; Peev, 1966; Liestøl, 1974; Corner, 1980; Fitzharris and Owens, 1984; Ballantyne, 1989a). Depositional landforms like 'roadbank tongues', may also be present on modified talus slopes. Roadbank tongues, as described by Rapp (1959), are tongue-shaped accumulations of avalanche debris, concave in profile, but flat-topped (sometimes with an asymmetric convexity) in section. Roadbank tongues are thought to build up through progressive deposition by avalanches following the same track. In contrast, fan tongues are thinner, fan- or splay-shaped veneers of debris deposited by avalanches unconstrained by topography (Rapp, 1959; Luckman, 1977; Ballantyne and Harris, 1994, p. 226-227).

2.5.11 Avalanche sediments

The sedimentary characteristics of avalanche-modified talus include an abundance of sharply angular debris produced by inter-clast collisions during transport. Many avalanche transported particles come to be perched on top of larger boulders, or occur as drapes of finer grained sediment over boulder surfaces (Luckman, 1977; Ballantyne and Harris, 1994, p. 226). Many avalanche landforms may, however, be polygenetic features. Luckman (1977), for example, suggested that tongue fans may reflect deposition by processes other than avalanches, and Blikra and Nemec (1993a, 1993b) have observed depositional sequences of intercalated avalanche, slushflow, and debris flow sediments. Blikra and Nemec suggested that the diagnostic features of avalanche deposits are: the large size of component clasts compared to the deposit thickness, uneven or discontinuous bed geometry (with some beds forming isolated lenses) openwork textures, sometimes with secondary inwashed fine sediment (sometimes bedded), normal grading and disorganised clast fabric.

These criteria were applied in Norway by Blikra and Nemec (1993a) to the Gardivick colluvial fan on the shores of Ørstafjorden, where they argued sub-aqueous debris flows are overlain by avalanche deposits of Younger Dryas and Holocene age. A second cone at Sunndalsøra, was shown to posses a different stratigraphy comprising interbedded snow flows and water-lain sediments. Dating of organic layers in both cones and mollusc shells in sediments at Gardivick suggested periods of enhanced avalanche activity during the Younger Dryas of *c.* 11-10 ka BP (*c.* 12.9-11.5 cal ka BP) and at around 4.6 ka BP. This latter phase is interpreted as representing a 'deterioration' of winter conditions following the Holocene Climatic Optimum. Superimposed on this general trend are short-term climatic fluctuations marked by the alternation of snow avalanche and surface wash activity (Blikra and Nemec, 1993a).

2.5.12 Slushflows

Slush avalanches are rapid mass movements of water-saturated snow or 'slush' (Washburn and Goldthwaite, 1958; Nyberg, 1985). Slushflows are caused by an increase in pore water pressure and the weakening of intergranular bonds within a snowpack, possibly in response to rapid thaw associated with raised temperatures (Onesti, 1985), or infiltration of rainfall (Hestnes, 1985). The possible effects on snow strength by increasing amounts of internal liquid water were described for snowpack in the Swiss mountains by Ambach and Howorka (1966), who suggested a positive relationship between the incidence of wet snow avalanches and the amount of free water within the snow cover. Slushflow activity resulting from snow melt is often confined to lower slopes where drainage is impeded. The effect of a slushflow is similar to that of a snow avalanche in terms of a redistribution of clasts downslope and the formation of perched debris deposits, often with drapes of finer sediment over boulders (Nyberg, 1985, 1987, 1989; Clark and Seppälä, 1988; Barsch *et al.*, 1993). The recorded volumes of sediment redistributed by slushflows are variable, with values for Karkevagge, Sweden ranging from <1 m^3 to 200-300 m^3 (Nyberg, 1985). Variations in the effectiveness of slushflows as agents of sediment transport were also illustrated by Gardner (1983b), who measured quantities of 2 m^3, 14 m^3 and 36 m^3 of rock debris for three wet snow avalanches in Canada. Gardner used these findings to argue that the erosive power of an individual slushflow can be very low, or even negligible depending on local conditions.

2.5.13 Creep.

Creep is the slow, downslope deformation of rock or soil and has long been recognised as an important agent of talus modification (e.g. Rapp, 1960a, Gardner, 1969; Pérez 1985, 1988, 1993). In an Andean paramo in Venezuela, daily fluctuations in temperature are responsible for the growth of needle ice and active particle creep in surficial sediments on fine-textured talus (Pérez, 1985, 1988, 1993). Creep may also involve downslope displacements of material along multiple, small-scale shear planes within a soil or fine-grained sediment, often in response to overburden pressures (Selby, 1993). The possible effectiveness of this process on talus slopes is strongly influenced by the volume and distribution of fine sediment within the deposit, as potential shear planes rarely bisect larger clasts. The operation of surficial creep by shear failures on a vegetated talus often leads to the development of terracettes and can represent an initial phase in the formation of translational failures.

2.6 Unmodified talus slopes in Britain

In Great Britain, talus slopes may be found below sea cliffs, at the foot of structural escarpments, such as limestone scarps or major sills, and on the lower slopes of many glacial troughs and corries (Ballantyne and Harris, 1994, p.219). Despite differences between sites, many talus accumulations in upland Britain hitherto described appear to exhibit the characteristic features of unmodified rockfall talus. There are relatively few studies describing modified talus slopes in Britain, although this may reflect a bias in the literature rather than rarity of talus modification.

2.6.1 Talus form

Several studies describe rockfall talus in Britain as exhibiting a steep upper rectilinear slope, a basal concavity and a degree of fall sorting, and hence most taluses have been interpreted as essentially unmodified forms. Minimum reported gradients of the upper rectilinear slope typically fall between 30° and 35.2°, whilst maximum angles for the upper slope range from 35° to 40° (Andrews, 1961; Statham, 1973a, 1976a; Ballantyne and Eckford, 1984). In this light, the average talus gradient of 25° recorded by Ball (1966) for repose slopes in north Wales seems unlikely to represent unmodified talus. Some variation exists within recorded mean gradients for different profiles on a single slope. For example, Ballantyne and Eckford (1984) observed maximum and minimum angles of 36.5° and 35.1° respectively for the upper rectilinear slopes of talus on An Teallach and Statham (1973a) reported a variation of 5° in the maximum gradients of talus slopes in Wales. The causes of such variations are reported to include debris piling up at low gradients behind large boulders, and where the talus is shallow, the gradient of the underlying bedrock (Ballantyne and Eckford, 1984).

An extensive basal concavity is a further feature of most taluses in upland Britain reported in the literature. Statham (1973a, 1976a) found that the taluses on Cader Idris and those flanking the Cuillin ridge on Skye, possess a distinct basal concavity. These observations were used in support of his rockfall talus model, in which he argued that a talus profile tends towards a straight slope with progressive burial of both the rockwall and basal concavity. Comparisons of different talus profiles on An Teallach by Ballantyne and Eckford (1984) showed that the lower slope is variable in length and degree of concavity. In addition, following observation of talus on the Lomond Hills, they suggested that the division between the upper rectilinear slope and concave lower slope is not always clear. Where the talus foot is submerged below water the basal concavity may also appear to be absent. Andrews (1961) suggested that the lack of an obvious basal concavity on the Wastwater taluses may be due to its presence below the water level. Statham (1973a) invoked a similar explanation when accounting for the straight profile of rockfall talus lopes above Llyn Cau in Wales. In this context, however, it is worth noting that research on arctic talus slopes (Howarth and Bones, 1972), suggested that erosion of the talus foot by wave action may inhibit the formation of a concavity.

Fall sorting is another common characteristic of talus slopes in Britain and has been observed in the Scottish Highlands (Statham, 1976a; Shaw, 1977; Ballantyne, 1981, 1984, 1991a; Ballantyne and Harris, 1994, p. 219), Wales (Tinkler, 1966; Statham, 1973a) and in the English Lake District (Hay, 1937; Andrews, 1961). Statham (1973a) identified a significant increase in mean clast size downslope on talus slopes in Cader Idris. Statham (1976a) also identified strong evidence of fall-sorting on talus slopes in the Cuillins on Skye. These findings were used by Statham (1976a) in support of his 'scree slope rockfall model' in which fall-sorting is attributed to the 'sieving' effect of the talus surface.

2.6.2 Talus age

The majority of talus slopes in Britain are either partly or wholly vegetated and even the most remote rockfall slopes in the high corries of Scotland often support a cover of moss and lichens (Ballantyne and Harris, 1994, p. 223). The extensive cover of vegetation on most taluses in Britain suggests that rockfall is relatively infrequent, and that many taluses are essentially relict features.

Estimates of present-day rates of rockfall delivery to the foot of cliffs in the British uplands are low, and it is difficult to see how current activity could have produced extensive taluses. A mean present-day rockfall retreat rate of 0.015 mm yr^{-1} has been calculated for rock faces on An Teallach and the Lomond Hills (Ballantyne and Eckford, 1984), and an identical value has been suggested for rockwalls in Snowdonia (Stuart, 1984; Table 2.1). Headwall retreat rates of this magnitude correspond to talus accumulation rates of 40 mm ka^{-1} on An Teallach, and 10 mm ka^{-1} in the Lomond Hills, and thus appear inconsistent with the large amounts of rockfall debris resident below rockwalls at these sites.

Harker (1901) attempted to explain the origin of talus slopes in the corries of the Cuillin Hills on Skye by suggesting that they formed during a period of sustained periglacial activity immediately following the retreat of the last glaciers. More recent research supports this assertion, and advocates that taluses in upland Britain formed, to a large extent, within the Late Devensian Lateglacial (Galloway, 1958; Ball, 1966; Tufnell, 1969; Ball and Goodier, 1970; Ryder and McCann, 1971; Kotarba, 1984; Ballantyne and Eckford, 1984; Ballantyne and Kirkbride, 1986, Ballantyne and Harris, 1994, p.224). By combining data from studies of Lateglacial protalus ramparts in the Scottish Highlands and Cumbria, Ballantyne and Kirkbride (1986) calculated a mean average amount of rockwall retreat of 1.35 m for the Loch Lomond Stade of *c.* 11-10 ka BP (*c.* 12.9-11.5 cal ka BP). This

Table 2.1. Calculated rockwall retreat rates for upland Britain, arctic environments and alpine environments.

Location	Lithology	Rockwall retreat rate ($mm\ yr^{-1}$) minimum	mean	maximum	Source
Great Britain, present day					
An Teallach	Sandstone	0.013	0.015	0.016	Ballantyne and
Lomond Hills, Fife	Dolerite	0.009	0.015	0.063	Eckford, 1984
Snowdonia	Volcanics	0.010	0.015	0.021	Stuart, 1984
Great Britain, Loch Lomond Stade					
Scottish Highlands	Various	1.64		3.29	Ballantyne and Kirkbride, 1987
Arctic Environments, present day					
Spitsbergen	Limestone	0.05		0.50	Rapp, 1960a
Swedish Lappland	Schist	0.04		0.15	Rapp, 1960b
Northern Finland	Various	0.07		0.18	Söderman, 1980
Yukon, Canada	Igneous	0.003		0.019	Gray, 1972
Franz Josef Land	Basalt	0.05		0.07	Suchodrovski, 1962
Arctic Environments, Holocene					
West Greenland	Volcanics	0.5		1.5	Frich & Brandt, 1985
NW Spitsbergen	Quartzite	0.10		0.72	André, 1985
Ellesmere Is, Canada	Limestone	0.30		1.30	French, 1976
Yukon, Canada	Metamorphic	0.02	0.073	0.17	Gray, 1972
Yukon, Canada	Igneous	0.007	0.018	0.03	Gray, 1972
Northern Finland	Various	0.04		0.94	Söderman, 1980
Alpine Environments, present day					
Polish Tatra Mts	Limestones	0.10	0.84	3.0	Kotarba, 1972
Polish Tatra Mts	Granites		0.7		Kotarba *et al.*, 1987
Front Range, Colorado	Various		0.76		Caine, 1974
French Alps	Various	0.05		3.0	Francou, 1988
Alpine Environments, Holocene					
Swiss Alps	Various	0.64		3.93	Barsch, 1977
Rocky Mts, USA	Various	0.3		4.6	Höllermann, 1983
Austrian Alps	Metamorphic	0.7		1.0	Poser, 1954
Blanca Mts, Colorado	Various	0.05	0.42	0.82	Olyphant, 1983

figure corresponds to mean maximum and mean minimum retreat rates of 3.38 mm yr^{-1} and 1.69 mm yr^{-1} respectively during the Stade. These rates are much higher than those reported for arctic environments, but the maximum value is similar to present-day maximum retreat rates for alpine cliffs (Table 2.1), suggesting that climatic conditions during the Loch Lomond Stade were similar to those experienced by present-day alpine cliffs, with numerous freeze-thaw cycles. Talus slopes in upland Britain may have received an enhanced input of rockfall debris during the Little Ice Age of the 17th and 18th centuries *AD* (Andrews, 1961; *cf.* Grove, 1972), although this suggestion currently remains hypothetical.

Therefore, the Late Devensian Lateglacial apparently represents the key period for the accumulation of talus slopes in the British Isles. Ballantyne and Harris (1994) argued that the retreat of the Devensian ice sheet exposed glacially-steepened slopes, and thus potentially unstable rockwalls, to a severe periglacial regime. The withdrawal of supporting glacier ice and the operation of macrogelivation processes is seen as responsible for the pronounced rockfall activity during and after the withdrawal of the last ice sheet. The large amounts of reworked rockfall debris in Loch Lomond Readvance glacial deposits provides indirect evidence of pronounced talus accumulation prior to the Loch Lomond Stade (Ryder and McCann, 1971; Benn, 1989). More direct evidence of a Lateglacial origin for taluses in Britain was presented by Kotarba (1984) who observed that taluses within Loch Lomond Readvance limits on the island of Rum, are less extensive than those outside these former ice limits. Similarly, Ballantyne and Eckford (1984) suggested that mature talus sheets on An Teallach are located outside the limits of the Loch Lomond Stade glaciers, and that talus accumulations within the limits of the Loch Lomond Stade are less well developed. These studies thus support a Lateglacial origin for much of the debris underlying talus slopes in upland Britain.

2.7 Modified talus slopes in Britain.

Talus slopes in Britain are essentially relict features on which erosion has replaced accumulation as the dominant geomorphic process during the Holocene (Ballantyne, 1984, 1991a; Ballantyne and Eckford, 1984; Ballantyne and Harris, 1994, p.224). The mechanisms of erosion on talus slopes in Britain include shallow sliding failures, debris flows, gully erosion, avalanche activity and soil creep in surficial layers.

2.7.1 Sliding failure

Small-scale sliding failures redistribute talus sediments downslope, whilst larger failures may even destroy rockfall accumulations. Two large sliding failures were mapped on talus in the Lomond Hills in Fife by Ballantyne and Eckford (1984), and both have resulted in extensive modification of talus slope form. The largest of these was reported to possess a headward scarp covering *c*. 6300 m^2, and from the concave profile of the shear plane, was interpreted as being a rotational slide. The second landslip was described as being less extensive and appears to represent a rockwall slab failure which impacted on to the talus below. Neither of these failures can be dated with any confidence, but from both historical evidence and the weathered nature of rock outcrops on the exposed backslopes of both slips, it is probable that these are ancient features. Ballantyne and Eckford speculated that the larger was possibly triggered by an earthquake associated with differential movement of crustal blocks along faults during localised glacio-isostatic uplift.

Deep rotational shear failures affecting talus, such as that on the Lomond Hills are rare. Slides on talus slopes are usually shallow and deformation normally occurs above a translational shear plane. Several failures of this type have been observed by the author on the taluses flanking the Trotternish escarpment. Sliding failures on talus are poorly represented in the literature, possibly due to the transient nature of slides, which often disaggregate and develop into debris flows.

2.7.2 Debris flows

Hillslope and valley-confined flows are currently active in upland Britain and both types are endemic on talus. The occurrence of debris flows in Scotland was mapped by Innes (1983b), who showed present-day activity to be concentrated in the Western Highlands with an additional focus in the Cairngorms. In addition, debris flows also tend to be concentrated on any rock-type that disintegrates into sand-rich regolith on weathering, for example, Torridon Sandstone and the granite of northern Arran or the Cairngorms (Innes, 1983a; Ballantyne, 1986a). Debris flows are not, however, confined to the Highlands of Scotland, but have also been reported in the uplands of northern England (e.g. Harvey, 1986, 1992, 1996; Carling, 1987; Harvey and Renwick, 1987; Wells and Harvey, 1987), Wales (Statham, 1976b; Addison, 1987) and Ireland (Prior *et al.*, 1970).

2.7.3 Debris flow morphology.

Ballantyne (1981) and Innes (1983a) argued that debris flows in Scotland are initiated on slopes steeper than 30°, and the latter suggested that the great majority of flows originate on slopes of 32-42°. Individual flows on talus accumulations redistribute material downslope from a zone of net erosion, often via a clearly defined flow track, to areas of deposition, in the form of marginal levées and terminal lobes. On the Black Mountain in Wales, flow tracks are typically 1.0-1.5 m wide and marginal levées are 0.3-0.4 m high; the debris flow profiles are concave and decline from gradients of 40° in the source area to 8° at the foot over a distance of *c.* 240 m, and thus represent a significant reduction in the average gradient of the original talus slope; the transition from erosion to deposition occurs at 16° (Statham, 1976b). On An Teallach, however, Ballantyne (1981) found that deposition succeeds erosion at much steeper gradients (20-28°), possibly reflecting greater flow viscosity at this site. Nevertheless, many similarities exist between debris flows around Britain. A flow on the Lomond scarp in Fife was shown to comprise the distinct headward source area, boulder levées, hummocky deposits and terminal lobes characteristic of debris flow (Ballantyne and Eckford, 1984). Luckman (1992) described similar features in the Lairig Ghru in the Cairngorms, where debris flows are currently active on Lateglacial talus. Here, individual flow tracks were shown to comprise channels up to 1.5 m deep and 5.0 m across. Depositional forms in the Lairig Ghru include levées up to 1.5 m in height and 1.5-2.0 m apart that terminate downslope at lobes up to 5.0 m across.

The amount of sediment transported by debris flows is variable. Statham (1976b) observed that flows in gullies on the Black Mountain transported between 8.4 and 11.5 m^3 yr^{-1}, and that these outputs were balanced by inputs generated by active erosion of the gully walls. Innes (1985a) demonstrated that individual flows in the Cairngorms had deposited between 6.0 m^3 yr^{-1} and 38.0 m^3 yr^{-1} of sediment, whilst those in Glen Coe had deposited between 18 m^3 yr^{-1} and 26 m^3 yr^{-1} of sediment. Individual events of a higher magnitude are not unknown, however; for example, a single flow event in the Ochils in central Scotland engulfed a house and deposited *c.* 350 m^3 of sediment (Jenkins *et al.*, 1988).

2.7.4 Debris flow deposits.

Sections through debris flow deposits generally display coarse, poorly-sorted diamictons that may be clast- or matrix-supported, and this seems to be the case in Great Britain as elsewhere. The coarse-grained nature of many deposits supports Innes' (1983a) conclusions that motion takes place predominantly by cohesionless grainflow, particularly where clay content is low (<3%). Innes's ideas are supported by the observations of Carling (1987), who argued that bouldery debris flow deposits in a tributary of the River Wear, County Durham, reflect low-viscosity grainflow with frequent particle collisions. In contrast, Wells and Harvey (1987) suggested that facies associated with valley-confined debris flow sediments in the Howgill Fells are characteristic of highly viscous debris flows containing a significant amount of water. From investigations of the clay-rich (11-15%) matrix in these deposits, Wells and Harvey (1987) concluded that motion had taken the form of laminar non-Newtonian slurry flow. It seems likely, however, that debris flows reworking coarse talus sediments may be more readily attributable to the process of cohesionless grainflow outlined by Innes (1983a).

Carling (1987) described sections through debris flow sediments in the northern Pennines. Distal deposits were shown to possess an open-work structure of locally-derived boulders with poorly-developed imbrication. In contrast, proximal deposits were characterised by poorly-sorted pebble, gravel and sand sized material with pockets of finer sediment and only a few large boulders. Linear structures were also observed in proximal sediments, and these were interpreted by Carling as evidence of normal and low-angled planar cross bedding. A weak fabric was evident with the long axes of prolate clasts aligned transverse to the local slope, though some rod-shaped clasts were oriented with the long axis downslope. Although these facies do not represent reworked talus sediments *sensu stricto,* many of the features observed by Carling (1987) are paralleled in the stratigraphy of Scottish debris cones containing reworked rockfall debris.

2.7.5 Debris flow chronology

Previously reported sections through debris cones exhibit organic horizons that intercalate with debris flow units. Such layers may have significant implications for slope evolution and permit radiocarbon dating of the timing of emplacement of overlying sediment units. A fluvially-reworked debris cone in Glen Etive described by Brazier *et al.* (1988) contains two organic layers, the lower within a sequence of debris flow units and the upper overlain by fluvial facies. A radiocarbon date of 4480±300 yr BP (5888-4283 cal ka BP) was obtained for the top of the lower organic horizon, and approximates the date of the final debris flow event on the cone. A radiocarbon date of 550±50 yr BP (650-508 cal ka BP) for the top of the upper organic layer is thought to represent a maximal age for the onset of fluvial reworking. In the light of these dates and associated pollen-stratigraphic evidence, Brazier *et al.* (1988) suggested that the debris flow facies represent paraglacial slope adjustment in the early Holocene followed by a period of prolonged stability. The more recent slope instability reflected in the fluvial facies appears to be associated with human interference including burning of the vegetation.

Investigations of debris cone deposits in Glen Feshie by Brazier and Ballantyne (1989) provided further evidence for increased slope activity in the late Holocene. Dating of buried organic-rich sediments and rootlets enabled calculation of an average annual accumulation rate of 50-60 m^3 of sediment over the last 300 years, which may represent a significant acceleration of slope processes in the late Holocene at this site. Innes (1983b) employed lichenometry to date debris flow activity in the Scottish Highlands. His findings suggested a substantial increase in the frequency of debris flows within the last 500 years, and that the majority of flows date from the past 250 years. These findings are supported by those of Thomas (1956) who interpreted gully forms in the Breacon Beacons as indicating erosion during only the past 500 years. Studies such as these have contributed to a growing body of evidence which suggests that hillslope instability in upland Britain is concentrated in the latter half of the Holocene (Ballantyne, 1991a, 1991b, 1993).

The cause of intensified debris flow activity in the last few centuries remains unclear. Several authors have suggested that increased erosion of upland drift slopes may be associated with climatic deterioration during the onset of the sub-Atlantic period (*c.* 2.5 ka BP, or, *c.* 2.7-2.3 cal ka BP), and also during the Little Ice Age of the seventeenth and eighteenth centuries AD (*cf.* Taylor, 1975; Lamb, 1977, 1982). This argument, however, rests partly on apparent coincidences in timing, but mainly on the view that climatic deterioration is somehow automatically associated with hillslope instability. The timing argument is difficult to sustain as the available evidence linking higher rates of slope processes to the 'Little Ice Age' is insufficiently precise. In addition, the increase in debris flow activity documented by Innes (1983b) largely post-dates the severest part of the 'Little Ice Age'. Nor is it conclusive that slope instability has any direct link with climatic deterioration. During the 'Little Ice Age', average annual temperatures in Britain were at most 0.6°c lower than at present (Lamb, 1977), and precipitation was up to 7% less than at present (Thom and Leger, 1976). Given that a break-up of the vegetation cover is the most likely cause of increased slope instability in the Late Holocene, it is not immediately clear why these average changes should have a pronounced effect (Ballantyne, 1991b). Increased storminess associated with phases of Holocene climate deterioration may, however, represent a possible underlying cause of enhanced mid to late Holocene debris flow activity. Brazier and Ballantyne (1989) argued that infrequent high magnitude storms of no apparent long-term climatic significance may have initiated a subsequent intensification of debris flow erosion given that the initial storm was violent enough to strip away surface vegetation, thus lowering the threshold for renewed debris flow activity.

More recently, Brooks *et al.* (1993a, 1993b), Brooks *et al.*, (1995), Brooks and Richards (1994) and Brooks and Collison (1996), have modelled the likelihood of shallow translational failure of drift slopes in terms of either soil maturity, slope gradient or climatic conditions, or combinations of each. These workers have suggested that internal soil hydrology becomes impeded with increasing podzolisation, and thus that soils of varying maturity will exhibit a different response to a given rainstorm. The model developed by Brooks *et al,* (1993a) and Brooks and Richards (1994) predicts that increasing soil development is associated with reduced slope stability, and that soils of varying maturity will respond differently to precipitation events of various synoptic origins. Significantly, this model associates increased rates of hillslope modification with proposed climatic deterioration early in the sub-Atlantic period (*c.* 2.5 ka BP, or, *c.* 2.7-2.3 cal ka BP; *cf.* Lamb, 1977,1982).

Enhanced slope activity in the late Holocene has also been attributed to anthropogenic influences. Innes (1983b, 1985a) suggested that recent debris flows in the Scottish Highlands were initiated by changes in land management practices during the 19th and 20th centuries *AD*, and that current rates reflect an ongoing period of rapid adjustment in slope systems following anthropogenic interference. Disruption of the vegetation cover by burning may have been an important trigger of erosion (Innes, 1983b, 1983c; Brazier *et al.*, 1988; Ballantyne, 1991a, 1991b; Whittington, 1991). Overgrazing may also have had a role in promoting slope instability in historic times (Harvey *et al.*, 1981; Pye and Paine, 1983; Ballantyne and Whittington, 1987; Ballantyne, 1991a, 1991b).

Arguments about the onset of hillslope activity during the Holocene have implications for talus development. Two organic-rich horizons within colluvial facies were observed by Innes (1983d) in a section through talus near The Storr on the Trotternish peninsula, northern Skye. The top of the lower organic layer was dated at 1990±70 yr BP (2118-1730 cal ka BP). However, it is not clear whether this represents a buried soil developed on debris flow deposits or on the original talus surface, and thus it is uncertain if this date represents the onset of slope instability at this site. It is evident, however, that the operation of slope processes at this location over the last 2000 years has been episodic, with phases of activity interrupted by periods of stability. The causes of this pattern of activity are also unclear. Innes (1983d) argued that climatic controls and their effect on the stability of the cliffs upslope could be invoked to explain the episodic nature of recent talus accretion on Trotternish. This assertion is consistent with the findings of Brooks *et al.* (1993a) and Brooks and Richards (1994) that suggest a period of accelerated slope failure at *c*. 2.5 ka BP, coincident with relatively wet climatic conditions (*cf.* Lamb, 1977, 1982). The association of *Plantago lanceolata* and microscopic charcoal found within organic-rich horizons in nearby talus deposits, however, may suggest that burning of vegetation (*cf.* Tipping, 1996) was responsible for destabilisation of talus slopes on Trotternish (Whittington, 1991).

2.7.6 Avalanche modified talus

The effects of avalanche activity in upland Britain are poorly documented, and consequently the role of avalanches in modifying debris slopes remains unclear. The frequency of avalanches in Scotland has been illustrated by Ward (1980, 1984a, 1984b), who showed that concentrations of avalanche activity exist in the Ben Nevis, Glen Coe, Lochnagar, Creag Meaghaidh and Cairngorm areas. Ward's findings were, however, based partly on reports in climbing journals, and it is notable that the areas of frequent avalanche activity that he identified are those most frequented by winter climbers. In reality, outside the Grampian Highlands, little is known about the frequency or effects of avalanche activity.

The majority of avalanches in the Cairngorms are small and take the form of cornice falls, sluffs of powder snow from free faces, and shallow dry- or wet-slab avalanches. Large avalanches, however, are not unknown, and have been observed to travel up to a few kilometres, and often involve a snow layer 2-3 m thick and 200-300 m wide. Excluding small-scale snow failure from steep cliffs, most avalanches are released from slopes of 35-45°, although free faces, smooth surfaces and slopes in the lee of major storms tend to respond most rapidly to the onset of avalanche conditions. The rarity of large-scale avalanches in Scotland reflects the lack of steep slopes of alpine dimensions and the relative mildness of present winter conditions, in which incursions of warm air may lead to thaw at any time, and thus inhibit the accumulation of a deep snowpack (Ballantyne and Harris, 1994, p.227). Profiles through a typical Scottish snow pack often reveal masses of wind-slab above an equigranular layer of old snow, with icy layers at all depths (Ward *et al.*, 1985). The lack of a well defined potential failure surface at depth inhibits the formation of very large avalanches of alpine proportions. However, any discontinuities in the snow pack are likely to promote instability, and wind-slab failures often slide over icy layers at depth. Dry-slab avalanches are released when snow densities are of the order of 250 kg m^{-3} or less, and snow temperatures are down to -10°c in the upper layers. Wet slab avalanches and sluffs occur when the snow is isothermal at melting point, and usually when densities exceed 450 kg m^{-3} (Ward *et al.*, 1985).

Either full-depth avalanches or the passage of an avalanche over snow-free ground are required to effect a modification of slope morphology (Gardner, 1970; Luckman, 1977; Ackroyd, 1986). Most avalanches in Scotland are characterised by shearing within the snow pack, and are therefore unable to entrain debris and modify the mountain slopes over which they pass. However, even full-depth avalanches in Scotland may have only a limited effect. The transport of a few boulders and patches of turf downslope were the only observed effects of two full-depth avalanches on Meall Uaine in Glen Shee (Davison and Davison, 1987). In addition, Ward's (1985) study of three talus cones in a corrie on Lochnagar revealed only minor modification of the rockfall slopes by avalanching. He demonstrated that avalanches were responsible for the presence of perched debris on boulders, bare patches on otherwise lichen-covered rocks, boulder holes in vegetated talus and scratch marks along boulder crests, but found no evidence for large-scale modification of the talus. Although the surveyed rockfall slopes possessed a slight concavity with gradients increasing from 29° at the base to 35° at the talus crest, Ward (1985) found no conclusive evidence for avalanche modification of these profiles.

At only a small number of high-altitude sites in Britain are the effects of avalanche activity on talus clearly displayed. Luckman (1992) described significant modification of taluses in the Lairig Ghru in the Cairngorms, where fresh accumulations of perched debris on large boulders, avalanche garlands and avalanche boulder tongues all indicate redistribution of rockfall material to the base of the slope and thus modification of talus morphology. Five roadbank tongues were also observed in Glen Luibeg below rock chutes on the western flanks of Derry Cairngorm. Luckman (1992) argued that the fresh faces on avalanche-transported debris in both the Lairig Ghru and Glen Luibeg indicate that these depositional features are actively accumulating. An avalanche impact site in Coire na Ciste on Ben Nevis also contains evidence of recent avalanche activity (Ballantyne, 1989a). A boulder rampart below the impact depression consists of clasts excavated from the pit by avalanches. Many of these possess sharply angular edges and lack signs of weathering or lichen growth. Ballantyne (1989a) argued that these characteristics represent evidence of active deposition by avalanches, and indicate a reworking of talus sediments from the rock gullies above Coire na Ciste. The passage of avalanches down to the impact site is also marked by the long, sweeping, low gradient concavity of the talus slopes above.

Though evidence for recent avalanche modification of talus is restricted to a limited number of sites, it is likely that increased avalanche activity occurred during the Loch Lomond Stade and possibly even during the 'Little Ice Age' of the seventeenth and eighteenth centuries AD. In Scotland, relict avalanche boulder tongues at the feet of vegetated talus slopes in the Lairig Ghru, Glen Feshie, Glen

Taitneach and on Skye, probably owe their formation to former periods of greater snow accumulation (Ballantyne, 1991c; Ballantyne and Harris, 1994, p.227).

2.7.7 Creep

Soil creep in surficial layers leads to the development of small terracettes on the talus surface. Such features are widespread on the vegetated surfaces of relict rockfall accumulations that contain a relatively large proportion of fine grained sediment. Ballantyne and Eckford (1984) argued that soil creep is responsible for the formation of terracettes on talus slopes in the Lomond Hills. That creep has been active in recent times is also evident from the accumulation of soil upslope of a wall built across the lower part of the Lomond scarp talus. In places, the upslope side of this wall has been entirely buried.

2.8 Summary

Unmodified rockfall talus slopes exhibit a steep, rectilinear upper slope at *c.* 35-36°, a basal concavity and some degree of fall sorting. Models that attempt to explain the formation of rockfall accumulations include 'the angle of repose model' (*cf.* Marr, 1900; Hobbs, 1931; Rapp, 1960a), 'the discrete rockfall model' (Statham, 1973a, 1976a; Kirkby and Statham, 1975), and 'the two facet model' (Francou and Manté, 1990; Francou, 1991). These models, however, make only scant reference to processes of sediment transport that modify talus form, and thus offer only a partial explanation of talus slope morphology.

In Britain, almost all upland talus slopes appear to be relict features of Late Devensian Lateglacial age. Estimated present-day rockfall accumulation rates are low. During the Holocene, erosion appears to have replaced rockfall deposition as the dominant geomorphic process on talus slopes. Both hillslope and valley-confined debris flows appear to have been the principal agents of talus modification at most sites in Britain. The effect of repeated debris flows has been to redistribute debris downslope, thus lowering the gradient of the talus and enhancing the overall degree of concavity. The underlying causes of erosion and reworking of relict talus slopes are currently elusive. Several studies, however, have advocated climate change and anthropogenic disturbance as possible causes of erosion of drift-mantled slopes in the British uplands. These studies raise the possibility that talus slopes may be much more sensitive to environmental change than has previously been appreciated. Thus, future investigations of modified talus accumulations and associated deposits may ultimately yield valuable data regarding former environmental changes.

2.9 Research questions

The existing literature on talus leaves several issues unresolved, and in doing so generates new lines of inquiry. The relative importance of mass transport in talus evolution requires further re-evaluation given the effectiveness of secondary process in modifying debris slopes. The origin of abundant internal fine sediment underlying relict talus slopes remains to be established. Previous studies have suggested that such fine material may represent pockets of till or older colluvium, and therefore have an exotic origin (Rapp and Nyberg, 1981; Blikra, 1994). The timing and possible causes of phases of talus modification by erosion and reworking are currently unknown; however, the presence of buried soil horizons and peat layers underlying talus slopes in the Scottish Highlands provides an opportunity to investigate this particular aspect of talus evolution.

Chapter 3

The field sites

3.1 Introduction

Five field sites were investigated in the course of the current research. Trotternish, northern Skye was chosen as the primary field location given the abundance of relict talus debris, and because this location supports clear morphological evidence for a long history of accumulation and reworking of rockfall sediment. Abundant deep gullies that are incised into the talus accumulation facilitate close examination of the internal structure of such deposits, and frequently reveal buried organic-rich horizons, interpreted to represent *in situ* palaeosols, that provide sources of evidence regarding the timing and possible causes of talus reworking. Investigations on Trotternish highlighted the inadequacies of existing models of talus accumulation and evolution, and led to the formulation of new ideas concerning the behaviour of talus slopes. Fieldwork was then extended to four mainland field sites where the generality of findings made on Trotternish was tested; these were Quinag (Assynt), Stac Pollaidh (Coigach), Baosbheinn (Wester Ross) and upper Glen Feshie (Cairngorms).

3.2 Trotternish

Trotternish is the largest of three peninsulas in northern Skye. It is dominated by an escarpment that runs north-south along its length for 23 km, culminating in The Storr at 719 m (Figure 3.1).

At its southern end the escarpment rises from low-lying land north-west of Portree to the first prominent top of Ben Dearg (552 m). At this location the steep east-facing scarp slope is already well developed, rising in cliffs *c.* 130 m high to

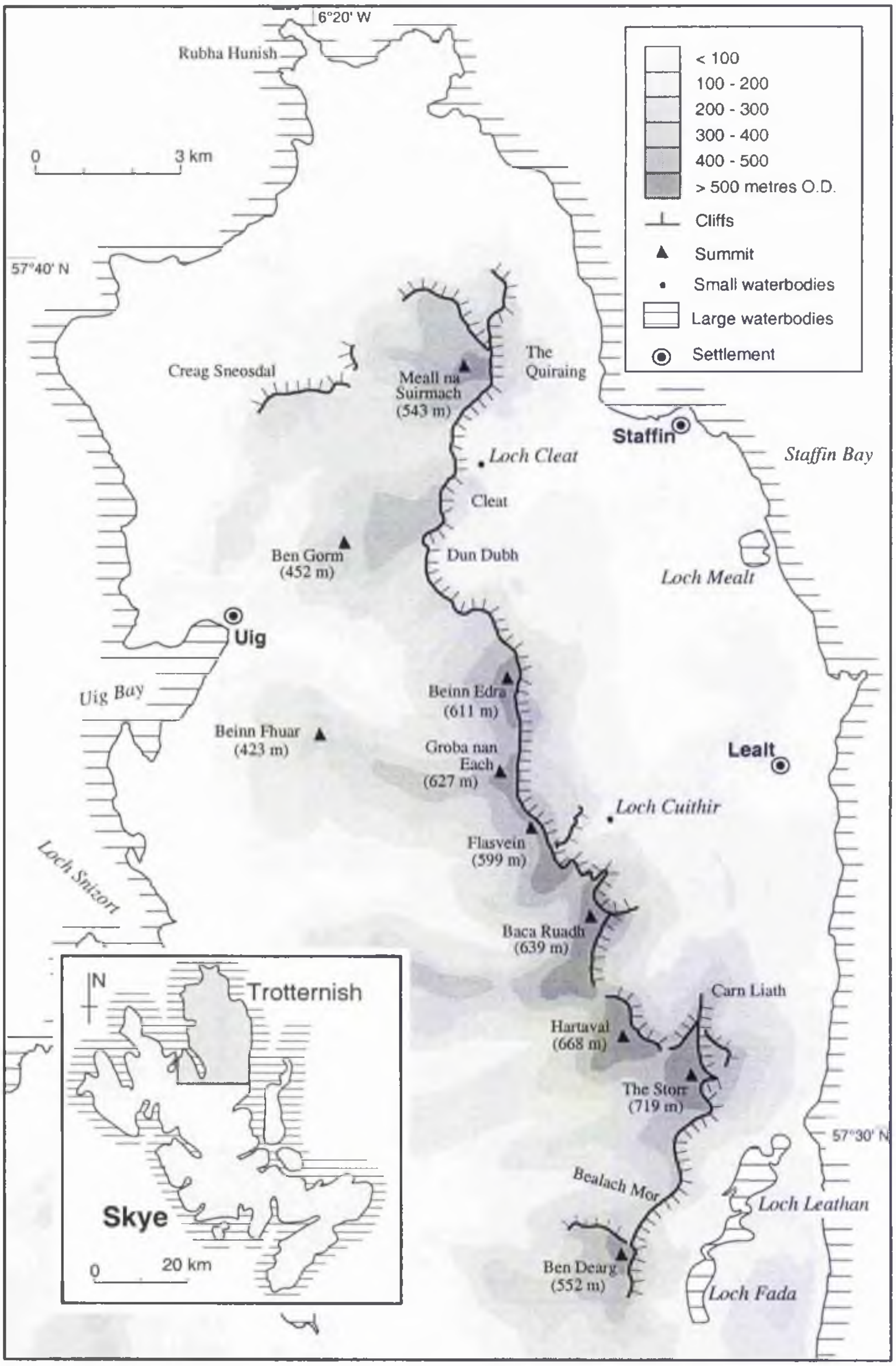


Figure 3.1. Introductory relief map of Trotternish, northern Skye

the summit plateau. The unbroken escarpment then runs north towards the spectacular nose of The Storr, one of eight tops above 500 m (Figure 3.2). The scarp cliffs contrast greatly with the gentle dip of the escarpment to the west, where fingers of high land extend westwards to form ancillary summits such as Ben Gorm and Beinn Fhuar. On the scarp face, multiple rock mass failures have sculptured the cliffs to form the most extensive area of landslip in Britain (Anderson and Dunham, 1966). Many of these rock slope failures predate the last glaciation (Ballantyne, 1991d, 1991e). However, it is the postglacial rockslides at The Storr and The Quiraing that are most striking.

3.2.1 Geology

The Trotternish escarpment consists of westward-dipping plateau basalts that overlie upper Jurassic sedimentary strata intruded by transgressive dolerite sills (Anderson and Dunham, 1966; Bell and Harris, 1986). The oldest rocks exposed on Trotternish are unfaulted Jurassic strata that overlie a basement complex of Torridon Sandstone and Lewisian Gneiss (Chester *et al.*, 1983). The Jurassic sequence exposed in north Skye comprise the Middle Lias Scalpa Sandstones, that crop out in the sea cliffs, and the overlying Staffin Bay and Staffin Shale formations (Bell and Harris, 1986). The Staffin Shale series is immediately overlain by Tertiary Palagonite tuffs. In total, the Jurassic sequence that underlies the broad coastal fringe of eastern Trotternish has a thickness of about 490 m (Anderson and Dunham, 1966).

Initial volcanic activity on Skye is thought to have begun around 59 Ma. The oldest volcanic rocks indicate violent eruptions that deposited numerous bombs in the accompanying finer-grained tuffaceous deposits (Bell and Harris, 1986). The majority of the lavas, however, were apparently formed in association with the quiet effusion of successive flows of basaltic magma, with only scattered ashy

Figure 3.2. Looking north towards the distant summit of The Storr (719 m) from Ben Dearg (552 m). Note the contrasting relief between the gentle dip of the escarpment to the west, and the steep east-facing basalt cliffs fringed by rock slope failures and talus debris. Two climbers can be seen near the summit of the large landslide block at the right-hand edge of the photograph.

tuffaceous bands testifying to occasional explosive episodes (Emeleus, 1983). In places, lake sediments grade into igneous material, suggesting that reworking processes were significant (Bell and Harris, 1986). Subaerial conditions at the time of effusion are further suggested by the weathered tops of some lava flows (Emeleus, 1983). The intrusion of a Tertiary olivine-dolerite sill complex into the Jurassic strata postdates the extrusion of flood basalts.

3.2.2 Glacial history

Although Trotternish was probably glaciated on several occasions during the Pleistocene, the known glacial history of Trotternish can be considered in two parts: first in terms of ice sheet glaciation during the Dimlington Stade of the Late Devensian *c.* 26-13 ka BP, and secondly in terms of locally nourished corrie glaciers of Loch Lomond (Younger Dryas) Stade age *c.* 11-10 ka BP (*c.* 12.9-11.5 cal ka BP).

Geikie (1873, 1878) argued that, during the last ice-sheet maximum, ice streams from mainland Scotland extended north-westwards across Skye and the Outer Hebrides, though ice moving from the mainland was deflected around an independent ice cap centred on the Cuillin Hills on Skye (Harker, 1901). Anderson and Dunham (1966) argued for northerly or north-westerly ice flow over Trotternish, and numerous ice-abraded outcrops show evidence for a northerly ice movement parallel to the escarpment (Ballantyne, 1990; Ballantyne and Benn, 1991). Ice flow also took place across the escarpment in the bealachs (cols) between summits (Anderson and Dunham, 1966), and Ballantyne (1990) argued that ice flow across the cols was north-easterly. This claim is supported by the alignment of roches moutonnées in cols and the alignment of streamlined drift ridges and the ice-moulded landslip blocks below the escarpment. Above these glaciated cols the summits support thick *in situ* blockfields and shattered rock, and appear to have remained ice free even during the ice sheet maximum (Anderson and Dunham, 1966; Ballantyne 1990, 1994; Ballantyne and Benn, 1991; Dahl *et al.,* 1997). A proposed periglacial trimline at an altitude of *c.* 518 m (Anderson and Dunham, 1966) has been refined by Ballantyne (1990) and Ballantyne and Benn (1991), who suggested that most of the peaks along the escarpment above 500 m remained ice free, and who reconstructed the form of the upper surface of the last ice sheet along the whole length of Trotternish. This trimline declines in altitude from 580-610 m at the southern end of the escarpment to 440-470 m in the north, over a distance of 24 km (Ballantyne, 1990, 1994; Ballantyne and Benn, 1991). Cosmogenic ^{36}Cl ages obtained for two samples from ice-scoured basalt outcrops at 480-490 m immediately south of The Storr yielded statistically indistinguishable ages of 17.4±1.3 cal ka BP and 17.6±1.4 cal ka BP, and this is interpreted as representing minimal dates for the onset of ice-sheet thinning (Stone *et al.*, 1998) at this location. Anderson and Dunham (1966) proposed that deglaciation was interrupted by four pauses with associated ice surface altitudes at 442 m, 396 m, 335 m and 152 m, but Ballantyne (1990) found no evidence for these events.

There is evidence in northern Skye for only one widespread readvance of ice following the wastage of the last ice sheet. This took place during the Loch Lomond Stade (Walker *et al.*, 1988). Interpretations vary as to the extent of the Loch Lomond Readvance on Trotternish. Charlesworth (1956) envisaged six principal groups of glaciers, including two lobes descending from The Storr, a large glacier below Hartaval and many small glaciers on the eastern flanks of Beinn Edra. Anderson and Dunham (1966), however, argued that both eastern and western slopes of the escarpment harboured readvance glaciers. In contrast, Ballantyne (1990) found evidence for only two small locally-nourished glaciers on Trotternish, one in Coire Cuithir and the other below The Storr. Their limits are inferred from lateral and hummocky moraines that often over-ride landslip blocks.

3.2.3 Periglaciation

Northern Skye supports both active and relict periglacial landforms. This is especially true of Trotternish, where most of the land above 500 m remained ice-free during the Late Devensian glacial maximum (Ballantyne, 1991c). On these former nunataks a mantle of locally-derived frost weathered detritus is common, and blockfields are well developed on some summits. The absence of such periglacial phenomena at the cols between summits indicates that they pre-date the downwastage of the Late Devensian ice sheet (Ballantyne, 1991c). However, not all relict periglacial features are confined to former Devensian nunataks. Frost-weathered bedrock, relict talus, fossil patterned ground and relict solifluction lobes all occupy sites once covered by the last ice sheet. These appear to be Late Devensian features formed in the interval between ice sheet downwastage and the end of the Loch Lomond Stade (Ballantyne, 1991c).

Both The Storr and Hartaval support active periglacial features formed through the operation of three sets of processes, namely, wind action, superficial cryoturbation and solifluction (Ballantyne, 1991c). The effect of wind has been to disrupt the soil and vegetation cover to create deflation scars bounded by eroding scarps. Within these deflation scars small-scale sorted patterns occur. In addition, shallow vegetated lobes with risers up to 1 m high indicate active solifluction on slopes above 580 m. These forms share the slopes with ploughing blocks, some of which have left unvegetated furrows up to 4 m long in their wake. The action of the wind is also evident in the accumulation of up to 2.9 m of Holocene aeolian sediment on the summit of the Storr (Ballantyne, 1998)

3.2.4 Rock slope failures

Landsliding on Trotternish runs along the whole length of the escarpment in a belt locally exceeding 2 km in width (Godard, 1965; Sissons, 1983). This landslip zone continues for a further 10 km around the northernmost peak towards Uig, where a subsidiary area of landslip is located (Ballantyne, 1991d, 1991e). The rock slope failures in this area consist predominantly (but not exclusively) of successive rotational slides in which deep, curved shear planes bisect geological boundaries in the underlying rock. A number of incipient rock slope failures where blocks detached from the crest have experienced little downslope displacement, are located in Coire Cuithir, and at Dun Dubh and Baca Ruadh (Ballantyne, 1986a; 1991d, 1991e). Farther out from the scarp are isolated tabular blocks such as Cleat, and shattered pinnacles of rock like the Old Man of Storr. Farther out still the landslip topography becomes subdued and degraded. This outer zone has been interpreted in terms of preglacial failure of the scarp slope, where Devensian ice has overridden the landslip blocks producing a more subdued topography (Godard 1965; Ballantyne, 1991d, 1991e). The sporadic occurrence of glacial drift in the outer zone appears to corroborate this interpretation (Anderson and Dunham, 1966).

Geology has exercised a significant control over the magnitude and mechanisms of these failures. Rock slope instability on Trotternish primarily reflects the superposition of thick Tertiary basalts over less competent Jurassic beds heavily intruded with sills (Anderson and Dunham, 1966; Sissons, 1983; Bell and Harris, 1986; Ballantyne, 1991d, 1991e). Sissons (1967, 1976) suggested that large scale landsliding in Scotland was most frequent during, or immediately after the retreat of the last glaciers, and this may be the case on Trotternish. This theory is consistent with the findings of Godard (1965) who argued that Lateglacial slope failures on Trotternish are primarily the result of collapse of glacially-steepened rock faces associated with withdrawal of lateral support of glacier ice. Rock slope instability during deglaciation is thought to be favoured by: (1) unloading of the Late Devensian ice sheet promoting joint dilatation and extension; (2) freezing of the scarp face under periglacial conditions resulting in the build-up of high cleft-water pressures; and (3) localised seismic activity of a magnitude sufficient to trigger failure on the glacially oversteepened cliffs associated with differential isostatic uplift (Ballantyne, 1991d, 1991e, 1997).

The Storr landslip is one of the most spectacular landslides on Skye, reaching out over *c.* 1500 m from the cliff face in a chaotic jumble of landslip slices of various ages (Godard, 1965; Anderson and Dunham, 1966). Cosmogenic ^{36}Cl exposure dating of two postglacial landslides at The Storr indicated exposure of the present-day cliff face at around *c.* 6.5±0.5 cal ka BP (Ballantyne *et al.,* 1997). Significantly, this date indicates failure at least 7 ka after ice-sheet deglaciation of the site, apparently excluding high cleft-water pressure associated with periglacial conditions as the immediate trigger of rock-face collapse. Glacial over-steepening of the cliff may have facilitated subsequent instability, although the long lag time between ice-sheet withdrawal and landslide initiation suggests that progressive joint extension and the shearing of rock bridges and asperities may be a significant cause of cliff failure (Ballantyne *et al.*, 1998; *cf.* Watters, 1972; Holmes, 1984; Selby, 1993).

3.2.5 Vegetational history

Studies of the vegetational history of Skye divide the terrestrial pollen record into two distinct periods, namely the Late Devensian Lateglacial (i.e prior to *c.* 10 ka BP, or *c.* 11.5 cal ka BP), and the Holocene (i.e. after *c.* 10 ka BP, or *c.* 11.5 cal ka BP). Nothing is known about the flora of the Inner Hebrides during any previous interglacial (Birks and Williams, 1983). The Quaternary vegetation record for Trotternish has been reconstructed from sediment cores obtained at four sites: Loch Cleat, Loch Mealt, Loch Cuithir and Loch Fada (Figure 3.1). Additional reference is made below to the vegetation record obtained from sites at Loch Ashik, Elgol and Sloch Dubh to the south of Trotternish.

The Lateglacial Vegetation of Trotternish

Pollen recovered from cores derived from the lochs of Trotternish are interpreted to be of Holocene age and to a large extent the Lateglacial vegetation of northern Skye must be inferred from sites elsewhere on the island.

Pollen derived from the Lateglacial sites of lochs Ashik, Elgol and Sloch Dubh revealed that the earliest plant communities were composed of pioneer species presumably growing on skeletal mineral substrates. These early communities contained significant amounts of Poaceae, Cyperaceae, Caryophyllaceae, Asteraceae and *Artemisia* ; however, *Salix* is the only recorded woody shrub. This initial episode of plant succession was followed by a rise in dwarf shrub heath and open grassland, with the dominant taxa being *Juniperus communis,* Empetraceae and Ericaceae. It is also possible that *Betula* flourished at this time, probably in more sheltered sites (Walker and Lowe, 1991). The thermal maximum is thought to have occurred early during the Late Glacial Interstadial (Walker and Lowe, 1990), and Walker and Lowe (1991) argued that the vegetational transition from pioneer to scrub vegetation reflected a rapid rise in temperature during the onset of interstadial conditions. However, a fall in terrestrial temperatutes beginning at *c.* 12 ka BP or earlier is thought to have been responsible for reductions in *Juniperus* cover prior to the onset of full Loch Lomond Stade conditions (Walker and Lowe, 1990).

The Loch Lomond Stade of *c.* 11-10 ka BP (*c.* 12.9-11.5 cal ka BP) is represented in lake cores as a lithostratigraphic change from predominantly organic to predominantly minerogenic accumulation. With mean average summer temperatures of *c.* 6° C and mean average winter temperatures of -17°C to -20°C (Atkinson *et al.,* 1987; Ballantyne, 1989b), tundra vegetation appears to have characterised much of northern Skye during this climatic revertance. Woody shrubs declined during the cold period and taxa associated with unstable soils such as

Asteraceae, *Rumex acetosa, Thalictrum,* Caryophyllaceae, Chenopodiaceae and *Artemisia* -type became dominants (Walker and Lowe, 1991). However, Walker and Lowe (1990) argued that the climatic oscillation associated with the Loch Lomond Stade was of such low amplitude and short duration, that its effects only registered in sites where plant communities were already existing close to critical climatic thresholds. They further suggested that in such areas even a slight change of climate would have been sufficient to disrupt the vegetation cover and promote soil erosion.

The Holocene Vegetation of Trotternish

The terrestrial vegetation record for the Holocene is well documented in northern Skye and broad similarities exist between pollen diagrams for different sites. Radiocarbon dates are available for a number of profiles and pollen-stratigraphic correlation has been undertaken (Williams, 1977; Birks and Williams, 1983; Lowe and Walker, 1991). Pollen-stratigraphic studies have shown that these sites possess a characteristic sequence of vegetation changes common to most early to mid-Holocene profiles on Skye.

A generalised vegetation succession from Loch Cleat (Lowe and Walker, 1991; Figure 3.1), provides an illustration of the Holocene paleoecology of Trotternish. The Loch Cleat record showed that *Juniperus*, species-rich grasslands, tall herbs and *Betula* characterised the earliest recorded vegetation succession following the Loch Lomond Stade. *Juniperus* was recorded as the first species to become dominant at 9990±130 yr BP (12,118-10,960 cal yr BP). The transition into the subsequent *Betula* phase is marked by a reduction in *Juniperus* and a rise in *Betula, Corylus* and *Salix* (Birks and Williams, 1983). *Betula* appears to have been dominant at around 9000±150 yr BP (10,298-9645 cal yr BP; Walker and Lowe, 1991). Species-rich grasslands probably remained locally frequent at this time, and

Pinus, Quercus and *Ulmus* do not appear to have been significant components of the local vegetation. The next significant changes are dated to *c.* 5 ka BP by which time *Betula, Corylus* and *Salix* were replaced largely by Poaceae. The decline in scrub cover continued up to the present, accompanying a rise in heathland species and increased evidence for cultivation. By *c.* 1 ka BP the landscape was apparently virtually treeless and abundant meadows and cereal cultivation may have been evident at sheltered locations (Lowe and Walker, 1991).

Loch Fada at the southern end of the Trotternish escarpment (Figure 3.1) contains microfossils of both Jurassic and Holocene age (Birks, 1970, 1973) and the latter are of importance in this discussion. It has been argued by Birks (1973) that basal horizons in the Loch Fada stratigraphy represent a Lateglacial sedimentation sequence formed during ice sheet wastage. However, Walker and Lowe (1990) argued that the Loch Fada profile described by Birks (1970) exhibits successive maxima (from the base) of *Lycopodium,* Poaceae/*Rumex, Empetrum, Juniperus, Betula* and *Corylus*, and thus represents a typical early Holocene vegetational succession. In the light of their arguments, the Loch Fada sediments may be interpreted as being of Holocene age and not of Lateglacial origin.

Palynological investigations of basal sediments from the Loch Fada core show the landscape to have been treeless, and almost shrubless, immediately after the Loch Lomond Stade. Such a paucity of vegetation cover may help explain the presence of inwashed minerogenic sediment at these levels. Pollen recorded from these basal sediments indicate cold conditions, and a plant community of alpine summit heath with abundant Cyperaceae, Poaceae and *Salix,* and the spores of *Hylocomium splendens, Polytrichum alpinum, Rhacomitrium* and *Huperzia selago* (Birks, 1973; Birks and Williams, 1983). This early community was succeeded by sub-alpine, species-rich grassland (Poaceae/*Rumex* assemblage) with locally important tall herb communities.

Vegetation communities dominated by Poaceae/*Rumex* were replaced by a *Juniperus* and Poaceae assemblage, probably in response to climate warming and increased soil stability (Birks, 1973). Species-rich turf communities of Poaceae, Brassicaceae and *Ranunculus acris*-type remained significant components in the local vegetation up until the rise in *Betula* coverage. The decline of grasslands was either a response to increased coverage by *Betula*, or to soil acidification caused by leaching. *Corylus* replaced *Betula* as the dominant species type at around 7500±120 yr BP (8487-7996 cal yr BP; Vasari, 1977), but *Betula, Salix* and tall herbs communities may have remained locally important. *Corylus* appears to have been more successful in northern Skye than elsewhere on the island, possibly due to either its tolerance of wind exposure, or the fertile basaltic soils of Trotternish, or perhaps both. Soil erosion was probably at a minimum during the *Corylus* period and it appears that a stable continuous vegetation cover had become established at this time (Birks, 1973). After this period the Loch Fada record is less clear; it is probable, however, that a decline in arboreal vegetation occurred during the mid to late Holocene as at Loch Cleat.

The pollen stratigraphy of Loch Mealt also in Trotternish (Figure 3.1), possesses the same general features as those at the nearby Loch Fada. These zones were originally interpreted as being of Lateglacial age, but Walker and Lowe (1990) have argued convincingly that the Loch Mealt record represents accumulation over approximately the last 10 ka radiocarbon years.

As at Loch Fada, the initial vegetation succession at Loch Mealt appears to have comprised an incomplete cover including Poaceae, *Lycopodium* and Cyperaceae, presumably on unstable substrates during or immediately after deglaciation. This early community was replaced by a Poaceae/*Rumex* assemblage of sub-alpine, species-rich grassland with locally important tall herb communities. *Juniperus* and *Betula* superseded species-rich grasslands with the rise in tree cover.

However, any tree growth that occurred during this time appears to have declined with the transition into the *Betula nana* subzone, interpreted to be indicative of the Loch Lomond Stade (Birks, 1973). However, in the light of Walker and Lowe's (1990) reassessment of the pollen record, Birks's (1970, 1973) and Birks and Williams's (1983), identification of *Betula nana* may represent a minor climatic revertence post-dating the Loch Lomond Stade.

Woodland was apparently more widespread during the subsequent *Betula* phase, but the arboreal maximum appears to have been reached in the latter part of the *Corylus* period. The arboreal maximum at Loch Mealt appears to have been characterised by a mixture of *Betula* and *Corylus* with significant amounts of *Alnus glutinosa, Pinus*, and with *Salix* possibly occupying wetter sites. However, it must be stressed that the amount of tree pollen found at sites on Trotternish is small compared to that recorded in locations farther south. What limited amounts of woodland that became established, seem to have done so at the expense of other taxa, namely the tall herb and wetland communities (Birks, 1973). The vegetation record derived from Loch Mealt is incomplete following the arboreal maximum, although it appears that tree felling by Neolithic settlers began some time between *c.* 5 ka BP and *c.* 4 ka BP, and that cereal cultivation was introduced to neighbouring areas at about the same time.

Basal sediments dated to 10,060±270 yr BP (12,543-10,486 cal yr BP) have been obtained from Loch Cuithir at the foot of the Trotternish escarpment (Figure 3.1). This places the vegetation succession reconstructed from this site firmly within the Holocene period (Vasari and Vasari, 1968). The earliest communities comprised significant amounts of *Juniperus* and Ericaceae indicative of the *Juniperus* zone in the regional pollen-stratigraphic sequence. *Betula* appears to have replaced *Juniperus* as the dominant vegetation type at around 9660±150 yr BP, (11,194-10,307 cal yr BP) which is consistent with the regional transition into the *Betula* period. The increase in *Corylus* after 9400±210 yr BP (10,994-9973 cal yr BP) was perhaps the next significant change in the local vegetation, giving rise to the *Corylus* phase. The *Corylus* period witnessed the decline of *Salix* and the rise of *Quercus, Pinus* and *Alnus*. Arboreal communities declined after *c.* 5 ka yr BP, with significant reductions in *Ulmus, Quercus* and *Betula.* Poaceae became dominant, possibly as the land was cleared for animal and plant husbandry (Vasari and Vasari, 1968).

Holocene vegetation changes: Summary

The vegetation sequence for the Holocene on Trotternish can be broken down into distinct phases. The earliest Holocene succession appears to be have been characterised by Poaceae and *Rumex*, although at some locations, this phase may have been preceded by a *Lycopodium* and Cyperaceae assemblage. *Juniperus* replaced the pioneer communities, but was itself superseded by successive maxima of Betula and *Corylus*. At around *c.* 5 ka BP there appears to have been a marked decrease in tree cover, accompanied by an expansion in grassland. This trend is characteristic of the final phase of the vegetation succession on Trotternish and is attributed to anthropogenic clearances and the diffusion of arable practices to Trotternish. This suggestion is supported by the presence of abundant *Plantago lanceolata* pollen and microscopic charcoal in local colluvial deposits (Whittington, 1991).

3.3 NW Scotland: Quinag, Stac Pollaidh and Baosbheinn.

The isolated mountains of Quinag, Stac Pollaidh and Baosbheinn in NW Scotland are sufficiently similar in terms of their geology, glacial history and vegetational development for them to be considered together. Quinag (58°13' N; 5°03' W) forms an impressive frost shattered ridge extending north-westwards from Loch Assynt (Figure 3.3). The mountain consists of a steeply undulating ridge culminating in Spidean Cóinich (764 m) and Sàil Gorm (776 m), and a promontory spur extending to Sàil Garbh (808 m). From the west the mountain appears as a steep rocky escarpment over 4 km long, over 450 m high and fringed by long mature talus slopes. It is on these slopes that investigations have been undertaken. Stac Pollaidh (58°02' N; 5°18' W; 613 m) to the south of Quinag, is a small, isolated hill characterised by a chaotic summit ridge of crags and rock pinnacles of Torridon Sandstone. The summit cliffs are surrounded on all sides by large mature talus slopes and it is these features that are of interest in this study (Figure 3.3). The Baosbheinn ridge with its summit of Sgórr Dubh (57°37' N; 5°34' W; 875 m), rises above the Flowerdale Forest in Wester Ross. The eastern flank of the mountain is punctuated by three corries that fall away into gently rising ground below. In contrast, the western face forms a steep rocky escarpment of Torridon Sandstone over 5 km long and fringed by mature talus slopes, and it is to these talus slopes that the current research has been directed (Figure 3.4).

3.3.1 Geology

Some of the oldest rocks in the British Isles are exposed in NW Scotland, which also possesses some of the clearest evidence for the westward dislocation of rocks associated with the Moine thrust zone. Summaries of the geology of the area can be found in Peach *et al.* (1907, 1913), Peach and Horne (1914), Johnson and Parsons (1979), Ballantyne *et al.* (1987), Johnstone and Mykura (1989), and Lawson (1995a). Lewisian rocks are the oldest in the succession and are interpreted as representing a residual fragment of the Laurentide continental shield. This Lewisian basement consists of a central Scourian Complex fringed by the strongly deformed Laxfordian Complex.

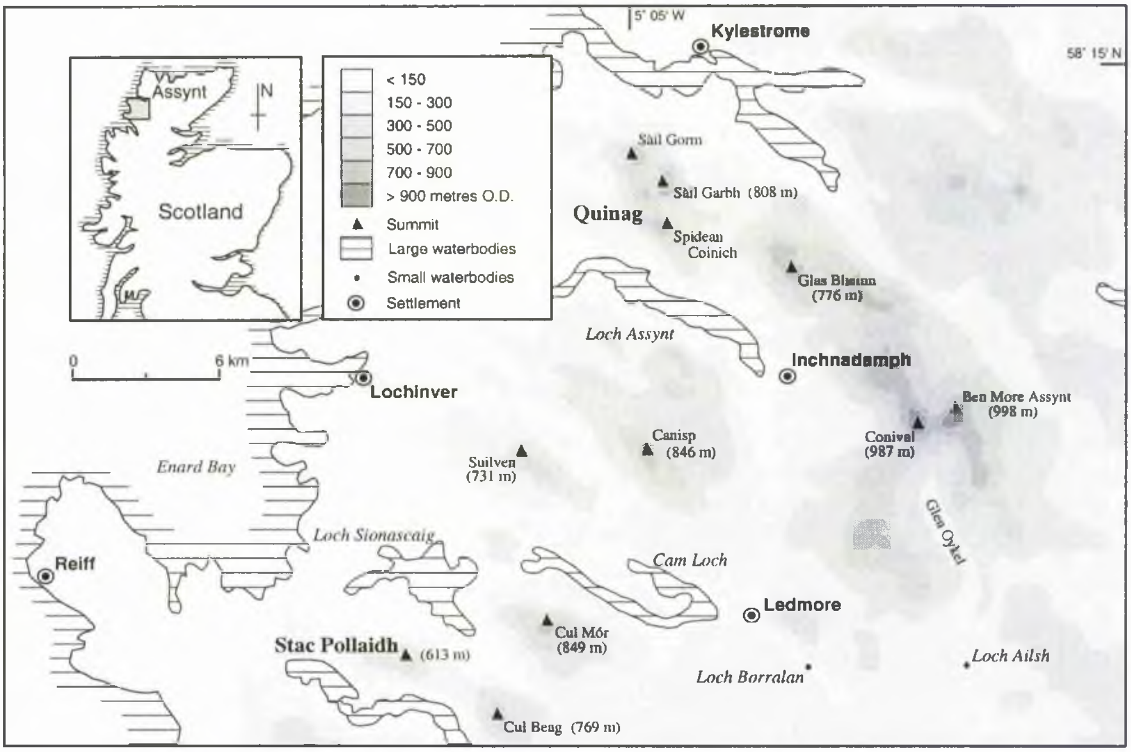


Figure 3.3. Introductory relief map showing the location of the Quinag and Stac Pollaidh field sites on the mainland of NW Scotland

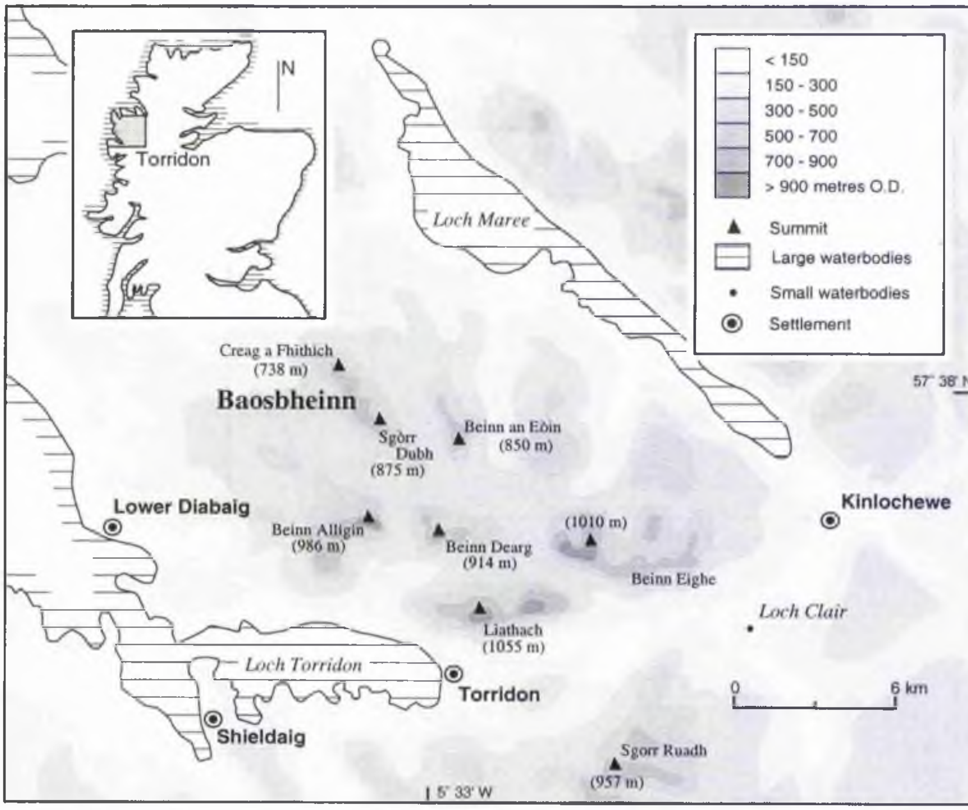


Figure 3.4. Introductory relief map showing the location of Baosbheinn, Wester Ross, NW Scotland.

Deposited on the eroded land surface of the Lewisian Gneiss, the Torridonian sequence of terrestrial sediments forms the next group in the succession. These rocks constitute the majority of outcrop on Quinag and underlie the whole of Stac Pollaidh and Baosbheinn. Torridon Sandstone forms the source rockwall for the talus accumulations on all three mountains. Laid down from the west under fluviatile and, more rarely, shallow lacustrine conditions, the Torridonian consists of reddish-brown arkosic and pebbly sandstones and conglomerates deposited in a semi-arid environment. A notable unconformity within the Torridonian sequence divides it into an older Stoer Group, and a younger, but more extensive, Torridon Group. Over much of its exposure the Torridonian is believed to have accumulated on a gently undulating Lewisian plain, though at a few sites (including Quinag) dramatic examples of Torridonian sediments infilling pre-existing valleys can be seen (Johnstone and Mykura, 1989; Lawson, 1995a).

In the *c.* 200 Ma interval between the deposition of the youngest Torridon Sandstones and the overlying Cambrian rocks, crustal deformations arched the Torridonian sequence into a series of large folds. Extensive planation followed and several hundreds of metres of Torridon sandstone were removed, in places exposing the older Lewisian rocks below. By the beginning of Cambrian times such erosion had created an almost level surface upon which the earliest Cambrian sediments were deposited. The oldest rocks of this sequence are hard, white quartzites comprising the False Bedded Quartzite and an upper Pipe Rock formations (Johnstone and Mykura, 1989; Lawson, 1995a). Although absent on Stac Pollaidh and Baosbheinn, these rocks form a cap that overlies the Torridonian slopes below Spidean Cóinich and Sàil Gorm on Quinag.

3.3.2 Glacial history

Though NW Scotland was repeatedly glaciated during the Pleistocene, the only glacial events now represented are those of Late Devensian age, namely the movement of the last ice sheet across the area during the Dimlington Stade of *c.* 26-13 ka BP, and the regeneration of local corrie glaciers during the Loch Lomond Stade of *c.* 11-10 ka BP (*c.* 12.9-11.5 cal ka BP). Uranium-series dating of calcite speleothems in Assynt (Atkinson *et al.*, 1986), and radiocarbon dating of reindeer antlers found in nearby cave deposits (Lawson, 1984; Murray *et al.*, 1993), suggested that Late Devensian ice-sheet build-up occurred after *c.* 26 ka BP. Study of the distribution of glacial erratics led Lawson and Ballantyne (1995) to propose a model for the build-up of the Late Devensian ice sheet across Assynt and Coigach. They argued that initial glacier development occurred in north- and east-facing corries on the higher mountains. In consequence, initial ice movement was apparently northwards and eastwards, depositing Lewisian and Cambrian erratics on Moinian outcrops. Striae and erratic carry suggest, however, that ice movement at the Late Devensian glacial maximum was dominantly north-westwards across Coigach and Assynt. Discovery of a periglacial trimline on Quinag at 650-700 m altitude permitted McCarroll *et al.* (1995) to suggest that the summits of Sàil Gorm, Sàil Gharbh and Spidean Cóinich remained above the ice sheet as nunataks. At this time ice flow seems to have been deflected westwards and northwards around the Quinag massif (Lawson, 1995b). The absence of any periglacial trimline on Stac Pollaidh led McCarroll *et al.* (1995) to argue that it was over-ridden by ice during the Late Devensian glacial maximum. The characteristics of the Late Devensian ice sheet in Wester Ross were broadly similar to those in Coigach and Assynt. The distribution of glacial erratics and striae indicate a westerly to north-westerly flow of ice around Baosbheinn during the maximum extent of the last ice sheet (Peach *et al.*, 1913; Ballantyne *et al.*, 1987). Ballantyne *et al.* (1987) have shown that the summit ridge of Baosbheinn above *c.* 750 m altitude, was a former nunatak above the surface of the Late Devensian ice sheet. However, in contrast to ice sheet decay in Coigach and Assynt, the retreat of the Late Devensian ice sheet around Baosbheinn was apparently interrupted by a glacial readvance at *c.* 13.5 ka BP termed the Wester Ross Readvance. On Baosbheinn, the limit of the Wester Ross Readvance is marked by lateral moraines rising to 450 m altitude below Creag an Fhithich, thus indicating the former presence of an ice stream of Wester Ross Readvance age in the Loch Maree trough (Robinson and Ballantyne, 1979; Ballantyne, 1986b; Ballantyne *et al.*, 1987).

Basal radiocarbon dates from lake sediments at Cam Loch in Assynt (Figure 3.3) indicate that NW Scotland experienced deglaciation by, or soon after *c.* 13 ka BP (Pennington, 1977). A radiocarbon date of 12,810±155 yr BP (15,669-14,553 cal yr BP) from organic silts at Loch Droma, Wester Ross (Figure 3.5), represents a minimum age for ice sheet deglaciation in this area (Kirk and Godwin, 1963), though Ballantyne *et al.* (1987) have argued that this date may be *c.* 1000 yr too old. The Loch Lomond Stade in Coigach and Assynt was characterised by limited glaciation of upland corries and valleys (Sissons, 1977; Lawson, 1986). A drift limit on Quinag indicates the former presence of a small Loch Lomond Stade glacier in the corrie between Spidean Cóinich and Sàil Garbh. The rest of the Quinag massif and the whole of Stac Pollaidh apparently escaped glaciation during the Loch Lomond Stade, and both areas were therefore exposed to severe periglacial conditions at this time. The Loch Lomond Readvance was more extensive to the south in Wester Ross. Sissons's (1977) reconstruction of Loch Lomond Stade glaciers in this area was revised by Ballantyne (1986b) and Bennet and Boulton (1993) to show a former ice field centred on Beinn Dearg, and several outlet glaciers, including two flowing northwards on either side of Baosbheinn.

3.3.3 Periglaciation

The mountains of NW Scotland support both active periglacial features and relict landforms that originated under the much colder climate of the Late Devensian period and, on some nunataks, possibly even earlier (Ballantyne, 1984, 1995). The three peaks of Quinag and the summit ridge of Baosbheinn apparently remained above the Late Devensian ice sheet and were therefore exposed to severe periglacial conditions throughout most of that time (Ballantyne *et al.,* 1987; McCarroll *et al.,* 1995). In consequence, these former nunataks exhibit particularly advanced frost weathering in the form of fractured bedrock, frost weathered regolith, shattered tors and blockfields. Relict periglacial phenomena are not, however, confined to former nunataks, but also occur on terrain formerly glaciated during the Late Devensian ice-sheet maximum, but not reoccupied by glacier ice during the Loch Lomond Stade. Talus slopes on Quinag and Stac Pollaidh, at least in part, reflect Late Devensian periglacial weathering of formerly glaciated rockwalls. The massive protalus rampart or rock glacier at the northernmost end of Baosbheinn represents large-scale rockslope failure of formerly glaciated slopes under periglacial conditions, probably occurring during the Lateglacial period (Ballantyne, 1986b; Sandeman and Ballantyne, 1996). The effects of Late Devensian weathering in the area are, however, largely dependent upon the underlying geology (Ballantyne *et al.*, 1987; McCarroll *et al.*, 1995). Quinag displays clear examples of Lateglacial shattered quartzite bedrock (Lawson, 1983; McCarroll *et al.*, 1995), solifluction lobes (Kelletat, 1970) and rockfall talus slopes (Ballantyne, 1995). In contrast, the range of relict periglacial landforms on Stac Pollaidh is limited by the narrow summit ridge and the steepness of the slopes below. Active periglacial features are rare on both Quinag and Stac Pollaidh. Active periglaciation on Baosbheinn appears to be restricted to granular breakdown of bedrock by microgelivation, localised solifluction and ploughing boulders, and reworking of Holocene niveo-aeolian sand deposits (Ballantyne *et al.*, 1987; Ballantyne and Whittington, 1987).

3.3.4 Vegetational history

The vegetational history of NW Scotland since deglaciation has been reconstructed from lake sediment cores extracted from Loch Sionascaig and Cam Loch (Pennington, *et al.*, 1972; Pennington, 1975, 1977; Haworth, 1976; Cranwell, 1977, 1984; Figure 3.3), Loch Droma (Kirk and Godwin, 1963), Loch Maree (Birks, 1972), Loch Clair (Pennington, *et al.*, 1972) and Glassnock (Robinson, 1977; Figure 3.5), and from peat profiles in the Loch Sionascaig area (Lamb, 1964; Birks, 1975; Figure 3.3).

During the withdrawal of the Late Devensian ice sheets the vegetation was dominantly of a herbaceous pioneer type colonising bare mineral substrates. By *c.* 13 ka BP the climate had ameliorated and frequencies of both *Empetrum* and *Juniperus* had increased to form a dwarf-shrub heath community. Some time after *c.* 13 ka BP, however, the coverage of both *Juniperus* and *Empetrum* declined and herb taxa became more widespread during a return to a more hostile climate, possibly associated with climatic deterioration during the Older Dryas (Pennington, 1995). The Bølling and Allerød periods (*c.* 13-11 ka BP), witnessed a recovery of *Juniperus*, *Empetrum* and Cyperaceae. Despite minor climatic fluctuations this period was apparently characterised by a complete and stable vegetation cover, though woodland (namely *Betula*) remained sparse. The Loch Lomond Stade (c. 11-10 ka BP, or *c.* 12.9-11.5 cal ka BP) was characterised by an increased incidence of disturbed soils within basin catchments and a return to open and discontinuous plant communities .

Early Holocene communities in NW Scotland were of an open dwarf shrub heath complex with significant frequencies of Poaceae, *Rumex, Lycopodium selago, Salix* and *Empetrum*. Soon after this early phase *Empetrum* declined and *Juniperus* expanded. However, changes in Wester Ross were rapid and by *c.* 9 ka

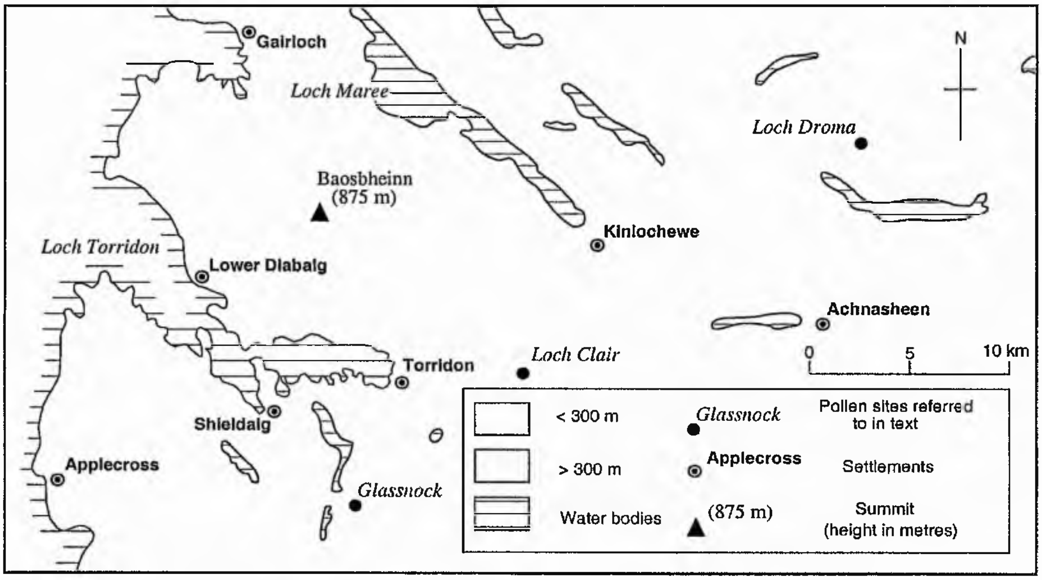


Figure 3.5. Some pollen sites in Wester Ross, NW Scotland.

BP both *Betula* and *Corylus* had increased at the expense of *Juniperus*. This transition appears to have occurred slightly later in Assynt, but by *c.* 8.5 ka BP the vegetation in this area was also characterised by a predominantly *Betula-Corylus*-ferns assemblage with some *Ulmus* and *Quercus*. This community was replaced by *Pinus-Betula* woodland sometime between *c.* 8.5 ka BP and *c.* 7.9 ka BP. At Loch Maree in Wester Ross, *Pinus* replaced *Betula* at *c.* 8.3 ka BP, and remained dominant until *c.* 4.2 ka BP (Birks, 1972). At nearby Loch Clair, however, *Pinus* increased at *c.* 6.5 ka BP, and was replaced by Poaceae and *Calluna* at around 2.9 ka BP (Pennington *et al.,* 1972). This diachroneity in forest history may reflect former changes in catchment hydrology, or the influence of fire, either natural in origin and related to former dry periods (Tipping, 1996), or associated with Neolithic forest clearances (Ballantyne *et al.*, 1987). Much of NW Scotland remained wooded for over four millennia in the early and mid Holocene but woodland began to decline just before *c.* 4 ka BP, and probably represents the consequence of increased wetness of peat surfaces inhibiting pine regeneration. The discovery of charcoal fragments within peat deposits dated to 3470±100 yr BP (3979-3455 cal yr BP) at Loch Sionascaig, also suggests that management of vegetation by early settlers had a possible influence on deforestation and the subsequent rise of heather moorland (Pennington *et al.*, 1972, 1995).

3.4 Glen Feshie

Glen Feshie is a steep-sided glacial trough incised into plateau uplands on the western fringes of the Cairngorm massif (Figure 3.6). Talus accumulations occur sporadically along the length of the valley, but this study concentrated on those talus slopes below Creag a' Chreagain and Creag na Gaibhre towards the head of the glen (56°59' N; 3°52' W). The geology of the Cairngorms consists of a central granitic complex (e.g. Harry, 1965; Harrison, 1986), surrounded by metamorphosed sedimentary rocks largely comprising schists of the Moine Series

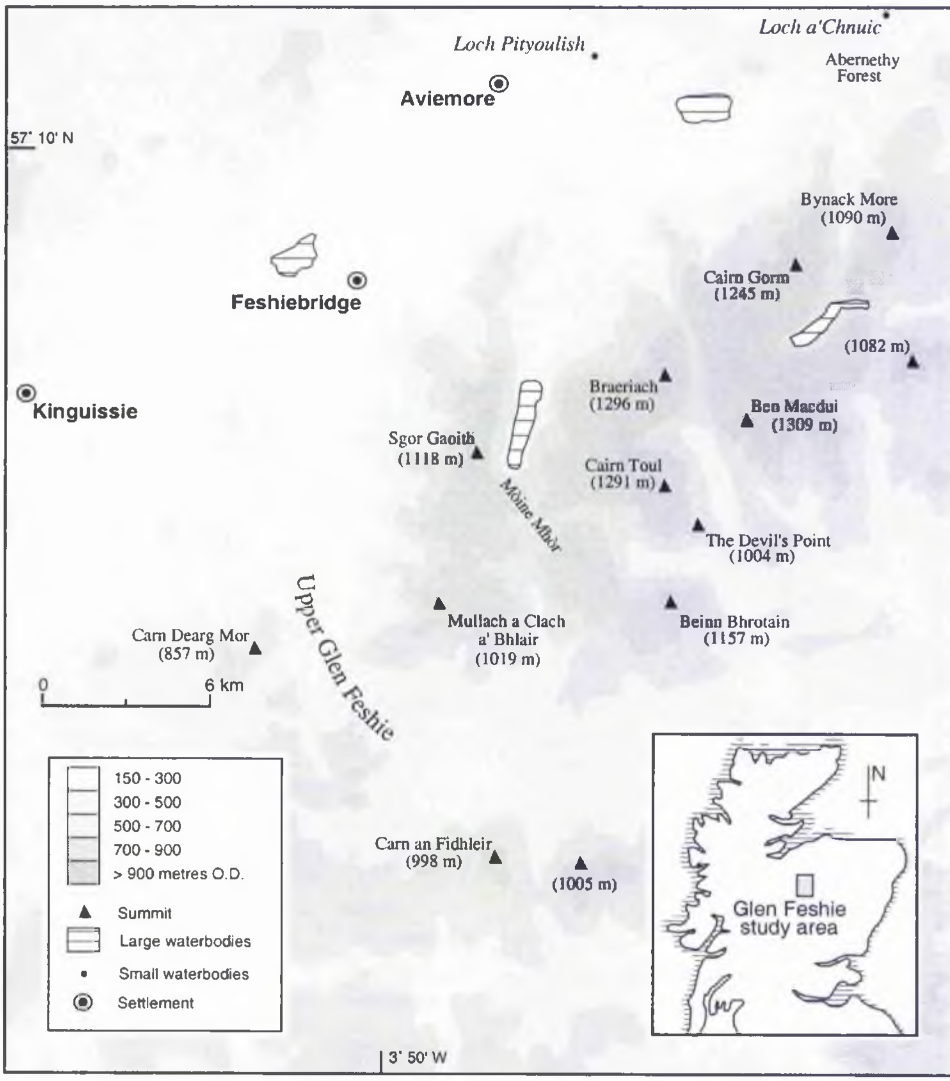


Figure 3.6. Introductory relief map showing the location of Glen Feshie, western Cairngorms.

quartz-feldspar granulites (e.g. Read, 1935; Johnstone, 1981). Schists constitute the underlying solid geology of upper Glen Feshie and it is these metamorphic rocks that form the source rockwalls above valley-side talus accumulations.

3.4.1 Glacial history

Despite the reservations of some early workers (Linton, 1949, 1951, 1955; Galloway, 1958) it is likely that both Glen Feshie and the main Cairngorm massif were entirely submerged below the Late Devensian ice sheet at its maximum extent and thickness (Sugden, 1970; Brazier *et al.*, 1996). However, the Cairngorms represent a landscape of highly selective glacial erosion. This may reflect the former presence of a thin cold-based ice cap over the high plateau with erosive warm-based ice streams occupying glacial troughs and breaches. The passage of warm-based ice down Glen Feshie appears to have been responsible for the destruction of a preglacial watershed in the upper reaches of the valley (Linton, 1949, 1951). Models of deglaciation in Glen Feshie and the Cairngorms range from those advocating active retreat of glaciers upvalley (Hinxman, 1896; Jamieson, 1908; Barrow *et al.*, 1912; Barrow *et al.*, 1913; Hinxman and Anderson, 1915; Bremmer, 1929), to rapid, large-scale stagnation of the ice sheet and *in situ* downwastage (Sugden, 1970). More recently, Brazier *et al.* (1996) have proposed five distinct periods of ice sheet decay, incorporating active down-wasting of invasive ice from Strathspey and the Dee valley, localised readvances within retreat phases, and the late development of a local ice cap with outlet glaciers centred on the Mòine Mhór. It is unclear if glaciers from this local mountain ice field descended into Glen Feshie, though a radiocarbon date of 13,151±390 yr BP (16,725-14,430 cal yr BP) from Loch Ettridge in the adjacent Spey valley indicates widespread deglaciation by that date (Sissons and Walker, 1974), and it appears that the whole valley was ice free by *c.* 11.2 ka BP (Bennett, 1996). With the exception of a small glacier in Coire Garbhlach, Glen Feshie remained unglaciated throughout the Loch Lomond

Stade (*c*. 11-10 ka BP, or *c*. 12.9-11.5 cal ka BP) and was therefore subject to severe periglacial conditions at this time (Sissons, 1979).

3.4.2 Periglaciation.

The Cairngorm massif supports an exceptionally varied assemblage of both relict and active periglacial phenomena (Ballantyne, 1996). Glen Feshie, however, displays a much more limited array of periglacial features, the most notable of which are mature, vegetated talus slopes, together with relict avalanche couloirs and boulder tongues. The talus slopes lie outside the limits of Loch Lomond Stade glaciation and have been interpreted as essentially relict Lateglacial features that have received only modest inputs of rockfall debris during the Holocene (Ballantyne, 1996).

3.4.3 Vegetational history.

Lateglacial sediments recovered from a site in Abernethy Forest (Birks and Mathewes, 1978), showed the earliest pioneer communities at *c*. 14-13 ka BP to consisted of sedge and grass taxa growing on the recently deglaciated substrate. By *c*. 13.5 ka BP, the vegetation had developed to resemble an arctic shrub-tundra with *Betula nana* and *Empetrum* as dominants. As colonisation by taller shrubs and trees became more widespread at *c*. 13 ka BP, *Juniperus* cover appears to have increased and tree *Betula* probably became more common. However, between *c*. 13 ka BP and *c*. 11 ka BP woodland appears to have declined and frequencies of *Artemisia* -type seem to have risen. Tipping (1985) attributed this phenomenon to increased aridity in the eastern Grampian region relative to the Western Highlands.

Holocene vegetation changes in the area of the Cairngorms have been reconstructed using sediments derived from Loch Garten (O'Sullivan 1974a, 1975), Loch Pityoulish (O'Sullivan, 1976) and Loch a'Chunuic (O'Sullivan, 1977), together with the peat sequence from Abernethy forest (Birks, 1970; Birks and Mathewes, 1978). These sites indicated that forest communities composed of *Betula* and *Corylus*, with a minor proportion of *Quercus* and *Ulmus*, developed early in the Holocene. *Pinus* spread to the region before *c.* 9 ka BP and was dominant for four millennia (Bennett, 1996). After *c.* 4 ka BP, there was a general decrease in treecover, especially of pine, and an increase in the coverage of *Calluna* and herb taxa. This change has been attributed to forest clearances and grazing of domestic stock (O'Sullivan, 1974a, 1974b, 1975), but the causes, role and timing of forest fire in the Cairngorms, as elsewhere in Scotland, are poorly understood (Bennett, 1996; Tipping, 1996).

Chapter 4

Talus slope form

4.1 Introduction

This chapter considers the distribution, morphology and surface relief of the relict talus slopes on Trotternish and at the four mainland field sites. The primary aim of this research is to establish the morphological characteristics of these slopes, and the implications of talus morphology for interpretation of formative processes and talus evolution. The chapter is organised into six sections. Following an outline of field and analytical methods (section 4.2) and a brief qualitative description of the distribution and morphology of the talus slopes studied (4.3), the chapter focuses on quantitative analysis of talus profiles (4.4) and the implications of the results in terms of proposed models of talus evolution (4.5). The principal results are summarised in the concluding section (4.6).

4.2 Methods

Investigation of talus morphology involved geomorphological mapping of the distribution and surface morphology of relict talus slopes in the five study areas, instrumental survey of slope form, and, on the Trotternish Peninsula, measurement of the dimensions of gullies incised into talus accumulations. For field mapping purposes, 1:5,000 scale base maps were produced from Ordnance Survey 1:10,000 sheets. Consultation of aerial photographs allowed the axes of large gullies and other conspicuous surface features to be added to the base maps prior to fieldwork, and these acted as an aid to the location of other slope forms. The accuracy of the map data was checked in the field by obtaining as many different viewpoints of the same site as possible, and subsequently by direct comparison with ground and aerial photographs, and, where applicable, with slope profile data.

On Trotternish, survey data were obtained using a Wild T1000 EDM (Electronic Distance Measuring) unit. To reduce problems of subjectivity, readings were taken at every five paces along the survey transect, although extra sightings were made at distinct breaks of slope. The dimensions of five gullies were also surveyed by EDM to determine the volume of sediment removed, and thus the impact of recent gully incision on talus morphology. Talus slopes on the mainland were surveyed using an abney level, ranging rods and a 30 m tape. Repeatability tests suggest that the abney level readings are accurate to within ± 0.5°. Sightings were made at 10 m, 20 m or 30 m intervals depending on the rate of change in slope gradient, and at obvious breaks of slope.

To allow quantitative analysis of the morphology of talus and gully profiles, five indices were calculated to describe slope form (Figure 4.1). Following Statham (1976a), talus maturity was calculated in terms of the H_o:H_i ratio, where H_o is the vertical height of the talus slope and H_i is the vertical height of the entire slope (talus plus rockwall; Figure 4.1a). The form of the upper straight slope is summarised by the mean rectilinear slope gradient (a°), the average slope angle above the basal concavity. The basal concavity is here defined as the lower part of the overall slope which exhibits a consistent downslope decrease in gradient. Three indices were calculated to assess overall slope concavity. The most straightforward of these (index A) is the length of the basal concavity expressed as a percentage of the total slope length (Figure 4.1b). Index B is dependent on the change in slope gradient along a given slope profile, and is calculated using the methodology of Maclean (1991), in which the mean gradient of the uppermost third of the slope profile is divided by that of the lowermost third (Figure 4.1c). In terms of index B, unity indicates a straight slope, and the value of the index increases with increasing

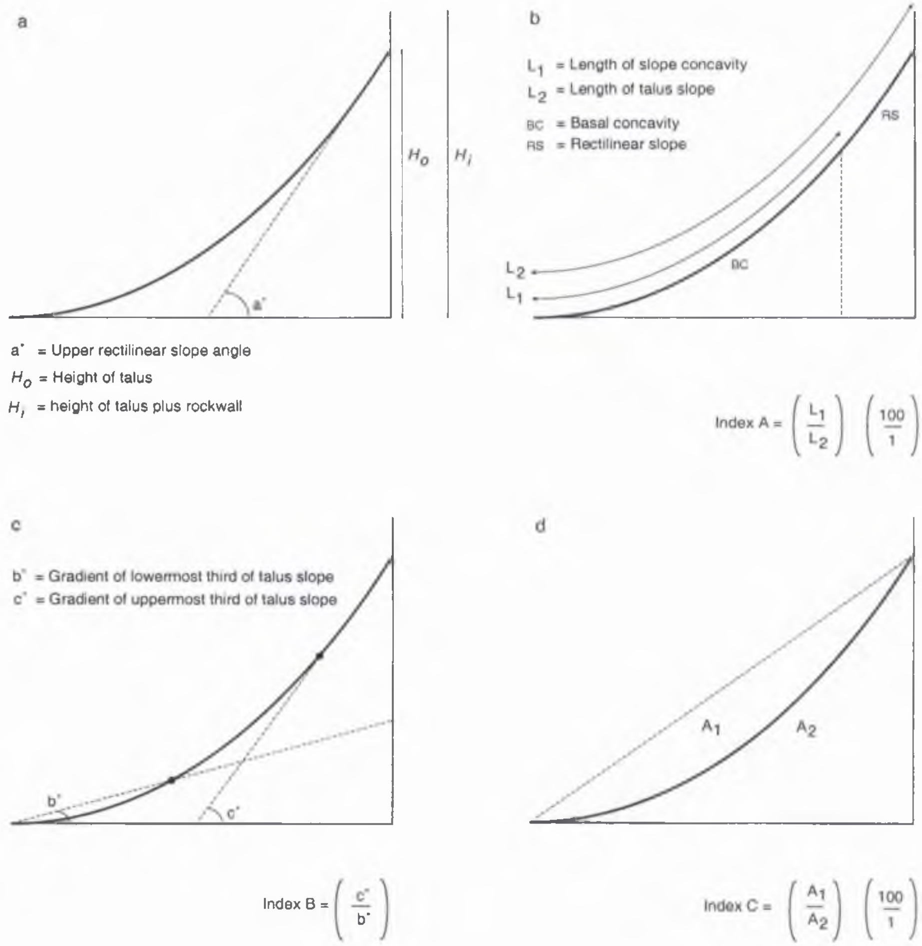


Figure 4.1. Definitions of slope paramaters adopted for the investigation of talus morphology.

overall concavity. Index C makes use of the 'departure from linearity index' proposed by Church *et al.* (1979) and is calculated by comparing the area of a right angled triangle, the hypotenuse of which is defined by the top and foot of a talus slope, and the area between the upper surface of the talus and the hypotenuse of the large triangle (Figure 4.1d). The area of the latter is expressed as a percentage of the whole triangle and reflects the depth of the slope concavity. These parameters describe different properties of slope concavity, namely relative length (index A), change in gradient (index B), and depth (index C).

4.3 Description and distribution

Talus debris forms an almost continuous sheet that extends north-south for 24 km along the length of the Trotternish Escarpment. Gullying is manifest on much of the talus, though erosion is locally concentrated (Figures 4.2-4.10). Talus accumulations extend *c.* 150-200 m downslope from the base of the rockwall in Trotternish. At some locations, however, such as Coire Cuithir (Figure 4.7), postglacial landslide blocks located below the main ridge have allowed talus to extend farther from the main cliff. The long profiles of some talus slopes are also extended at a few sites where their uppermost parts form a shallow debris mantle over bedrock, as on the western flanks of Carn Liath (Figure 4.5), and below the summit of Hartaval (Figure 4.6). Rockfall accumulation at such sites is implied by the presence of a distinct rockwall, and evidence of fall sorting of large clasts at the surface. In profile, however, these extended 'debris slopes' are irregular, and the declivity of the underlying rock is interpreted as reflecting subglacial modification of the escarpment prior to accumulation of rockfall debris, rather than headwall burial associated with a mature talus slope. Although most of the Trotternish talus appears to have accumulated by discrete particle fall events, area 2 supports evidence of two larger rock slope failures (Figures 4.4 and 4.11). These features

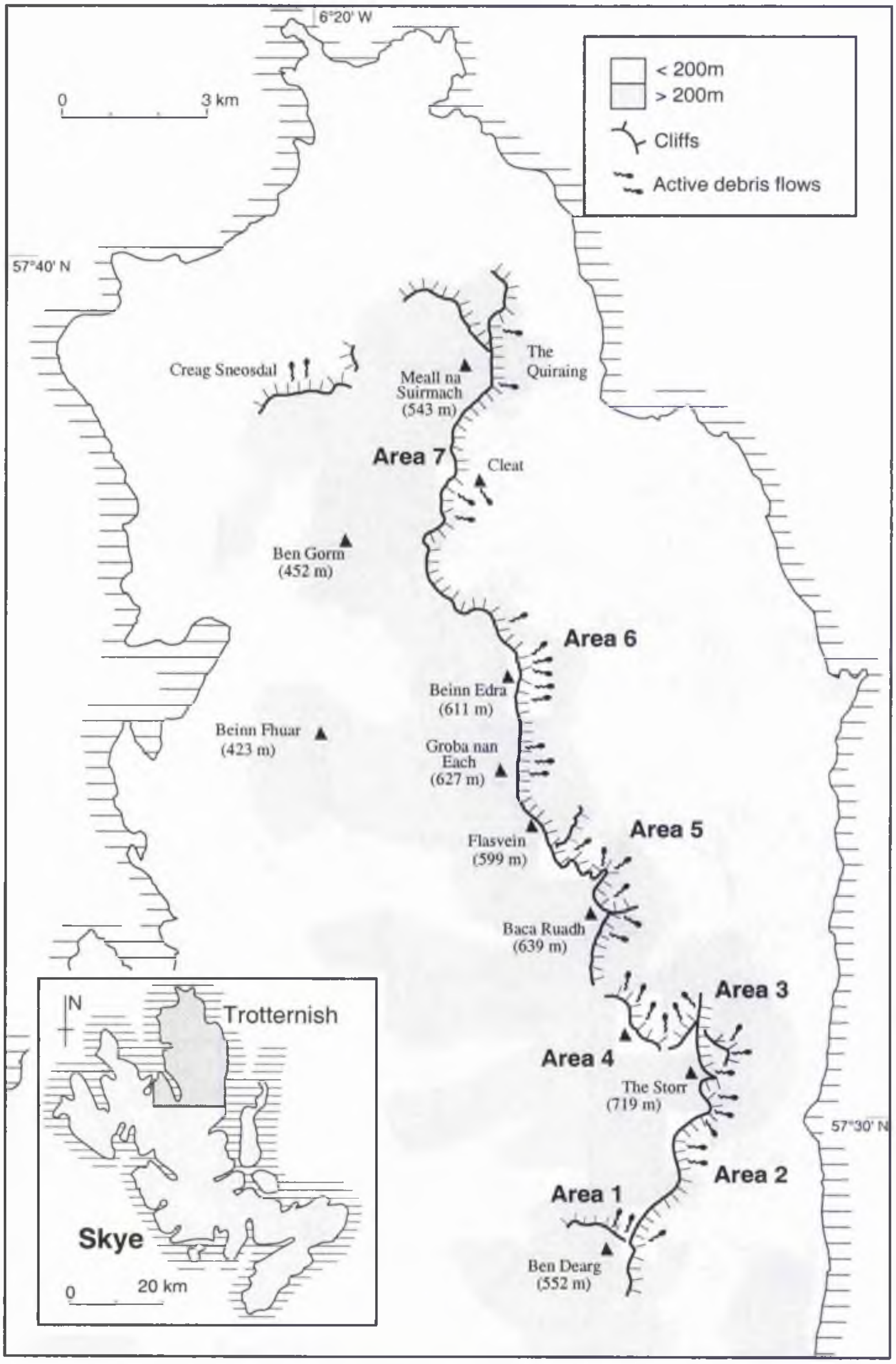


Figure 4.2. The location of study areas 1 - 7, Trotternish, northern Skye. Concentrations of recent debris flow activity are also indicated.

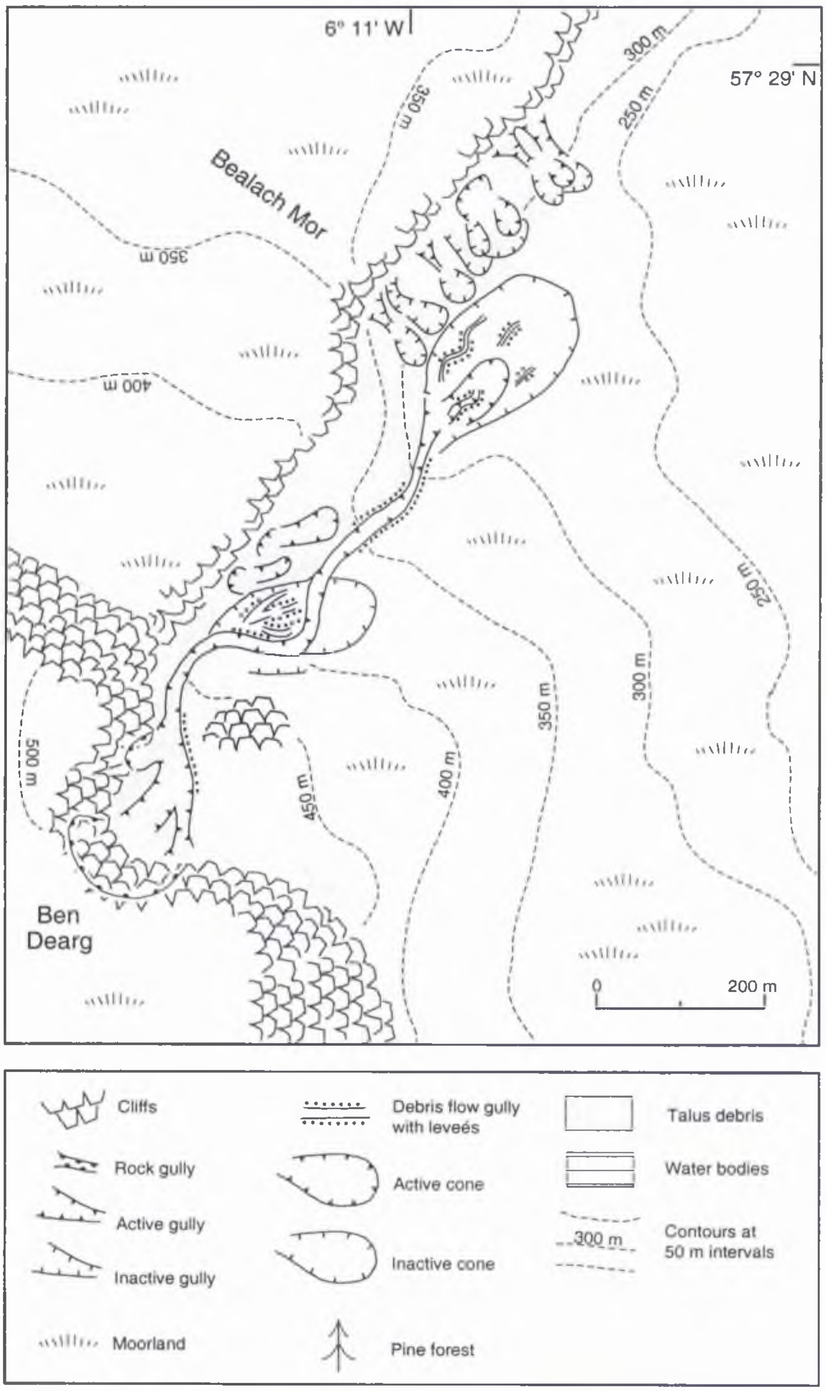


Figure 4.3. Talus debris and associated slope failures below the summit of Ben Dearg, area 1, Trotternish, northern Skye.

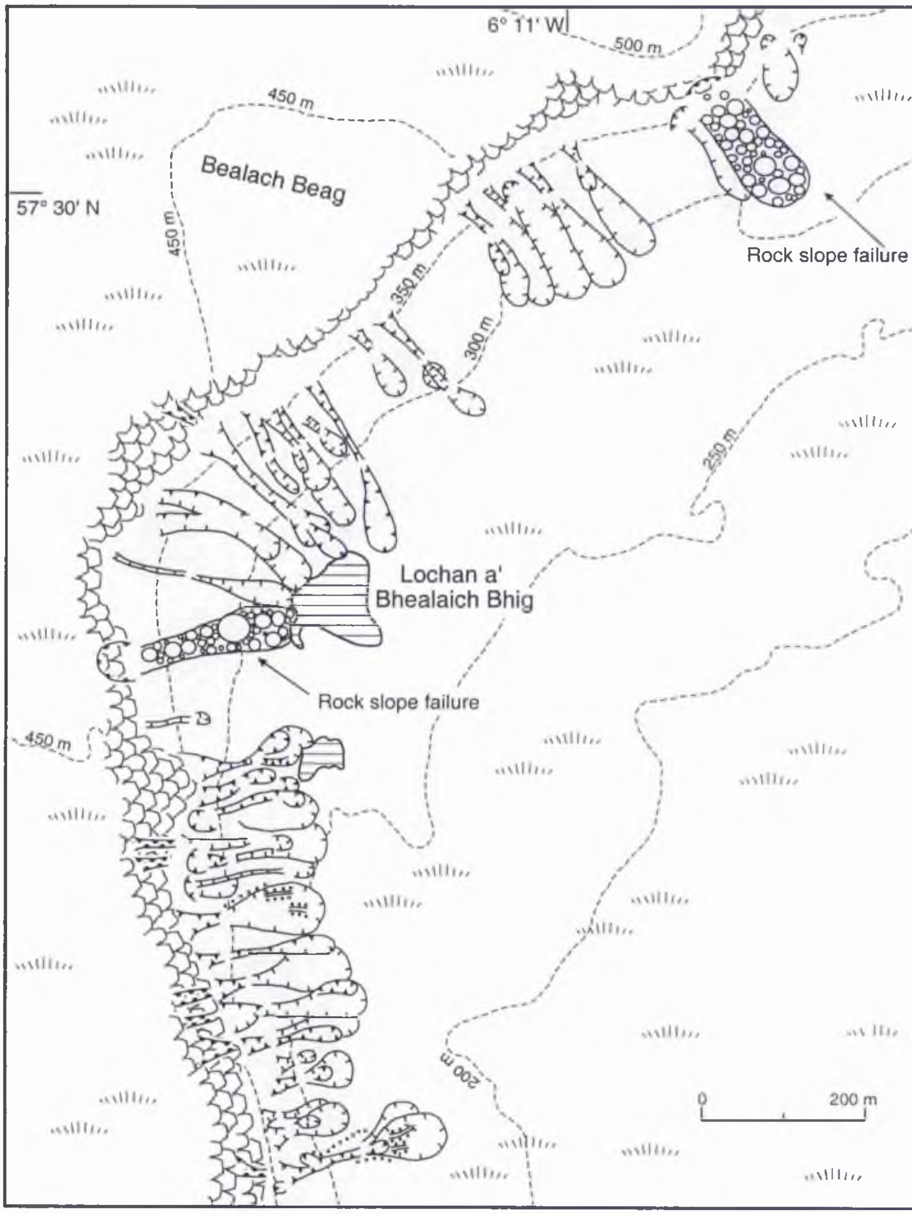


Figure 4.4. Talus debris and associated slope failures south of the Storr on Trotternish, area 2, northern Skye. (Key as in Figure 4.3)

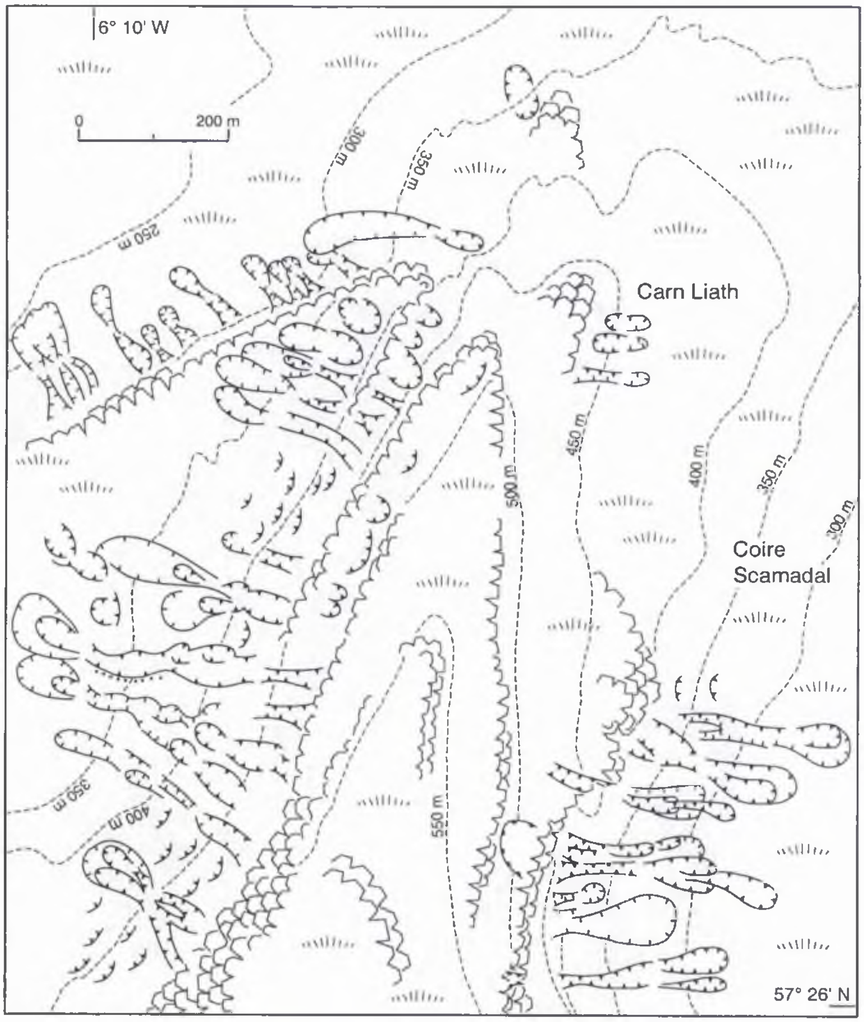


Figure 4.5. Talus debris and associated slope failures surrounding the Carn Liath spur, Trotternish escarpment, area 3, northern Skye. (Key as in Figure 4.3).

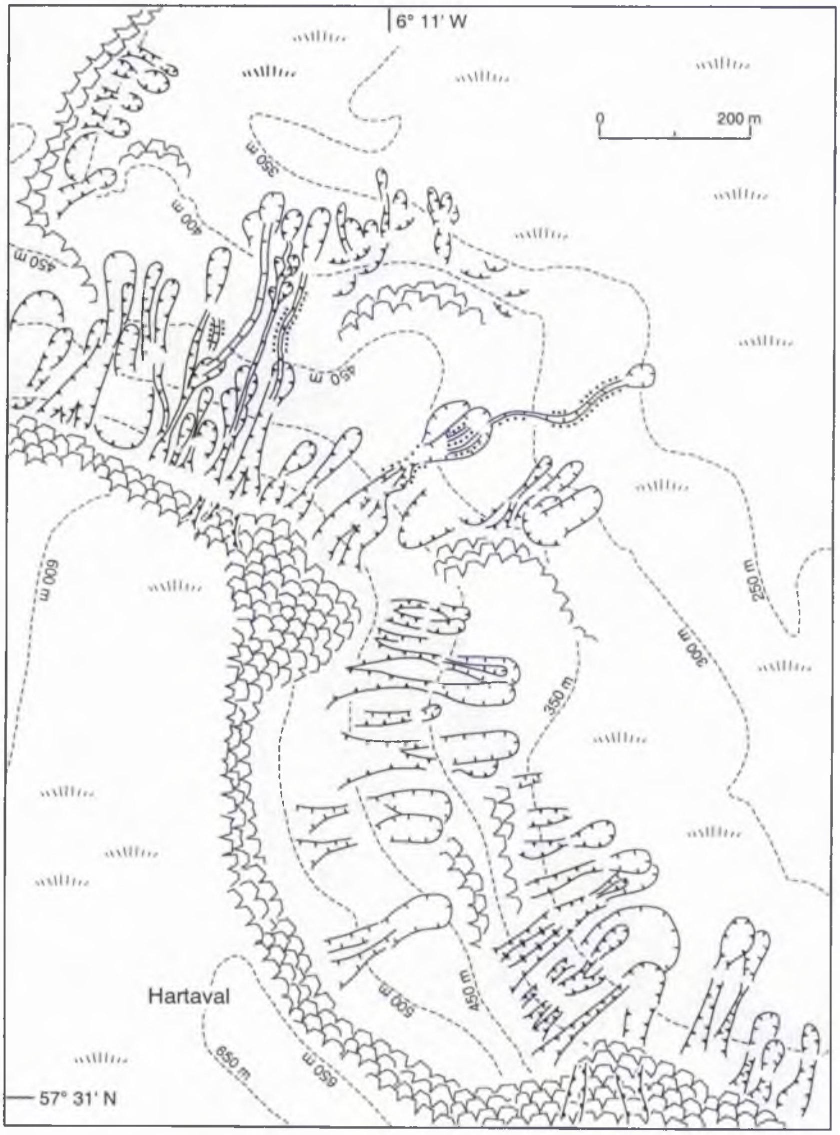


Figure 4.6. Talus debris and associated slope failures below the summit of Hartaval, area 4, Trotternish, northern Skye. (Key as in Figure 4.3).

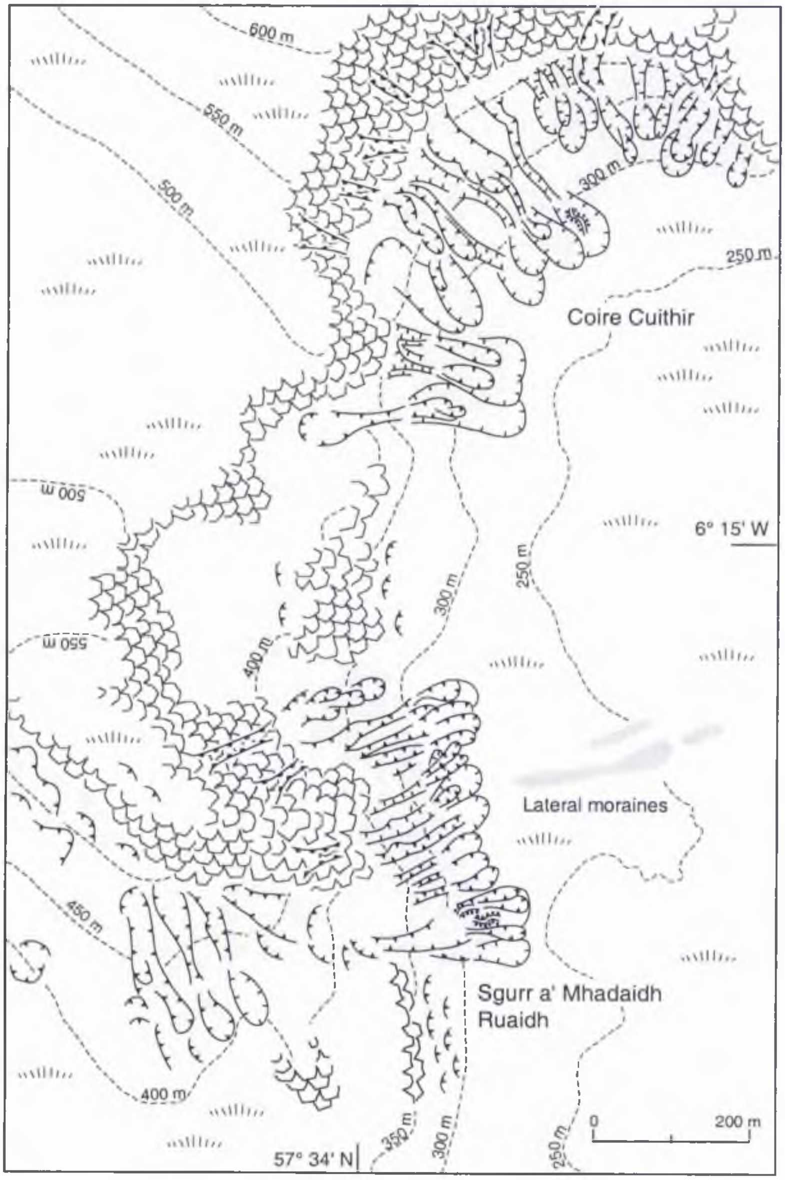


Figure 4.7. Talus debris and associated slope failures in the vicinity of Coire Cuithir, area 5, Trotternish, northern Skye. (Key as in Figure 4.3).

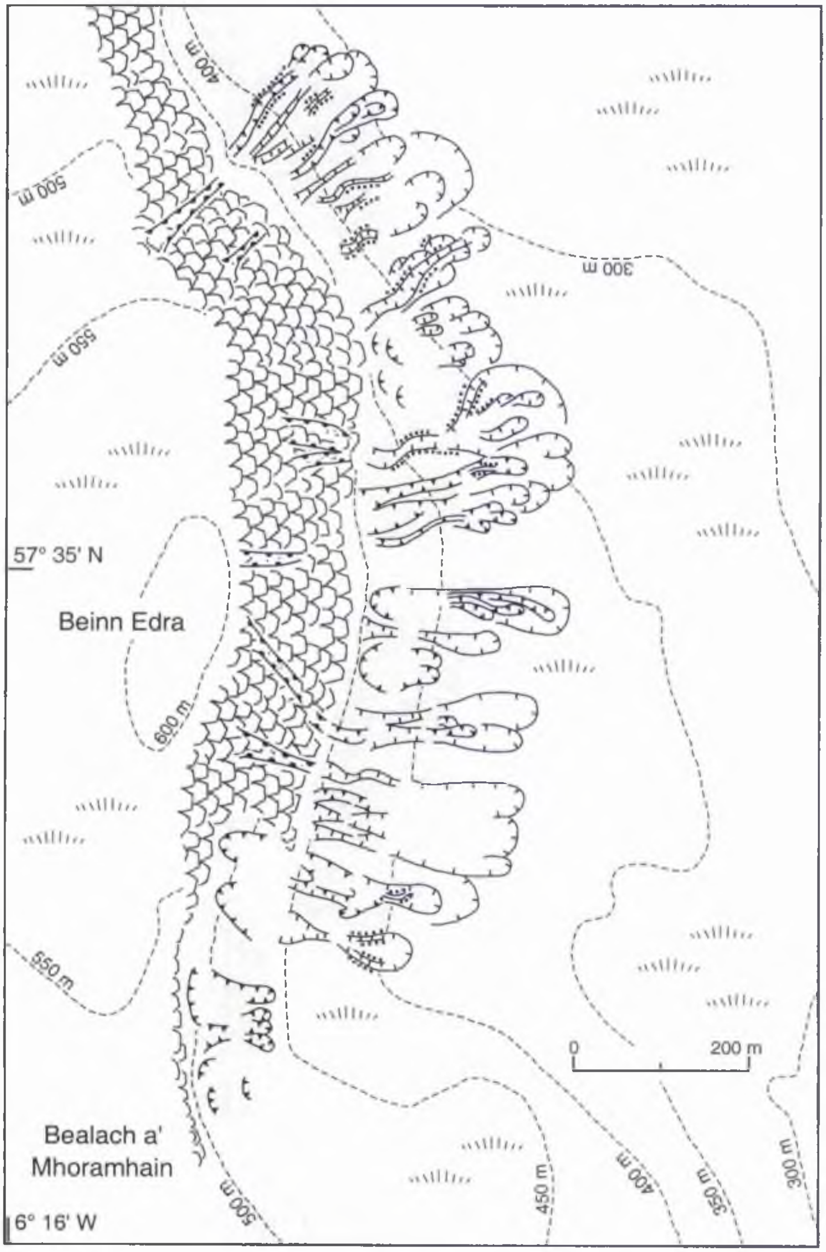


Figure 4.8. Talus debris and associated slope failures in the immediate vicinity of Beinn Edra, area 6, Trotternish, northern Skye. (Key as in Figure 4.3).

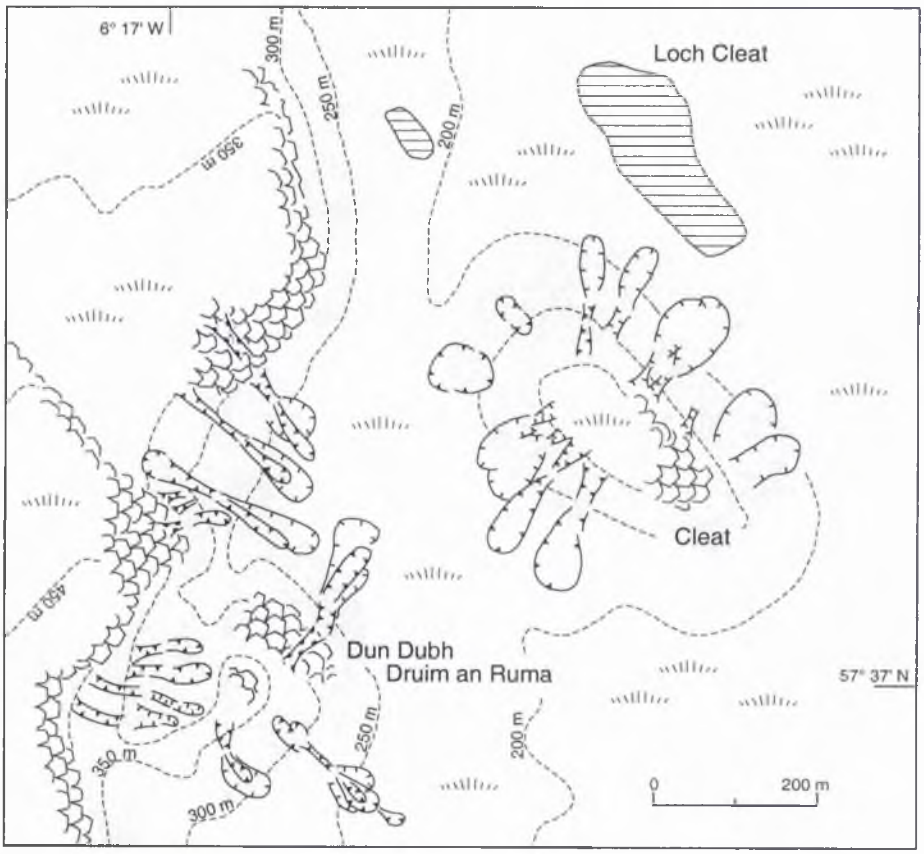


Figure 4.9. Talus debris and associated slope failures in the immediate vicinity of Cleat, area 7, Trotternish, northern Skye. (Key as in Figure 4.3).

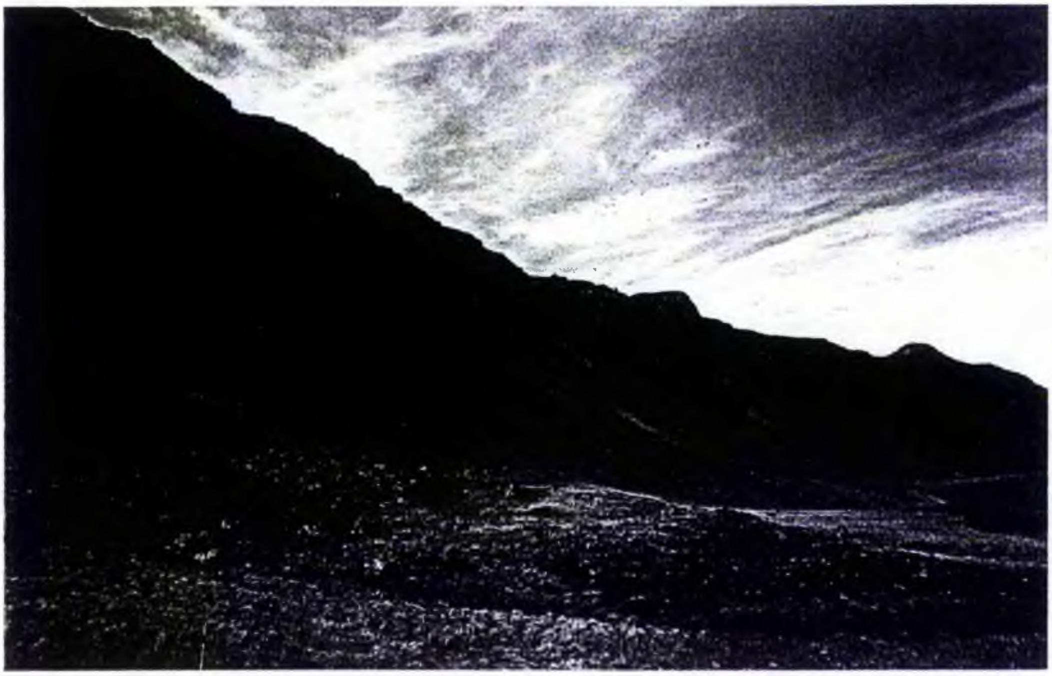


Figure 4.10. Relict talus slopes south of The Storr, area 2, Trotternish, northern Skye. Note the deeply incised gullies indicating erosion and downslope transport of talus debris.

Figure 4.11. Rock slope failure above Lochan a' Bhealach Bhig, area 2, Trotternish, northern Skye.

are superimposed on the upper surface of the talus and thus postdate the main phase of rockfall accumulation.

Talus debris on the western flanks of Quinag forms a continuous sheet below the summit cliffs (Figures 4.12 and 4.13). The sites of larger rock slope failures are marked by two irregular lobate boulder deposits. Unlike the rockslide debris on Trotternish, however, these deposits are partly buried by adjacent talus sediments, and are thus believed to predate the most recent phase of talus accumulation or reworking. The summit crags of Stac Pollaidh are encircled by a broad talus sheet of variable length (Figure 4.14). On the south-west flank of Baosbheinn talus also occurs as an uninterrupted sheet (Figures 4.15 and 4.16). The talus accumulations at all of these sites are apparently relict features, as ungullied sections of the talus slopes support a complete cover of grasses, sedges and woody shrubs (Figures 4.17 and 4.18). In upper Glen Feshie steep slopes of apparent rockfall origin were investigated at the foot of isolated valley-side cliffs (Figure 4.19). These slopes also appear to be relict features and support a partial cover of mature pine trees (*Pinus sylvestris*) and woody shrubs.

In sum, therefore, all of the slopes investigated have the appearance of laterally-continuous rockfall talus sheets rather than isolated talus cones, and all completely bury the underlying bedrock. The presence of widespread vegetation cover and rarity of fresh clasts on the slope surfaces at all sites indicate that, in common with most taluses in upland Britain, these are essentially relict accumulations that currently experience a low rate of sediment delivery from the source rockwalls upslope (*cf.* Harker, 1901; Ball, 1966; Tufnell, 1969; Ball and Goodier, 1970; Ryder and McCann, 1971; Ballantyne and Eckford, 1984; Kotarba, 1984; Ballantyne and Harris, 1994, p. 223). Moreover, the widespread occurrence of gullies incised into the talus accumulations at all of the sites investigated suggests

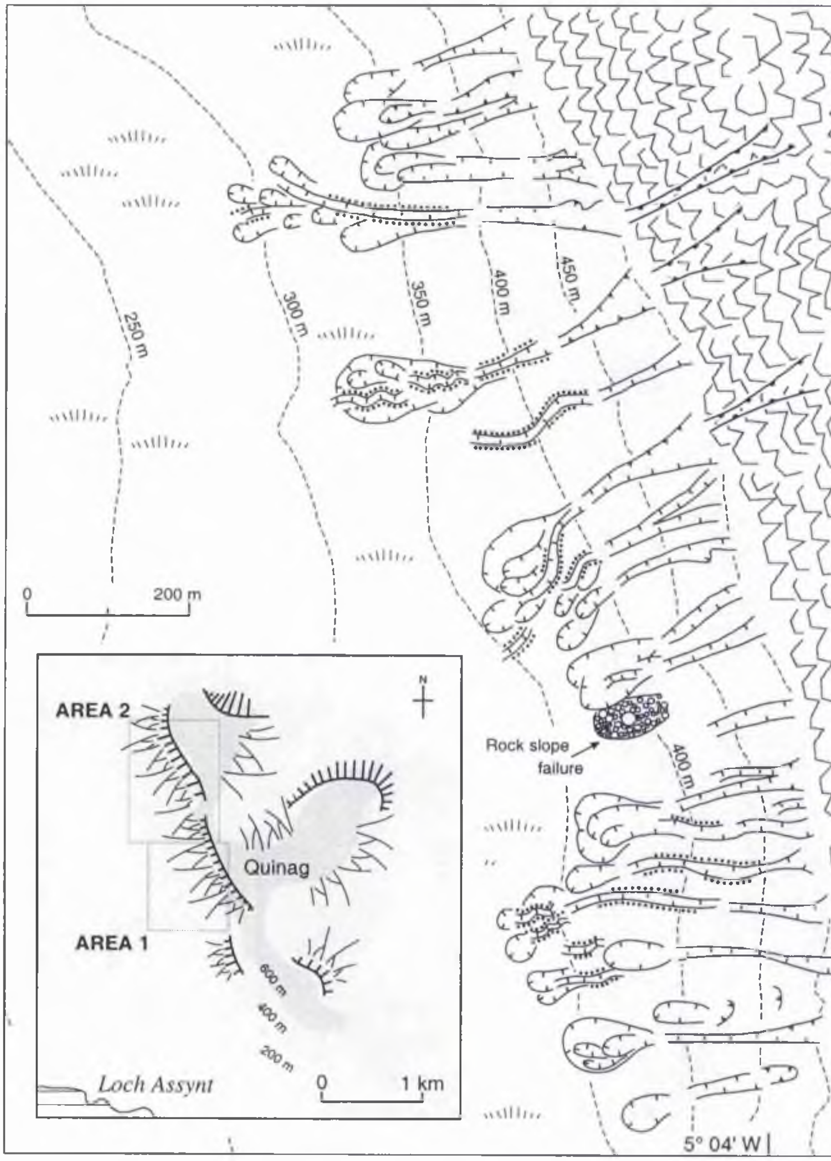


Figure 4.12. Talus debris and related slope failures at area 1 below the summit ridge of Quinag, Assynt. (Key as in Figure 4.3).

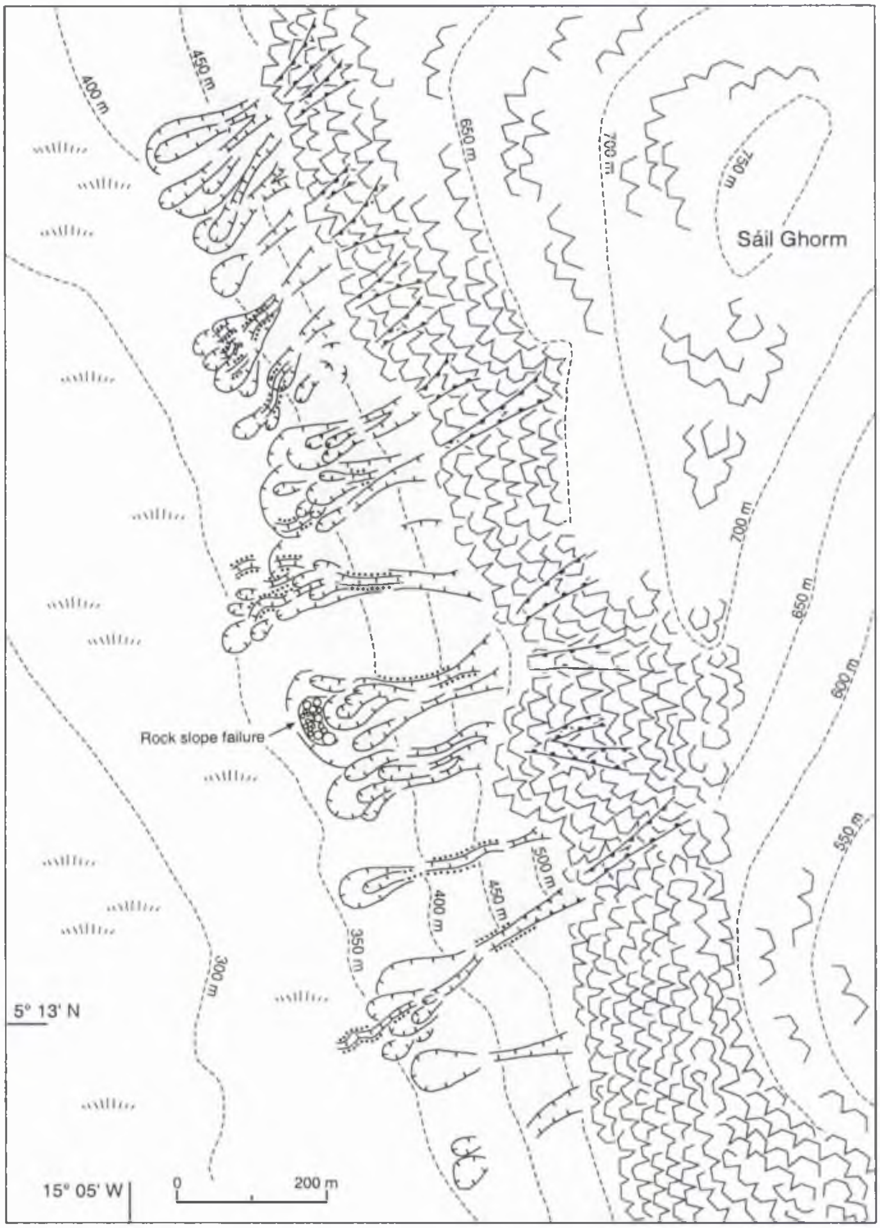


Figure 4.13. Talus debris and related slope failures at area 2 below the summit ridge of Quinag, Assynt. (Key as in Figure 4.3).

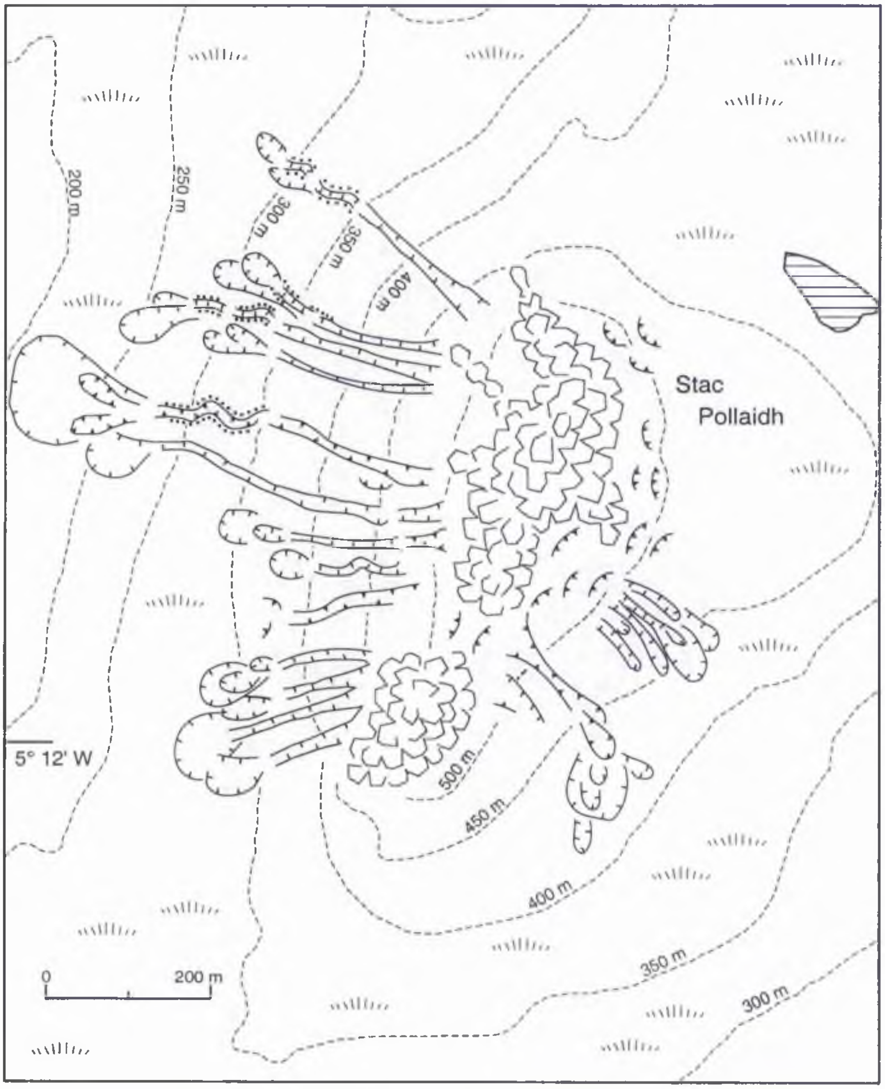


Figure 4.14. Talus debris and associated slope failures encircling the summit cliffs of Stac Pollaidh, Coigach. (Key as in Figure 4.3).

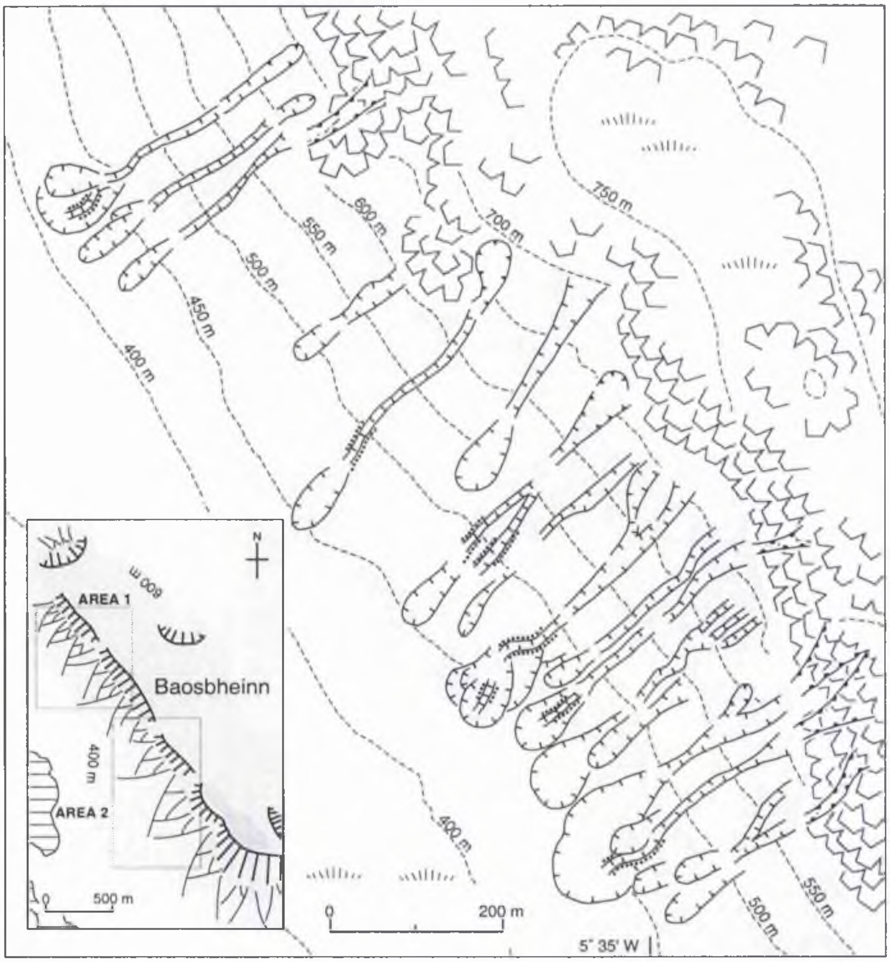


Figure 4.15. Talus debris and associated slope failures at area 1 below the western face of Baosbheinn, Wester Ross. (Key as in Figure 4.3).

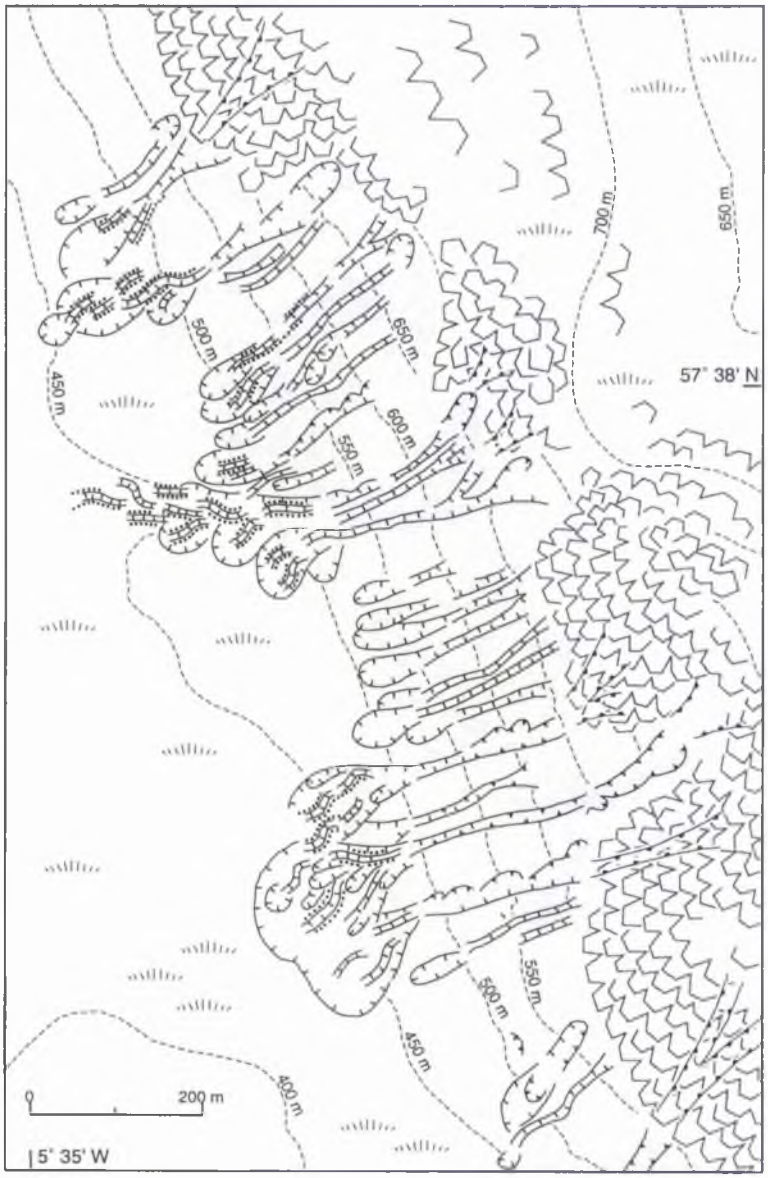


Figure 4.16. Talus debris and associated slope failures at area 2 below the western face of Baosbheinn, Wester Ross. (Key as in Figure 4.3).

Figure 4.17. Vegetated relict talus slopes below the western face of Quinag, (looking north from the southern limit of area 1 in Figure 4.12).

Figure 4.18. Vegetated relict talus slopes and evidence of recent debris flow activity below the northernmost summit of Stac Pollaidh, Coigach.

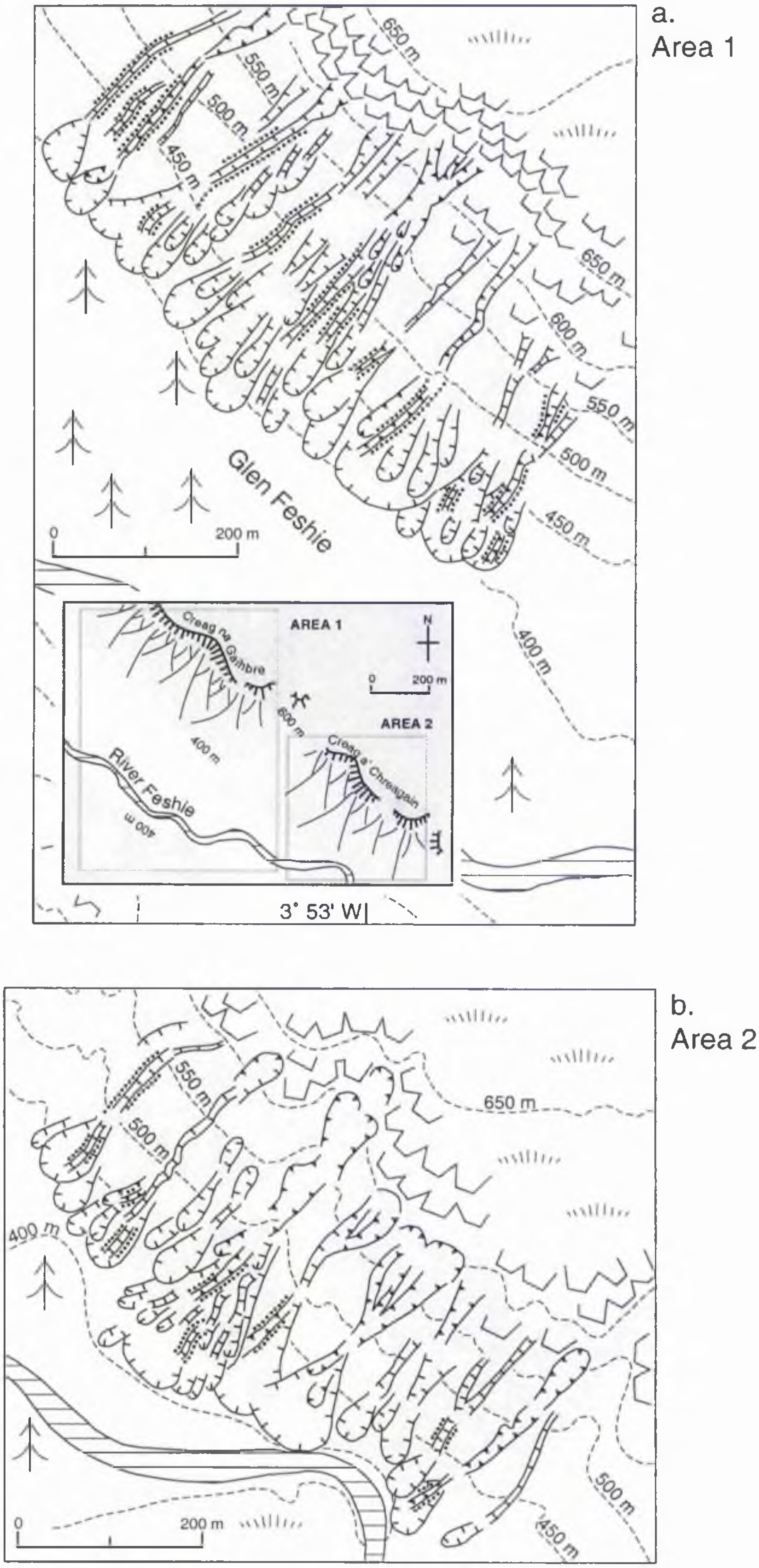


Figure 4.19. Talus debris and associated slope failures below valley-side cliffs in upper Glen Feshie. (Key as in Figure 4.3).

that erosion has replaced accumulation as the dominant mode of geomorphic activity operating on these slopes.

4.4 Slope form

4.4.1 Slope profiles

All surveyed talus slopes possess a near-rectilinear upper slope and a basal concavity (Figures 4.20-4.25), features hitherto associated with mature rockfall-dominated talus slopes (Howarth and Bones, 1972; Chandler, 1973; Statham, 1973a, 1976a; Kotarba, 1976; Francou and Manté, 1990; Francou, 1991). The mean gradients of the upper rectilinear slopes at the five field sites range from 35.1° to 38.9° (Tables 4.1a and 4.1b). These averaged gradients are similar to those measured on talus slopes in other parts of upland Britain, for example 32-40° in Wales (Tinkler, 1966; Statham, 1973a), 33-38° in the Cuillin Hills of Skye (Statham, 1976a) and 32-39° for sites elsewhere in Scotland (Ballantyne and Eckford, 1984; Ward, 1985). All but two of the 43 surveyed rectilinear slope gradients fall within an overall range of 32.8° to 42.9°, which is again broadly consistent with previous observations of upper slope gradients both in upland Britain and elsewhere, but profiles C and G on Trotternish (Table 4.1a) yielded gradients of 47.1° and 45.0° respectively, both significantly steeper than any previously recorded. There is also some evidence for systematic differences in mean rectilinear slope gradients between sites. The mean rectilinear slope gradients for the three sites on Torridon Sandstone terrain (35.1° on Quinag; 36.5° on Stac Pollaidh; 37.7° on Baosbheinn) fall below the equivalent values for Trotternish (38.8°) and Glen Feshie (38.9°), and dispersion diagrams (Figure 4.26) also highlight between-site differences in the ranges of rectilinear slope gradients recorded, though there is some overlap due to variability of all distributions. Testing, using the Mann-Whitney two sample test, nonetheless revealed that the rectilinear slope gradients measured on Stac Pollaidh and Quinag are significantly

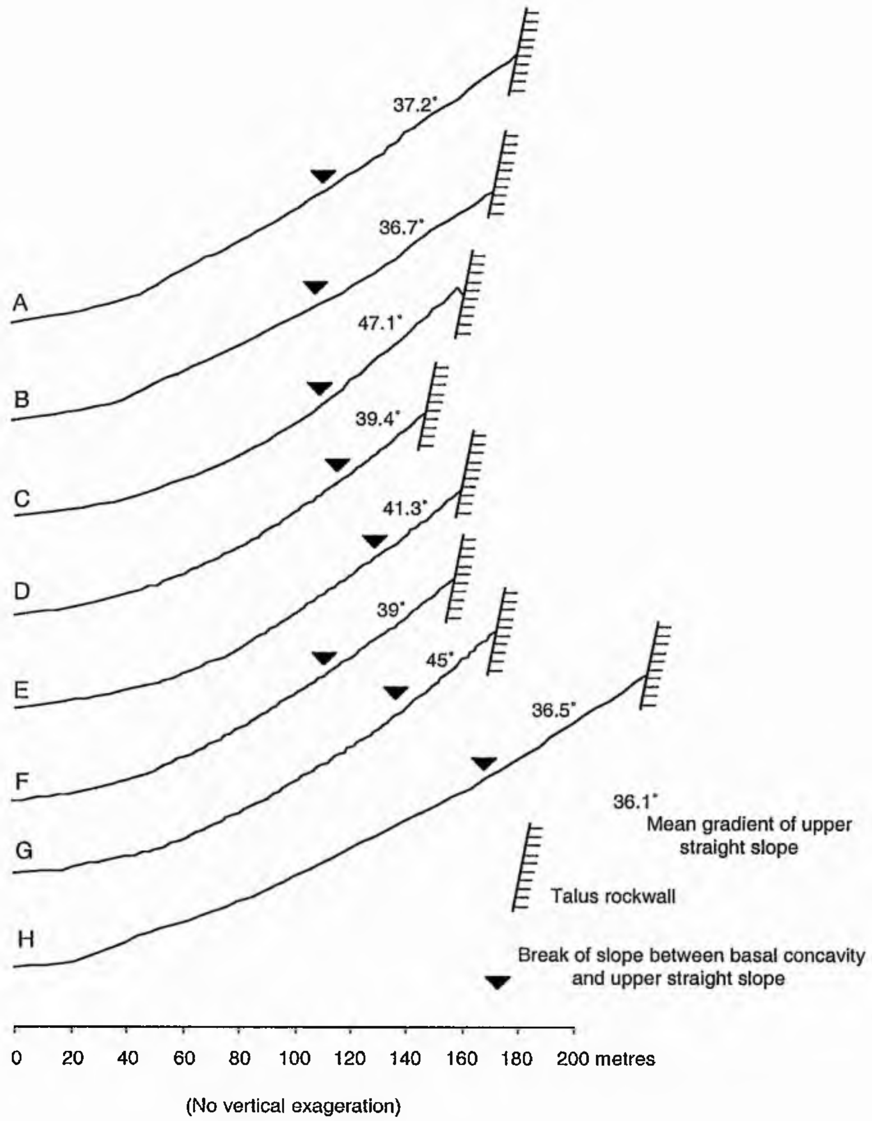


Figure 4.20. Talus profiles A - H, area 2, Trotternish escarpment.

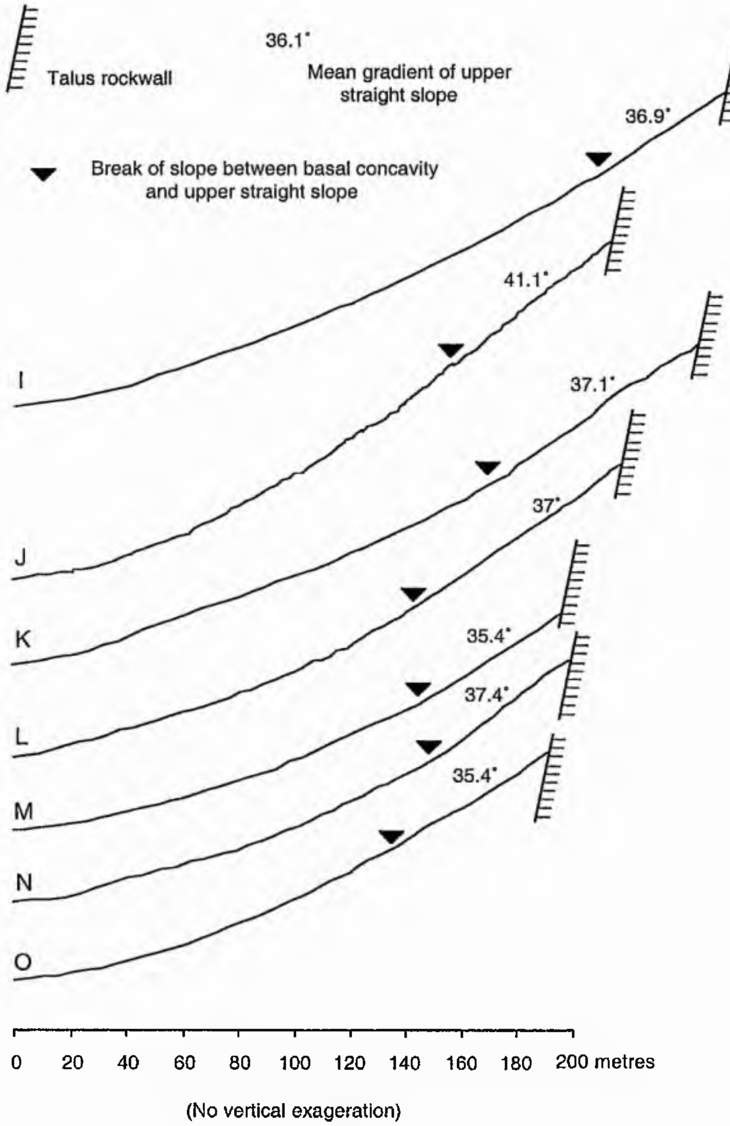


Figure 4.21. Talus profiles I - O, area 2, Trotternish escarpment.

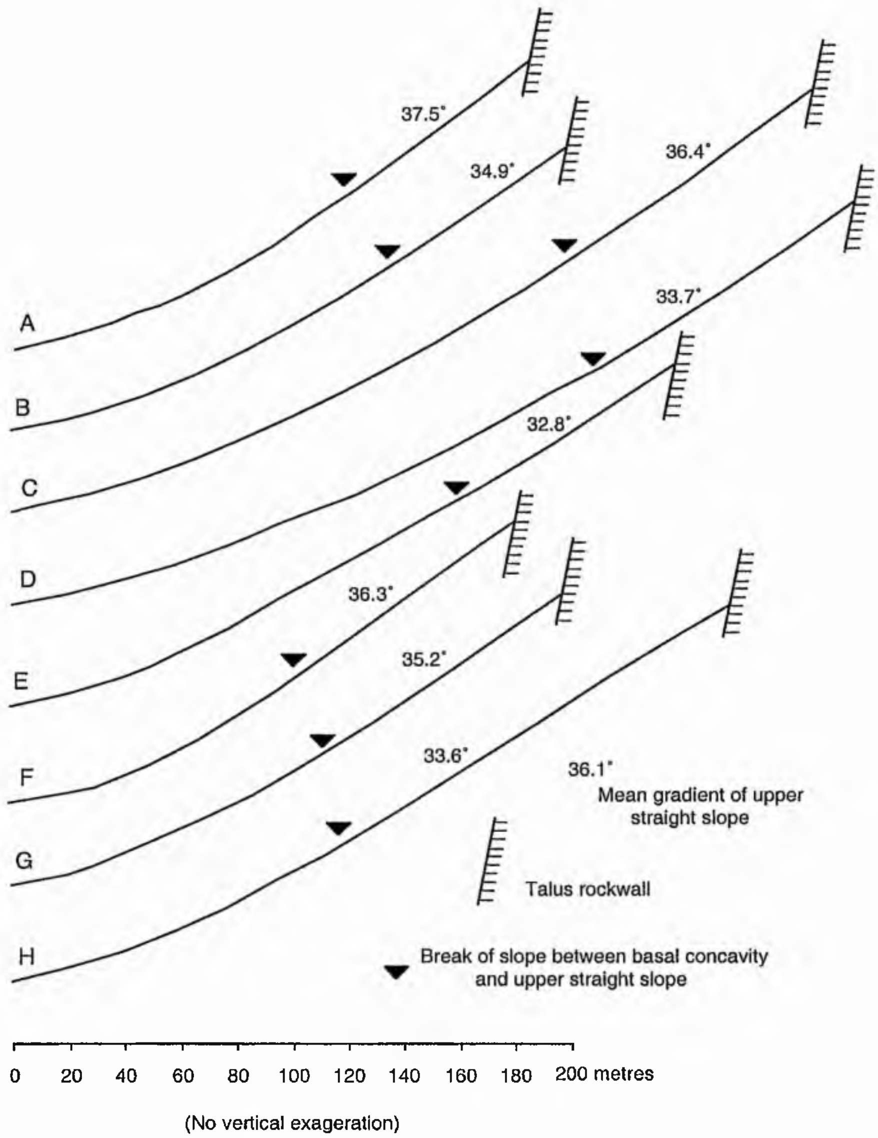


Figure 4.22. Talus profiles A - H, Quinag, Assynt.

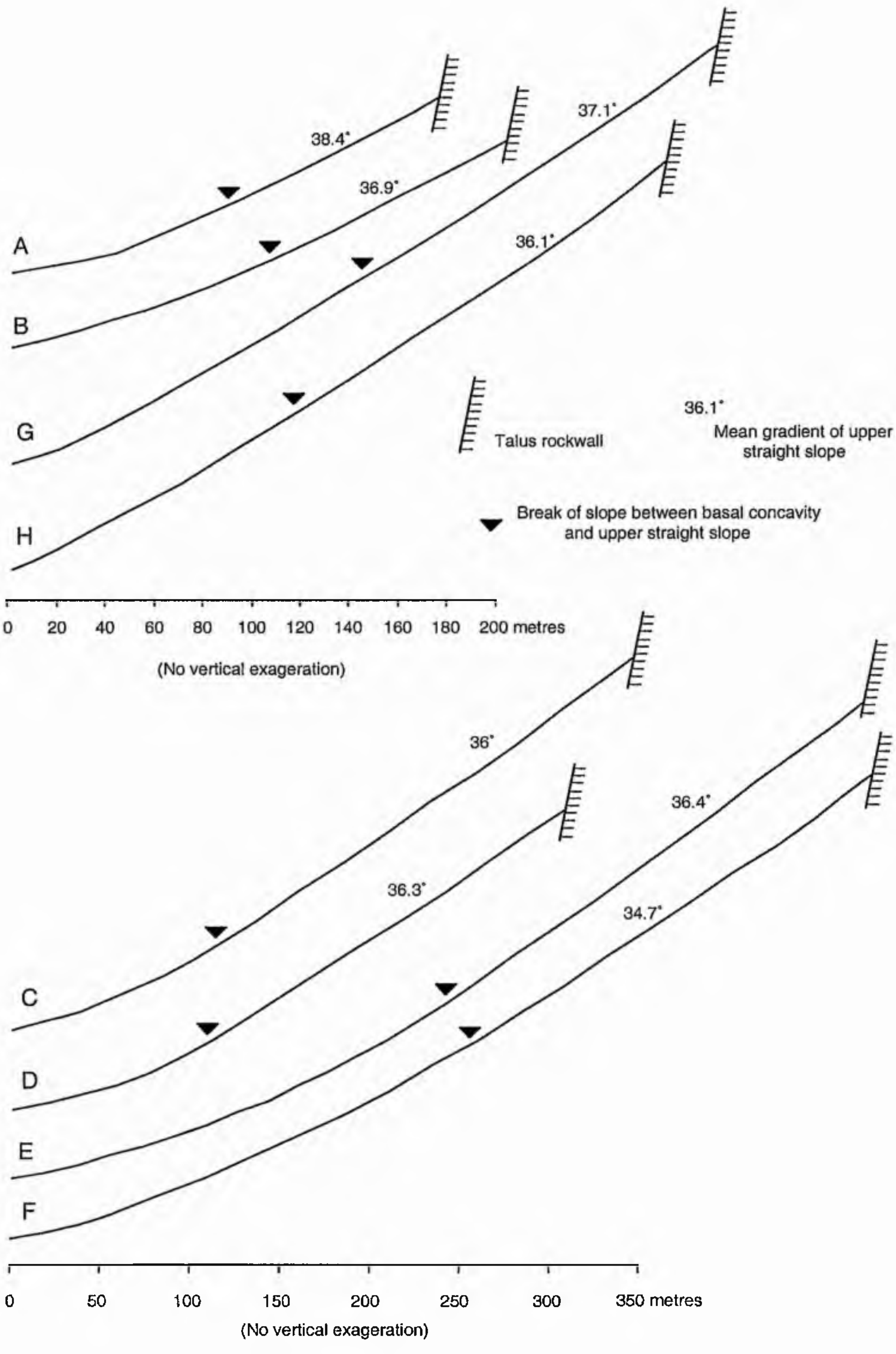


Figure 4.23. Talus profiles A - H, Stac Pollaidh, Coigach.

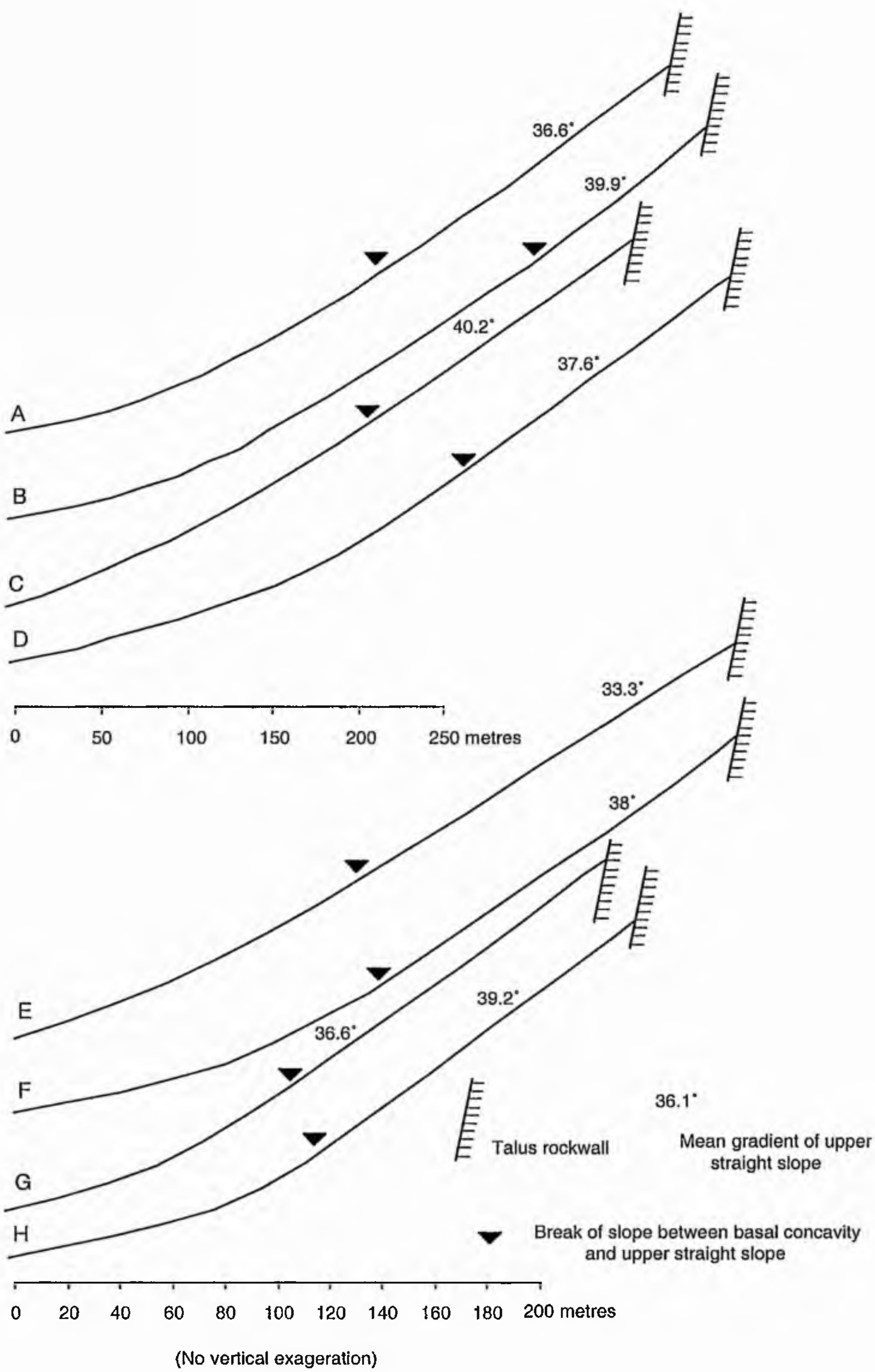


Figure 4.24. Talus profiles A - H, Baosbheinn, Wester Ross.

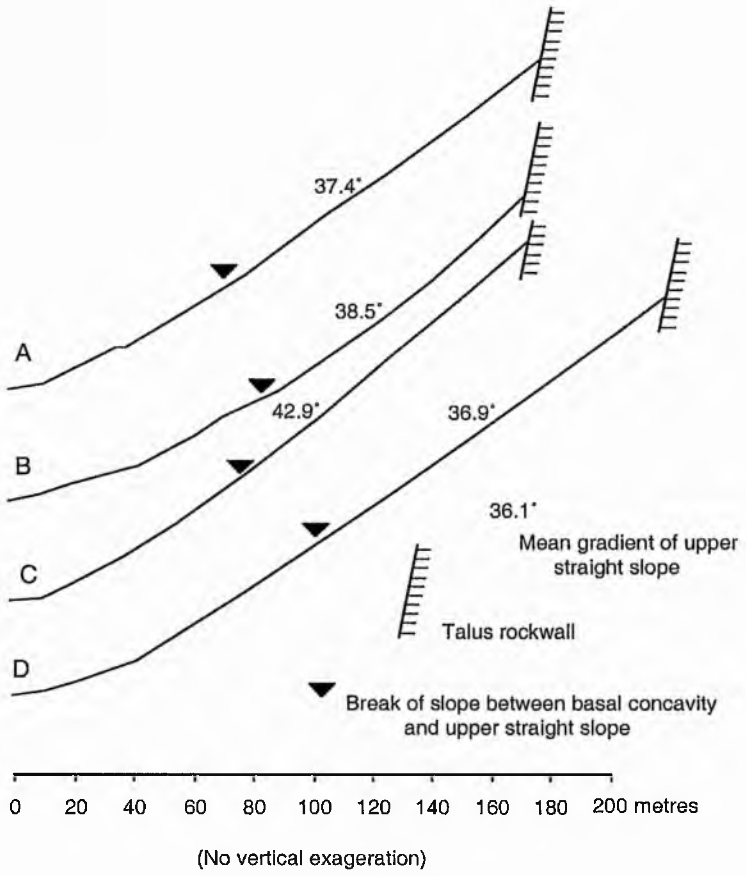


Figure 4.25. Talus profiles A - D, upper Glen Feshie.

Table 4.1a. Indices used in the description of talus slope form, Trotternish

Profile	H_o:H_i ratio	Straight slope gradient (°)	Index A (%)	Index B	Index C (%)	
Talus profiles						
A	0.52	37.2	64.2	2.11	19.8	
B	0.48	36.7	70.7	1.99	20.9	
C	0.48	47.1	68.6	7.03	27.5	
D	0.47	39.4	78.3	2.98	27.3	
E	0.53	41.3	82.2	3.18	29.5	
F	0.56	39.0	75.0	4.48	24.7	
G	0.58	45.0	76.6	3.52	29.7	
H	0.71	36.5	76.7	2.31	18.3	
I	0.75	36.9	79.9	2.25	19.5	
J	0.70	41.1	71.7	2.39	21.5	
K	0.69	37.1	69.9	2.20	18.8	
L	0.62	37.0	62.5	2.39	21.7	
M	0.51	35.4	76.3	3.00	26.2	
N	0.51	37.4	70.2	2.44	26.2	
O	0.46	35.4	69.4	3.44	23.4	
	0.57	38.8	72.8	3.05	23.1	- Mean
	0.03	0.89	1.45	0.33	1.01	- Standard error
Gully profiles						
U	-	38.8	70.1	2.60	34.5	
V	-	36.5	81.2	3.72	23.7	
W	-	27.1	73.2	1.58	21.3	
X	-	33.7	77.2	1.94	23.6	
Y	-	20.3	64.8	2.71	30.9	
Z	-	34.5	54.4	1.88	9.30	
	-	31.8	70.2	2.41	23.9	- Mean
	-	2.81	3.91	0.32	3.57	- Standard error

Table 4.1b. Indices used in the description of talus slope form at the mainland study sites.

Profile	H_o:H_i ratio	Straight slope gradient (°)	Index A (%)	Index B	Index C (%)	
Quinag						
A	0.51	37.5	55.6	1.94	18.0	
B	0.49	34.9	58.7	1.92	17.8	
C	0.59	36.4	61.8	2.03	17.6	
D	0.59	33.7	67.6	2.11	17.7	
E	0.48	32.8	69.2	1.70	12.5	
F	0.46	36.3	54.9	2.01	17.5	
G	0.68	35.2	56.8	1.86	15.8	
H	0.74	33.6	46.6	1.57	12.0	
	0.57	35.1	58.9	1.89	16.1	- Mean
	0.04	0.57	2.58	0.06	0.88	- Standard error
Stac Pollaidh						
A	0.91	38.4	53.8	2.13	17.0	
B	0.93	36.9	62.5	1.61	12.8	
C	0.77	36.0	35.5	1.75	14.9	
D	0.80	36.3	36.1	1.77	12.5	
E	0.85	36.4	44.8	2.06	18.3	
F	0.84	34.7	51.7	1.88	15.7	
G	0.83	37.1	53.9	1.19	8.0	
H	0.82	36.1	42.4	1.26	7.6	
	0.84	36.5	47.6	1.71	13.35	- Mean
	0.02	0.37	3.36	0.12	1.39	- Standard error
Baosbheinn						
A	0.66	36.6	52.4	2.03	18.3	
B	0.62	39.9	74.5	2.09	20.0	
C	0.56	40.2	59.5	1.66	11.3	
D	0.70	37.6	59.4	2.46	20.4	
E	0.78	33.3	46.9	1.41	9.8	
F	0.74	38.0	48.4	2.48	21.3	
G	0.50	36.6	44.8	1.81	16.1	
H	0.54	39.2	46.4	2.51	22.1	
	0.64	37.7	54.0	2.06	17.4	- Mean
	0.04	0.79	3.55	0.15	1.64	- Standard error
Glen Feshie						
A	0.75	37.4	43.0	1.55	11.7	
B	0.77	38.5	48.5	2.13	20.7	
C	0.89	42.9	42.9	1.57	12.8	
D	0.82	36.9	45.2	1.50	12.6	
	0.81	38.9	44.9	1.69	14.4	- Mean
	0.03	1.32	1.31	0.15	2.10	- Standard error

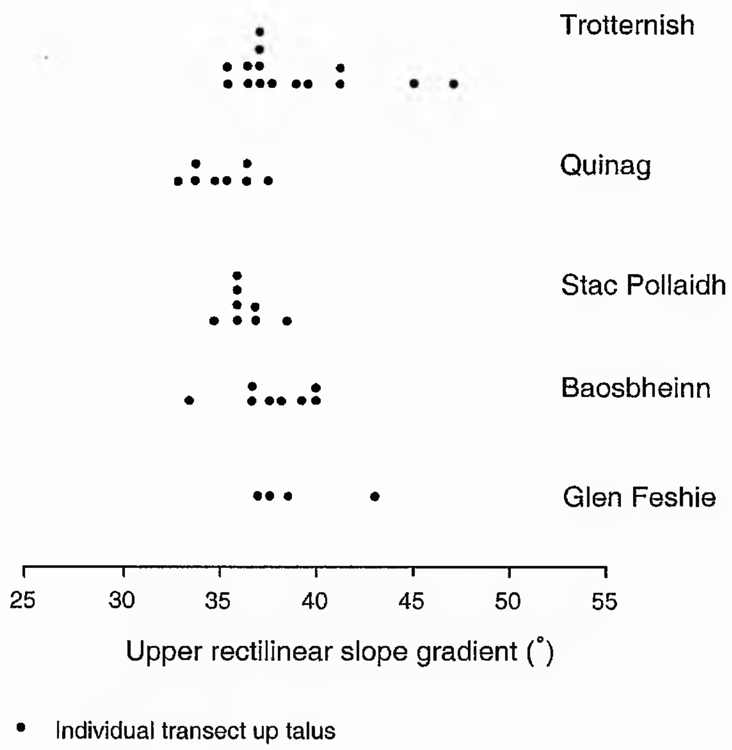


Figure 4.26. Upper slope gradients of talus slopes.

lower (at $p<0.05$) than those recorded in Glen Feshie and on Trotternish. These differences suggest that underlying geology may influence the gradient of the upper rectilinear slope, possibly through differences in clast calibre and shape (*cf.* Statham, 1976a). However, the most striking feature of the gradient data is the very wide overall range (32.8° to 47.1°), which appears incompatible with any simple mechanical interpretation of such slopes as representing the 'angle of repose' of coarse cohesionless debris, determined by the frictional strength of clast-to-clast contacts. The wide range of gradients surveyed on the upper rectilinear slopes suggests that some form of debris reworking has reduced the straight-slope gradients of some relict taluses well below the theoretical maximum that might be expected in terms of the angle of internal friction of coarse debris (Statham, 1975, 1976a). Putting the argument another way, it is difficult to envisage why some profiles at a single site exhibit much steeper rectilinear slope gradients than their immediate neighbours, unless the latter have been reduced by some secondary reworking. This point is returned to below.

The surveyed talus slopes on Trotternish are all dominantly concave in profile (Figures 4.20 and 4.21), and exhibit mean index A, B and C values, as defined above, of 72.8 ± 1.45%, 3.05 ± 0.33, and 23.1 ± 1.01% respectively, where the range is expressed in terms of one standard error from the mean value (Table 4.1a). The same summary indices for talus profiles surveyed at the three field sites on the NW mainland (Figures 4.22-4.24) range from 47.6 ± 3.36% to 58.9 ± 2.58% for index A, 1.71 ± 0.12 to 2.06 ± 0.15 for index B, and 13.4 ± 1.39% to 17.4 ±1.64% for index C (Table 4.1b). In terms of all three indices, therefore, the values calculated for the sites on the NW mainland are markedly less than those calculated for the Trotternish slopes. This indicates that the basal concavities associated with the latter not only occupy a larger relative proportion of the overall slope, but also are associated with a much more marked reduction in gradient and a deeper overall slope concavity. Talus slopes in upper Glen Feshie appear to be generally the least concave in profile (Figure 4.25), with mean A, B and C indices of 44.9 ± 1.31%, 1.69 ± 0.15 and 14.4 ± 2.10%) respectively (Table 4.2). Dispersion plots confirm the differences in concavity between the Trotternish profiles and those of the mainland sites (Figure 4.27), showing that although there is some between-site overlap, the individual index values calculated for the Trotternish profiles extend well beyond those calculated for individual profiles at the other sites. These differences are confirmed by statistical testing (Mann-Whitney two-sample test) which demonstrates no significant differences between the mainland profiles in terms of any of the concavity indices, but that the concavity of the Trotternish sites is significantly greater (at $p<0.05$) than that of all the mainland sites in terms of all three indices. There are several possible explanations for such differences. According to Statham's (1976a) rockfall model of talus slope accumulation, they may reflect talus maturity, with a high degree of concavity being associated with relatively immature slopes with low $H_o:H_i$ ratios (i.e. as talus extends progressively up the headwall, the rectilinear slope extends over the basal concavity, reducing overall concavity). Alternatively, relatively extensive basal concavities may reflect more effective reworking of talus debris from the upper slope by other processes, as implied by the 'two facet' model proposed by Francou and Manté (1990) and Francou (1991). The validity of these competing explanations is examined in section 4.5 below.

4.4.2 Slope surface morphology

Widespread reworking of talus debris at all sites is apparent in the abundant morphological evidence of debris flow activity (Figures 4.3-4.19). Most debris flows have their source areas immediately below the rockwall at the crest of upper rectilinear slopes, where they emanate from gullies. Some of these are deep, steep-sided and apparently active, whilst others are older, infilled features with degraded, vegetated sides. Downslope from many gullies are sinuous, parallel bouldery levées

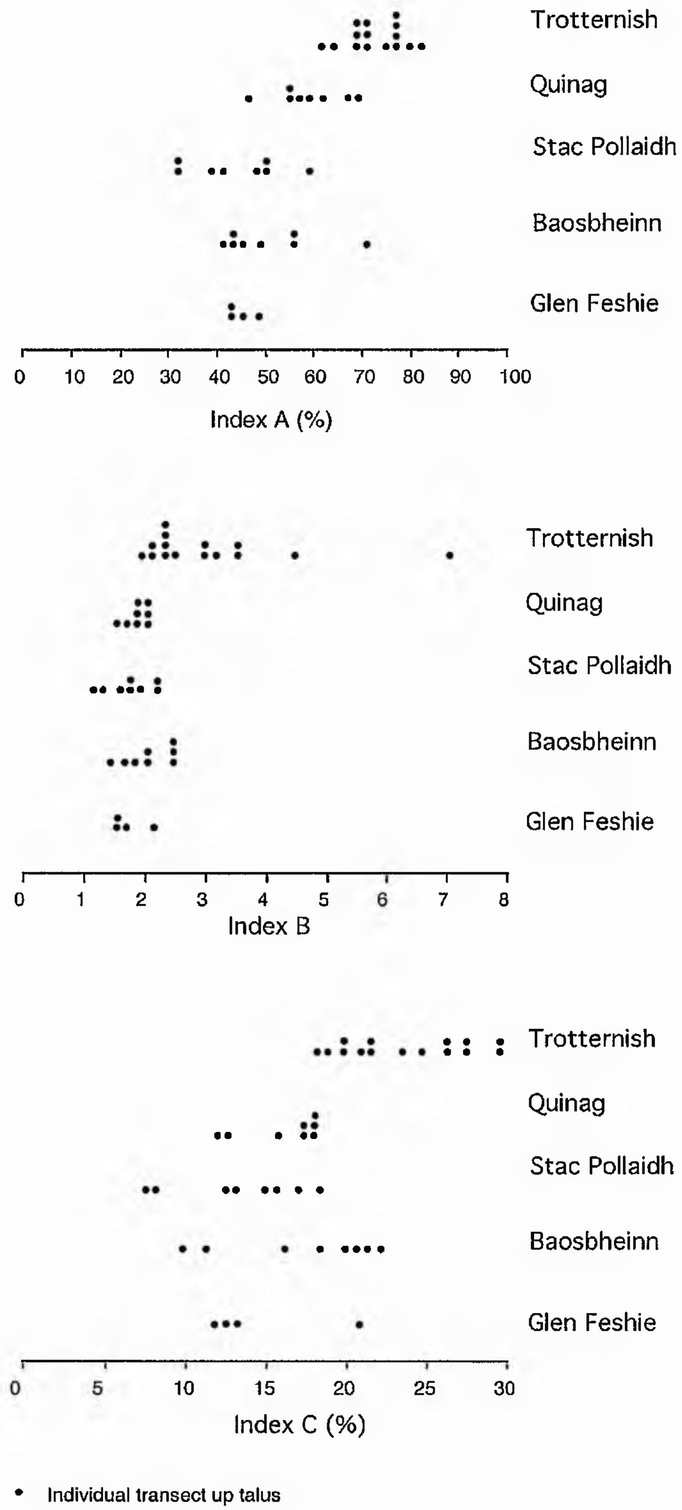


Figure 4.27. The degree of overall slope concavity of transects up talus slopes in terms of index A, B and C defined above.

characteristic of laterally-confined debris flows (e.g. Pierson, 1980; Innes, 1983c; Nieuwenhuijzen and van Steijn, 1990; Figure 4.28). These levées frequently run out on to slope-foot debris cones that support a complex microrelief of shallow channels, levées and bouldery flow lobes (Figure 4.29). The depths of active gullies on the Trotternish talus slopes are often greater than 4 m, but those at the mainland sites rarely exceed 3 m in depth. Measured in terms of frequency per kilometre of talus (Table 4.2), the concentration of gullies also proved to be slightly higher on Trotternish, with a mean value of 16.5 km^{-1} measured over all seven mapped sectors, compared with 13.0 km^{-1} at Quinag, 7.6 km^{-1} at Stac Pollaidh, 15.1 km^{-1} at Baosbheinn and 15.4 km^{-1} in upper Glen Feshie. These figures imply that the mean across-slope spacing of gullies is about 130 m on the Stac Pollaidh slopes, but considerably less (60-77m) at the other sites. These figures, however, take into account only conspicuous gullies, and do not incorporate all possible sites of inactive, degraded gullies.

Previous studies of the effects of repeated debris flows on talus suggest that the long-term result is a general reduction in the upper slope gradient and the extension of the basal concavity (e.g. Statham 1976b; Luckman, 1992; Ballantyne and Harris, 1994, p.230). Comparison of profiles surveyed up six gullies (U to Z in Figure 4.30) with those of adjacent ungullied talus slopes confirms that debris flow activity on Trotternish has reduced the inclination of the rectilinear slope. The mean upper slope gradient measured in the gullies is 31.8°, *c.* 7° lower than the equivalent figure for the rectilinear slope of ungullied talus (Table 4.1a), a difference significant at the $p<0.01$ level (Mann-Whitney two sample test). However, comparison of concavity indices calculated for the six surveyed gullies indicates no significant difference between these and the indices calculated for profiles surveyed up ungullied talus. This could indicate that the assumption of an increase in overall slope concavity due to reworking by debris flows is unsubstantiated. Alternatively, this evidence may imply that most if not all parts of

Figure 4.28. Recently deposited parallel levées that terminate in a small debris flow lobe downslope. The flow tack originates in the gully at the foot of the rockwall. The large, partially overridden boulder in the foreground is approximately 130 cm long.

Figure 4.29. A debris cone deposited at the foot of a relict talus slope. Quinag, NW Scotland. Note the contrast in surface relief between the relatively smooth ungullied talus in the middle distance and the bouldery debris cone in the foreground. The cone supports numerous indistinct debris flow lobes and palaeochannels.

Table 4.2. Concentrations of individual debris flow gullies per unit length of talus on Trotternish and at mainland field sites.

Site	Area	Concentration (km^{-1})
Trotternish	1	12.3
Trotternish	2	19.4
Trotternish	3	17.2
Trotternish	4	20.4
Trotternish	5	18.9
Trotternish	6	16.6
Trotternish	7	11.0
		16.5 - Mean
Quinag	1	14.5
Quinag	2	11.4
		13.0 - Mean
Stac Pollaidh	1	**7.6**
Baosbheinn	1	11.4
Baosbheinn	2	18.7
		15.1 - Mean
Glen Feshie	1	13.0
Glen Feshie	2	17.7
		15.4 - Mean

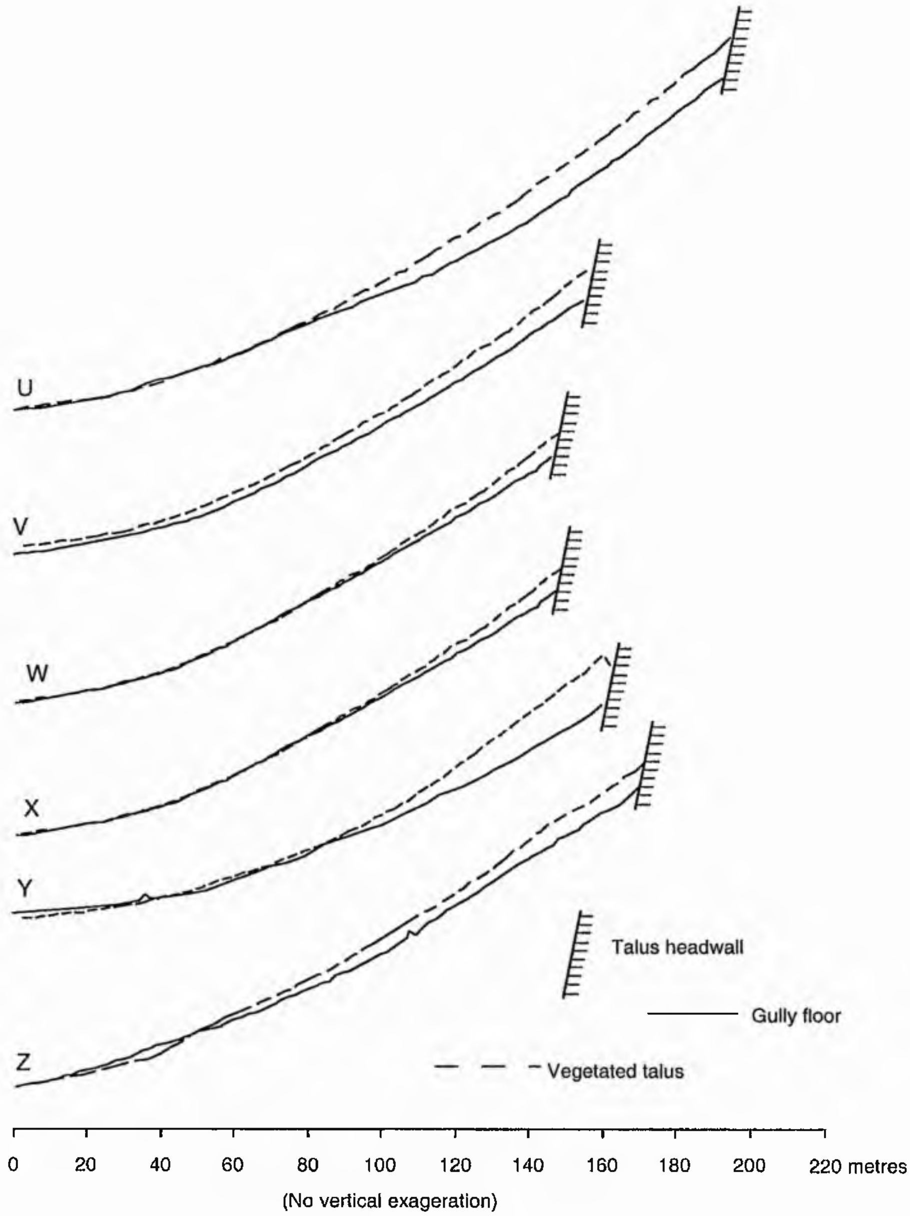


Figure 4.30. A comparison of transects up gullied and ungullied talus, area 2, Trotternish, northern Skye.

the talus have experienced reworking by debris flow activity at some time, so that differences in concavity between gullied and (apparently) ungullied sections of the slope are not apparent.

The latter conclusion is supported by the presence on the 'ungullied' parts of the Trotternish talus slopes of a subdued topography of depressions and shallow, vegetated runout lobes. These are interpreted as the degraded scars of translational failures and the deposits associated with ancient debris flows. This observation suggests that much or all of the talus may have experienced past reworking by sliding failure, gullying and debris flow activity, and may thus explain the similarity in concavity exhibited by profiles surveyed up gullied and 'ungullied' talus. It may also account for the highly variable upper slope gradients (35.4-47.1°) measured on 'ungullied' upper rectilinear slopes on Trotternish, in the sense that slopes with lower gradients may reflect more extensive former reworking than those with high gradients. In general, few areas of the upper rectilinear slopes on Trotternish appear to have escaped reworking and gully development at some time in the past, again implying that to consider such slopes as exclusively the product of rockfall accumulation is probably oversimplistic. Moreover, the coexistence of both active and degraded gullies on the same talus implies that though gullying and associated debris flow activity have affected most or all parts of the upper slopes, the loci of such talus reworking have shifted through time.

Degradation of older gullies on Trotternish can be illustrated by comparing the relatively large volumes of mature active gullies, for example Z (2500 m^3) and X (1270 m^3), with those of partly infilled forms, for example Y (560 m^3) and W (870 m^3). Comparison of the size of debris cones downslope of these gullies indicates that total sediment delivery to the foot of the talus has been of a similar order of magnitude at all four locations, despite differences in the size of the source gullies. The large size of some relict cones in comparison with the limited volume of the gullies upslope (for example Y and W), supports the proposition that many gullies have been infilled and regraded since cone formation. These observations support initial interpretation outlined above, namely that the irregular micro-relief between present-day gullies represents degraded slope failures, infilled gullies and ancient debris flow lobes.

In contrast, significant portions of the 'ungullied' talus surfaces at the three sites on the NW mainland support much more limited morphological evidence for former slope failure or gully development. This suggests that less extensive reworking of talus debris on upper slopes has occurred than has been the case on the Trotternish slopes, an observation consistent with the generally shallower depths of active gullies at these sites. In upper Glen Feshie, even active gullying is often confined to the uppermost metre or so of the talus, and past reworking activity appears to have been similarly superficial. This morphological contrast between the extent and depth of upper slope reworking evident on the Trotternish talus slopes and the more limited reworking of upper slopes that was observed at the mainland sites offers a plausible explanation for the lower levels of overall slope concavity exhibited at the latter. If valid, this interpretation supports the proposition suggested above, that slope profile form has been strongly influenced by reworking of upper slope deposits, and is not simply a consequence of rockfall deposition.

4.4.3 Slope form: summary

The principal conclusions that emerge from the above analyses of slope form are as follows.

1. The relict, vegetated valley-side drift accumulations at all five study sites support slope profiles consistent with their interpretation as mature,

rockfall-dominated talus slopes, namely a steep upper rectilinear (or near-rectilinear) slope and a basal concavity.

2. The gradients of the upper rectilinear slopes range from 32.8° to 47.1°. Though the lower part of this range is consistent with observations on talus slopes in other areas, the highest values measured exceed any previously recorded. Some of the between-site variance in upper slope gradients may reflect the influence of underlying geology (for example on clast size or shape), but large within-site variance seems to imply that processes other than rockfall accumulation have influenced upper slope gradient.

3. All four mainland field sites exhibit a similar degree of overall slope concavity. The talus slopes on Trotternish, however, are characterised by significantly deeper and longer concavities than the mainland sites.

4. Talus surface relief is dominated at all sites by gully incision on upper slopes and by debris flow deposition on lower slopes. The Trotternish slopes exhibit the deepest gullies and the highest concentration of active or recently-active features, and 'ungullied' portions of the talus slopes on Trotternish support numerous depressions and shallow runout lobes that apparently represent the degraded remnants of former gullies, failure scars and debris flows. At the mainland sites, active gullies are shallower and ungullied areas support more limited evidence of former erosion and downslope redeposition of sediment. This contrast suggests that both the large variability in upper slope gradients and the greater degree of concavity evident on Trotternish may be attributable to more extensive and pronounced reworking of sediment, primarily by debris flows, than is the case on the mainland talus slopes.

4.5 Implications

Since the abandonment of the simplistic notion that talus slopes represent deposits of coarse, cohesionless debris resting at an 'angle of repose' controlled only by the frictional strength of accumulated detritus, the evolution of rockfall-dominated slopes has previously been explained in terms of two competing models, namely the 'discrete particle rockfall model' (Statham, 1973a, 1976a; Kirkby and Statham, 1975), and, more recently, 'the two facet model' (Francou and Manté, 1990; Francou, 1991). The extent to which these provide a plausible explanation of talus form is considered here in the light of the evidence outlined above.

4.5.1 The discrete particle rockfall model: an examination

The 'discrete particle rockfall model' outlined in chapter 2 predicts that increasing talus maturity (represented by the ratio between the vertical height of the talus accumulation, *Ho*, and that of the entire slope, *Hi*) is associated with both an increase in the gradient of the upper rectilinear slope (reflecting a decrease in the kinetic energy of falling clasts) and a reduction in overall slope concavity as the rectilinear slope extends downslope, burying the upper part of the concavity.

These predictions were tested using the data in Tables 4.1a and 4.1b by plotting the relationships between the measured rectilinear slope gradients and the *Ho:Hi* ratio (Figure 4.31), and between the calculated concavity indices and the *Ho:Hi* ratio (Figures 4.32-4.34). Figure 4.31 reveals that there is no relationship between rectilinear slope gradient and talus maturity, thus refuting the predictions of the model in this respect. However, testing of the 'discrete particle rockfall model' by plotting the slope concavity indices against the *Ho:Hi* ratio yields an equivocal result that is more difficult to interpret. Most plots for individual sites (Figures 4.32-4.34) indicate no significant correlation between concavity and the *Ho:Hi*

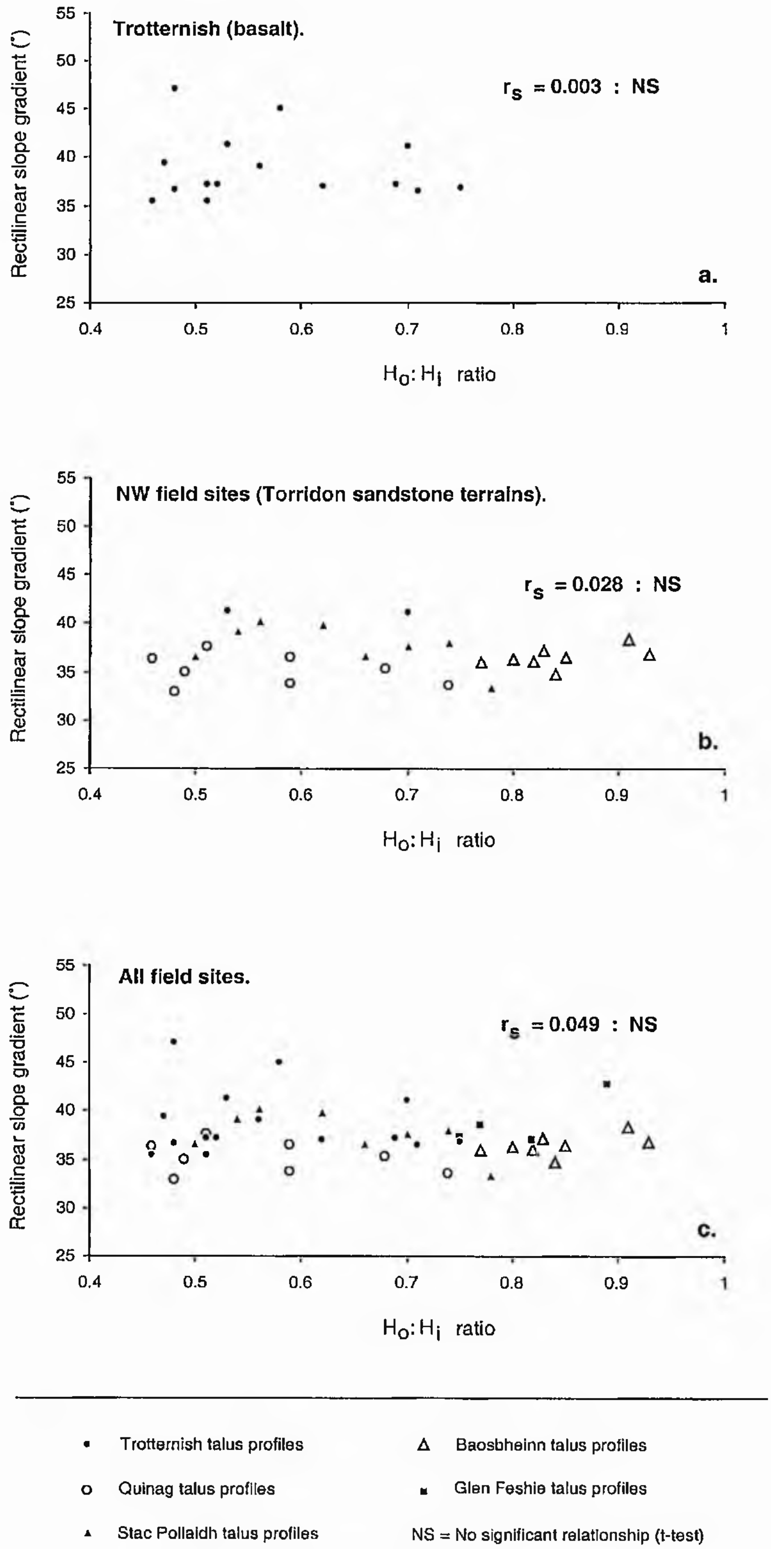


Figure 4.31. The relationship between talus slope maturity (expresed by the $H_o : H_i$ ratio), and the gradient of the upper rectlinear slope.

ratio, with the exception of a strong positive correlation (counter to the predictions of the model) between concavity index A and the *Ho:Hi* ratio for the Stac Pollaidh talus profiles (Figure 4.32c), and a weak negative correlation (consistent with the model) between concavity index C and the *Ho:Hi* ratio for the Trotternish profiles (Figure 4.34a). In general, this result indicates that the predictions of the model are not substantiated. However, aggregation of the concavity data for all five sites results in a significant negative correlation for concavity against the *Ho:Hi* ratio in terms of all three concavity indices (Figures 4.32f, 4.33f and 4.34f). In contrast to the results obtained for individual study sites, this finding indicates a relationship between increasing maturity and decreasing slope concavity, thus apparently satisfying the second prediction of the model.

Talus slope reworking, primarily by debris flow, offers a possible explanation for the equivocal findings reported above. The long-term effect of repeated debris flow activity on talus accumulations is erosion of debris from the upper slope and redeposition of such debris near the talus foot, thus lowering the height and gradient of the rectilinear slope and enlarging the basal concavity (Statham 1976b; Luckman, 1992; Ballantyne and Harris, 1994, p.230). Lowering of the upper slope may potentially lead to progressive reduction of talus height and therefore of the *Ho:Hi* ratio. Consequently, the net effect of debris flows on talus may be an apparent reduction of slope maturity accompanied by increasing overall concavity. As a result, the long profiles of relict talus slopes progressively modified by repeated debris flows may ultimately resemble those of relatively immature taluses with low *Ho:Hi* ratios and a high degree of concavity. Thus downslope redistribution of debris eroded from the upper slope rather than the kinetic energy of falling particles impacting talus surfaces (Statham, 1973a, 1976a; Kirkby and Statham, 1975) may explain the negative relationship between the concavity indices and the *Ho:Hi* ratios for the aggregated data. Although speculative, this argument is supported by the observed differences between talus slopes on Trotternish, which

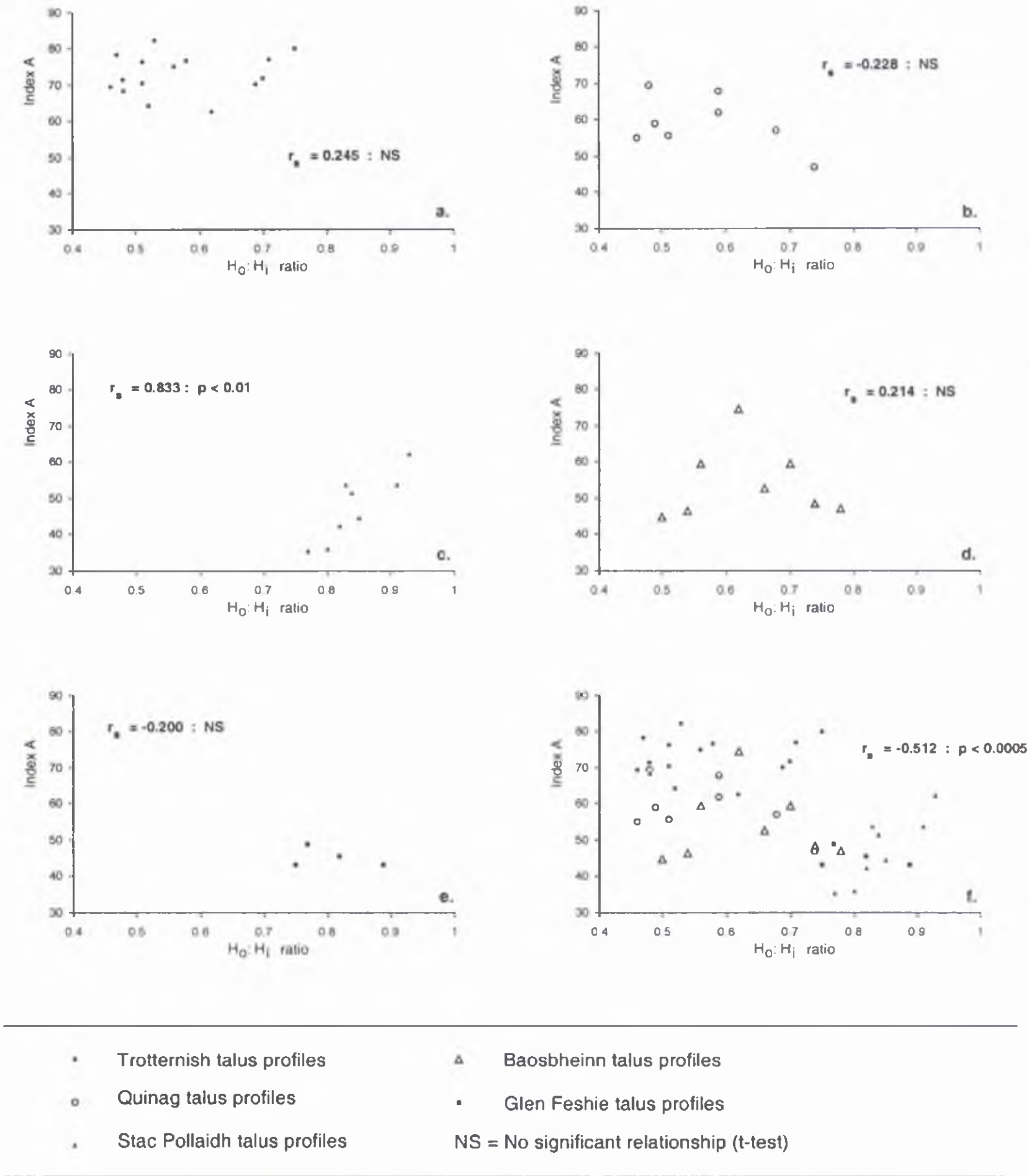


Figure 4.32. The relationship between talus slope maturity (expresed by the $H_o:H_i$ ratio), and index A of overall slope concavity for study sites in the Scottish Highlands.

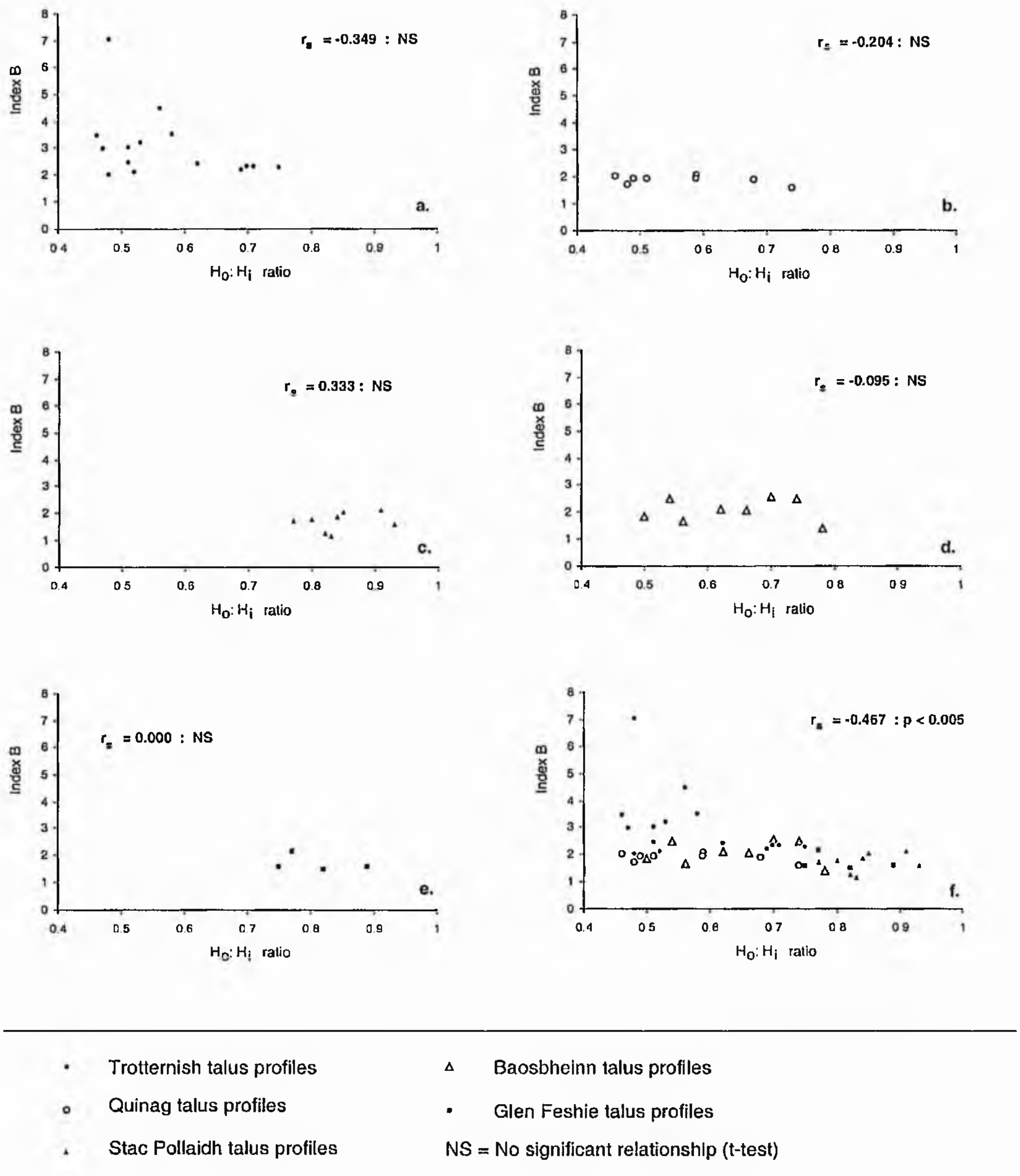


Figure 4.33. The relationship between talus slope maturity (expresed by the H_0:H_i ratio), and index B of overall slope concavity for study sites in the Scottish Highlands.

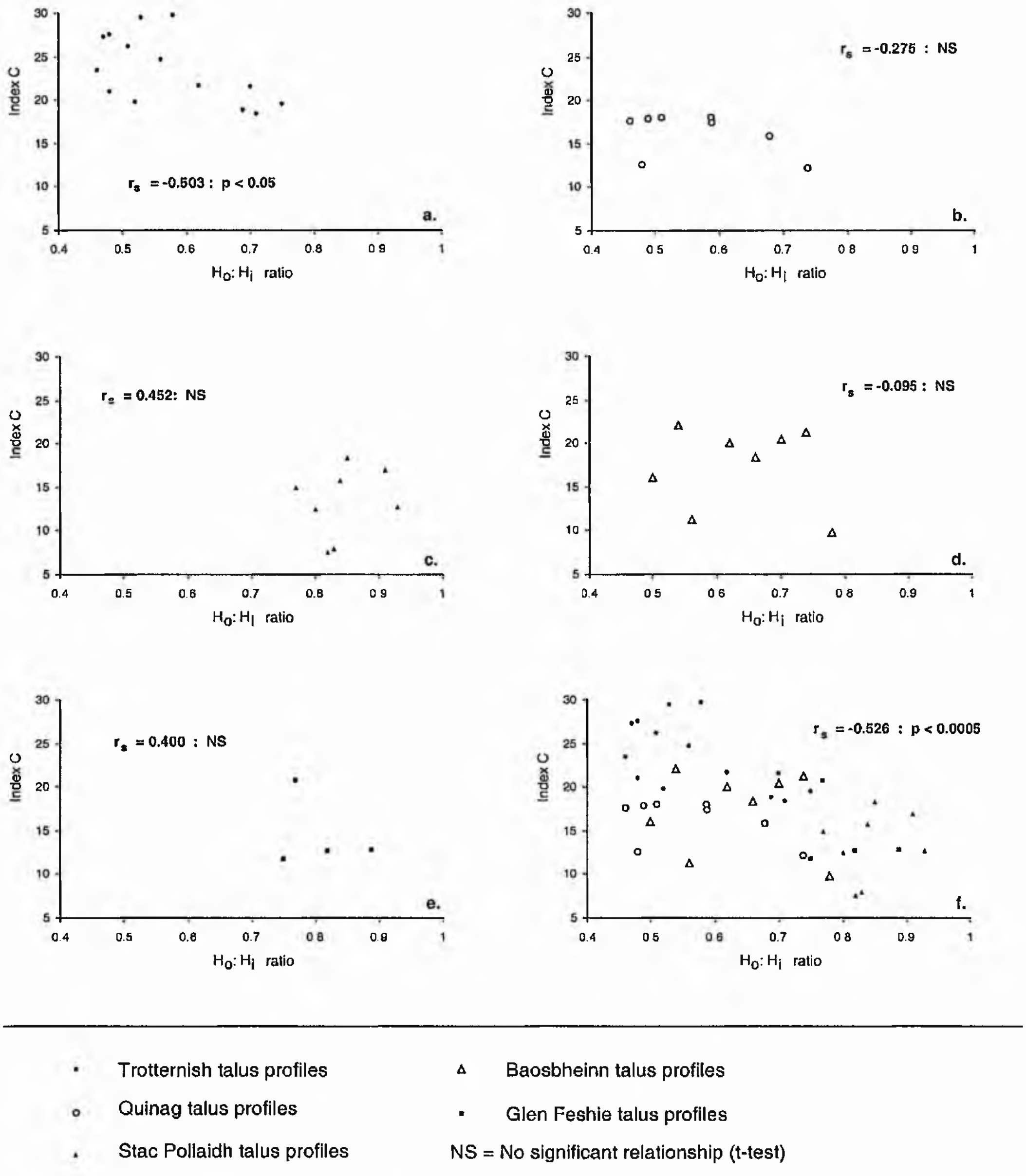


Figure 4.34. The relationship between talus slope maturity (expresed by the H_o:H_i ratio), and index C of overall slope concavity for study sites in the Scottish Highlands.

support evidence for abundant relict slope failures and a high mean gully concentration, and those surveyed at Stac Pollaidh, where evidence for reworking is much more limited and gullies are more widely spaced. The former are characterised by generally high concavity indices and low *Ho:Hi* ratios, the latter by low concavity indices and high *Ho:Hi* ratios. When combined in the aggregated data set, a significant negative correlation emerges that is absent (in all cases but one) for the individual sites. Thus the significant negative correlations evident for the aggregated data are apparently consistent with the predictions of the 'discrete particle rockfall model', but may actually reflect the operation of a completely different set of controls.

Alternatively, it is conceivable that the differences between the long profiles of talus slopes at different sites may reflect the initial form of glacially-modified rock slopes prior to the accumulation of overlying rockfall detritus. Depth to bedrock measurements for the upper parts of talus slopes on Trotternish range from 1.9 m to 5.0 m with a mean of 3.6 m, and are thus similar to depths reported for talus accumulations in other areas (e.g. Rapp, 1960b; Young, 1972; French, 1976). This suggests that talus accumulations in the Scottish Highlands, like those in many other areas, take the form of relatively thin mantles of debris above bedrock. One possible implication is that talus profiles may be influenced by the topography of the underlying bedrock. If so, consistent differences in talus profiles between different areas may reflect to some extent the form of the underlying glacially-modified bedrock slope, which is itself liable to reflect rock structure and resistance.

Irrespective of the possible causes, the negative relationship evident between the three concavity indices and the *Ho:Hi* ratio for the aggregated data (Figures 4.32f, 4.33f and 4.34f) may be explained in more than one way, and thus offers only equivocal support for the validity of the 'discrete particle rockfall model'. The lack of any significant relationship between upper slope gradient and talus maturity (Figure 4.31) and between concavity and maturity at individual sites in all cases but one (Figures 4.32-4.34) suggests that the model offers limited explanation for the long profile form of the surveyed slopes, and thus for talus slope evolution at these sites.

4.5.2 The two facet model: an examination

The 'two facet model' (chapter 2) differs from previous interpretations of talus form, in that it envisages a transition from a transport-dominated upper straight slope characterised by coeval deposition and downslope mass transport of rockfall debris, to an accumulation-dominated basal concavity (Francou and Manté, 1990; Francou, 1991). In contrast to the 'discrete particle rockfall model', it predicts that talus slopes tend towards an increasingly concave profile with maturation. In addition, Francou and Manté (1990) and Francou (1991) proposed that taluses overlooked by steep, massive rockwalls exhibit a consistent break of slope at 33-34° between the transport-dominated upper straight slope and the accumulation-dominated basal concavity.

Testing of the first prediction using the data in Tables 4.1a and 4.1b provides no evidence of a positive relationship between concavity and talus maturity (represented by the *Ho:Hi* ratio) for either individual sites or for the aggregated data set (Figures 4.32-4.34), apart from the positive correlation between concavity index A and the *Ho:Hi* ratio evident for the Stac Pollaidh slopes (Figure 4.32c). The predictions of the model in this respect are thus not satisfied. Moreover, the gradients of the 43 surveyed talus slopes at the transition between the basal concavity and the upper rectilinear slope (Figure 4.35) exhibit a wide range of 27-39°, apparently inconsistent with the notion of a constant transitional gradient of 33-34°. However, for 60.5% of the surveyed transects the transitional gradient falls

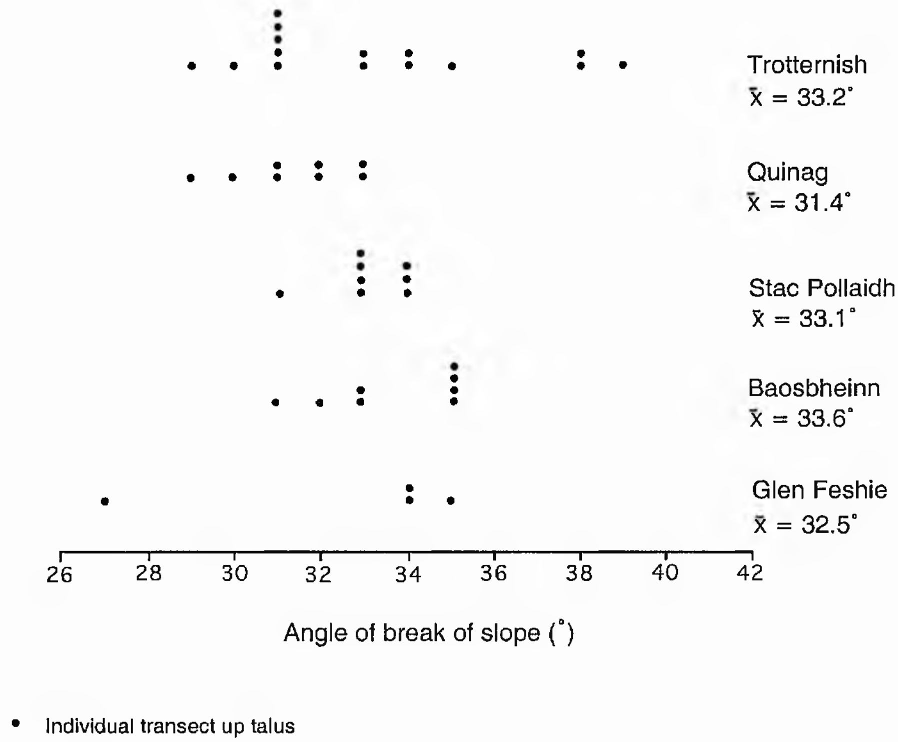


Figure 4.35. Gradient of the principal break of slope between the transport-dominated upper straight slope and the accumulation-dominated basal concavity, for transects surveyed up talus at all five study sites.

between 32° and 35° (±1° outside the range predicted in the 'two facet model'), and for 84% of the transects it falls within the range 31-36° (±2° outside the specified range). The mean transitional gradients for the five field sites, moreover, fall within the narrow range 31.4-33.6°, with an overall mean of 32.8°. This suggests some degree of conformity with the predictions of the 'two facet model' of talus slope form, but that overall the model offers an incomplete description of the relict taluses of the Scottish Highlands.

The 'two facet model' was developed to explain the form of active alpine taluses that experience both accumulation and reworking of rockfall debris on the upper straight slope. Francou and Manté (1990; Francou, 1991) maintained that on such slopes, progressive downslope removal of surface debris is accompanied by deposition of rockfall particles, thus preventing significant lowering of the talus surface and preserving a fairly constant angle of inflexion between the upper straight slope and the basal concavity. In contrast, most talus slopes in Scotland are essentially relict features that currently experience very low rates of rockfall delivery from cliffs upslope, so that reworking of debris has replaced rockfall accumulation as the dominant geomorphic process (Ballantyne and Eckford, 1984; Kotarba, 1984; Ballantyne and Harris, 1994, p.223). Consequently, sediment removed from the upper parts of these relict taluses is unlikely to be replaced by fresh rockfall deposits, leading to significant lowering of the upper sections of talus. As noted above, one probable consequence is reduction of the *Ho:Hi* ratio, so that any relationship between concavity and talus maturity is obscured. Modification of talus profiles by debris flow activity may also explain the large range of gradients (Figure 4.35) measured at the transition between the basal concavity and the upper rectilinear slope. In sum, the results of testing of the 'two facet model' do not necessarily negate modelling of talus behaviour in terms of a deposit-transport system at the upper slope and an accumulation-dominated system at the basal concavity, but suggest that the model may apply only to talus slopes where downslope reworking of debris is balanced by renewed deposition of rockfall particles on the upper slope. Its applicability to essentially relict talus accumulations dominated by reworking of sediment without compensatory replacement appears limited.

4.6 Conclusions

A pervasive feature of the literature on relict taluses in upland Britain is that virtually all those investigated exhibit the morphological characteristics of unmodified rockfall-dominated slopes, namely, a steep upper rectilinear slope and a basal concavity. Paradoxically, there is also abundant evidence for widespread modification of relict talus slopes by debris flow activity (e.g. Statham, 1976b; Innes, 1983c; Addison, 1987; Luckman, 1992). Ballantyne and Harris (1994, p. 222) noted that the impression of largely unmodified rockfall-dominated talus slopes may be misleading, '...as researchers investigating talus slopes are liable to avoid areas that have experienced obvious modification'. Whilst there is doubtless some truth in this comment, the observations and analyses presented above (sections 4.3 and 4.4) suggest that not only are the supposedly diagnostic criteria of 'a steep upper rectilinear slope and a basal concavity' a poor indication of truly unmodified rockfall talus accumulations, but also that reworking of upper slope sediments by slope failure and particularly by debris flow activity may actually be at least partly responsible for the formation of the basal concavity.

The slope profiles at all five study sites are here interpreted as representing those of mature talus slopes modified to varying degrees by downslope mass transport of coarse sediment, primarily by repeated debris flow activity. This conclusion is supported by widespread evidence of past and present gully erosion on upper slopes, and associated debris cone formation at the talus foot. Different sites appear to have experienced different degrees of modification, which is most evident on Trotternish, and less so at the mainland field sites. This contrast may explain the generally greater degree of concavity exhibited by transects measured up talus on Trotternish compared to those surveyed up mainland slopes. Yet despite the widespread morphological evidence for post-depositional erosion and reworking of sediment, the form of all surveyed slopes is dominated by an upper straight slope and basal concavity, demonstrating that these two characteristics alone cannot be used as diagnostic criteria for identification of rockfall accumulations that are unmodified by reworking processes.

This conclusion is borne out in section 4.4 by tests of two models of talus evolution using data derived from the survey of 43 long profiles on five areas of relict talus. These tests show that neither the predictions of the 'discrete particle rockfall model' of Statham (1973a, 1976a) nor those of the 'two-facet model' of Francou and Manté (1990; Francou, 1991) are substantiated by these data. The former model makes no allowance for downslope redistribution of debris by mechanisms other than rockfall impact. The latter recognises the importance of sediment transport down the upper straight slope and redeposition of sediment on the basal concavity, but assumes that a constant supply of rockfall debris replaces that lost by mass-movement on the upper slope, which is not the case for the relict taluses investigated here. Thus while the 'two-facet model' offers a conceptual framework that is consistent with the observations described above for widespread reworking of upper slopes, it fails to provide a comprehensive explanation for the form of the relict talus slopes investigated in the Scottish Highlands.

In sum, both models fail to account fully for the behaviour of relict talus slopes on which reworking has replaced rockfall accumulation as the dominant mode of geomorphic activity. An alternative evolutionary model pertinent to the development of such slopes is outlined in chapter 8. The hypothesis that the morphology of the relict talus slopes studied has been strongly affected by debris flow activity and other forms of reworking is tested further in the following chapter, in which the internal structural and sedimentological characteristics of the relict talus accumulations are investigated.

Chapter 5

Internal structure

5.1 Introduction

This chapter considers the nature and implications of the internal architecture of talus slopes on Trotternish and at the four mainland field sites. The aims of this research are first to establish the general characteristics of the internal structure of relict talus accumulations, and secondly to determine the processes responsible for the deposition and reworking of rockfall debris. These findings enable aspects of the evolution of the investigated talus slopes to be reconstructed, and thus permit further critical examination of existing theories of talus development.

Theories of talus development have hitherto concentrated largely on explanation of the surface characteristics of talus slopes, notably slope form and the downslope sorting (or otherwise) of clasts at the surface. Few studies have attempted to investigate the internal structure of talus accumulations, although there is evidence from a limited number of observations that talus deposits contain abundant fine sediment at depth in addition to coarse rockfall debris (Wasson, 1979; Church *et al.,* 1979; Åkerman, 1984; Selby, 1993; Salt and Ballantyne, 1997). This chapter considers first the characteristics of sediments exposed in vertical sections through the relict talus slopes in the five study areas, and then the implications of internal sedimentary structures for the interpretation of talus evolution. The work discussed in this chapter will be carried forward into subsequent chapters that consider the origin of constituent sediments, the history of talus accumulation and reworking at the study sites, and the general behaviour of talus accumulations over time.

5.2 Methods

Mapping of relict talus slopes both on Trotternish and the Scottish mainland (chapter 4) revealed numerous natural sections, mainly along the sides of gullies, in which talus facies are exposed. At some sites individual sediment units could be traced for several metres upslope along gully walls. However, at the majority of gully sections, *in situ* depositional facies are obscured by gully wall collapse, and it was necessary to excavate vertical sections in gully sides to permit investigation of intact talus stratigraphies (Figures 5.1 and 5.2). All sections examined were excavated in the mid-slope zone of the upper rectilinear slope, where bedrock exposures in gully floors indicate a minimum talus thickness of 2.0-5.0 m, though individual talus accumulations apparently thicken downslope from the top of the basal concavity. All sections were logged in detail on graph paper and photographed.

5.3 Talus structure 1: Trotternish

Logging of talus facies on Trotternish was confined to area 2, immediately south of The Storr (Figures 4.4 and 5.1). Sections logged in this area included intact gully walls together with individual pits excavated in the sides of slope failures.

5.3.1 Talus stratigraphy

Sections through talus exposures on Trotternish reveal that the uppermost 1.5-5.0 m of the accumulation, rather than comprising the framework of openwork clasts characteristic of the surface of active taluses, are composed of stacked sediment units, in many cases separated by thin organic-rich horizons (Figures 5.3-5.8). Individual beds are aligned sub-parallel to the surface. The thickness of

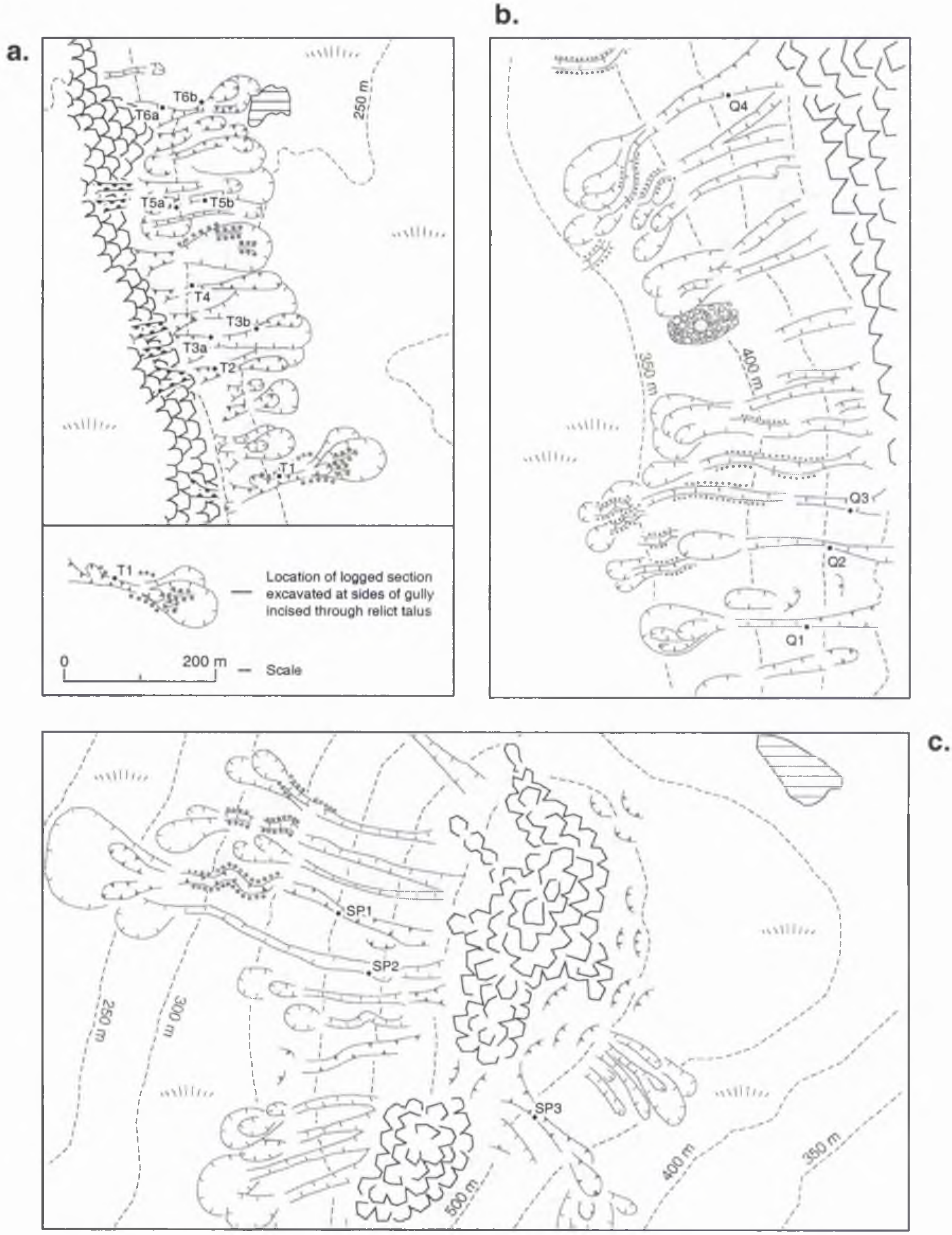


Figure 5.1. The location of logged sections excavated through relict talus slopes at; (a.) area 2 on Trotternish, (b.) area 1 below Quinag in Assynt, and , (c.) Stac Pollaidh in Coigach. Key as in Figure 4.3.

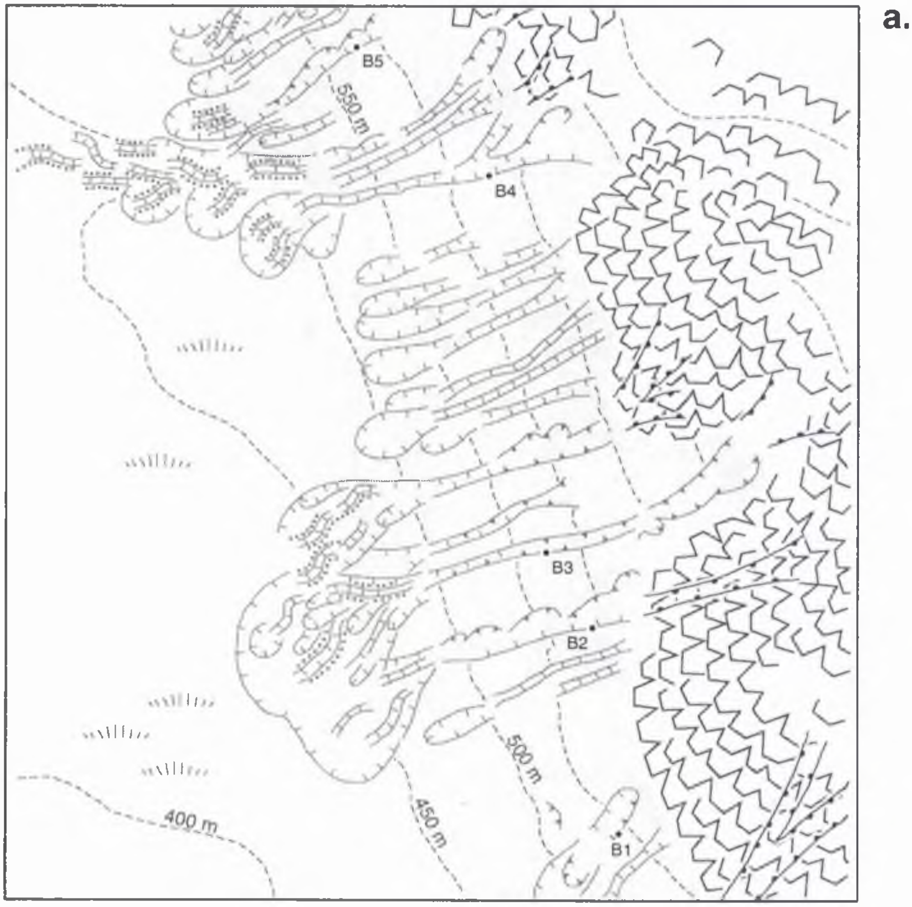


Figure 5.2. The location of logged sections excavated through relict talus slopes at; (a.) area 2 below Baosbheinn, Wester Ross, and, (b.) upper Glen Feshie. Key as in Figures 4.3 and 5.1.

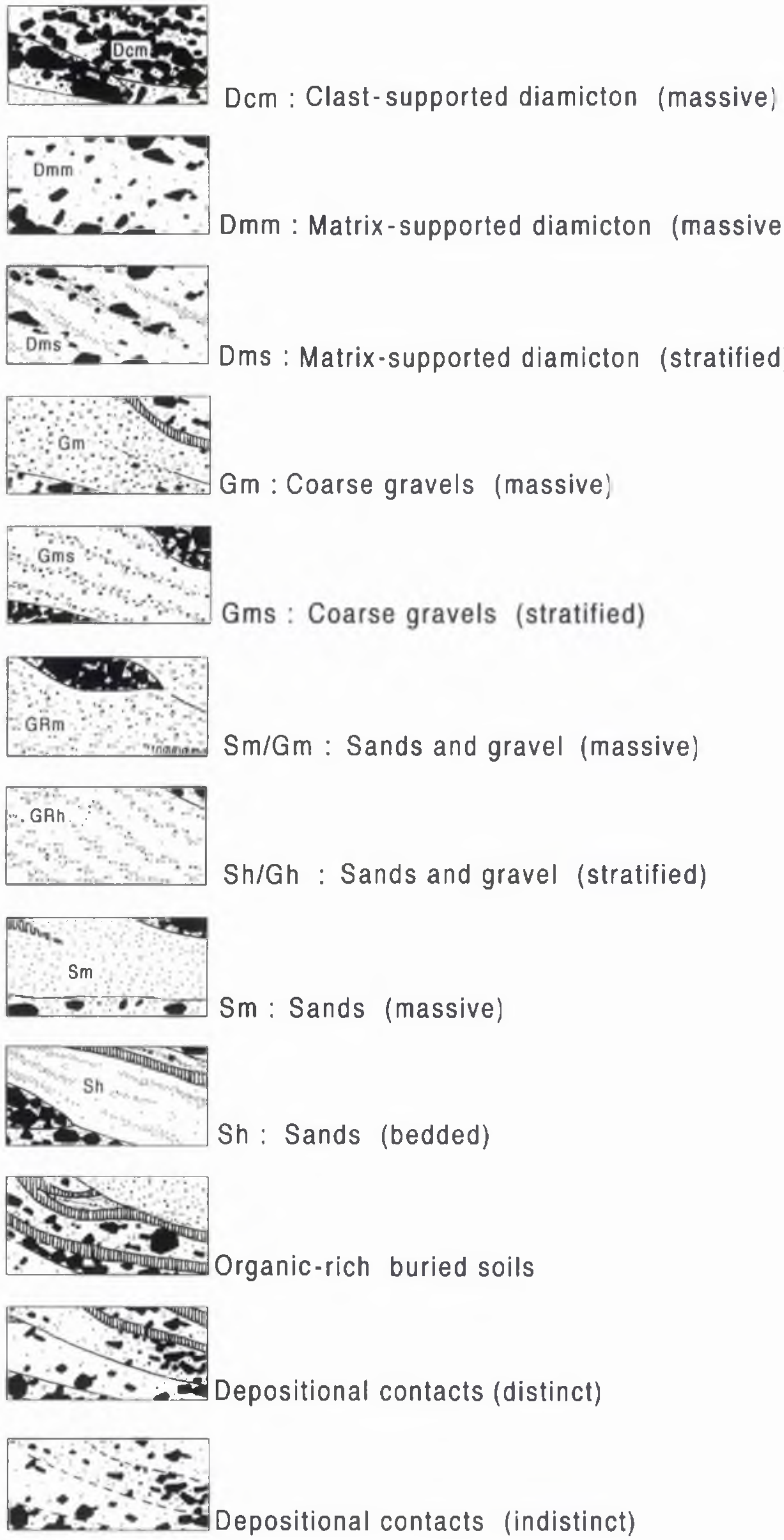


Figure 5.3. Symbols used in lithofacies logs.

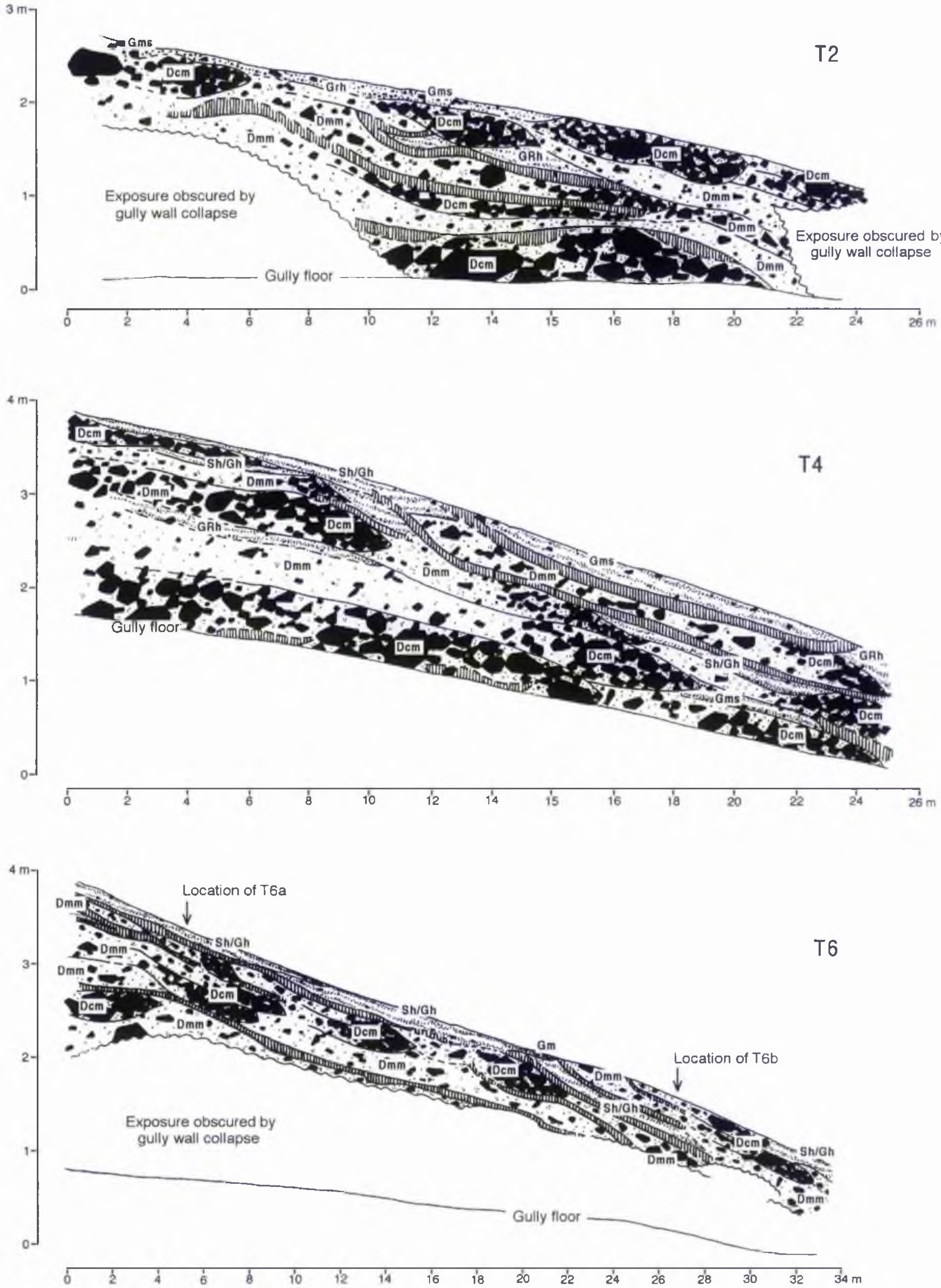


Figure 5.4. Sections T2, T4 and T6 showing talus facies exposed in gully side walls, Area 2, Trotternish, northern Skye. T6 contains the smaller sections of T6a and T6b. For convenience of representation the inclination of the above sections (T2, T4 and T6) is shown at less than the true gradient of *c.* 35°. Key as in Figure 5.3.

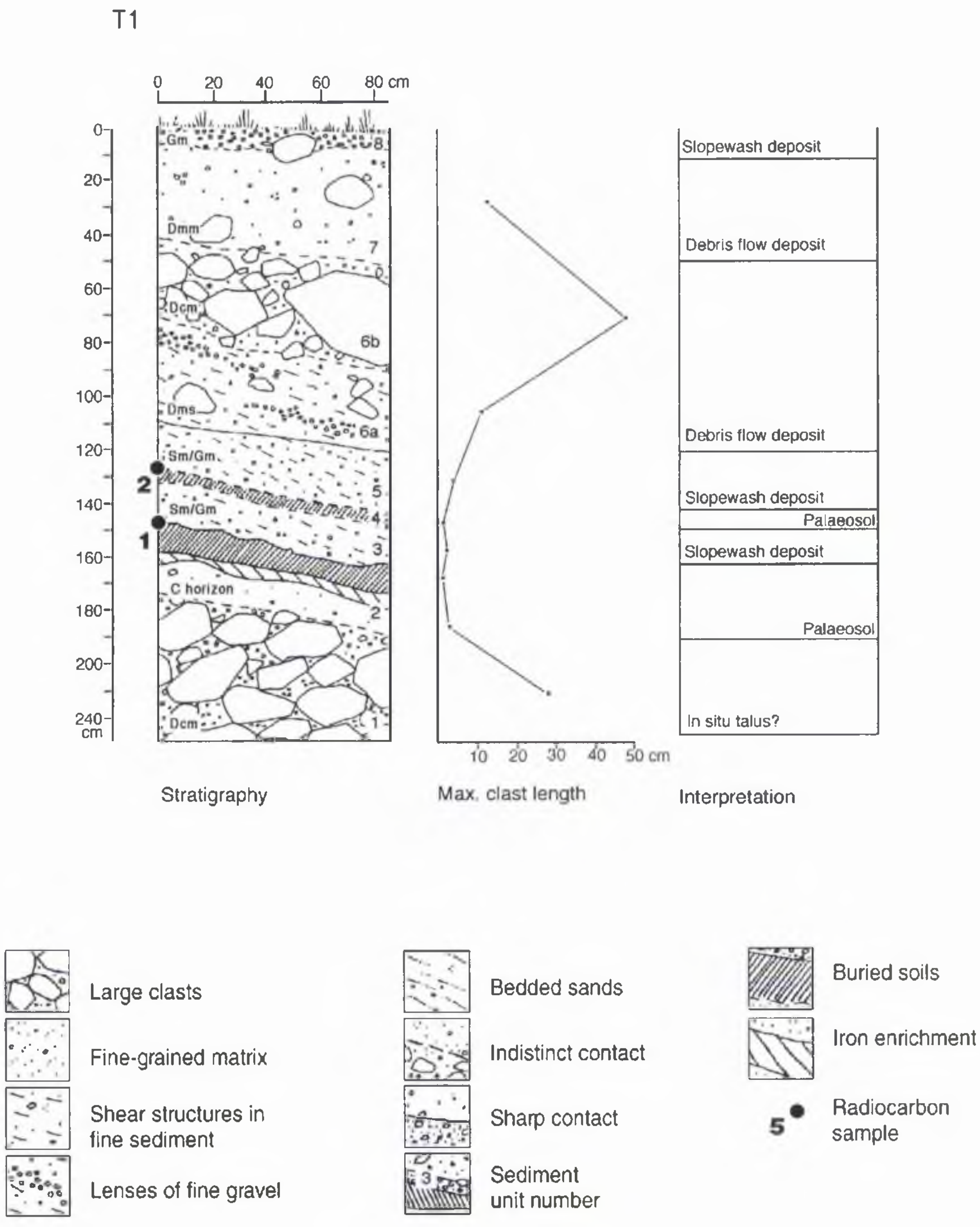


Figure 5.5. Talus section T1, Area 2, Trotternish, northern Skye. Key as in Figure 5.3.

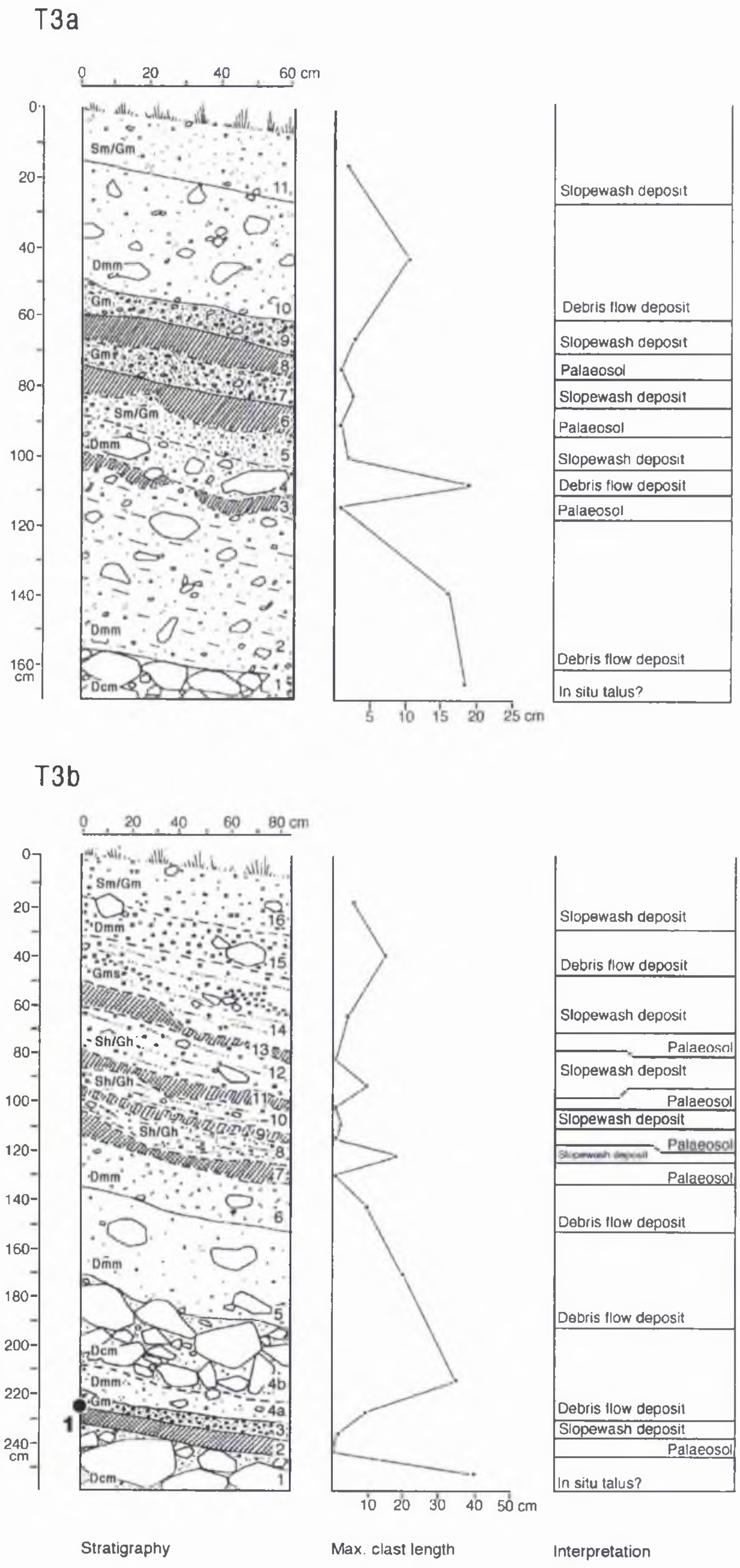


Figure 5.6. Talus sections T3a and T3b, Area 2, Trotternish, northern Skye. Key as in Figures 5.3. and 5.5.

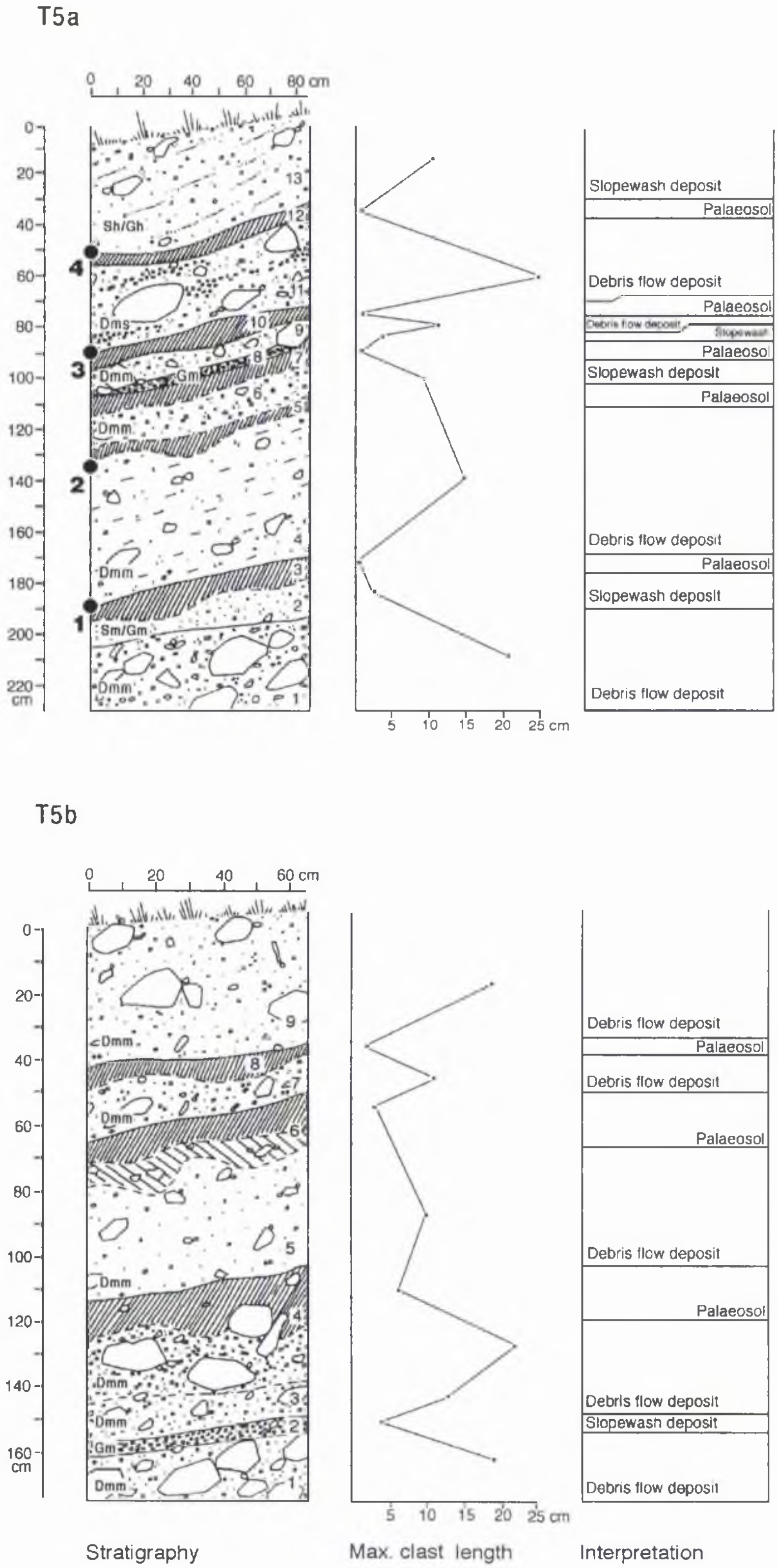


Figure 5.7. Talus sections T5a and T5b, Area 2, Trotternish, northern Skye. Key as in Figures 5.3. and 5.5.

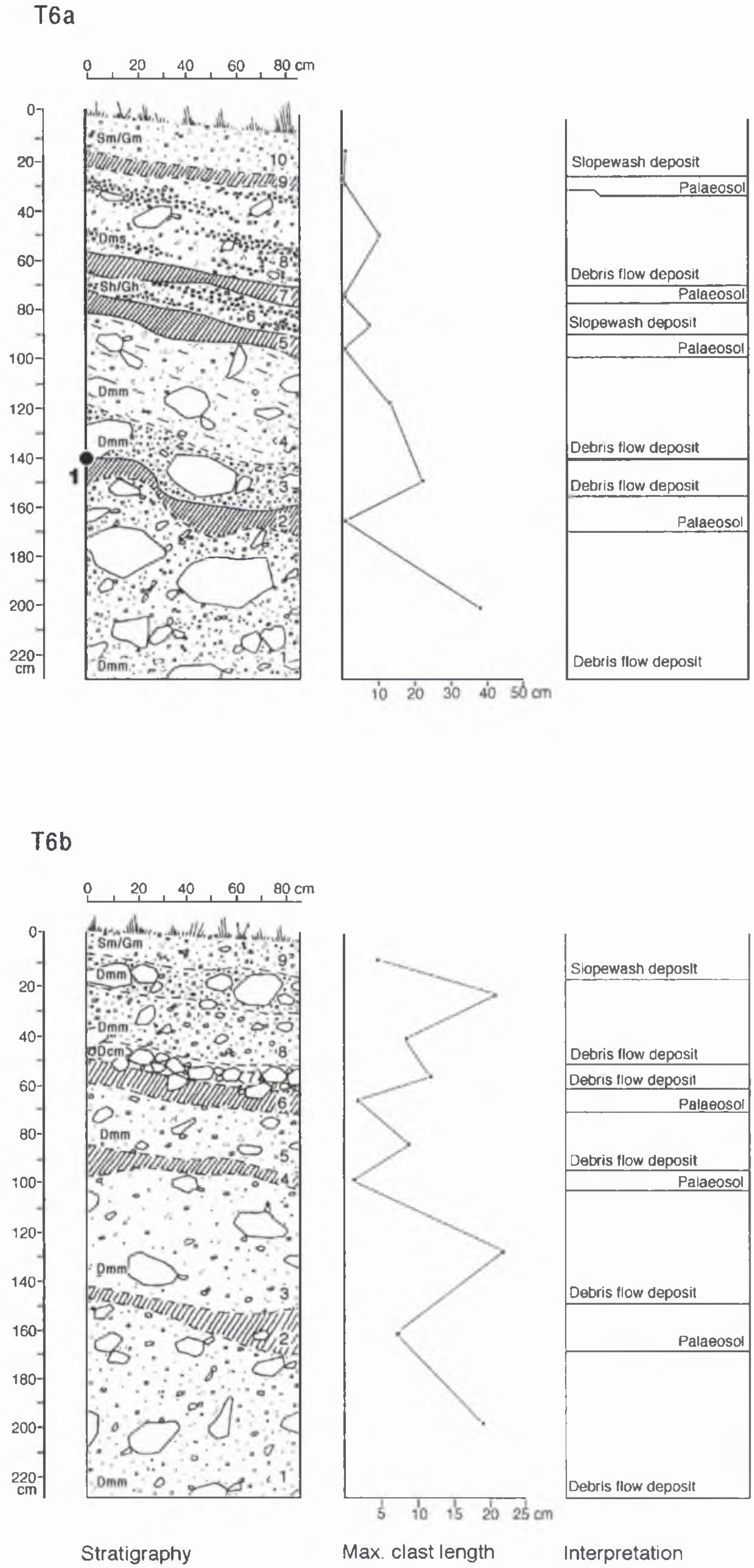


Figure 5.8. Talus sections T6a and T6b, Area 2, Trotternish, northern Skye. Key as in Figures 5.3. and 5.5.

individual sediment units is highly variable but rarely exceeds 100 cm. Beds are often continuous over 10-15 m downslope (Figure 5.4) but pinch out both upslope and downslope to form elongate lenticular structures. Contacts often appear to be conformable over short distances, but truncation of both inorganic sediment units and organic-rich layers indicate erosion of the upper surfaces of some beds and hence unconformities in the depositional sequence (Figure 5.4). The complex organisation of superimposed sediment units exhibited at sections T2, T4 and T6 appears inconsistent with an origin by discrete particle rockfalls, and suggests a complex history of erosion and mass transport of talus debris over a prolonged time period. The variable character of individual sediment units further indicates a wide range of processes responsible for the reworking and deposition of talus debris. Three different sediment facies were identified in the logged talus sections, and each of these is described in more detail below.

5.3.2 Diamictic facies

At the base of some sections, exemplified by sections T1 (Figure 5.5), T3a and T3b (Figure 5.6), are massive clast-supported diamictons. These units are tightly packed and display a high degree of clast interlocking, and, with the possible exception of unit 1 in section T1, lack an obvious preferred orientation of clasts. Clast size is variable although few exceed 50 cm in length. Interstitial fine sediments in these basal layers are characterised by poorly-sorted sand and gravel. Clast-supported diamictons are not, however, confined to the base of sections but also occur at variable depths below the surface. Unlike the basal clast-supported layers, clast-supported diamictons in the upper parts of the talus are often loosely compacted, and sometimes exhibit a crude preferred downslope orientation of component clasts.

Matrix-supported diamictons occur at various depths below the surface and are more common than their clast-supported counterparts. Clasts again vary considerably in size but are usually smaller than those contained within clast-supported diamictons, and rarely exceed 25 cm in length. These units may be clast-rich (e.g. section T5a, unit 1; Figure 5.7), or matrix-rich (e.g. section T5a, unit 4; and, section T5b, unit 5 ; Figure 5.7). Some matrix-supported diamicton beds, for example unit 6 in section T1 (Figure 5.5) and unit 4 in section T3b (Figure 5.6), exhibit an increase in the size and concentration of clasts towards the upper contact. Within individual matrix-supported units, upward coarsening is often accompanied by a rise in the concentration of clasts downslope, and some matrix-supported diamictons grade into clast-supported terminal 'lobes' over relatively short distances (Figure 5.4).

The matrix of some diamictons, for example unit 5 in section T3b (Figure 5.6) and unit 5 in section T5b (Figure 5.7), is dominated by fine sand, whilst that of others, such as unit 1 in section T6a and unit 8 in section T6b (Figure 5.8), is mainly composed of coarse-grained sand and gravel. Some matrix-supported diamictons exhibit stratification sub-parallel to the surface, often in the form of discrete lenses of gravel within a sandy matrix (e.g. section T1, unit 6a, Figure 5.5; and, section T5a, unit 11, Figure 5.7), or multiple thin beds (<2 mm) of fine sand (e.g. section T3a, unit 2, Figure 5.6; and, section T5a, unit 4, Figure 5.7).

Various origins may be invoked to explain the formation of these diamict facies. As noted above, the basal sediment units at sections T1 (Figure 5.5), T3a and T3b (Figure 5.6) are characterised by massive clast-supported diamictons that immediately overlie bedrock. Whilst these units lack the openwork structure of surficial rockfall debris described for active taluses, they are similar in character to previously reported unreworked talus deposits elsewhere (e.g. Carniel and Scheidegger, 1974; Wasson, 1979; Church *et al.*, 1979; Åkerman, 1984; Pérez, 1988, 1993; Nemec, 1990; Selby, 1993; Blikra, 1994; Salt and Ballantyne, 1997), and are interpreted as such. The provenance and significance of the fine-grained interstitial sediments within these basal units is considered in chapter 6.

Stratified matrix-supported diamictons are interpreted as the product of internal shearing or flow, and are thus suggestive of mass transport. Examples of upward coarsening (inverse grading) and bouldery terminal lobes (Figure 5.4), are also indicative of sediment reworking (Pierson, 1980; Takahashi, 1981, Nieuwenhuijzen and van Steijn, 1990, Bertran and Texier, 1994). Such diamict facies, although variable in character, have strong affinities with debris flow facies reported for other environments (e.g. Wasson, 1979; Suwa and Okuda, 1980; Rapp and Nyberg, 1981; Wells and Harvey, 1987; Eyles *et al.*, 1988; Eyles and Kocsis, 1988; Nieuwenhuijzen and van Steijn, 1990; Derbyshire and Owen, 1990; Owen, 1991; Ballantyne and Benn, 1994; Bertran and Texier, 1994; van Steijn *et al.*, 1995; Coussot and Meunier, 1996).

To test the proposition that the stacked diamictons above the basal clast-supported units represent reworking of older sediments by debris flow, the orientation and dip of samples of fifty clasts with elongation (long axis:intermediate axis) ratios ≥ 1.5 were measured for fourteen representative units. The results (Figure 5.9) were subjected to eigenvector analysis (Mark, 1973), which demonstrated that, with only one exception, the orientation of the principal eigenvector (V_1) lay within $\pm 26°$ of the slope aspect, confirming that the preferred orientation of clasts lies broadly in a downslope direction (Table 5.1). The V_1 dip values fell within a range of 19°-31°, less than that of the local slope gradient, indicating a tendency for clasts to be imbricate upslope. Both features are characteristic of debris flow deposits (Lindsay, 1968; Eyles and Kocsis, 1988, Ballantyne and Benn, 1994, Salt and Ballantyne, 1997). Following the method proposed by Benn (1994), an isotropy index ($I=S_3/S_1$) and an elongation index

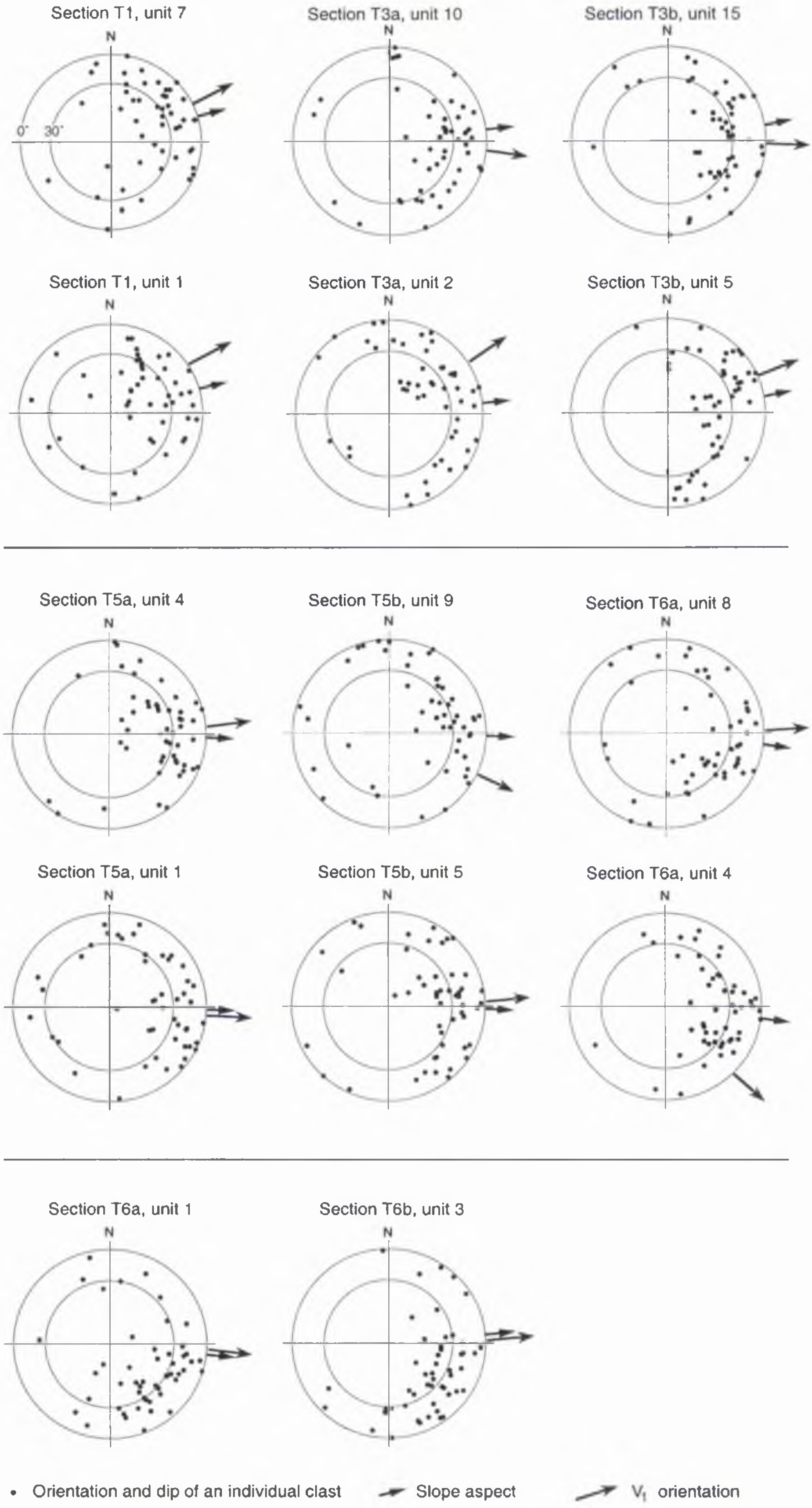


Figure 5.9. The orientation and dips of 50 elongate clasts contained within depositional facies in sections T1, T3a, T3b, T5a, T5b, T6a and T6b, Trotternish, northern Skye.

Table 5.1. Eigenvector V_1 and S_1 values for diamicton units contained within sections through talus slopes at study sites.

Section	Depth	Unit	Slope Aspect	V_1 Orientation	V_1 Dip	S_1
Trotternish samples						
T1	25 cm	7	74°	64	28°	0.534
T1	200 cm	1	74°	57°	24°	0.591
T3a	30 cm	10	83°	97°	28°	0.588
T3a	130 cm	2	83°	57°	26°	0.528
T3b	30 cm	15	80°	91°	28°	0.616
T3b	160 cm	5	80°	67°	31°	0.559
T5a	155 cm	4	92°	84°	31°	0.635
T5a	220 cm	1	92°	94°	19°	0.539
T5b	20 cm	9	91°	115°	28°	0.555
T5b	95 cm	5	91°	87°	24°	0.601
T6a	40 cm	8	97°	88°	27°	0.647
T6a	110 cm	4	97°	132°	29°	0.647
T6a	200 cm	1	97°	96°	30°	0.662
T6b	120 cm	3	84°	87°	24°	0.601
Mainland samples						
Q1	80 cm	3	265°	262°	24°	0.574
Q2	65 cm	4	271°	263°	22°	0.599
SP1	40 cm	8	197°	201°	28°	0.544
SP2	50 cm	6	195°	173°	20°	0.634
SP3	25 cm	5	42°	44°	24°	0.697
B1	90 cm	2	221°	239°	33°	0.635
B4	25 cm	2	258°	262°	22°	0.599
B5	20 cm	3	250°	201°	20°	0.532
F2	60 cm	X	228°	244°	14°	0.571

T = Trotternish B = Baosbheinn F = Glen Feshie

Q = Quinag SP = Stac Pollaidh

($E=1-S_2/S_3$) were calculated for each sample and plotted on a fabric shape triangle (Figure 5.10). All but one sample plot within the field identified by Benn (1994) as representative of debris flow deposits, and with one exception, outside the field identified by Benn as being characteristic of *in situ* rockfall debris. Interestingly, a sample derived from unit 1 of section T1, initially interpreted as representative of *in situ* talus, falls within the debris flow envelope, suggesting that this unit may also have undergone mass transport. These findings strongly support the initial interpretation of the stacked diamictons as debris flow deposits.

The general downslope orientation of clasts and linear structures within matrix-rich sediments have previously been considered indicative of planar shearing within mobile debris flows (*cf.* Lindsay, 1968; Pierson and Costa, 1987, Wells and Harvey, 1987). The absence of miniature shear structures in some matrix-supported diamicton facies may reflect poor preservation of such features due to variations in matrix characteristics, or lower levels of internal deformation within some diamictons during failure. There is no evidence, however, to support Bingham-type deformation within these debris flow deposits. Inverse grading and coarse-grained terminal lobes similar to those evident in sections T2, T4, T6 (Figure 5.4) have previously been explained in terms of dispersive forces generated through particle collisions within the flowing mass (Bagnold, 1954; Takahashi 1981, 1991). The above observations are therefore consistent with those models that consider that individual flows behave as dilatant fluids characterised by internal shearing sub-parallel to the surface, resulting in a cohesionless flow of debris (Pierson, 1980; Takahashi 1981, 1991; Costa, 1984; Nieuwenhuijzen and van Steijn, 1990).

5.3.3 Sand-rich and gravel-rich facies

In addition to diamict facies, all sections contain layers of sand and gravel in which clasts are largely absent. Although some gravel-rich units, for example unit

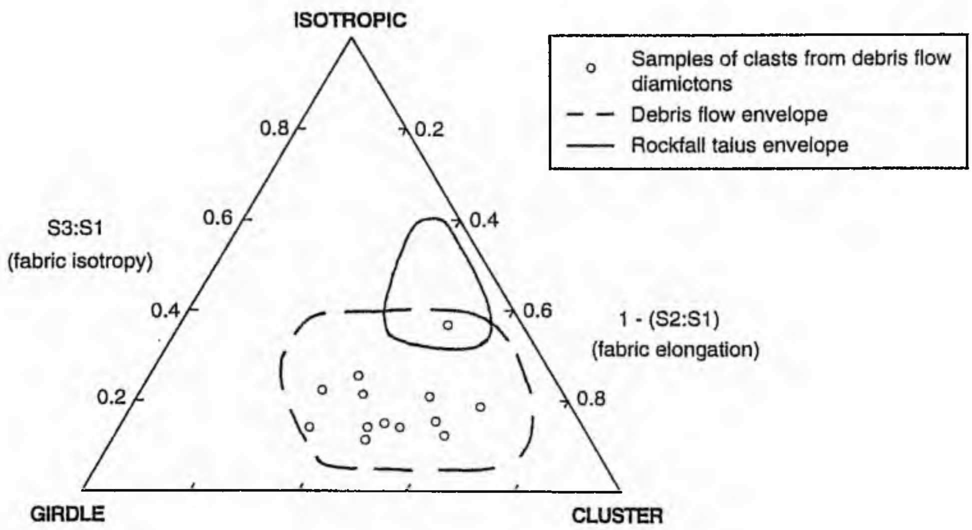


Figure 5.10. Fabric shapes of deposits contained within sections excavated through talus on Trotternish and characteristic fabric shape envelopes of debris flow and rockfall sediments (after Benn, 1994).

13 in section T5a (Figure 5.7), attain thicknesses in excess of 40 cm, most are thinner than the diamicton units. Many are several metres long but pinch out both upslope and downslope to form thin elongated horizons. The composition of beds is variable. Several layers, for example unit 11 in section T3a (Figure 5.6) and unit 10 in section T6a (Figure 5.8), are relatively fine-grained, comprising poorly-sorted sand with some gravel, whilst others, for example unit 9 in section T3a, unit 7 in section T3a (Figure 5.6) and unit 2 in section T5b (Figure 5.7) are dominated by coarse gravel. Several beds, for example unit 12 in section T3b, unit 14 in section T3b (Figure 5.6) and unit 6 in section T6a (Figure 5.8), exhibit a crude statification sub-parallel to the surface, whilst others, including unit 11 in section T3a (Figure 5.6) and unit 2 in section T5a (Figure 5.7) are massive.

These sand- and gravel-rich facies are similar to slopewash (overland flow) deposits reported elsewhere (e.g. Wells and Harvey, 1987; Carling, 1987; Eyles and Kocsis, 1988; Eyles *et al.*, 1988; Brazier *et al.*, 1988; Brazier and Ballantyne, 1989; Derbyshire and Owen, 1990) and are interpreted as such. These horizons may represent eluviation of fines from recently immobilised debris flows upslope (Takahashi, 1991), or reworking of unvegetated shallow translational failures and the surfaces of debris flow deposits during rainstorms. Bedding has previously been considered representative of fluctuations in discharge, or variations in sediment concentration during individual slopewash events (Wells and Harvey, 1987; Carling, 1987). The extensive deposits of bedded sand and gravel evident immediately below the surface at sections T4 and T6 (Figure 5.4), may, however, represent several discrete slopewash events. In particular, the 120 cm deep succession of bedded sand and gravel and intercalated *in situ* organic-rich layers in section T3b (Figure 5.6) suggests successive episodes of slopewash activity over a prolonged time period. Depositional sequences such as these indicate that low magnitude mass transport of finer grades of debris are at least locally important in modifying talus slopes.

5.3.4 Organic-rich horizons

Thin organic-rich layers are often intercalated with rockfall, debris flow and slopewash facies (Figures 5.11 and 5.12). The majority of such layers are oriented sub-parallel to the slope and are continuous downslope over several metres (Figure 5.4). Loss on ignition values for these units range from 11% to 46% by weight, and those that yielded the highest loss on ignition are distinctly peaty in composition. The nature of the minerogenic component of such layers largely reflects the composition of the underlying sediment unit.

Similar organic-rich layers evident in sections cut through talus slopes elsewhere have been interpreted as buried soils that developed on former ground surfaces (Pierson, 1982). Clearly defined examples like unit 2 at section T1 (Figures 5.5 and 5.11) are highly organic (46% loss on ignition), and exhibit iron enrichment and *in situ* weathering of clasts at their lower contact. Palaeosols are, however, highly variable in organic content and structure. Such differences probably reflect palaeosol maturity (and hence period of formation), as well as variations in parent material, local drainage and preservation. Some organic layers exhibit truncation or degradation through inwashing of dominantly minerogenic sediment from upslope.

5.3.5 Summary

The following points emerge from logging and analysis of sections though the relict talus accumulations in Trotternish.

1. Internal structure is characterised by stacked clast- and matrix-supported diamictons and sand- and gravel-rich units that are sometimes separated by thin organic-rich horizons. Individual sediment units are often several

Figure 5.11. Section T1. Note the two buried soils intercalated with sediment units. The lowermost palaeosol is apparently developed on *in situ* rockfall debris. The overlying colluvial facies represent debris flow and surface wash deposits.

Figure 5.12. Section T5.a. Multiple buried soils and intercalated debris flow diamictons and surface wash sands and gravels.

metres to tens of metres in length and tend to pinch out upslope and downslope. Contacts between individual beds often appear to be conformable over short distances, but truncation and erosion of beds are also evident. The organisation of multiple superimposed sediment units suggests a complex history of accumulation and intermittent reworking of talus debris.

2) Some basal clast-supported diamictons are interpreted as representing *in situ* rockfall debris. Depositional structures within stratigraphically higher diamictons, strongly suggest they were emplaced by debris flows, a conclusion reinforced by fabric analyses that show strong preferred downslope orientation of component clasts. The presence of linear shear structures and inverse grading within these diamict facies suggest that debris flow movement was dominated by cohesionless grainflow.

3) Layers of sand and gravel are suggestive of slopewash deposition. Such layers may be massive or bedded. These slopewash sediments probably represent eluviation of fine-grained sediment from recently immobilised debris flows upslope (Takahashi, 1991), or reworking of older unvegetated slope failures during rainstorms.

4) Thin organic-rich horizons are often intercalated with the diamictons and sand- and gravel-rich layers. These are interpreted as *in situ* soils developed on former ground surfaces prior to burial by debris flow and slopewash sediments, and indicate prolonged periods of talus slope stability.

5.4 Talus structure 2: mainland sites

The generality of the findings made on Trotternish was tested by extending the investigation of talus structure to the four mainland field sites. With the exception of sites in upper Glen Feshie, natural sections formed by gully erosion at these sites were obscured by gully wall collapse, and hence investigation of talus structures was confined to narrow pits excavated in collapsed gully sides.

5.4.1 Talus stratigraphy

As on Trotternish, sections through talus at the mainland sites revealed stacked sediment units of variable composition, occasionally separated by thin organic-rich horizons (Figures 5.13-5.20), though at Quinag, Baosbheinn and Stac Pollaidh the depth of studied units above apparently unreworked debris is markedly less than that at the Trotternish sites. Sediment units appear to be continuous over several metres and orientated roughly parallel to the surface. Contacts are conformable over short distances, although truncation of unit 5 in section SP2 may indicate the presence of an unconformity at the base of unit 6 (Figure 5.15). Sections F1 and F2 in upper Glen Feshie are largely unobscured by gully wall collapse and exhibit lenticular sediment units that pinch out both upslope and downslope (Figure 5.20). In general, therefore, the internal structure of mainland talus slopes appears to be remarkably similar to that exposed in the Trotternish sections (*cf.* Figures 5.11, 5.12, and 5.21).

5.4.2 Diamictic facies

A common feature of all of the talus sections logged in Torridon Sandstone terrain in the NW Highlands (Figures 5.13-5.19), is the presence of a thick basal unit comprising a coarse, massive diamicton, usually clast-supported but sometimes

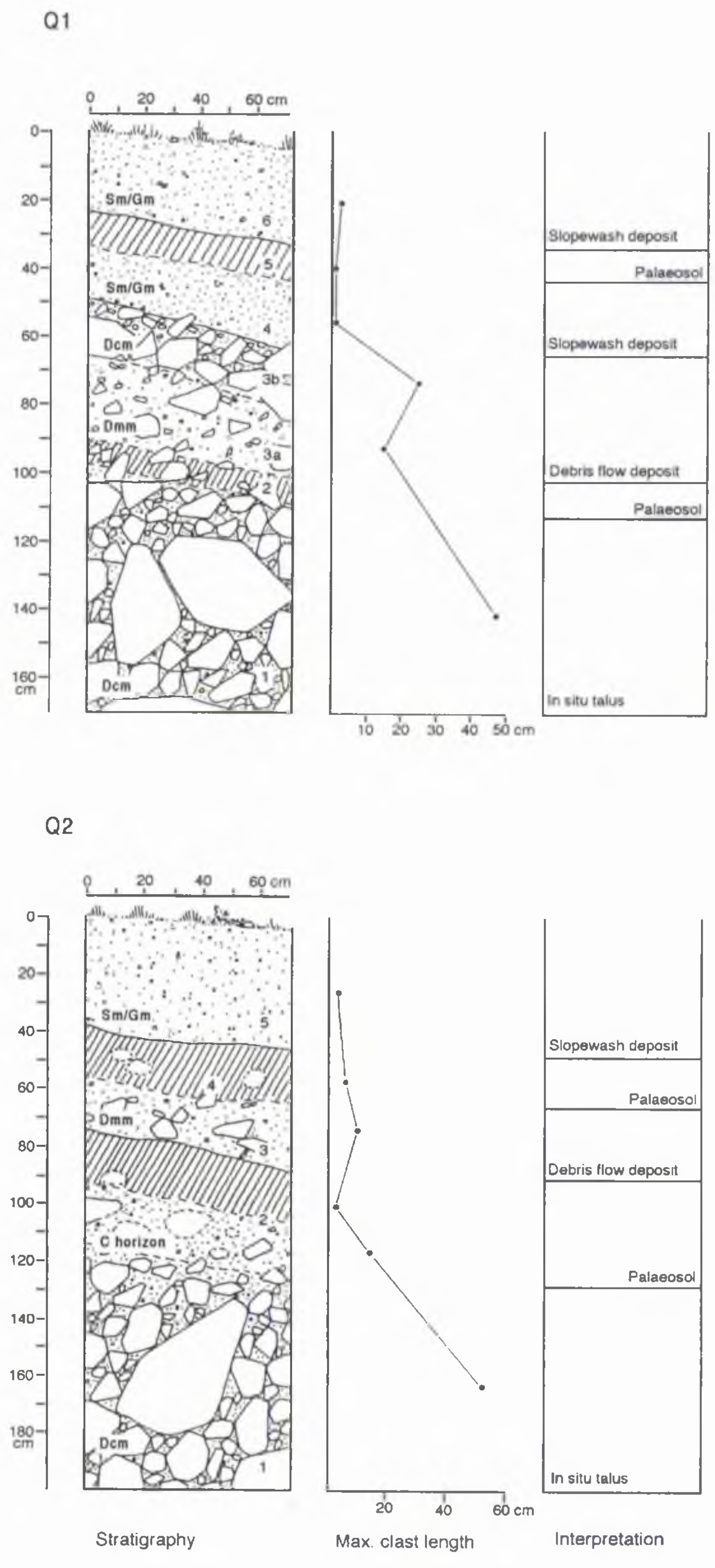


Figure 5.13. Talus sections Q1 and Q2, Quinag, Assynt. Key as in Figures 5.3. and 5.5.

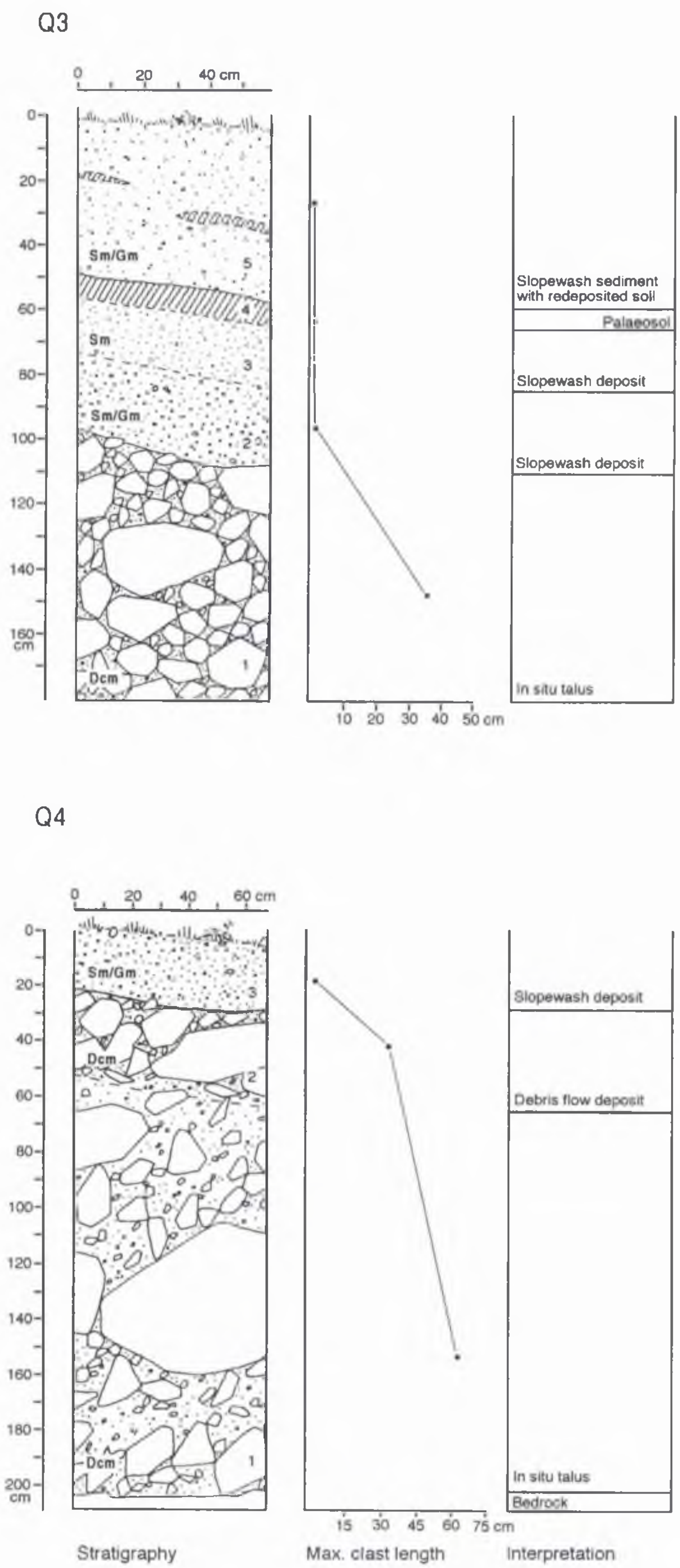


Figure 5.14. Talus sections Q3 and Q4, Quinag, Assynt. Key as in Figures 5.3. and 5.5.

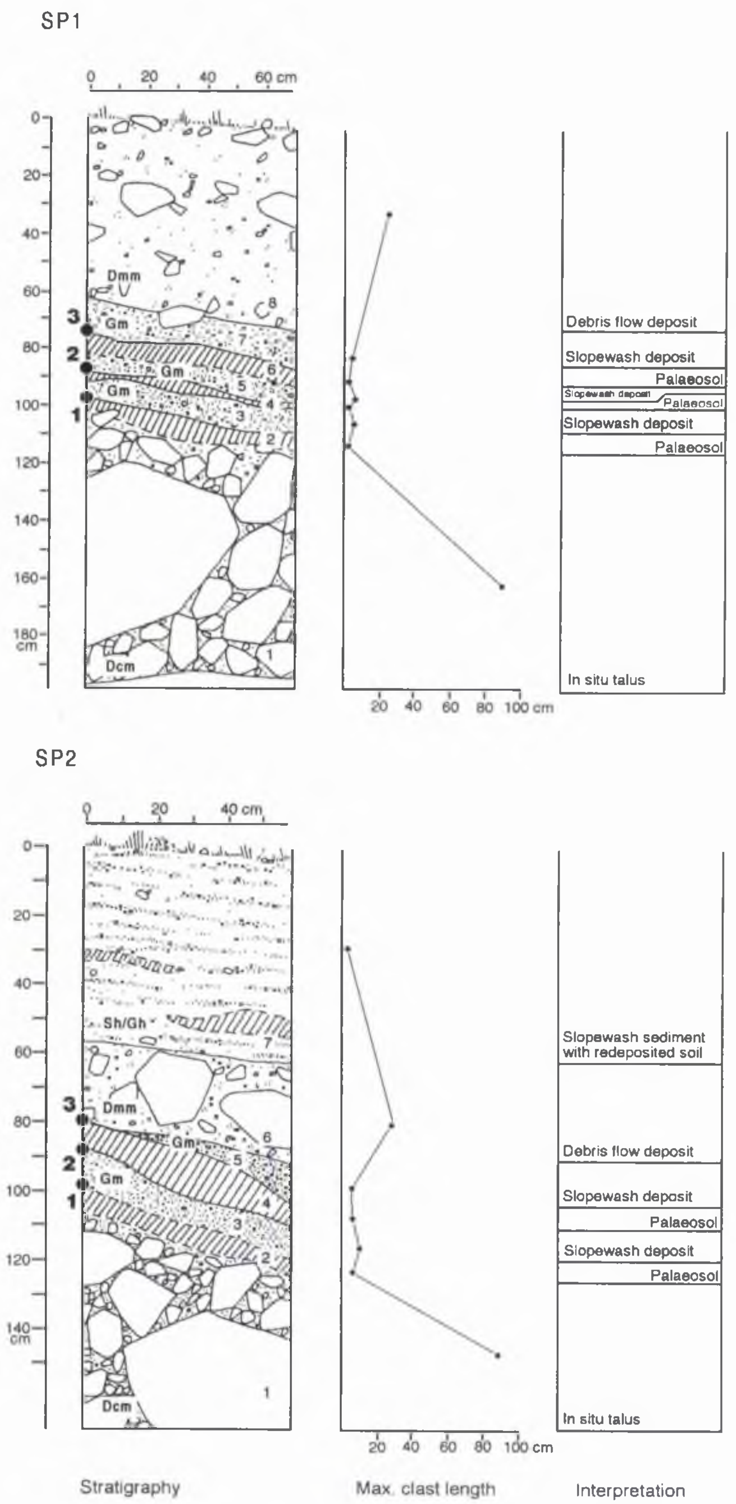


Figure 5.15. Talus sections SP1 and SP2, Stac Pollaidh, Coigach. Key as in Figure 5.3. and 5.5.

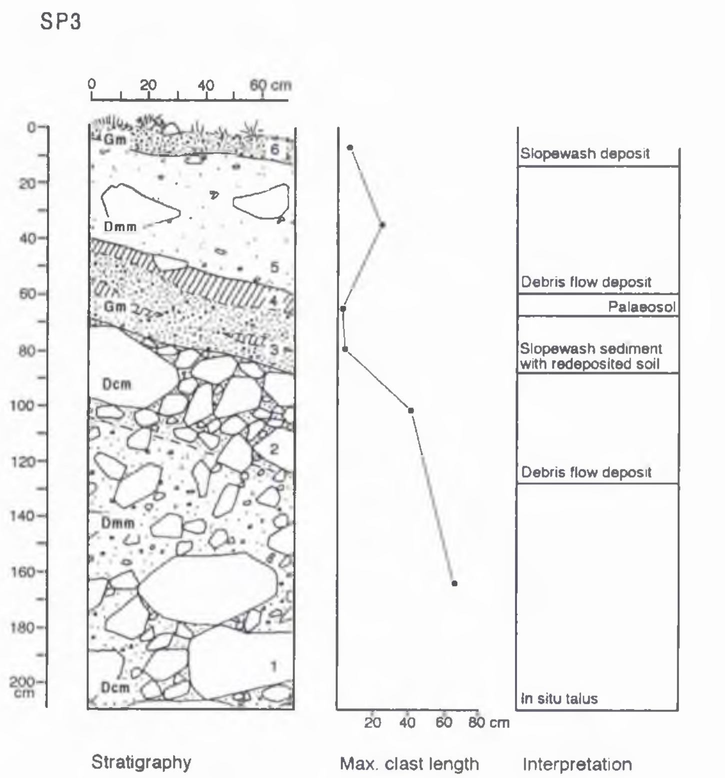


Figure 5.16. Talus section SP3, Stac Pollaidh, Coigach. Key as in Figures 5.3. and 5.5.

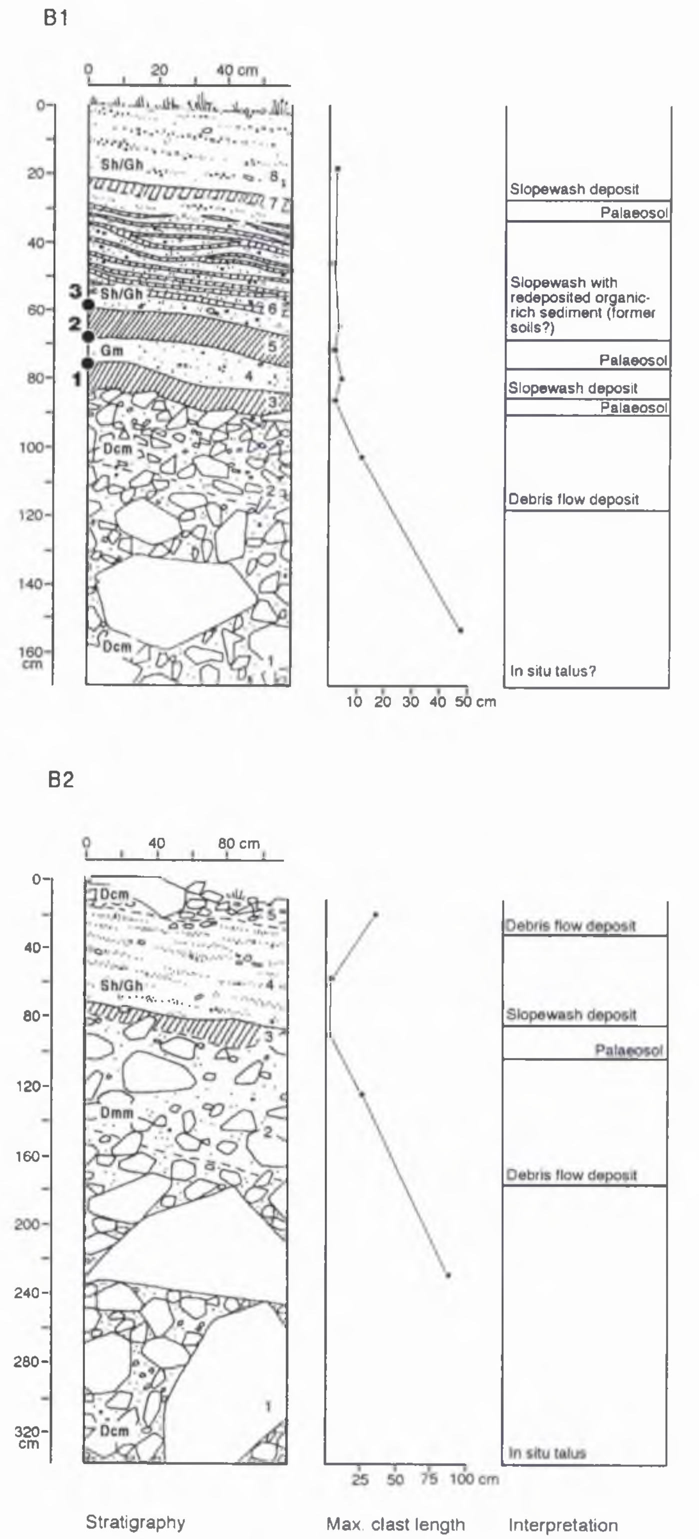


Figure 5.17. Talus sections B1 and B2, Baosbheinn, Wester Ross. Key as in Figures 5.3. and 5.5.

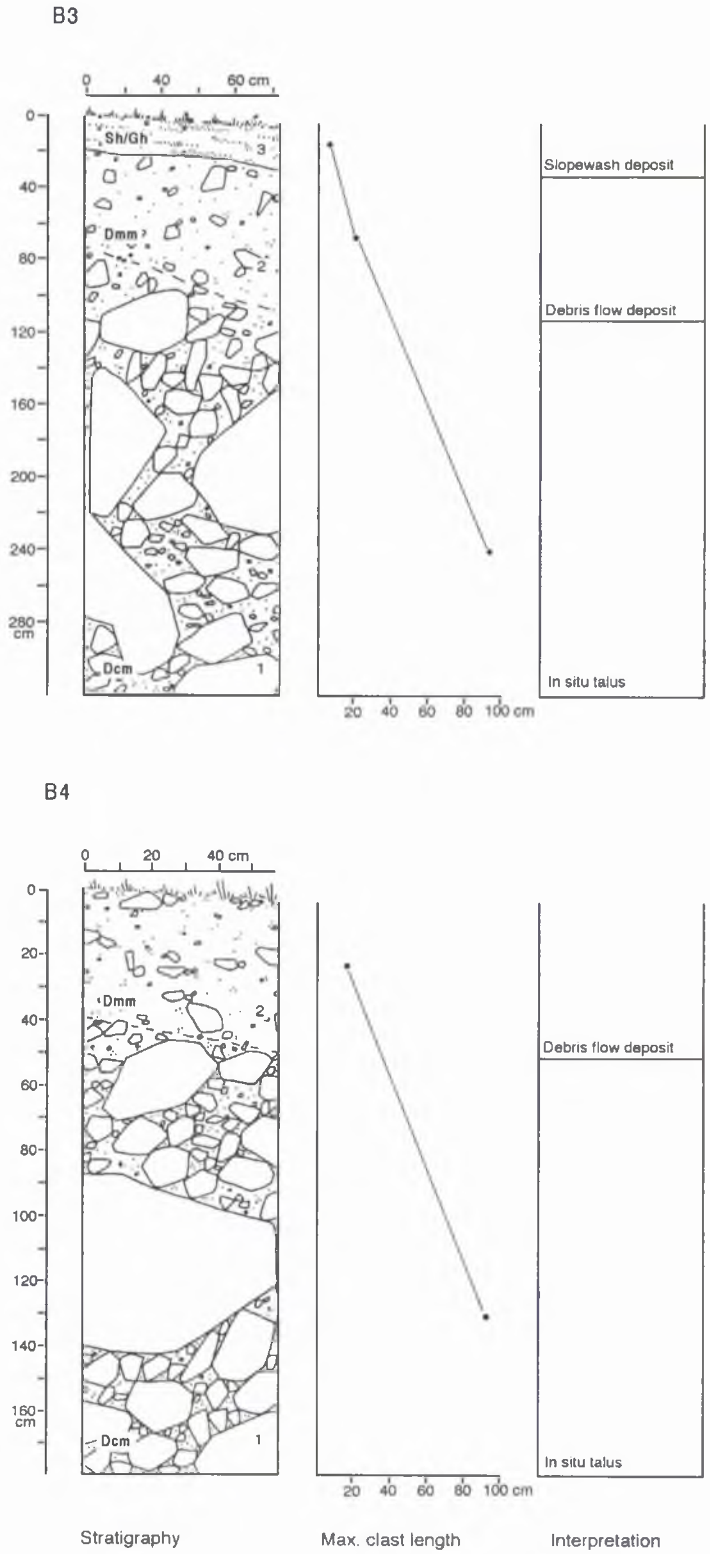


Figure 5.18. Talus sections B3 and B4, Baosbheinn, Wester Ross. Key as in Figures 5.3.and 5.5.

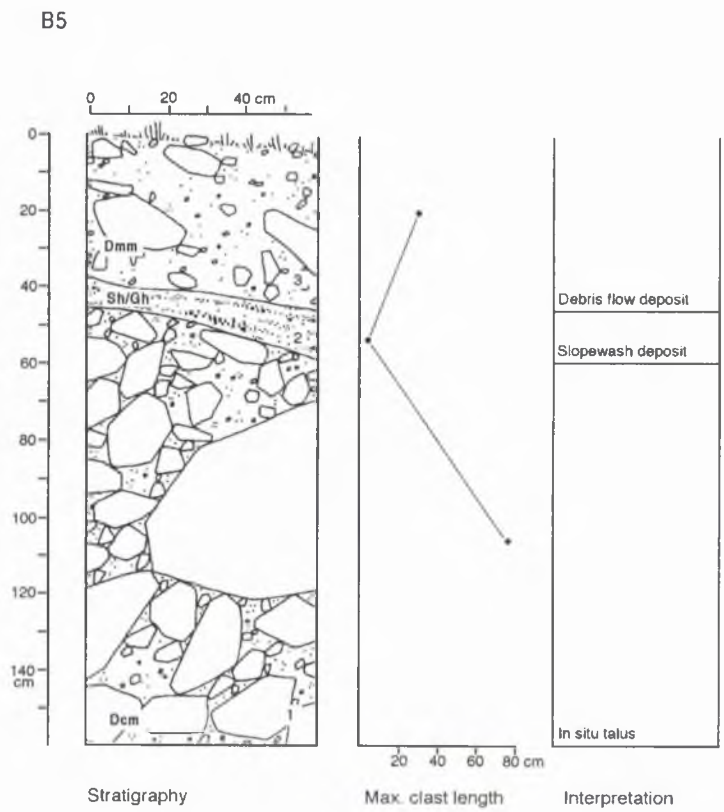
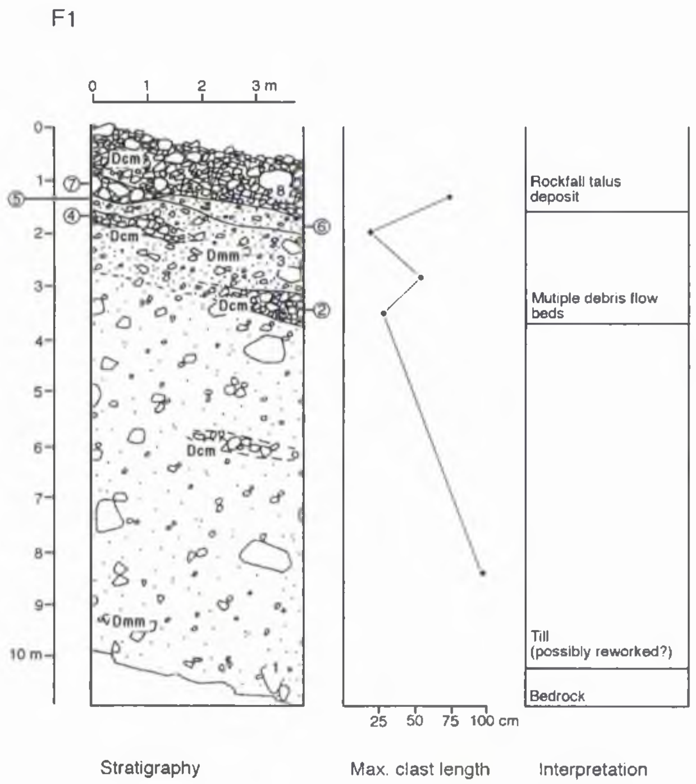


Figure 5.19. Talus section B5, Baosbheinn, Wester Ross. Key as in Figures 5.3.and 5.5.



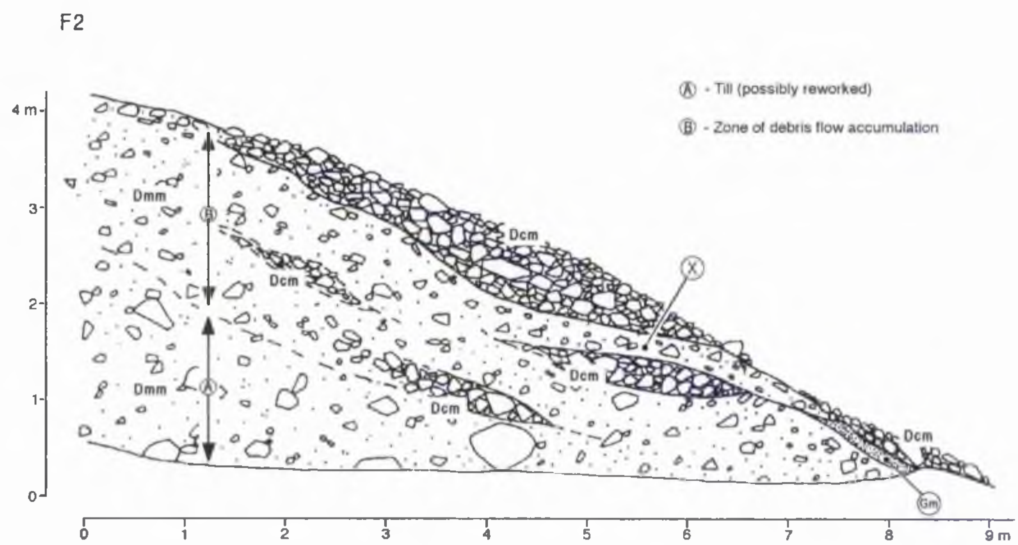


Figure 5.20. Talus sections F1 and F2, upper Glen Feshie, western Cairngorms. Key as in Figures 5.3. and 5.5.

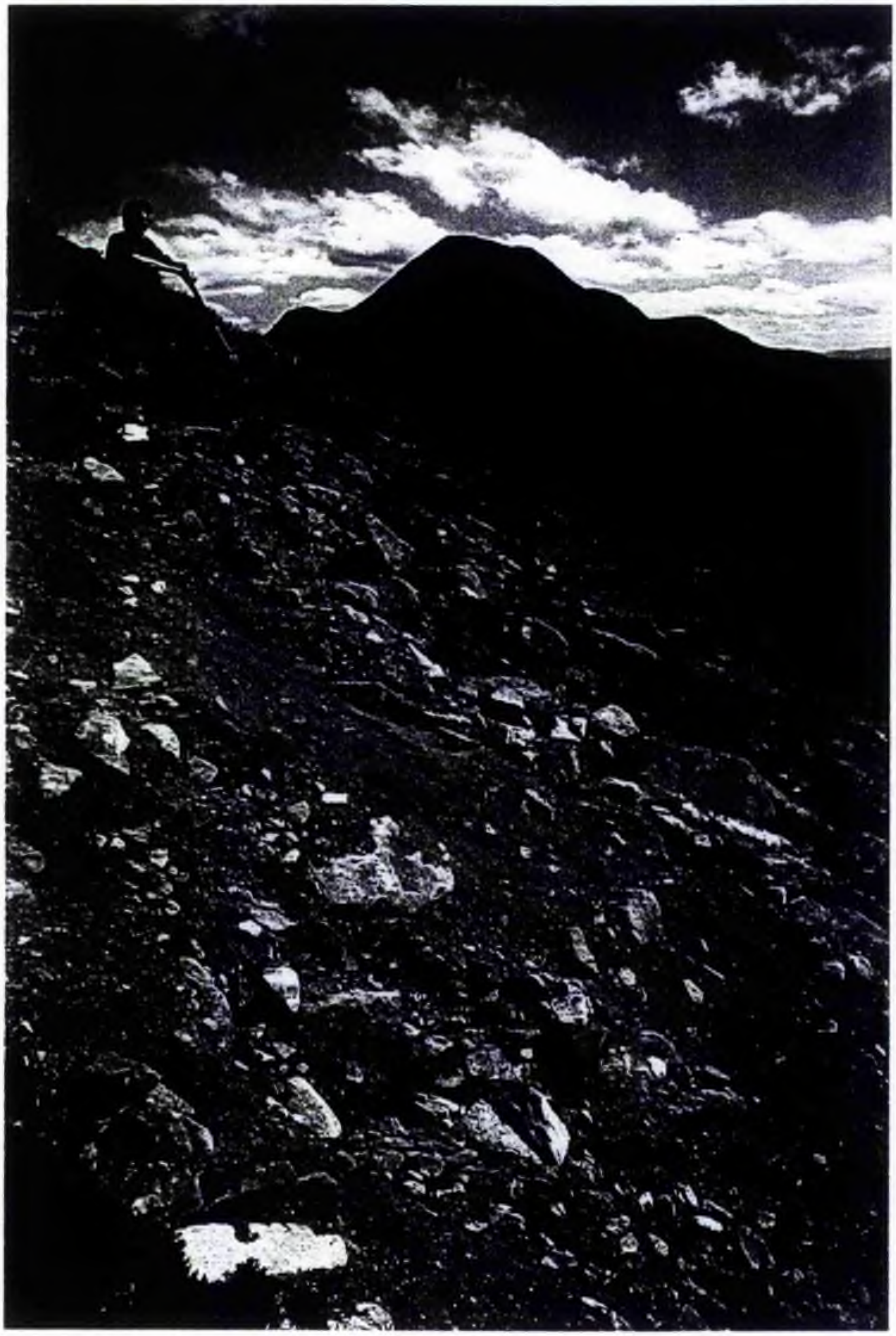


Figure 5.21. Stacked clast- and matrix-supported debris flow diamictons exposed at a gully side cut through a relict talus slope at Stac Pollaidh, Coigach.

matrix-supported though with a high concentration of clasts (e.g. section Q4, unit 1, Figure 5.14; section SP3, unit 1, Figure 5.16). Basal units are characterised by tight packing and an apparent absence of preferred clast orientation. Component clasts sometimes exceed 100 cm in length. Inter-clast voids are infilled by poorly-sorted coarse felsic sand, typical of that produced by granular disaggregation of Torridon Sandstone (Ballantyne, 1984). Structurally, such units resemble the basal clast-supported diamictons evident in some sections on Trotternish, and like these appear to represent unreworked rockfall debris similar in character to that observed at the surface of active talus slopes (*cf.* Carniel and Scheidegger, 1974; Wasson, 1979; Church *et al.,* 1979; Åkerman, 1984; Pérez, 1988, 1993; Nemec, 1990; Selby, 1993; Blikra, 1994; Salt and Ballantyne, 1997). An implication of this interpretation is that the overlying zone of reworked sediment is generally thinner at these mainland sites than the equivalent zone represented on Trotternish. Clast-supported diamictons also occur in stratigraphically-higher positions in some of the sections excavated through talus accumulations of Torridon Sandstone (e.g. section Q1, unit 3b; Figure 5.13), but these differ in being less compact and in exhibiting a preferred downslope orientation of component clasts.

Matrix-supported diamictons are also evident in the upper parts of most sections cut through talus slopes in the NW Highlands, but these exhibit evidence of reworking by mass-transport processes. This includes crude stratification, looser packing and inverse grading (e.g. section Q1, unit 3; Figure 5.13). As on Trotternish, such characteristics appear consistent with deposition of sediment by debris flows. This proposition was tested by measurement of clast fabrics (Figure 5.22) and eigenvector analyses (Table 5.1), and produced very similar results to those obtained for apparent debris flow facies on Trotternish. With one exception, the orientation of the principal eigenvector (V_1) was found to lie within ±22° of the slope aspect, and V_1 dip values fell within the range 14-33°, generally lower than the local slope gradient and therefore indicative of a tendency for clasts to be

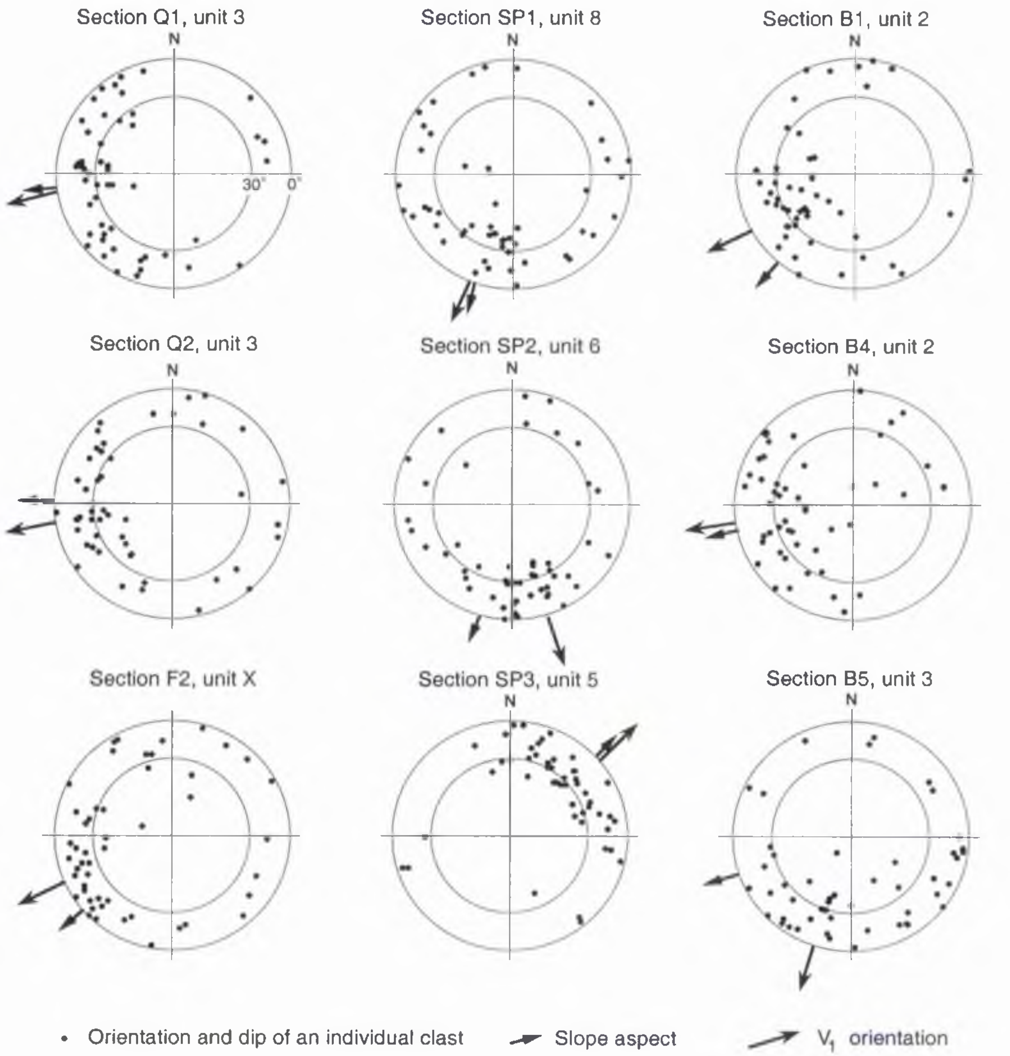


Figure 5.22 The orientation and dips of 50 elongate clasts contained within depositional facies in sections Q1, Q2, B1, B4, B5, SP1, SP2, SP3 and F2 through talus slopes on the Scottish mainland .

imbricate upslope. As noted in the context of the Trotternish samples, both features are characteristic of debris flow deposits emplaced during the reworking of older sediment from upslope (Lindsay, 1968; Eyles and Kocsis, 1988; Ballantyne and Benn, 1994). As before, an isotropy index and an elongation index were calculated for each fabric, and the results plotted on a fabric shape triangle (Figure 5.23) following the procedure devised by Benn (1994). The results reveal that the mainland samples occupy a similar field to that occupied by the Trotternish samples (compare Figures 5.10 and 5.23), and thus fall within the field suggested by Benn (1994) as being typical for debris flow deposits, and well outside the field that he identified for unreworked rockfall talus. These results appear to confirm that the matrix-supported diamictons in the upper parts of sections excavated through talus slopes in Torridon Sandstone terrain, like those on Trotternish, represent talus debris that has been reworked by debris flow. The structures evident in such mainland sections (preferred downslope orientation and upslope imbrication of clasts, together with crude stratification and inverse grading), similar to those evident in the Trotternish sections, seem to indicate movement predominantly by cohesionless grainflow.

A rather different picture emerges from two sections exposed in steep schistose valley-side drift accumulations in Glen Feshie (sections F1 and F2; Figure 5.20). At these sites the lower unit comprises a tough, apparently overconsolidated matrix-supported diamicton, quite unlike the clast-rich basal units of the relict taluses on Trotternish and in the NW Highlands. This unit, which reached a thickness of >7 m in section F1, is interpreted as an *in situ* till, though shear structures and lenses of clast-supported diamicton suggest that it may have experienced paraglacial reworking, probably by debris flows (*cf.* Ballantyne and Benn, 1994). This conclusion is supported by fabric and eigenvector analysis of a single sample (unit 'X') from a matrix-supported diamicton at section F2 (Figure 5.20), which shows affinity with the inferred debris flow deposits at the other field

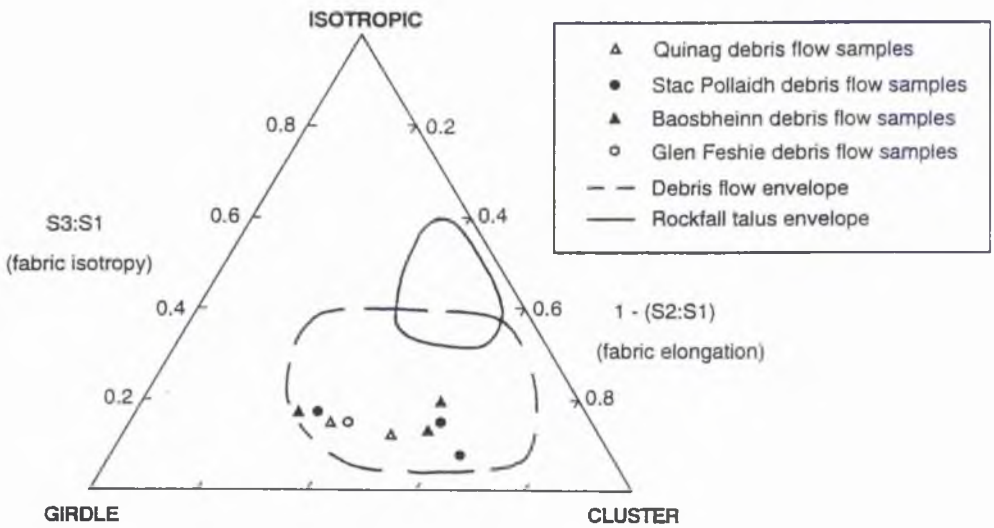


Figure 5.23. Fabric shapes of samples of clasts contained within debris flow diamictons at sections excavated through talus on the Scottish mainland, and characteristic fabric shape envelopes of debris flow and rockfall sediments (after Benn, 1994).

sites. Paradoxically, clast-supported diamictons up to 1 m thick occur at the very top of the sediment sequence at the Glen Feshie sites, and appear to represent a cover of *in situ* coarse rockfall debris. Overall, the structure of the Glen Feshie exposures suggests that they consist of till, presumably emplaced by the last ice sheet, partially reworked by paraglacial debris flows then overlain by a thin layer of Lateglacial and Holocene rockfall debris (Figure 5.24). The 'talus' slopes of Glen Feshie would thus appear to be significantly different from those on Trotternish and in the NW Highlands in that the underlying drift accumulation is primarily glacigenic in origin and only superficially modified by rockfall accumulation.

5.4.3 Sand-rich and gravel-rich facies

Sand- and gravel-rich facies occur in the near-surface zone of most sections cut in talus accumulations in Torridon Sandstone terrain, but are largely absent from the Glen Feshie sections, suggesting that the latter have not been significantly affected by slopewash. At the field sites in NW Scotland, individual gravel-rich layers are up to 45 cm thick and appear to be continuous downslope for several metres, though unit 5 in section SP2 (Figure 5.15) pinches out upslope, apparently truncated by erosion before emplacement of the overlying debris flow unit. The character of such beds is variable. Some layers, for example unit 3 in section Q3 (Figure 5.14), are dominated by moderately well sorted fine sand, whilst others such as units 3, 5 and 7 in section SP1 (Figure 5.15) are characterised by poorly-sorted fine gravel. Gravel-rich and sand-rich facies also exhibit marked variation in the degree of stratification. Some, such as units 2 and 5 in section Q3 (Figure 5.14), are massive and apparently structureless, whereas others, notably unit 7 in section SP2 (Figure 5.15) and unit 2 in section B5 (Figure 5.19), are markedly stratified by alternating fine- and coarse-grained layers of sediment aligned sub-parallel to the surface.

Figure 5.24. Section F1. A coarse, openwork rockfall deposit is interpreted as immediately overlying matrix-supported diamictons consisting of reworked glacigenic drift. The tape is 600 cm long.

The characteristics of these units closely resemble both those of the slopewash layers intercalated with debris flow deposits evident in the Trotternish talus sections, and also those of slopewash deposits reported in upland Britain and elsewhere (e.g. Wells and Harvey, 1987; Carling, 1987; Brazier *et al.,* 1988; Eyles *et al.,* 1988; Eyles and Kocsis, 1988; Brazier and Ballantyne, 1989; Derbyshire and Owen, 1990). In common with those of Trotternish, they are accordingly interpreted as reworking by surface wash of finer sediments from older deposits upslope, particularly immobilised debris flows and unvegetated failure scarps and gully walls. However, the presence of lenses or thin beds of apparently reworked organic-rich sediment within some slopewash facies, for example in unit 5 of section Q3 (Figure 5.14) and in unit 6 of section B1 (Figure 5.17), indicates incorporation of organic soils within slopewash, and thus possible erosion of stable vegetated surfaces upslope.

5.4.4 Organic-rich horizons

Several sections cut through talus slopes in the NW Highlands exhibit thin organic-rich horizons, intercalated with sediment units, that are often continuous for several metres downslope. Evidence of *in situ* weathering associated with these horizons is limited to the lower contact of unit 4 and unit 2 in section Q2 (Figure 5.13). These organic-rich horizons, in common with those reported on Trotternish and elsewhere (e.g. Pierson, 1982), appear to represent buried soils that developed on former ground surfaces during periods of slope stability. Organic material contained within these horizons is similar to the fibrous plant remains typical of upland peats. The composition of the minerogenic component of these buried soils resembles that of the underlying parent material, although inwashing of sediment cannot be ruled out for those horizons intercalated with slopewash deposits. Differences in soil maturity and the presence or otherwise of inwashed minerogenic sediment may account for variations in the structure of individual units. The absence of buried palaeosols in several excavated sections in NW Scotland and in upper Glen Feshie possibly reflects erosion of ground surfaces prior to the emplacement of overlying sediment units. Alternatively, talus slopes at these locations may not have been sufficiently stable over prolonged time periods to permit the formation of mature organic-rich soils.

5.4.5 Summary

The following generalisations emerge from logging and analysis of sections though the relict talus accumulations on the Scottish mainland.

1) Massive, predominantly clast-rich diamictons at the base of talus sections in the NW Highlands are interpreted as unreworked rockfall deposits. These basal layers are overlain by stacked diamictons, and finer-grained sediment units dominated by sand and fine gravel. The stacked diamictons, in common with those excavated on Trotternish, are interpreted as debris flow deposits, an interpretation confirmed by fabric and eigenvector analyses that reveal strong preferred downslope orientation of component clasts. The sand- and gravel-rich horizons are interpreted as slopewash deposits, apparently representing reworking of finer grades of sediment from upslope.

2) Some sections excavated through talus slopes in the NW Highlands exhibit thin layers of organic-rich sediment intercalated with debris flow and slopewash units. These horizons, like those exhibited on Trotternish, are interpreted as *in situ* soils developed on former ground surfaces, and representing periods of slope stability. These buried soils indicate the intermittent nature of mass transport of sediment over a prolonged time period.

3) Sections through apparent 'talus' slopes in upper Glen Feshie comprise a basal unit of tough, overconsolidated matrix-supported diamicton interpreted as *in situ* till. Fine-grained shear structures, and fabric and eigenvector analyses of a sample of component clasts from a single matrix-supported diamicton, suggest that the till has experienced paraglacial reworking by debris flow. Paradoxically, these apparently glacigenic sediments are overlain by a thin veneer of clast-supported diamicton interpreted as an *in situ* rockfall deposit. This finding suggests that 'talus' slopes in upper Glen Feshie are significantly different from those on Trotternish and in the NW Highlands, in that the underlying drift accumulation is primarily glacigenic in origin and only superficially modified by rockfall accumulation.

5.5 Conclusions

With the conspicuous exception of the sections examined in Glen Feshie, all of the sections logged through the upper parts of relict talus slopes in Trotternish and on the Scottish mainland exhibit strong affinity in terms of their structural characteristics. Several general conclusions can therefore be proposed on the basis of these observations, conclusions that have an important bearing not only on our understanding of the history of relict talus accumulations in upland Scotland (chapter 7), but also for our general understanding of the nature of talus development (chapter 8).

A particularly important conclusion is that the upper parts of relict talus slopes, rather than comprising the openwork framework of coarse debris evident on the surfaces of active taluses, is characterised by complex sequences of stacked sediment units of variable composition. These indicate that at least the uppermost 2-5 m of the sections examined have experienced reworking by processes other than rockfall, and hence that the present form of these slopes cannot be attributed to rockfall accumulation alone. Under the zone of reworked sediments, some sections (particularly those on the mainland) exhibit a basal layer comprising a massive, tightly-packed clast- or matrix-supported diamicton that is here interpreted as representing unreworked rockfall debris. The source of the fine sediment that occupies the interstices in this layer, and indeed the fines in the overlying reworked layers, is considered in the next chapter.

Secondly, the depositional structures (crude stratification, inverse grading and upslope imbrication of clasts) exhibited by diamictons stacked above the basal rockfall layer suggest emplacement by debris flows, a conclusion that is strongly supported by fabric and eigenvector analyses of samples of component clasts. Such units dominate all sections above the basal layer, indicating that debris flow has been the dominant agent of sediment reworking and slope modification. Generally thinner sand- and gravel-rich layers intercalated with debris flow diamictons are interpreted as surface wash deposits, possibly reflecting eluviation of fines from recently immobilised debris flows upslope, or reworking of unvegetated surfaces during rainstorms.

Thirdly, organic-rich horizons that separate inferred debris-flow and wash deposits in most of the logged sections appear to represent *in situ* palaeosols. These indicate that episodes of sediment reworking at particular locations were interrupted by periods of stability conducive to soil development, and thus suggest that reworking of talus debris has operated intermittently over a prolonged timescale. The absence of buried soils in several excavated sections in NW Scotland may reflect localised erosion of former ground surfaces prior to burial by the overlying sediment units. Where present, such organic-rich layers present the opportunity for dating the timing of reworking events by radiocarbon assay, and thus for establishing the synchroneity or otherwise of talus reworking at different sites (chapter 7).

It is also worth noting that, in general, the observations of subsurface structure indicate a greater depth of reworking within the talus accumulations on Trotternish than within their counterparts in NW Scotland. This contrast appears consistent with the analyses of talus slope morphology discussed in chapter 4, which suggest that the Trotternish taluses have been more extensively reworked than those of the mainland field sites. The examination of talus structure in upper Glen Feshie, however, sounds a cautionary note, in that it demonstrates that the morphology of scarp-foot sediment accumulations is not an infallible guide to their origin. The Glen Feshie slopes closely resemble rockfall talus slopes, but investigation of their internal structure suggests that they comprise mainly Late Devensian glacigenic deposits overlain by only a thin veneer of Lateglacial and Holocene rockfall debris. The possibility that the basal diamictons exposed in sections through the talus slopes in Trotternish and in NW Scotland may also partly reflect a glacigenic rather than rockfall origin is considered in the following chapter.

In sum, the above findings demonstrate that rockfall accumulation has not been the sole agent of talus development, and that reworking (primarily by debris flow) has played an important role in talus slope evolution. In a wider context, these findings lend support to those models that envisage mass-transport as well as rockfall deposition on the upper rectilinear slope (Statham and Francis, 1986; Francou and Manté, 1990; Francou, 1991). It is also evident from the above findings that fine-grained sediment is abundant within relict talus accumulations, and has probably played a critical role in facilitating slope reworking. Debris flows on steep hillslopes generally occur when a build-up of pore water pressures within unconsolidated sediments causes a reduction in shearing resistance, leading to failure and flow. In fine sediments where drainage through internal voids is impeded, shallow failure and flow of debris is common on steep slopes during intense rainstorms (Rapp and Nyberg, 1981; Innes, 1983a; Zimmerman and Haeberli, 1992). It is thus likely that the abundance of fine-grained material within the Scottish talus accumulations has influenced slope evolution by facilitating downslope mass-transfer of sediment by debris flow. The characteristics and origins of the fine fraction within these slopes is considered in chapter 6, and the wider implications of talus reworking for our understanding of talus slope evolution are discussed in chapter 8.

Chapter 6

Talus sediments

6.1 Introduction

This chapter considers in more detail the sedimentological characteristics of debris flow and slopewash deposits in exposures cut through talus slopes. Attention is focused on the provenance of constituent sediments, and in particular the origin of the fine (< 2 mm) fraction in talus sections. These investigations were largely confined to talus accumulations on Trotternish, which were shown in the previous chapter to be structurally representative of relict talus slopes elsewhere in the Scottish Highlands. Some attention is also given to the sedimentological characteristics of diamictons exposed in section in Upper Glen Feshie, which, on the basis of their structural characteristics, were considered in the previous chapter to be primarily glacigenic in origin. The final part of this chapter examines the implications of talus sedimentology for talus slope evolution and the magnitude of rockwall retreat.

The evolutionary behaviour of talus slopes has often been modelled on the assumption that such slopes are underlain by free-draining, openwork accumulations of coarse rockfall debris, in which frictional strength represents the dominant control on slope stability and hence limiting gradients (e.g. Statham, 1973a, 1976a; Carson, 1977). The investigations reported in the previous chapter, however, confirm previous observations that indicate the presence of abundant fine material at depth within talus accumulations (Wasson, 1979; Church *et al.*, 1979; Åkerman, 1984; Selby, 1993). This in turn suggests that such fines have been important in permitting a build-up of porewater pressures within talus sediments, resulting in sliding failure and consequent reworking by debris flows (*cf.* Statham and Francis, 1986; Salt and Ballantyne, 1997). The source of fine sediment within talus accumulations, however, has received little attention, and is a prime focus of the research outlined below.

6.2 Textural characteristics: Trotternish

This section reports the results of analyses of the textural characteristics of bulk sediment samples withdrawn from sediment units exposed in gully-wall sections cut into the talus accumulations in Trotternish. The aim of this research was to establish the size composition of both the coarse and the fine components of different sediment units, and from such findings to derive estimates of the proportion of fine (< 2 mm) sediment present within the talus.

6.2.1 Methods

Particle size analyses were performed on bulk sediment samples from twelve debris flow units and six slopewash units exposed by excavation of the sides of gullies within area 2 (Figure 4.4) in Trotternish. Laboratory analyses were confined to particles finer than 64 mm (-6 ϕ). As the debris flow deposits also contain clasts > 64 mm in width, measurements were made in the field of the proportion of overall sample weight represented by clasts with intermediate axes ≥ 64 mm. This was achieved by excavating five large bulk sediment samples (each > 250 kg) from individual debris flow units, separating out all clasts ≥ 64 mm in width, and weighing separately the two components (≥ 64 mm and < 64 mm) of each bulk sample using a spring balance. The results yielded an overall mean value of 55.0% by weight ≥ 64 mm, with a standard error of 5.2%. For all samples, particles finer than 64 mm were wet-sieved at 1 ϕ intervals down to 500 μm (1 ϕ), and the granulometry of sediment finer than 500 μm was analysed using a Coulter Counter LS 100.

6.2.2 Results

The results (Figure 6.1a) show marked contrasts between the grain-size distributions of slopewash deposits and debris flow units. The wash layers are dominated by sand (57-64% by weight), with minor components of silt (4-18% by weight), and fine gravel (17-39% by weight). Slopewash samples are also characterised by a negligible (< 1% by weight) clay content and contain no particles coarser than 8 mm (-3 ϕ). The above textural characteristics indicate deposition by surface flow of low competence, and appear entirely consistent with interpretation of these units as the product of slopewash. The debris flow samples contain < 1% clay and < 9% silt by weight, but, in contrast to the wash samples, the sand fraction represents only 14 - 24% of the total weight of samples due to the presence of numerous clasts, including boulders up to and occasionally exceeding 200 mm in diameter (Figures 6.2 and 6.3). These differences confirm the operation of two very different depositional processes, and thus lend support to the sub-division of talus sediments into debris flow and slopewash units advocated in chapter 5.

Overall, fine-grained (< 2 mm) sediment accounts for 61.1 - 82.8% by weight of the sampled slopewash units, with a mean of 72.0% and a standard error of 3.2%. In contrast, sediment finer than < 2 mm constitutes only 15.4 - 33.2% by weight of the debris flow units, with a mean value of 26.4% and a standard error of 1.6% (Figure 6.1b). This mean figure is slightly lower than the equivalent value of *c.* 30% by weight calculated by Salt and Ballantyne (1997) for the proportion of sediments finer than 2 mm within inferred debris flow facies evident in a single section cut through a relict talus accumulation at Knockan in Assynt on the mainland of NW Scotland. However, given the much higher proportion of fine sediment present in the slopewash deposits, it seems reasonable to suggest that the overall proportion of sediment finer than 2 mm present in the Trotternish talus accumulations is of the order of *c.* 27 - 30 % by weight.

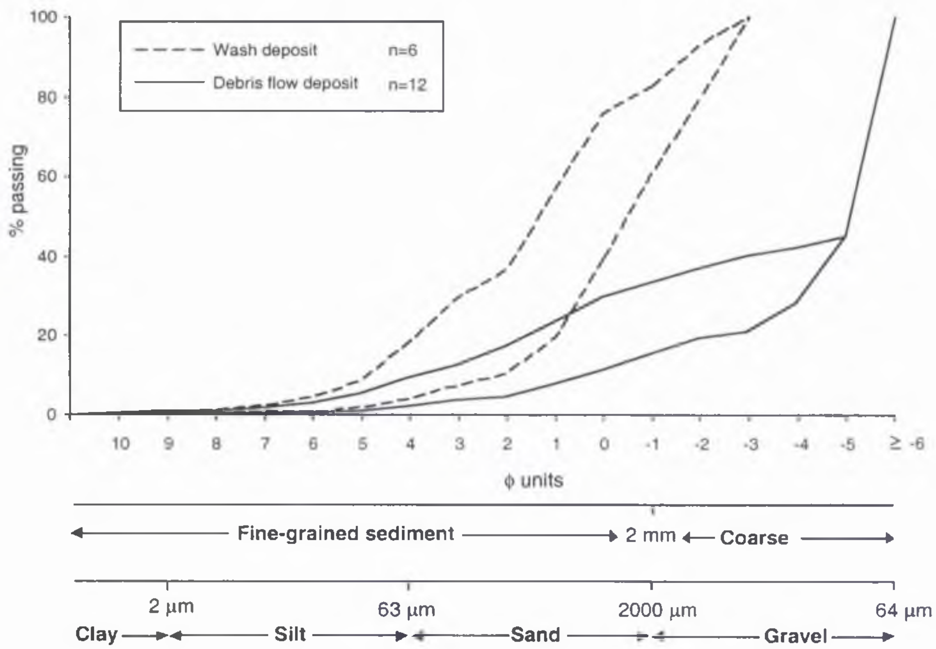


Figure 6.1a. Particle size envelopes for samples of sediment from debris flow and slopewash deposits exposed in sections cut through talus slopes on Trotternish, northern Skye.

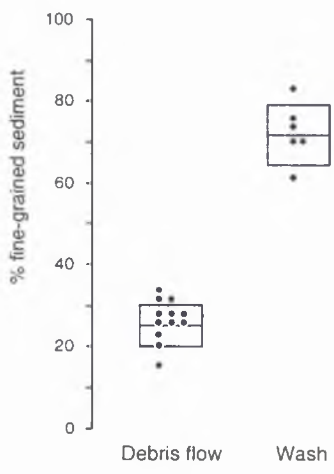


Figure 6.1b. Percentage fine-grained sediment (< 2 mm / -1 ϕ) within debris flow and slope wash deposits exposed in sections cut through talus slopes on Trotternish, northern Skye.

Figure 6.2. Boulders embedded in a matrix-supported diamicton revealed at a gully side cut through a talus deposit, area 2, Trotternish. The concentration of clast-supported boulders near the geological hammer may represent the terminal lobe of a former debris flow.

Figure 6.3. Typical concentration of boulders within stacked debris flow deposits evident at a gully side cut through talus in area 2, Trotternish. The intervening clast-free layers are interpreted as representing surface wash deposits.

6.3 Origin of talus debris: Trotternish

There are several possible origins for the fine fraction of talus accumulations on Trotternish. As noted in chapter 4, the overall form of the talus slopes at this location is consistent with a rockfall origin, with post-depositional mass transport of rockfall debris downslope. In terms of this interpretation, the fine sediment present may represent: (1) granular disintegration of the rockwall by weathering processes, with fine particles falling on to and being washed into the talus; (2) inwash of fines derived from plateau-top deposits above the crest of the rock face; (3) *in situ* weathering of fallen clasts (*cf.* Statham and Francis, 1986); or (4) addition of exotic fines blown on to the talus surface from another source. Alternatively, the large amount of fine-grained sediment present may indicate that the supposed 'talus' accumulations are primarily glacigenic in origin, but modified by the subsequent addition of rockfall debris and reworked by debris flows, an interpretation consistent with both the surface form and internal structure of paraglacially-reworked tills in recently-deglaciated terrain. In an investigation of paraglacial reworking of steep valley-side glacigenic deposits following recent glacier retreat at Fåbergstølsdalen in Norway, for example, Ballantyne and Benn (1994, 1996) found that not only does the initial form of such slopes closely resemble those characteristic of rockfall talus accumulations, but also that paraglacial resedimentation of glacigenic sediment by debris flows and wash has produced internal structures similar to those observed in the upper parts of the talus accumulations on Trotternish (chapter 5). The research outlined below investigates these various possibilities.

6.3.1 Methods

Investigations of sediment origin were confined to samples of both clasts and finer-grained particles withdrawn from debris flow units within the Trotternish talus accumulations. To establish the origin of the sediments underlying the talus slope, various attributes of the deposit were compared with those of nearby accumulations of till, wind-blown sand and frost-weathered debris (Figures 6.4 and 6.5). Clasts from talus and till deposits were compared in terms of aggregate clast shape and angularity . In terms of finer-grained sediment (< 8 mm / -3 ϕ), the grain-size and mineral magnetic characteristics of samples from the talus were compared with those of samples from till, wind-blown sand and frost debris.

6.3.2 Rockfall versus glacigenic origin

To establish whether the talus sediments may contain a glacigenic component, comparative analyses were carried out on the coarse (≥ 64 mm) and fine (< 8 mm) factions of samples withdrawn from talus and till deposits. The clast (≥ 64 mm) components were compared in terms of clast shape and angularity using the procedures outlined by Benn and Ballantyne (1993, 1994). To establish whether significant differences are evident in aggregate clast shape, the lengths of the three orthogonal axes of samples of 50 clasts were measured for 14 samples from debris flow units underlying the talus slopes, and 3 samples from nearby till exposures. Angularity was assessed by assigning all sampled clasts to an angularity category (very angular, angular, sub-angular, sub-rounded or rounded; no well-rounded clasts were present in either set of samples) using the criteria of Benn and Ballantyne (1994). For all samples, the aggregate clast shape was calculated in terms of C_{40} and C_{50} indices, which respectively measure the percentage of clasts with c:a axial ratios ≤ 0.4 and ≤ 0.5 (Benn and Ballantyne, 1993). The results (Figure 6.6) indicate a C_{40} range of 30 - 68% (mean = 49%) and a C_{50} range of 66 - 92% (mean = 78%) for the 14 talus samples. The three till samples yielded a C_{40} range of 34 - 48% (mean = 43%) and a C_{50} range of 66 - 82% (mean = 73%). Testing, using the Mann-Whitney two sample test, revealed no significant difference between the aggregated C_{40} and C_{50} results for the talus samples and

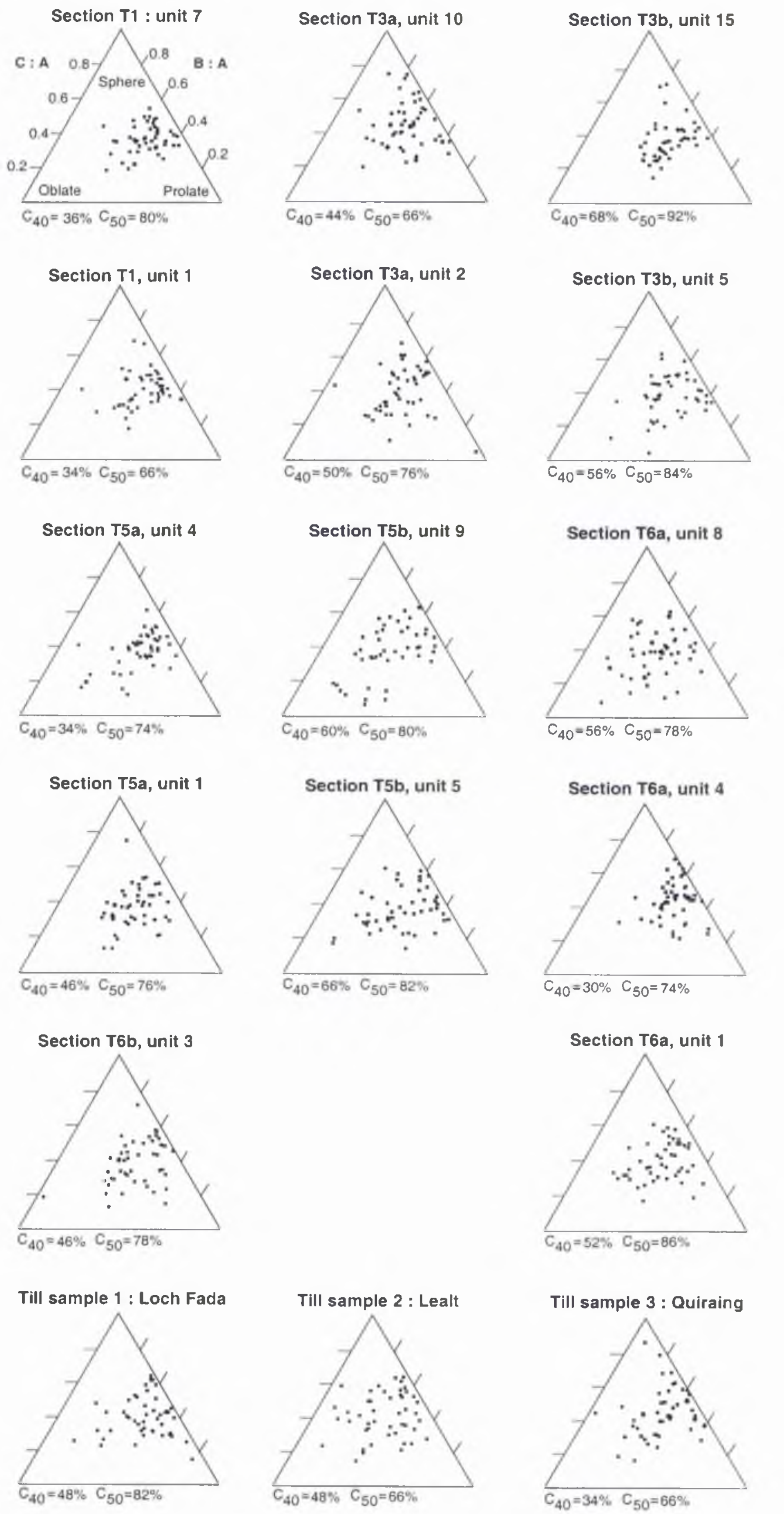


Figure 6.6. Particle shape triangles for samples of 50 clasts withdrawn from diamictons exposed in sections cut through talus and till deposits on Trotternish, northern Skye.

those for the till samples. These findings suggest that though the till clasts are generally more equidimensional, a feature consistent with modification of clast shape by traction at the glacier bed (Drake, 1970, 1972; Boulton, 1978; Ballantyne, 1982; Benn and Ballantyne, 1994), the two groups of samples cannot be distinguished on the basis of aggregate clast shape characteristics alone.

Aggregate angularity was assessed in terms of the RA index, which represents the percentage of clasts in each sample that falls into the combined categories of very angular, angular, and sub-angular. The results (Figure 6.7) show that in all cases the talus samples are characterised by generally more angular clasts than the till samples. For the latter, the range of RA values is low (12 - 36%), indicating that the majority of clasts in the tills have experienced edge-rounding, another characteristic of material that has been modified by subglacial abrasion (Boulton, 1978; Benn and Ballantyne, 1984). In contrast, the talus samples yielded RA indices of 72 - 99%, with modes in the angular or sub-angular categories. Testing, using the Mann-Whitney two-sample test, confirmed a significant difference between the two sets of samples at $p < 0.01$. The shape and angularity contrasts between samples of clasts from talus and from till are particularly evident in a plot of the RA values for each sample against the equivalent C_{40} values (Figure 6.8), which shows that till and talus samples plot in different fields. In sum, this result indicates that the majority of clasts sampled from the talus accumulations are not of glacigenic origin.

This conclusion is reinforced by two further considerations. First, several basalt clasts in the till samples exhibited striae indicative of subglacial abrasion, but no striated clasts were found in the talus samples. Secondly (though less conclusively, in view of differences in location) petrological analyses of sampled clasts revealed that all of the clasts sampled from the talus deposits are of local

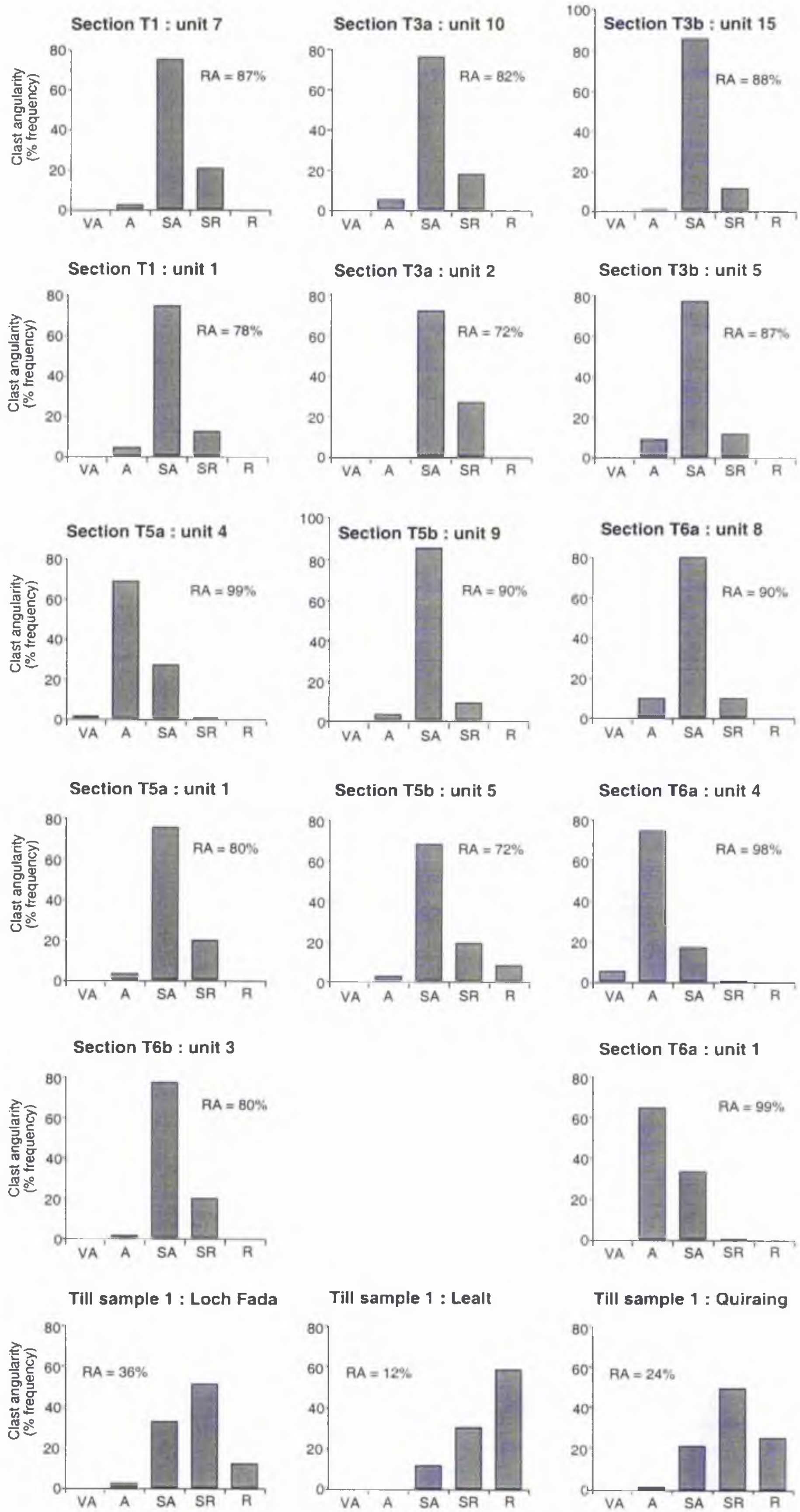


Figure 6.7. Angularity characteristics of samples of 50 clasts withdrawn from diamictons exposed in sections cut through talus and till deposits on Trotternish, northern Skye.

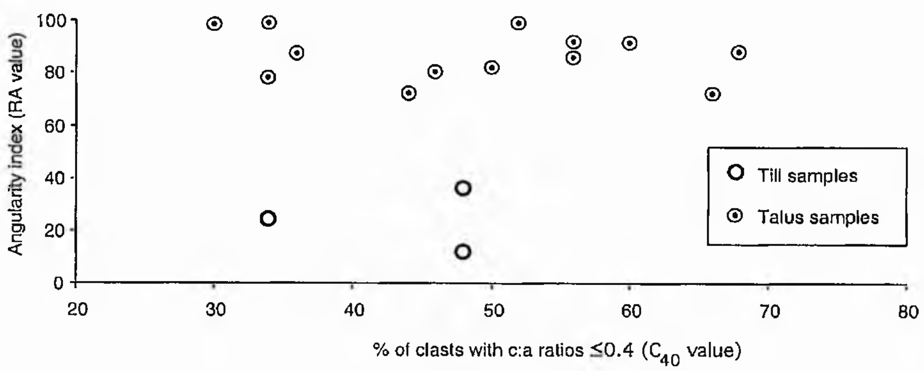
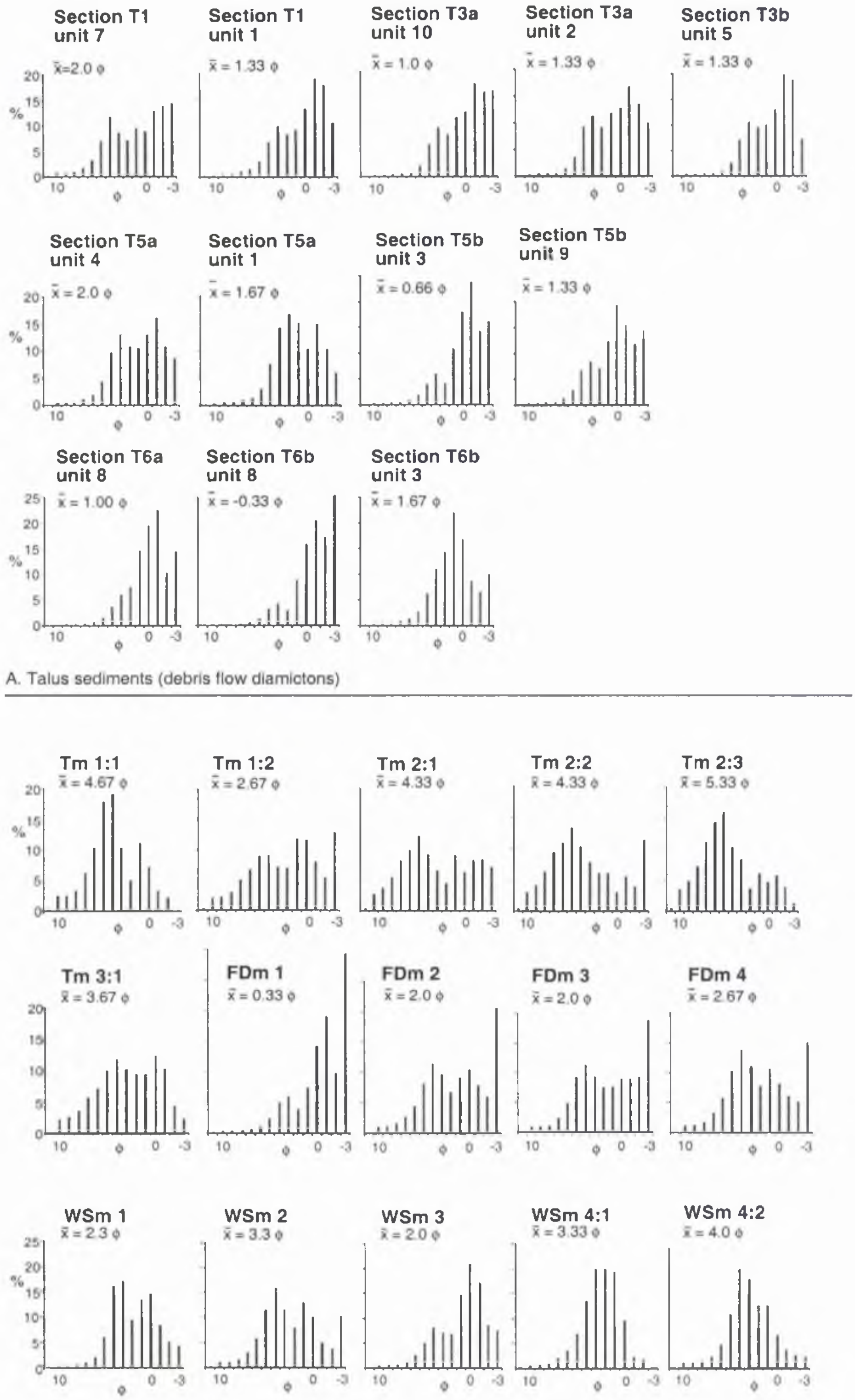


Figure 6.8. A comparison of samples of 50 clasts withdrawn from diamictons exposed in sections cut through talus and till deposits in the immediate vicinity of the Trotternish escarpment, northern Skye, in terms of aggregate clast shape, expressed by the C_{40} value, and aggregate clast angularity, represented by the RA value.

provenance (Tertiary basalts and tuffs) whereas a small number of sedimentary and igneous intrusive erratics were observed in sampled tills.

The particle-size distributions of twelve samples of finer (< 8 mm or < -3 ϕ) sediment from diamict units in talus and six equivalent samples from the three till exposures also reveal marked differences between the two sets of samples (Figure 6.9). With one exception, the dominant mode for the talus samples lies in the coarse sand to fine gravel range (1 ϕ to -3 ϕ, or 0.5 - 8.0 mm), whilst that for the till samples falls, again with one exception, in the coarse silt to fine sand range (5 ϕ to 3 ϕ or 32 - 125 μm). This distinction is reflected in differences in the graphic means calculated for sediment finer than 8 mm: those of the talus samples range from -0.33 ϕ to 2.0 ϕ, and those of the till samples from 2.67 ϕ to 5.33 ϕ (Figure 6.9), a difference significant at $p < 0.001$ (Mann-Whitney two-sample test). Further testing of paired grain-size distributions, using the Kolmogorov-Smirnov two-sample test, showed that, with only two exceptions, all the talus samples differ from all the till samples at $p < 0.01$, thus highlighting marked differences between the granulometry of the two groups of samples. Silt plus clay (< 63 μm) constitute between 28 - 57% of till samples, probably reflecting comminution of fines by subglacial abrasion, but < 15% of all of the talus samples, again suggesting that the talus sediments have not experienced subglacial modification.

Mineral magnetic analyses were also performed to test if the compositional properties of the diamict units within the talus deposits are different from those of the till samples. Following the recommendations of Oldfield *et al.*, (1985) and Smith (1985), magnetic measurements were performed on a grain-size specific basis. Analyses were conducted on two discrete size fractions of 1.4 mm to 8 mm (-0.5 ϕ to -3.0 ϕ) and < 1.4 mm (< -0.5 ϕ), as these ranges encompass the two dominant modes evident on most of the grain-size distributions of talus samples (Figure 6.9). Using the method described by Walden *et al.* (1996), sub-samples for



Section T1 unit 7	- Talus sample	**FDm 1**	- Frost debris sample
Tm 1:1	- Till sample	**WSm 1**	- Wind-blown sediment

Figure 6.9. Particle size distributions for the fine-grained fraction (<8 mm / -3 ϕ) of talus sediments, glacial till, wind-blown sand and frost weathered debris located adjacent to the Trotternish ridge. The above distributions relate directly to samples collected for mineral magnetic assay. Tic marks at 5% on y axes of graphs.

both size fractions were first measured in terms of low and high frequency mass specific magnetic susceptibility, using a Bartington MS2 susceptibility meter. Measurements of saturation isothermal remnant magnetism (SIRM) were subsequently performed using a Molspin 1A magnetometer with the artificial magnetic fields produced by a Molspin pulse magnetiser. A 'saturation' (SIRM) field of 1000 mT, and backfields of 40 mT, 100 mT and 300 mT were used.

Figure 6.10 summarises the results in terms of SIRM plotted against the 100 mT backfield ratio. SIRM is the highest amount of magnetic remanence that can be imparted in a sample by applying a large magnetic field. The value of SIRM is largely proportional to the concentration of remanence-carrying ferrimagnetic and canted anti-ferromagnetic iron oxide minerals in the sample. The 100 mT backfield ratio is a demagnetisation parameter that can be obtained by applying one or more reversed magnetic fields to the previously saturated sample. It is concentration-independent and reflects the overall balance between ferrimagnetic and canted anti-ferromagnetic iron oxide minerals. Figure 6.10 shows not only that the diamict units sampled from talus facies contain significantly higher concentrations of magnetic minerals than the till samples, but also that the assemblage of mineral types differs, as the higher 100 mT backfield ratios for the talus samples appear to indicate a greater proportion of canted anti-ferromagnetic minerals in these sediments. These differences are consistent for both size fractions analysed.

In sum, the comparative analyses of clast angularity and fine fraction (< 8 mm) granulometry reveal significant differences between the till and talus samples that are consistent with subglacial abrasion and comminution of the former but not the latter. The absence of erratics and striated clasts in the talus samples also indicates that the Trotternish talus deposits are not of glacigenic origin, as both are present in nearby till exposures. The observed differences in mineral magnetic characteristics of the two groups of samples appear to confirm a difference in

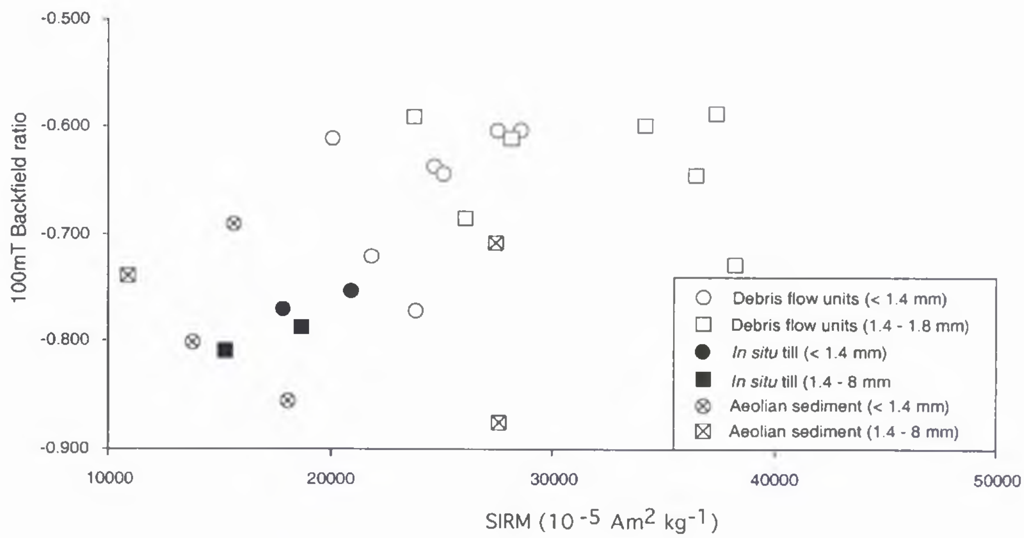


Figure 6.10. A comparison of the magnetic properties of two discrete size fractions (<1.4 mm and 1.4 - 8 mm) of sediment withdrawn from debris flow diamictons exposed in sections cut through talus slopes in area 2, Trotternish, against the same size fractions of nearby till and wind-blown sand deposits in terms of SIRM against the 100 mT backfield ratio.

composition. The above analyses thus suggest that the talus sediments are not of glacigenic origin, and indeed provide no evidence for inclusion of any glacially-transported sediment. It seems reasonable to conclude from these analyses that the coarse clastic debris within the talus accumulation is exclusively of rockfall origin. The provenance of the fine fraction is considered further below.

6.3.3 Origin of the fine fraction in talus

Rejection of a glacigenic origin for the fine-grained fraction of the talus sediments implies that these reflect either addition from outside the talus accumulation or *in situ* weathering of surface and subsurface clasts. The latter possibility has been mooted by Statham and Francis (1986) to explain the translational failure of the upper parts of mature taluses. They suggested that during the late stages of talus development, weathering of clasts produces fines that progressively infill interstitial voids, ultimately permitting build-up of porewater pressures and thus failure and redistribution of debris, but provided no evidence to substantiate this hypothesis. Indeed, in the context of the Trotternish talus accumulation, production of significant quantities of fines through *in situ* weathering and granular disaggregation of rockfall clasts appears very unlikely, given the angularity of constituent debris (Figure 6.7). Granular disaggregation on a scale commensurate with the observed percentage of fines would be expected to have produced a high proportion of subrounded or rounded clasts, but there is no evidence for this. Moreover, granular disaggregation tends to affect only exposed clast surfaces on Scottish mountains, and is negligible in subsurface locations (Ballantyne and Harris, 1994, p. 171). Finally, during sampling of clasts from talus deposits it was observed that almost all consisted of sound rock; very few samples, mainly of tuff, exhibited evidence of superficial weathering. Collectively, these considerations suggest that *in situ* weathering of rockfall clasts represents at most a very minor contribution to the abundance of fine material present in the talus accumulations.

It also seems very unlikely that the plateau above the rockwall crest represents a potential source of fine material. This supports only a thin cover of till or regolith, and is extensively covered by up to one metre of blanket peat, with numerous outcrops of ice-scoured basalt. Critically, the plateau slope follows the regional dip of the plateau lavas (Anderson and Dunham, 1966), implying that any past redistribution of sediment from the crest by wash would have been to the west, away from the rockwall and the talus slopes. Inspection of the slope crest above the Trotternish Escarpment provided no evidence for present or former transport of fine sediment over the crest on to the talus slopes below.

The possibility that the fines represent inblown windblown sediment of exotic origin was investigated by comparing the particle size distributions of fine ($\leq$ 8 mm or $< -3\ \phi$) sediments in the talus deposits with those of five samples collected from aeolian deposits on the summit plateau of The Storr, 2 km to the north (*cf.* Ballantyne, 1998). Although the aeolian sediments are highly variable in granulometry (Figure 6.9), the graphic mean grain sizes for the talus samples are significantly coarser than those for the aeolian samples at $p < 0.01$ (Mann-Whitney two-sample test). The magnetic characteristics of three samples of aeolian sediment, summarised in terms of SIRM against the 100 mT backfield ratio (Figure 6.10), also proved to be different for both size fractions from those of fines from the diamict units in the talus sediments. These results suggest that the fine sediment in the talus is not dominated by particles of wind-blown origin, though again the possibility that a minor component of aeolian sediment is present in the talus deposits cannot be excluded.

Exclusion of *in situ* weathering, downwash of plateau-top deposits and inblown aeolian sediment as the primary sources of fine sediment in the talus deposits implies that the most likely source of such sediment is granular weathering of the rock face, with fine particles falling on to and being washed into the accumulating talus. An attempt was made to test this proposition by comparing the granulometry of the twelve talus samples with that of four samples of *in situ* frost-weathered basalt from the summit plateau of The Storr (Figure 6.9). Though the range of mean grain sizes for the former is statistically indistinguishable from that for the latter (Mann-Whitney two-sample test), the forms of the two sets of distributions differ, as all of the frost-debris samples are strongly bimodal with a dominant mode at 8 mm (-3 ϕ) that is, with only one exception, absent from the talus samples.

A stronger argument for a rockwall source is provided by the recent finding by Ballantyne (1998) that the aeolian deposit which mantles the summit plateau of The Storr (Figure 6.5) reflects small-scale weathering of the adjacent cliff face and transport of dislodged particles upwards on to the plateau during storms. Ballantyne calculated that a total volume of 45,000 m^3 of aeolian sediment derived from the adjacent rockwall has accumulated on the plateau of The Storr over the past *c.* 6.5 - 7.3 ka. If such abundant quantities of fine sediment has been blown upwards to accumulate on the plateau, it seems reasonable to expect that the products of granular weathering of the cliff will also have travelled downwards in similar or greater volumes to accumulate in the talus deposits downslope. In an analogous situation in Gaspésie, Québec, Hétu (1992) observed both up-scarp and down-scarp transport of weathered material during storms, with some sediment being deposited near the scarp crest and some being redistributed over talus downslope. Finally, in their recent study of the structure and sedimentology of a talus exposure in Assynt, NW Scotland, Salt and Ballantyne (1997) employed petrological analysis of the fine fraction and analysis of the characteristics of quartz grains to demonstrate that fine sediment within the talus at this site had originated through granular disintegration of the rockwall and redistribution of grains within the talus downslope. In the light of this evidence, it seems reasonable to conclude that granular weathering of the rockwall above the Trotternish talus slopes has provided the primary source of fine material within the talus.

6.3.4 Origin of valley-side drift: Glen Feshie

Although the above findings strongly suggest that talus debris on Trotternish originated from cliffs upslope, the internal structure of apparent 'talus' slopes in upper Glen Feshie has earlier been interpreted in terms of partially reworked till, overlain by a thin veneer of rockfall debris (chapter 5). To test this hypothesis, various sedimentological attributes of the valley-side drifts in Glen Feshie were compared with those of nearby valley-floor till exposures using some of the methods outlined above.

Figure 6.11 shows the clast shape and angularity characteristics of three sediment facies in upper Glen Feshie, namely till exposures, diamictons interpreted as till in the valley-side drifts, and clast-supported deposits interpreted as representing an overlying veneer of rockfall debris. In terms of clast shape, samples of clasts from the basal matrix-supported diamictons in the valley-side drifts (interpreted as reworked till) yielded C_{40} values of 16% and 46% (mean 31%) and C_{50} indices of 34% and 62% (mean 48%). Clasts from the overlying 'rockfall' debris yielded higher values for both indices, with a C_{40} range of 46 - 90% (mean 71%) and a C_{50} range of 75 - 98% (mean 89%). Two samples from valley-floor till exposures give C_{40} values of 30% and 35% (mean 32%) and C_{50} values of 48% and 60% (mean 54%). Although the number of samples in each category is too low to permit valid statistical testing, the close similarity in the results for the matrix supported-diamictons within the valley-side drifts and those

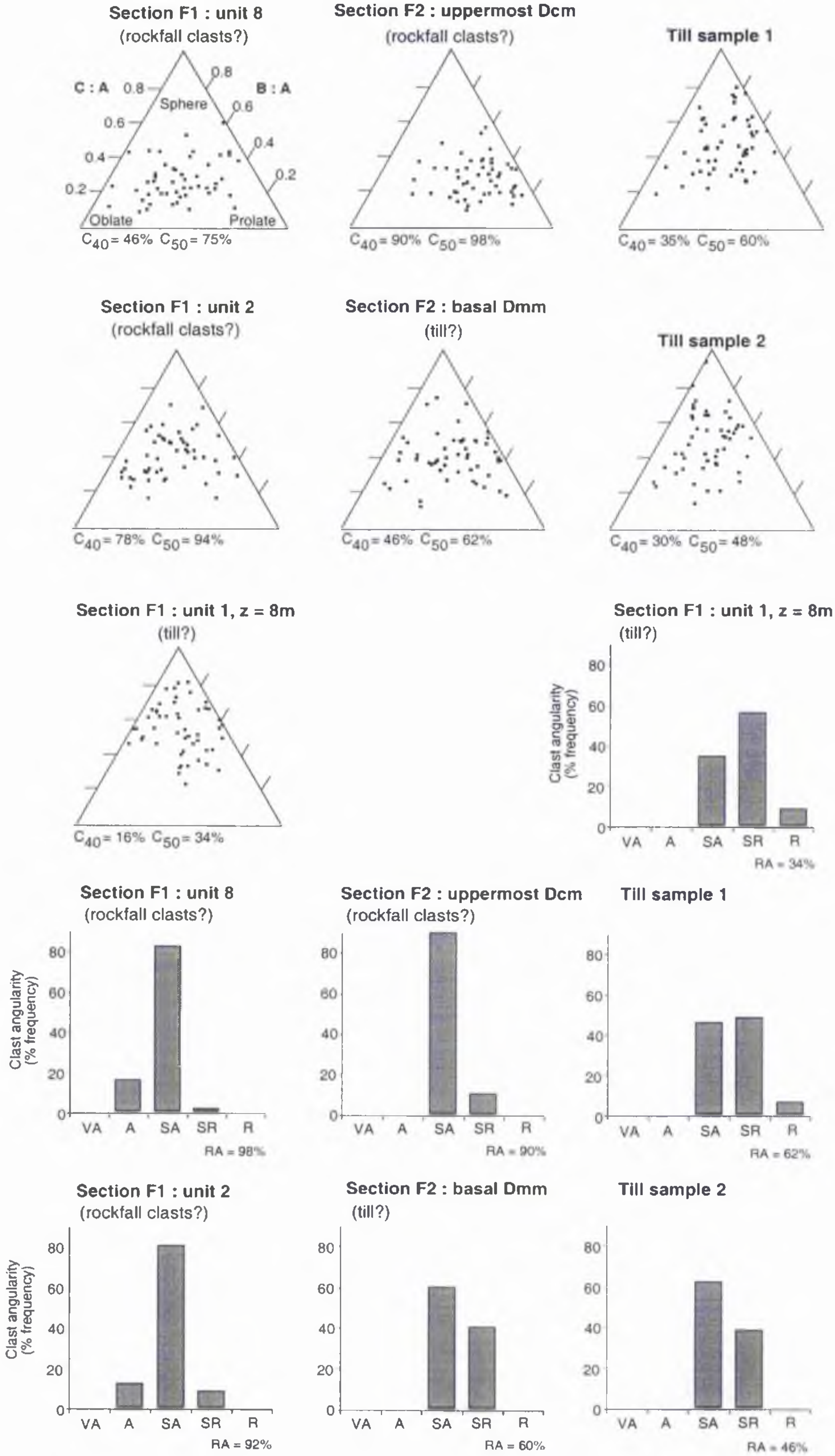


Figure 6.11. Particle shape triangles and angularity characteristics of samples of 50 clasts withdrawn from diamictons exposed in sections cut through valley-side drift accumulations, and valley-floor till deposits in upper Glen Feshie, western Cairngorms.

for the two till samples are consistent with interpretation of the former as being glacigenic in origin. Conversely, the much higher C_{40} and C_{50} indices calculated for the overlying veneer of clast-supported debris indicates a different origin, and is consistent with the interpretation of this layer as a rockfall deposit.

This conclusion is strongly supported by measurements of clast angularity made on the same samples. The RA index values for the 'rockfall' deposits are uniformly high (90 - 98%), but those for the two samples from the matrix-supported diamicton within the valley-side drift are much lower (34% and 60%) and overlap with the RA values of 46% and 62% measured for till clasts. Plots of RA against C_{40} and C_{50} for all seven samples (Figure 6.12) reveal that the samples from the matrix-supported diamictons occupy a similar clast shape / clast angularity field to the till samples, but that the samples from the overlying clast-supported debris fall well outside this field. Moreover, the relatively low C_{40}, C_{50} and RA indices for clasts samples from the matrix-supported diamictons in the valley-side deposits are consistent with those of clasts modified by subglacial abrasion and fracture (Boulton, 1978; Ballantyne, 1982; Benn and Ballantyne, 1994), and thus with a glacigenic origin.

Finally, the granulometric characteristics of samples of fine (< 8 mm) sediments from the basal matrix-supported and upper clasts-supported units of the valley-side drifts in Glen Feshie were compared with those of the nearby till exposures (Figure 6.13). This proved less conclusive, though the graphic mean grain sizes for the two samples from the matrix-supported diamictons (1.33ϕ and 2.33ϕ) fall within the range for the three till samples (1.33 to 3.67ϕ), whereas the three samples from the overlying clast-supported layer tend to be slightly coarser (1.00-1.67ϕ). Collectively, however, the above analyses of clast shape, clast angularity and fine-fraction granulometry provide strong support for the inference made on the basis of structural characteristics in the previous chapter, namely that

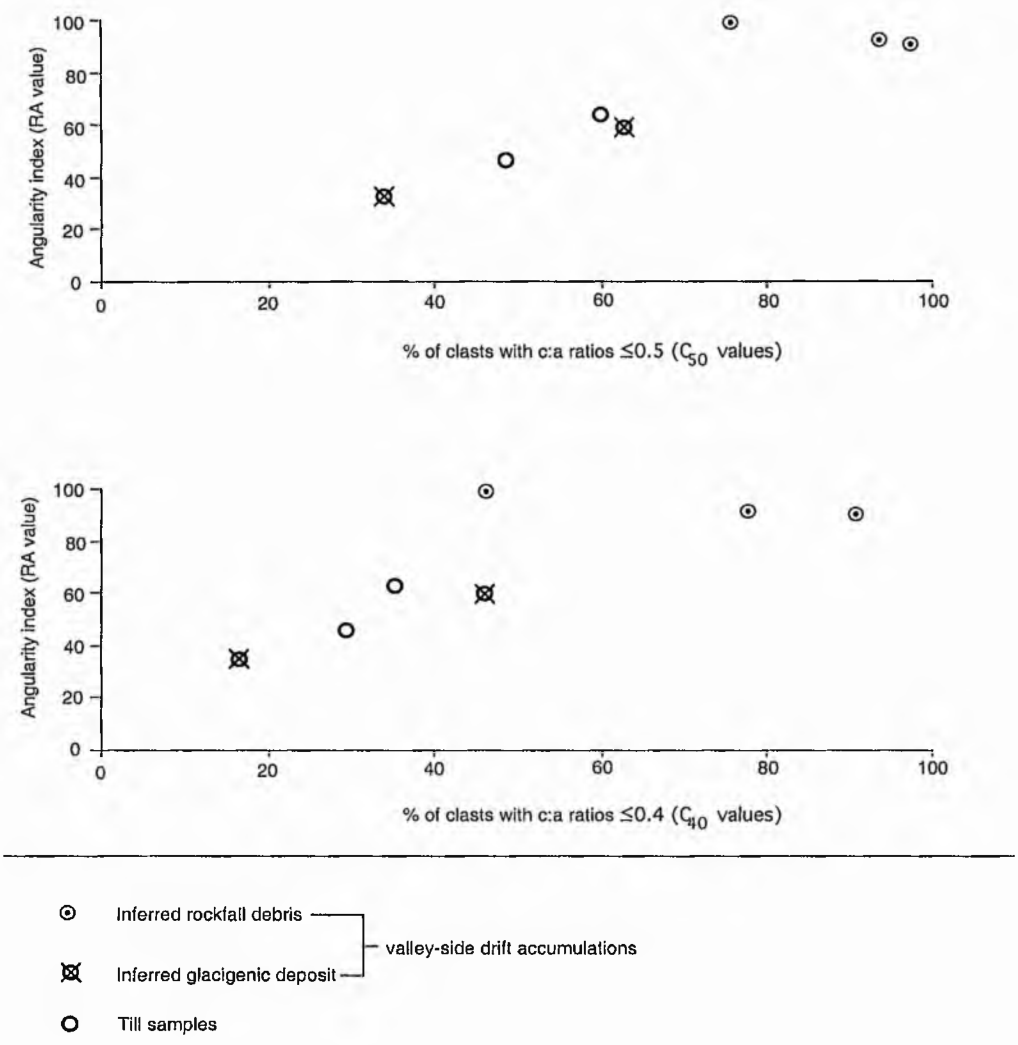


Figure 6.12 A comparison of samples of 50 clasts withdrawn from diamictons exposed in sections cut through valley-side drift against nearby valley-floor till deposits in upper Glen Feshie, western Cairngorms, in terms of aggregate clast shape, expressed by the C_{40} and C_{50} values, and aggregate clast angularity, represented by the RA value.

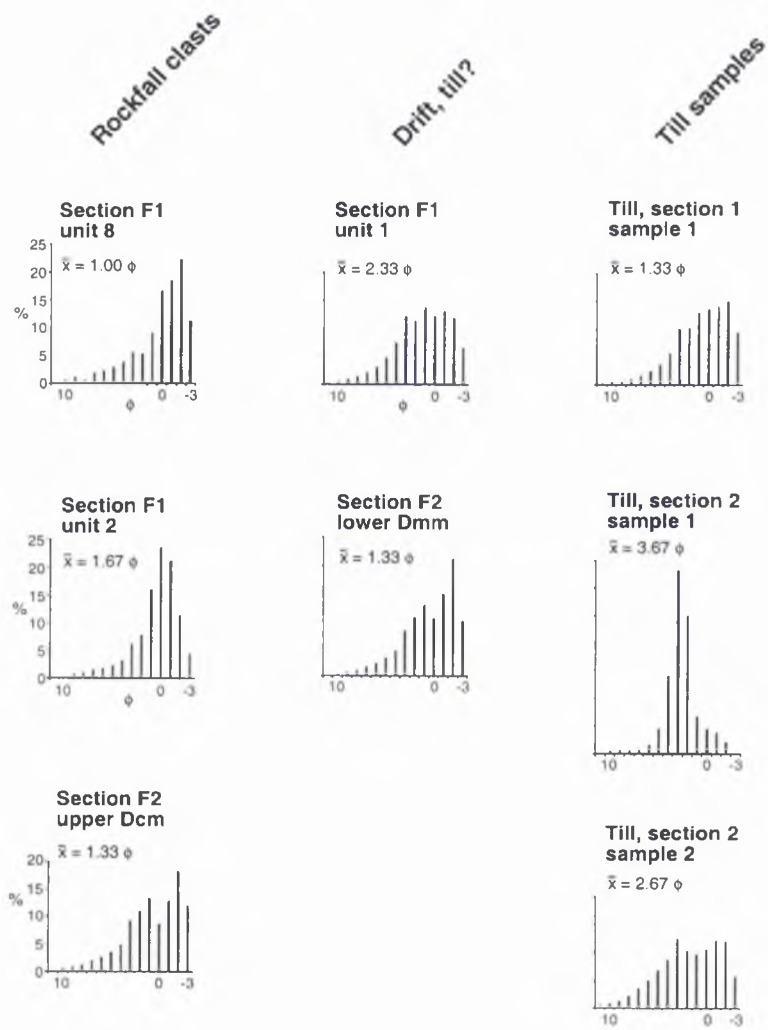


Figure 6.13. Particle size distributions for the fine-grained fraction (<8 mm / -3 ϕ) of inferred rockfall and glacigenic diamictons exposed in section in valley-side drift, and nearby valley-floor till accumulations in upper Glen Feshie. Tic marks at 5% on y axes of graphs.

the bulk of the supposed 'talus' slopes in Glen Feshie actually comprises reworked till deposits overlain by a layer of rockfall debris. Such slopes are therefore sedimentologically, structurally and genetically distinct from 'true' rockfall talus accumulations such as those of Trotternish and the study sites in the NW. Highlands. At these sites there is no evidence of incorporation of glacigenic sediment, implying that these taluses have developed largely or exclusively as a result of rockfall deposition and subsequent reworking of debris derived exclusively from the cliffs upslope.

6.3.5 Origin of talus debris: summary

1. The aggregate angularity of clasts from talus deposits on Trotternish is significantly greater than that of clasts in nearby till exposures. Moreover, both striated clasts and erratics are present in the till deposits, but absent from talus samples. These differences imply that clast-size sediment contained within talus diamictons on Trotternish is not glacigenic in origin.

2) Samples of fine-grained (< 8 mm) sediment from talus diamictons are significantly coarser than the corresponding fine fraction of nearby tills. Furthermore, mineral magnetic analyses of fine sediment samples suggest that the talus deposits contain a higher concentration of magnetic minerals and a greater proportion of canted anti-ferromagnetic minerals than the tills. These differences indicate that fines contained within talus diamictons are unlikely to be of glacigenic origin.

3) The angularity of clasts within the talus suggests that weathering of talus debris is unlikely to have constituted a major source of fine sediment in the talus accumulations. Similarly, there is no evidence favouring plateau-crest origin for such sediment, and both granulometric and mineral magnetic

analyses indicate that the majority of fines are not of aeolian origin. The deposition of large quantities of sediment derived from cliffs on the plateau of The Storr (Ballantyne, 1998) suggests that the majority of fine-grained sediment within the Trotternish talus accumulations is derived from granular weathering of the rockwall upslope, a conclusion consistent with previous observations (Hétu, 1992; Salt and Ballantyne, 1997).

4) Comparison of talus debris in upper Glen Feshie with nearby till sections, in terms of aggregate clast shape, clast angularity and fine fraction granulometry confirms the structural interpretation (chapter 5) of the valley-side drifts at this site as glacigenic deposits overlain by a veneer of rockfall clasts.

6.4 Implications

The high (*c.* 27-30% by weight) proportion of fine sediment present within the talus accumulations on Trotternish appears to indicate syndepositional accumulation of both fine and coarse debris from the rockwall. If this has indeed been the case throughout the history of talus accumulation, it has important implications for our understanding of slope processes and talus slope evolution. Several authors have modelled the latter on the assumption that talus accumulations are essentially openwork and free-draining (e.g. Statham, 1973a, 1976a; Kirkby and Statham, 1975; Carson, 1977). Free-draining sediments are, however, unlikely to experience translational failure (and consequent debris flow) resulting from build-up of porewater pressures and an associated reduction of shearing resistance. For this reason, such models have focused on the influence of particle kinetics and the possible role of 'dry avalanching' in explaining the form of talus slopes. However, the findings reported above, together with previous observations on the characteristics of sediments underlying both active and relict taluses (Wasson, 1979; Church *et al.*, 1979; Åkerman, 1984; Selby, 1993; Salt and Ballantyne, 1997) suggest that an infill or matrix of fine sediment at shallow depth is a general or at least widespread property of talus accumulations. This in turn implies the possibility (indeed the likelihood) of episodic translational slope failure operating on the steepest parts of talus slopes during exceptionally prolonged or intense rainstorms (Common, 1954; Baird and Lewis, 1957; Caine, 1980), particularly when antecedent moisture conditions are high (Church and Miles, 1987; Kotarba *et al.,* 1987).

In this context, it is notable that debris flows have been widely documented on both active and relict talus slopes in upland Britain (e.g. Statham, 1976b; Innes, 1983c; Addison, 1987; Luckman, 1992; Ballantyne and Harris, 1994, p. 230) and in a wide range of other environments (e.g. Jahn, 1976; Rapp and Nyberg, 1981; Larsson, 1982; Kotarba and Strömquist, 1984; van Steijn *et al.,* 1988; Jonasson *et al.,* 1991; Kotarba, 1992; van Steijn *et al.*, 1995). This also suggests that an abundance of fine debris within talus accumulations is a widespread feature of such deposits, and that the sedimentological composition of the Trotternish talus is typical rather than anomalous. In more general terms, the findings reported above suggest that models that treat talus slopes simply as accumulations of free-draining coarse debris have limited value in explaining the development and behaviour of such slopes.

A second implication of the research reported above arises from the confirmation that what initially appeared to be relict accumulations of rockfall debris in upper Glen Feshie actually comprise a shallow veneer of rockfall detritus mantling a much thicker accumulation of reworked till. Morphologically, the drift slopes at this site appear characteristic of rockfall talus accumulations, with upper rectilinear slopes 37°-43° rising above a distinct basal concavity (chapter 4). However, the internal structural and sedimentological characteristics of these slopes indicate that they developed through initial deposition of glacigenic sediments, paraglacial reworking of such sediments, and finally accumulation of a thin cover of rockfall debris. Interestingly, both Gardner (1982) and Ballantyne and Benn (1994) have noted that, in steep-sided glaciated valleys, collapsed lateral moraines and paraglacially-reworked valley-side drifts rest at gradients similar to (and thus closely resemble) rockfall talus slopes. Other authors have also suggested that some 'talus' accumulations may contain a component of older colluvium or till (e.g. Church *et al.,* 1979; Rapp and Nyberg, 1981). These observations suggest that there may exist a continuum of valley-side drift accumulations, ranging from those that consist entirely of reworked glacigenic sediments to those that comprise both rockfall debris and earlier deposits (such as those in upper Glen Feshie), to talus slopes *sensu stricto* that are composed entirely of deposits derived from a source rockwall upslope. The results presented in this chapter suggest that all such accumulations contain an abundance of fine material, and are thus susceptible to translational failure and reworking by debris flow. Given that their overall textural composition is similar, it is not surprising that they ultimately evolve into similar slope forms. Steep valley-side debris accumulations may therefore be seen as an example of geomorphic equifinality, in which deposits of differing origin ultimately adopt a similar form.

A final implication of the research reported above concerns the finding that a large proportion of the fine sediment present in the Trotternish talus accumulations appears to be derived from granular disintegration of the rockwall upslope. Some indication of the magnitude of rockwall recession due to granular weathering can be made by dividing an estimated volume of accumulated fine sediment by the approximate area of the contributing rockwall. To achieve this, the total area of a 480 m long stretch of rockwall, located in the southern portion of area 2 (Figure 4.4), was calculated from enlarged 1:10,000 Ordnance Survey maps as planimetric area divided by cos α, where α is the average gradient of the rockwall measured from contours. The area of the 480 m length of rockwall was calculated as *c.* 44,100 m^2. The volume of the talus accumulation downslope was calculated by dividing it into five component segments, each containing a representative cross section through the talus deposit constructed using EDM slope profile data (chapter 4). The thickness of the talus deposit was estimated by assuming a regular decline in the underlying bedrock, and constrained by depth to bedrock measurements and by the height of nearby gully walls. The area of each cross section was multiplied by the length of its respective across-slope segment, and the results were summed to give a total volume of *c.* 315,900 m^3 for the talus deposit. Allowing 30% for internal voids, this indicates a total volume of *c.* 221,100 m^3 of debris, and division of this figure by the rockwall area gives *c.* 5 m of rockwall retreat (averaged over the cliff face) since deglaciation. Given that internal fines represent *c.* 27 - 30% of the total volume of talus debris, it seems reasonable to suggest that the component of overall rockwall retreat due to granular weathering has been of the order of 1.3-1.5 m since deglaciation. Assuming a local deglaciation age of *c.* 17 cal ka BP on the basis of the ^{36}Cl cosmogenic exposure ages obtained by Stone *et al.,* (1998), the above values suggest that the averaged rockwall retreat rate since deglaciation has been of the order of 0.3 mm yr^{-1}, of which roughly 0.08-0.09 mm yr^{-1} may be attributed to granular disintegration rather than detachment of clast-sized debris. These averages, however, conceal the likelihood that the main phase of talus accumulation occurred under periglacial conditions during the latter part of the Late Devensian glacial substage, rather than under the milder conditions of the Holocene. If it is assumed that the talus accumulations are essentially of Late Devensian age, then approximate maximum rockwall retreat rates can be calculated by dividing the total amount of average rockwall retreat by the period between deglaciation at *c.* 17 cal ka BP and the end of the Loch Lomond Stade at *c.* 11.5 cal ka BP, a period of roughly 5,500 years. This suggests that the average Late Devensian rockwall retreat rate was *c.* 0.9 mm yr^{-1}, of which granular disintegration was responsible for about 0.24-0.27 mm yr^{-1}.

Although the above figures must be regarded as no more than approximate, they make interesting comparison with other data relating to rockwall retreat rates. First, at a local level, Ballantyne (1998) has calculated that plateau-top aeolian accumulations on the summit of The Storr imply an average rockwall retreat rate of 0.06-0.07 mm yr^{-1} since *c.* 7.2-6.9 cal ka BP, on the assumption that all of the plateau-top sediment at that site represents grains blown upwards from adjacent cliffs during storms. Although the relative proportion of fine sediment blown up the scarp face and that which falls on to talus slopes below is unknown, the high wind velocities required to entrain and transport sediment upscarp (Hétu, 1992; Ballantyne, 1998) suggest that the latter probably exceeds the former. This inference is supported by the slightly larger figure of 0.08-0.09 mm yr^{-1} calculated above for the contribution of granular disintegration to rockwall retreat on the assumption of uniform delivery of fine sediment to talus slopes since deglaciation at *c.* 17 cal ka BP. More significantly, Ballantyne's findings suggest that the contribution of granular disintegration to rockwall retreat and the transfer of fines to the surfaces of talus slopes downslope did not cease at the end of the Late Devensian Lateglacial, but continued to operate into the Holocene. If the bulk of the clast-sized debris in the talus accumulations is of Late Devensian age, as previous studies of relict talus accumulations in upland Britain have suggested (e.g. Ball, 1966; Tufnell, 1969; Ball and Goodier, 1969; Ryder and McCann, 1971; Ballantyne and Eckford, 1984; Kotarba, 1984; Ballantyne and Kirkbride, 1987; Ballantyne and Harris, 1994; Salt and Ballantyne, 1997), then it appears possible that granular disintegration may have constituted the major element of rockwall retreat under the milder conditions of the Holocene. This in turn raises the interesting possibility that talus accumulations of essentially Late Devensian age may have become progressively enriched with fine sediment during the Holocene, possibly rendering them increasingly liable to failure and sediment reworking. This suggestion resembles the proposal made by Statham and Francis (1986) that failure and reworking of the upper slopes of talus accumulations reflect progressive infilling of voids by fine sediment, only in this case the main source of the fines is granular weathering of the rockwall upslope rather than (as they envisaged) progressive *in situ* weathering of talus debris.

The proposal that granular disintegration is currently the major component of rockwall retreat is supported by comparison of the average figure of 0.08-0.09 mm yr^{-1} calculated above, and Ballantyne's (1998) figure of 0.06-0.07 mm yr^{-1} based on the volume of the Storr aeolian deposits, with estimates of current rockwall retreat in upland Britain that are based on the accumulation of coarse debris over vegetation cover. The latter range from 0.009 mm yr^{-1} to 0.063 mm yr^{-1}, with a mean of around 0.015 mm yr^{-1} (Ballantyne and Eckford, 1984; Stuart, 1984; Table 2.1). Though caution is necessary in comparing sites with different lithologies, the available data suggest that the inferred cliff face retreat rate due to granular weathering of the Trotternish scarp is several times larger than those calculated for studied rockwalls elsewhere in upland Britain on the basis of the volume of recent accumulations of coarse rockfall debris. This strongly suggests that small-scale weathering currently predominates over fall of clast-sized fragments as an agent of rockwall recession in upland Britain.

Finally, it is instructive to compare the inferred rates of overall rockwall retreat (0.3 mm yr^{-1} over the *c.* 17 cal ka since deglaciation; up to 0.9 mm yr^{-1} if it is assumed that the bulk of talus accumulation took place before the end of the Late Devensian Lateglacial) with rockwall retreat rates measured or inferred from the volume of talus accumulations in arctic and alpine environments (Table 2.1). Even the upper figure of 0.9 mm yr^{-1} appears conservative (though of the same order of magnitude) in comparison with the range of 1.64-3.29 mm yr^{-1} estimated for rockwall retreat at various sites in upland Britain during the Loch Lomond Stade on the basis of the volumes of Stade protalus ramparts (Ballantyne and Kirkbride, 1987). However, the figure of 0.9 mm yr^{-1} exceeds most estimates for rockwall retreat in arctic environments and lies close to the average rates calculated for alpine environments (Table 2.1). This may suggest that during the main period of talus accumulation the Trotternish scarp experienced conditions analogous to those of present-day alpine cliffs, with numerous freeze-thaw cycles. However, as noted by several previous authors, interpretation of retreat rates in terms of climatic factors is hazardous, as glacially-steepened cliffs are liable to experience frequent rockfall events following deglaciation irrespective of climatic circumstances (Ballantyne and Kirkbride, 1987; Ballantyne and Harris, 1994). To what extent the accumulation of talus in Lateglacial times reflects paraglacial influences, such as glacial steepening and progressive extension of joints following debuttressing by ice, remains a matter for conjecture.

6.5 Conclusions

Observations of internal structure (chapter 5) showed that abundant fine-grained sediment underlies talus slopes in the Scottish Highlands. These findings suggested the need for re-examination of the sedimentological composition of relict talus slopes, which have previously been modelled in terms of coarse, free-draining debris. Several general conclusions can be drawn from the investigations of talus sedimentology reported above.

Textural analyses suggest that the overall proportion of internal fine-grained sediment (< 2 mm) present in the Trotternish talus accumulations is of the order of 27-30% by weight, which accords well with previous results from Assynt on the Scottish mainland (Salt and Ballantyne, 1997). Comparative analyses of clast characteristics, granulometry and magnetic properties of talus sediments on Trotternish and those of nearby till exposures exclude a glacigenic origin for the former, which are inferred to have built up as a result of syndepositional accumulation of both rockfall clasts and the products of granular weathering of the rock face. Similar analyses of supposed 'talus' accumulations in Glen Feshie, however, confirmed that the latter are primarily of glacigenic origin, but overlain by a thin veneer of rockfall debris. This result suggests the existence of a continuum of steep valley-side sediment accumulations, all morphologically resembling talus slopes, but ranging from those consisting almost entirely of reworked glacigenic deposits to 'true' talus slopes composed exclusively of debris derived from the rockwall above.

Two conclusions are particularly pertinent for the further understanding of the history of talus development and reworking. The volume of the talus sediment resident below a basalt cliff at the southern end of the Trotternish escarpment implies *c.* 5 m of rockwall retreat (averaged over the face) since deglaciation at around 17 cal ka BP, suggesting an average rockwall retreat rate of *c.* 0.3 mm yr^{-1} during this period, of which perhaps 0.08-0.09 mm yr^{-1} is attributable to granular weathering of the cliff face rather than fall of clast-sized particles. Though it seems likely that the bulk of rockfall deposition occurred during the Late Devensian Lateglacial (i.e. prior to *c.* 11.5 cal ka BP), there is evidence from the accumulation of aeolian sediment on the nearby summit of The Storr that granular weathering of the face persisted into Holocene times, and may currently represent the prime mode of rockwall recession. This raises the possibility that during the Holocene the Trotternish talus slopes have experienced progressive enrichment of fine (< 2 mm) sediment.

Secondly, the abundance of fines underlying Trotternish talus slopes (and, by inference, those studied on the NW mainland of Scotland) suggests that it is inappropriate to model the evolution of such accumulations in terms of free-draining openwork deposits whose morphology is dictated by the kinetics of particle fall and possible redistribution of debris by 'dry avalanches'. The infill of fines at all talus sites implies the probability of translational failure and debris flow due to the build-up of porewater pressures during rainstorms, a notion strongly supported by the abundant morphological evidence of failure and debris flow both at the study sites (chapter 4) and in a wide range of other environments.

Taken together, these two conclusions suggest first the need for a revised model of talus slope evolution that takes into account the role of intermittent surface failure and downslope redistribution of sediment by debris flows, and secondly, the possibility that studied talus slopes may have become more susceptible to reworking during the Holocene owing to progressive enrichment by fine sediment derived from granular weathering of source rockwall. These two themes are considered further in the next two chapters, which consider respectively the history of reworking of the talus slopes in Trotternish and on the NW mainland (chapter 7), and the development of a general model of talus slope development that incorporates the effects of intermittent sediment reworking by debris flow activity (chapter 8).

Chapter 7

The history and possible causes of talus reworking

7.1 Introduction

After an introduction and a description of methods employed, this chapter is divided into two parts. The first (section 7.3) concerns the timing of the reworking of talus debris in the Scottish Highlands. The second (section 7.4) reviews the evidence for possible causes of talus slope instability. Findings reported in previous chapters have demonstrated the abundance of slope failures, primarily associated with gully incision and repeated debris flow activity, on relict talus on Scottish mountains. Erosion and redistribution of rockfall talus detritus has been interpreted as being responsible for the burial of former ground surfaces, and thus the preservation of stacked sequences of *in situ* palaeosols within talus accumulations at study sites (chapter 5). The results of radiocarbon dating of organic-rich buried soils and analysis of constituent sub-fossil pollen are reported below. Work discussed in this chapter, as in those before, is synthesised in chapter 8, in which a schematic model of the evolution of rockfall talus slopes by erosion and downslope mass transport is presented.

There is mounting evidence in the literature for accelerated rates of landscape change in upland Britain during the latter half of the Holocene (Ballantyne, 1991b). In particular, attention has been directed towards the research on flood plain aggradation, channel incision and the evolution of river terraces (e.g. Crampton, 1969; Richards, 1981; Acreman, 1983; Harvey *et al.*, 1984; Macklin and Lewin, 1986; Robertson-Rintoul, 1986), catchment sediment yields (e.g. Dearing *et al.*, 1981; Snowball and Thompson, 1990, 1992), the modification of drift-mantled slopes by solifluction (e.g. Sugden, 1971; Mottershead, 1978; Chattopadhyay, 1982; Ballantyne, 1984, 1986c, 1987), landsliding (e.g. Simmons and Cundill, 1974; Ibsen and Brunsden, 1997), gullying and slope-foot debris cone formation (e.g. Strachen, 1976; Statham, 1976b; Harvey *et al.,* 1981; Innes, 1983a, 1985a; Ballantyne and Eckford, 1984; Ballantyne, 1986a; Harvey and Renwick, 1987; Brazier *et al.,* 1988; Brazier and Ballantyne, 1989; Harvey, 1992, 1996) and surface wash (e.g. Simmons *et al.*, 1975; Tipping, 1995; Evans, 1996). Significantly, such research has highlighted the possibility of an intensification of mass movement activity in mountainous terrain in upland Britain during the late Holocene (Ballantyne, 1991b), a finding that has implications for the timing of apparently recent erosion of relict talus debris in the Scottish mountains.

7.2 Methods

Gully walls incised through the upper slopes of relict talus accumulations in the Scottish Highlands permit close inspection of internal structure. Depositional facies underlying talus slopes at field sites occasionally comprise discrete organic-rich layers, many of which are interpreted as representing *in situ* buried soils (chapter 5). Sections through talus were logged on graph paper and photographed to record the precise stratigraphic position of buried soil horizons prior to sampling of such layers for radiocarbon assay and analysis of constituent palynomorphs.

The top and bottom 5 mm of some *in situ* buried soils were sampled for radiocarbon assay. Overlying and underlying minerogenic sediments were carefully removed using a small trowel, and finally with a sharp penknife. Samples were collected using a scalpel (cleaned regularly with fresh water and disposable tissues), sealed in aluminium foil and placed in clearly labelled, air-tight bags for cold storage. Samples were submitted to the NERC Radiocarbon Laboratory at East Kilbride for either conventional ^{14}C radiocarbon dating, or pre-treatment and forwarding to the University of Arizona NSF-AMS facility where aliquots of prepared gas underwent accelerator-beam measurement. Radiocarbon ages were transformed to calendar years using the calibration programme CALIB rev. 3.0 of Stuiver and Reimer (1993) and the calibration data of Stuiver and Becker (1993). Calendar age ranges are quoted in the text at the $\pm 2\sigma$ level. For convenience of comparison, previously published ^{14}C radiocarbon dates are also converted to calendar age ranges using the CALIB rev. 3.0 programme.

Buried palaeosols were also sampled for analysis of constituent sub-fossil pollen using 10 cm and 30 cm stainless steel monolith tins (Figure 7.1 and 7.2), and sealed in clearly labelled, air-tight bags for cold storage. Samples were prepared for pollen analysis by standard HCl, NaOH, HF and acetolysis treatment (Faegri and Iversen, 1989). The addition of tablets of *Lycopodium* permitted subsequent calculation of pollen and charcoal concentrations in samples. Samples were mounted on slides using silicone oil, and pollen counting and identification was undertaken at a magnification of X600. A minimum of 300 total land pollen grains was counted for traverses of each slide, and all grains encountered were recorded against categories of their preservation status. Pollen type nomenclature follows that of Stace (1991), amended by Bennett *et al.*, (1994). Selected palynomorph data are illustrated as a percentage of total land pollen. Occasional reference is also made to calculated pollen concentrations to verify peaks in the pollen percentage totals of individual taxa. Microscopic charcoal concentrations are expressed in values of $cm^2\,cm^{-3}$, and visual comparison with the calculated charcoal to pollen ratio is intended to negate problems of false peaks in charcoal concentration potentially caused by variations in rates of sediment accumulation (*cf.* Swain, 1973; Patterson *et al.*, 1987). Pollen diagrams were produced using the programmes TILIA and TILIA-GRAPH (Grimm, 1991). For convenience of

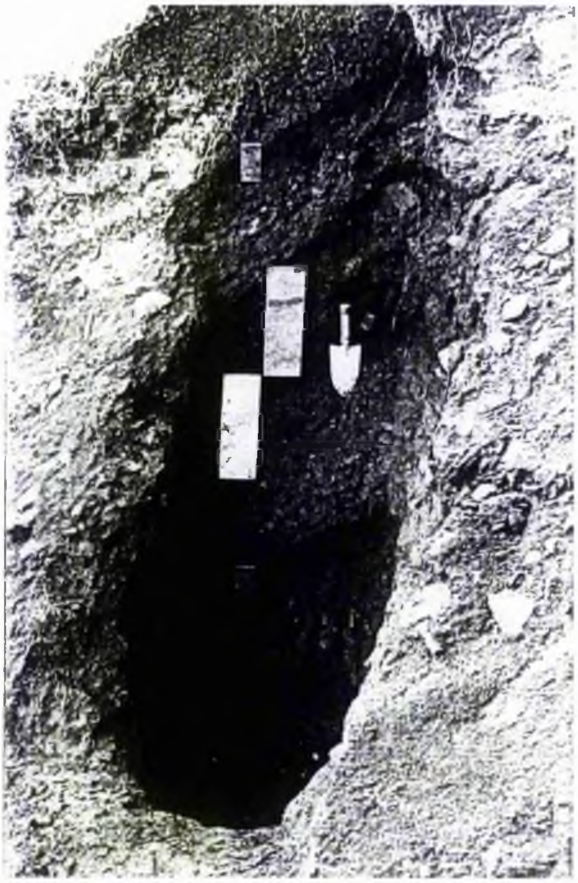


Figure 7.1. An arrangement of 10 cm and 30 cm stainless steel monolith tins for the collection of samples of buried soils at section T5,a cut through a relict talus accumulation at area 2, Trotternish.

Figure 7.2. A single 30 cm stainless steel monolith tin (extracted from section T1, area 2, immediately south of The Storr, Trotternish) containing two buried soil horizons and intercalated sediment units.

representation, calculated pollen percentages of <2% for an individual taxon at a given level are indicated by crosses, the number of which signifies the actual number of grains encountered.

7.3 History of reworking of relict talus slopes

The upper surfaces of relict talus slopes studied, in particular those on Trotternish, support widespread evidence of erosion and downslope mass transfer of rockfall detritus (chapter 4). Most slope failure scars are now vegetated and apparently relict. However, fresh debris flow deposits emanating from gullies upslope are suggestive of recent talus slope reworking, and many gullies, particularly those on Trotternish, appear to be intermittently active at present. Radiocarbon dating of soils overridden by gravitational slope failures was undertaken to determine the general chronology of erosion and downslope redistribution of talus debris. The results are reported below.

7.3.1 Radiocarbon dating

Seventeen radiocarbon dates were obtained for buried palaeosols underlying relict talus on Scottish mountains (Figure 7.3). However, certain limitations apply to the interpretation of ^{14}C dates for former soils. The bulk organic content of an individual soil may have experienced a long history prior to burial (Matthews, 1993). Consequently, a ^{14}C age for a buried soil underlying talus reflects the time elapsed since emplacement of overlying debris, but also the radiocarbon age of the constituent organic carbon prior to overriding by sediment (Matthews, 1980, 1981, 1993). The value of the latter may be interpreted as reflecting the 'mean radiometric residence time' (Geyh *et al.*, 1971), or 'apparent mean residence time' (AMRT; Scharpenseel and Schiffmann, 1977) of the organic component of the palaeosol. One implication of this is that a ^{14}C date for the top of a buried soil provides only a

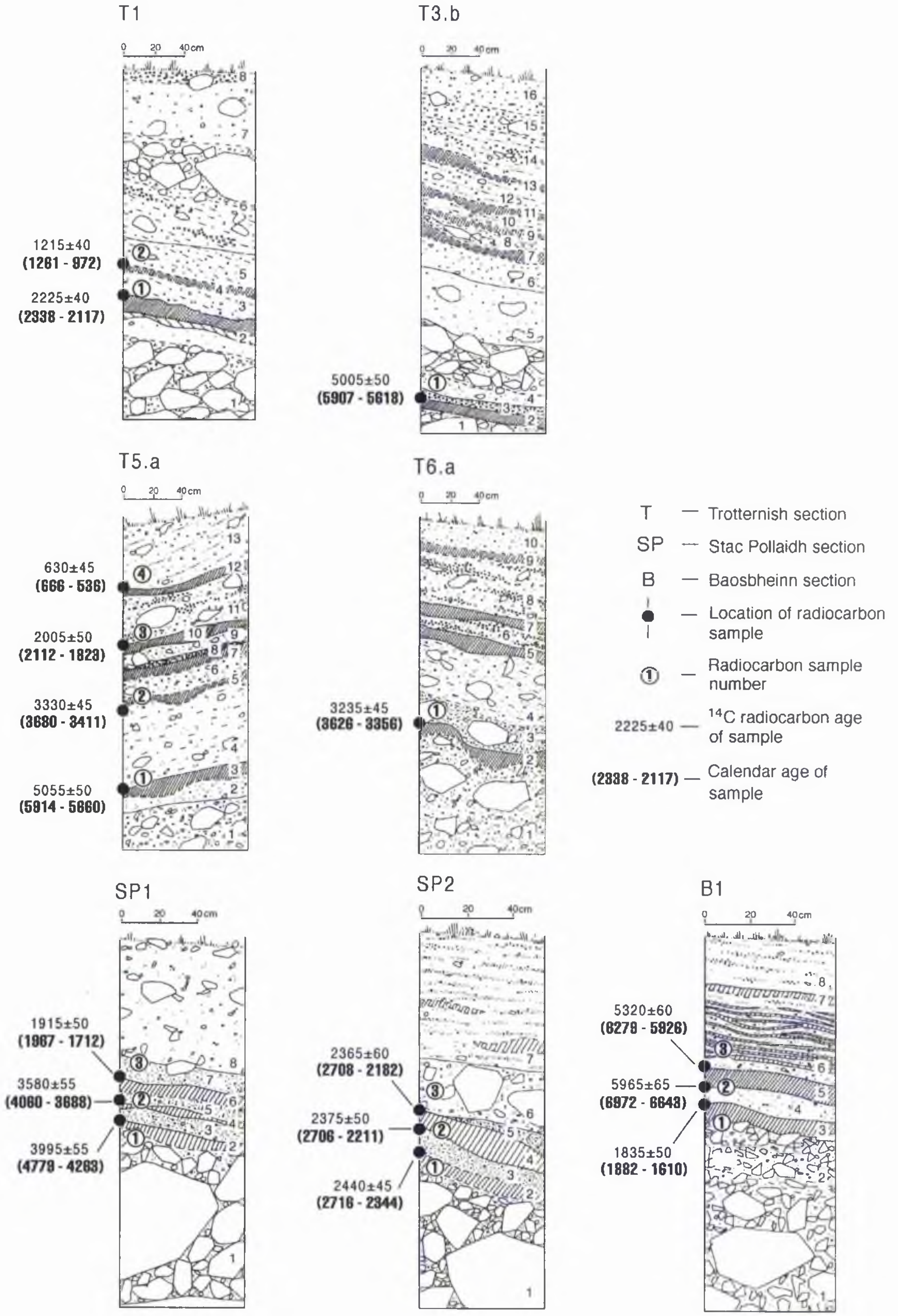


Figure 7.3. ^{14}C radiocarbon dates and calibrated calendar ages for buried soils underlying relict talus slopes in the Scottish Highlands. ^{14}C dates were transformed to calendar years using the conversion programme CALIB 3.0 rev. of Stuiver and Reimer (1993) and the calibration data of Stuiver and Becker (1993). Calendar age ranges are quoted at the 2σ level. No vertical exaggeration of scale. Key as in Figures 5.3 and 5.5.

maximal estimate of the timing of emplacement of overlying sediment. Furthermore, prior to burial, the age of organic material in a soil undergoes constant rejuvenation by the addition of fresh plant matter at the surface, and thus the AMRT of constituent organic carbon at burial is less than the true age of the soil (Scharpenseel and Becker-Heidmann, 1992; Wang *et al.*, 1996). Therefore, a radiocarbon date obtained for a buried soil must be regarded as minimal for the onset of soil formation (Matthews, 1980, 1981, 1993).

Careful sampling may, however, reduce such problems of AMRT. The ^{14}C age of a soil increases with depth (e.g. Scharpenseel, 1972, 1975; Matthews, 1980, 1981, 1991, 1993; Ellis and Matthews, 1984; Matthews and Caseldine, 1987; Wang *et al.*, 1996), possibly reflecting progressive down-profile mixing of particulate organic carbon, and consequently relatively close estimates of the date of burial and the onset of soil formation may be obtained if sufficiently thin samples are collected for the top and base of palaeosols respectively (Matthews, 1981, 1993; Harris *et al.*, 1987; Scharpenseel and Becker-Heidmann, 1992), a procedure adopted during the current work. Of the seventeen samples submitted for radiocarbon assay, fourteen were collected from the top of buried soils and thus yield maximal ages for the deposition of overlying sediment units. The three remaining samples correspond to the base of buried soils, and thus represent minimal ages for the onset of soil formation and periods of talus slope stability.

Trotternish

The timing of talus reworking on Trotternish is reconstructed using eight calibrated radiocarbon dates for buried soils revealed at gully sides (Figure 7.3 and Table 7.1). In addition to this data set, there are four previously published radiocarbon dates for organic layers overlain by talus debris (Innes, 1983d). Innes interpreted diamictic sediment overlying buried organic horizons as representing

Table 7.1. Radiocarbon ages for buried organic-rich palaeosols underlying relict talus slopes at study sites.

Section	Radiocarbon sample No.	Unit No.	Sample depth (cm)	Laboratory code	Radiocarbon age (^{14}C years BP)	$\delta^{13}C$ $^0/_{00}$	Calibrated age* calendar years BP (2σ level)
Trotternish samples							
T1	1	2	148	SRR-5652	2225±40	-29.2%	2338-2117 †
T1	2	4	126	SRR-5653	1215±40	-28.8%	1261-972 †
T3.b	1	2	225	SRR-5654	5005±50	-28.8%	5907-5618 †
T5.a	1	3	190	SRR-5655	5055±50	-24.9%	5914-5660 †
T5.a	2	5	134	SRR-5656	3330±45	-26.5%	3680-3411 #
T5.a	3	10	89	SRR-5657	2005±50	-27.9%	2112-1823 †
T5.a	4	12	50	SRR-5658	630±45	-27.2%	666-536 †
T6.a	1	2	141	SRR-5659	3235±45	-27.2%	3626-3356 †
Trotternish samples (Innes, 1983c)							
-	-	-	*c.* 170	SRR-2013	2450±40	-	2716-2349 #
-	-	-	*c.* 160	SRR-2012	1990±70	-	2118-1730 †
-	-	-	*c.* 135	SRR-2011	1240±40	-	1264-1008 #
-	-	-	*c.* 125	SRR-2010	720±40	-	708-563 †
North-west Highland samples							
SP1	1	2	97	SRR-5895	3995±55	-28.0%	4779-4263 †
SP1	2	4	88	SRR-5896	3580±55	-27.9%	4060-3688 †
SP1	3	6	74	SRR-5897	1915±50	-28.2%	1967-1712 †
SP2	1	2	98	AA-24174	2440±45	-28.6%	2716-2344 †
SP2	2	4	87	AA-24175	2375±50	-28.6%	2706-2211 #
SP2	3	4	79	AA-24176	2365±60	-28.5%	2708-2182 †
B1	1	3	76	AA-24171	1835±50	-27.3%	1882-1610 †
B1	2	5	68	AA-24172	5965±65	-27.7%	6972-6643 #
B1	3	5	59	AA-24173	5320±60	-28.1%	6279-5926 †

† Maximal age for the the burial of soil layers.
# Minimal age for the onset of pedogenesis.

*Radiocarbon ages were transformed to calibrated calendar age ranges using the conversion programme of Stuiver and Reimer (1993) and the calibration data of Stuiver and Becker (1993). The calibrated age range presented above is given at the 2σ level.

coarse rockfall detritus and inwashed interstitial fine particles. In the light of current findings (chapter 5), however, these deposits are here reinterpreted as reflecting intermittent debris flow accumulation associated with reworking of talus detritus. In terms of this interpretation, radiocarbon dates published by Innes for the base of buried soils on Trotternish (SRR-2013 and SRR-2011; Table 7.1), represent minimal dates for the onset of pedogenesis at the upper surface of debris flow deposits, and radiocarbon ages for the tops of buried soils (SRR-2012 and SRR-2010; Table 7.1) represent maximal dates for overriding by sediment redeposited from upslope. The analyses that follow examine respectively the evidence for the onset of erosion and reworking of relict talus debris on Trotternish, possible hiatuses during the period of sediment accumulation, some rates of sediment deposition, apparently synchronous reworking of different sectors of the slope, and finally the timing of periods of talus stability.

Radiocarbon dates of 2225±40 yr BP (2338-2117 cal yr BP) and 5005±50 yr BP (5906-5617 cal yr BP) were obtained for the tops of the lowermost palaeosols at sections T1 and T3.b respectively (Figure 7.3). These buried soils are interpreted as immediately overlying *in situ* rockfall talus, and the above radiocarbon ages are therefore inferred as representing the commencement of reworking of rockfall detritus at these locations. However, a radiocarbon date of 5050±50 yr BP (5915-5660 cal yr BP) was obtained for the top of soil unit 3 at section T5.a. This soils is interpreted as being underlain by older debris flow and surface wash deposits, indicating earlier local reworking of talus debris. Furthermore, the lowermost buried soil (sediment unit 2) at section T6.a, which apparently overlies a massive debris flow diamicton, yielded a date of 3235±45 yr BP (3626-3356 cal yr BP), also raises the possibility of early or mid Holocene origin for reworking of talus debris at this location. Thus the calibrated radiocarbon dates for the lowermost buried soils at sections T1, T3.b, T5.a and T6.a, suggest at least localised reworking of talus prior to *c*. 6 cal ka BP, though the upper *c*. 1.3 to

2.3 m of talus debris at excavated sections through talus on Trotternish, apparently representing the bulk of the deposit, reflect accumulation during the late Holocene after *c.* 6 cal ka BP.

Contacts between individual sediment units appear conformable over short distances (Figure 7.3), implying that deposition of multiple superimposed sediment units was largely uninterrupted by erosion throughout the period of accumulation. At section T5.a, however, soil unit 3 yields a maximal date of 5050±50 yr BP (5913-5659 cal yr BP) for overriding by a thick debris flow diamicton (sediment unit 4). A sample from the base of a soil (unit 5) developed on the upper surface of the sediment unit 4 yields a minimal date of 3330±45 yr BP (3680-3411 cal yr BP). These dates indicate that at least *c.* 2 cal ka apparently separates burial of the lower soil and initial pedogenesis at the upper, a result apparently inconsistent with the accumulation of a single intervening debris flow diamicton, the emplacement of which is interpreted to be rapid. This anomaly appears to represent a hiatus in sediment aggradation at this location, possibly reflecting erosion of the surface of the lower soil (unit 3) prior to the emplacement of overlying diamictic debris (unit 4), or alternatively, erosion of the top of sediment unit 4 prior to the development of the upper soil (unit 5) now represented. The latter hypothesis is in conformity with abundant evidence of reworking of debris flow tops by surface wash (chapter 5). Although erosion surfaces are not apparent in narrow vertical sections excavated through talus (Figures 5.5-5.8 and 5.14-5.19; Figure 7.3), the above interpretation appears to be consistent with laterally-extensive gully sections unobscured by side-wall collapse that exhibit numerous cross-cutting relationships between individual beds (Figure 5.4). One implication of this finding is that the depositional sequences evident at individual sections may be incomplete, thus sounding a cautionary note for the reconstruction of talus history from internal structure evident at only a limited number of sections through the deposit.

Assuming that most contacts are conformable, however, dating of superimposed buried soils permits tentative reconstruction of rates of sediment accumulation. Radiocarbon dates of 2225±40 yr BP (2338-2117 cal yr BP) and 1215±40 yr BP (1262-972 cal yr BP) were obtained for buried soils (units 2 and 4 respectively) overlain by wash sediments at section T1. These dates suggest that slope wash deposition at this location corresponds to approximately 45 cm of surface aggradation over a period of between *c.* 0.9 to 1.4 cal ka. In addition, radiocarbon dating of buried soils above and below a thinly bedded sequence of multiple debris flow deposits and slope wash sediments (sediment units 5 to 11 at section T5.a; Figure 7.3), indicates approximately 55 cm of accumulation over a period of between *c.* 1.3 to 1.9 cal ka. These results suggest relatively long phases of talus evolution characterised by minor reworking and low rates of surface aggradation. Such behaviour is in contrast to the inferred rapid emplacement of thick, discrete debris flow diamictons (e.g. section T1, unit 6, and section T5.a, unit 4), that often comprise the bulk of the deposit. These contrasting modes of talus slope evolution are considered further in chapter 8.

Coincidence of timing is evident for ground surface burial at section T3.b (unit 2) and at section T5.a (unit 3) at *c.* 5.9-5.6 cal ka BP, and may represent a contemporaneous reworking event at two different sectors of the slope. Similar maximal calendar ages are also evident for the overriding of unit 2 at section T1, unit 3 at section T5.a and the lowermost organic layer described by Innes (1983d), from which radiocarbon sample SRR-2012 is derived, and may indicate synchronous local reworking of talus at *c.* 2.3-1.7 cal ka BP. Furthermore, a correspondence of timing for the burial of unit 12 at section T5.a and the uppermost organic layer described by Innes (radiocarbon sample SRR-2010), suggests concurrent reworking of two different portions of the talus slope at *c.* 0.7-0.5 cal ka BP. These findings indicate apparent correspondence between the timing of sediment deposition at section T5.a and the section by Innes (1983d), a result that lends support to reinterpretation of the latter in terms of debris flow accumulation rather than rockfall deposition and inwashing of fines. More generally, the above coincidences of timing for overriding of different sectors of the Trotternish talus slope may represent evidence of three phases of broadly synchronous localised reworking of the talus sediments (i.e. at *c*. 5.9-5.6 cal ka BP, *c*. 2.3-1.7 cal ka BP and *c*. 0.7-0.5 cal ka BP).

Assuming that the buried organic layers described by Innes (1983d) represent *in situ* soils, dates obtained for these horizons permit calculation of minimal periods of talus slope stability at this location. Radiocarbon dates published by Innes (Table 7.1), suggest an initial period of stability after *c*. 2.5 cal ka BP that lasted for at least *c*. 0.6±0.4 cal ka, and a second stable period beginning at *c*. 1.1 cal ka BP and lasting for a minimum of *c*. 0.5±0.2 cal ka. A maximal age of *c*. 2.3-2.1 cal ka BP for burial of the upper soil (sediment unit 5) at section T1, however, coincides with the first period of stability suggested above, and thus represents further evidence of the localised nature reworking. Thus individual buried soils do not necessarily indicate widespread talus slope stability.

Talus sites on the NW mainland

Nine samples of organic-rich sediment underlying talus slopes in the NW Highlands were submitted for ^{14}C radiocarbon assay (Figure 7.3). Six dates were obtained for buried soils at two sections (SP1 and SP2) excavated through talus at Stac Pollaidh. In addition, three radiocarbon dates were returned for samples collected from buried organic layers within talus sediments on Baosbheinn (section B1). However, some of these dates appear anomalous and require circumspect interpretation.

Radiocarbon dates for the tops of three buried soils within talus deposits at Stac Pollaidh (section SP1; Figure 7.3), appear to represent reliable maximal ages for the burial of former ground surfaces. The lowermost soil (sediment unit 2), interpreted as developed on *in situ* rockfall detritus, yields a maximal date of 3995±55 yr BP (4779-4263 cal yr BP) for the deposition of overlying surface wash sands and gravels, and thus approximates the onset of talus slope reworking at this location. Samples submitted for the tops of two stratigraphically higher palaeosols at section SP1 yielded dates of 3580±55 yr BP (4060-3688 cal yr BP; sediment unit 4), and 1915±50 yr BP (1967-1712 cal yr BP; sediment unit 6), that represent maximal ages for the emplacement of overlying surface wash sediments at both these levels. The above dates indicate approximately 35 cm of surface wash accumulation over *c.* 2.3 to 3.1 cal ka, thus representing a low rate of accumulation of reworked talus sediment. The bulk of the deposit overlying buried soils at section SP1 appears, however, to reflect the rapid emplacement of a single debris flow unit.

In terms of their morphology, organic-rich layers (sediment units 2 and 4) sampled for radiocarbon assay at section SP2 (Figure 7.3) are structureless, contain numerous rootlets (subsequently removed from radiocarbon samples), exhibit no constituent clasts or obvious textural variations, and are thus suggestive of decomposed Ao horizons of *in situ* buried soils. However, three radiocarbon samples collected from different stratigraphic levels within these organic-rich layers collectively yield a maximal age range of only 2485-2305 yr BP (2716-2182 cal yr BP; Table 7.1), and thus exhibit a negligible age variation with depth. This result suggests that processes other than *in situ* pedogenesis may have influenced these dates. Some possible explanations of this anomaly are as follows. Firstly, it may reflect downwash of younger, particulate carbon from the upper organic horizon (sediment unit 6), thus lowering the apparent ^{14}C ages of stratigraphically lower samples (Figure 7.3). Physical mixing of bulk organic carbon may be facilitated by the free-draining, coarse, felsic sands that comprise much of the intervening deposit. Secondly, though rootlets were removed from radiocarbon samples prior to submission for dating, the high degree of similarity between the dates obtained may reflect contamination of the lower organic-rich layer by incorporation of undetected rootlet fragments (possibly decomposed) from above. Thirdly, despite morphological evidence to the contrary, the possibility that either the upper layer (sediment unit 4) or both horizons (sediment units 2 and 4) represent fragments of former soils eroded and redeposited from upslope cannot be excluded. The absence of a significant increase in radiocarbon age with depth at the upper organic layer (sediment unit 4), a characteristic previously attributed to *in situ* soils buried beneath diamictic sediment (e.g. Matthews, 1980, 1981, 1991, 1993; Ellis and Matthews, 1984; Matthews and Caseldine, 1987), may support the suggestion that sediment unit 4 represents a redeposited organic sediment derived from eroded soils upslope. Finally, organic-rich sediment sampled from section SP2 and submitted for radiocarbon assay may have become contaminated, either during collection, cold storage or transit. It is difficult however, to conceive where such contamination may have originated given the careful extraction and subsequent stowage of individually sealed and clearly labelled samples (section 7.2). In terms of reconstructing the history of downslope mass transfer of rockfall debris at Stac Pollaidh, the above findings are open to two possible interpretations. Either they represent a maximal age for burial of sediment unit 2, and thus approximate the onset of talus reworking at this location, or they provide a date for overriding of sediment unit 4 by slopewash sands and gravel.

Samples of organic-rich sediment underlying talus debris at Baosbheinn and submitted for radiocarbon assay collectively yield an ambiguous result. A date of 1835±50 yr BP (1882-1610 cal yr BP) for the lowermost organic layer (section B1, unit 3; Figure 7.3) appears to be inconsistent with ages of 5320±60 yr BP (6279-5926 cal yr BP), and 5965±65 yr BP (6972-6643 cal yr BP) obtained for the top and base respectively of an overlying organic horizon (sediment unit 5). There are no clear grounds for determining the specific cause of this apparently anomalous relationship; however, several possibilities are explored below. Radiocarbon dates obtained for the upper organic horizon (sediment unit 5) may reflect inwashing of older organic carbon from eroded soils upslope, or contamination during collection, transit or cold storage. In this case, a maximal date of *c.* 1.6 to 1.9 cal ka BP for overriding of the stratigraphically lower organic layer by sands and gravel may approximate the onset of surface wash deposition at this location. If so, the broad correspondence between this calibrated calendar age and that for burial of sediment unit 6 at section SP1 (*c.* 1.7 to 2.0 cal ka BP), may be inferred to indicate a possible phase of generally synchronous reworking of relict talus in the NW Highlands. Alternatively, the upper organic horizon may represent an *in situ* soil, an interpretation consistent with the apparent increase in ^{14}C age with depth which is similar to that previously observed within buried, mature *in situ* palaeosols in southern Norway (Matthews, 1980, 1981, 1991, 1993; Ellis and Matthews, 1984; Matthews and Caseldine, 1987). In terms of this possibility, the anomalous date returned for the lowermost radiocarbon sample may reflect contamination during collection, transport or cold storage. The possible source of such contamination is however, unknown, and difficult to envisage. One possible implication of this interpretation is that reworking of talus debris at Baosbheinn predates *c.* 6 cal ka BP and thus originates in the first half of the Holocene.

The problems discussed above of truncation, contamination, and the apparent mean residence time (AMRT) of buried soils highlight the potential for erroneous interpretation of individual radiocarbon dates obtained for such layers. Despite specific problems associated with individual dates, consistent agreement between study sites in terms of the broad timing of overriding of former talus surfaces suggests that radiocarbon ages reported above (Table 7.1) represent a reasonably reliable, albeit incomplete, chronology for talus reworking in northern

Skye and the NW Highlands of Scotland. However, radiocarbon dates for the base of buried soils, and interpreted above as approximating minimal ages for the commencement of talus slope stability, are of limited use in terms of reconstructing the general behaviour of relict talus slopes. The principal difficulty associated with such dates is that a radiocarbon age for decomposed organic material accumulated on, for example, the upper surface of a debris flow diamicton, partly reflects the age of emplacement of the underlying deposit. Put another way, a minimal date for the onset of pedogenesis at a specific stratigraphic level is partly dependent upon the timing of an antecedent phase of talus reworking. Furthermore, there is evidence (see above) for soil formation and concomitant reworking of relict talus debris at different sectors of the slope, and thus minimal ages obtained for buried soils may not be representative of phases of widespread talus slope stability, but only localised soil development. Consequently, whilst radiocarbon dates for the base of soils may effectively be used in association with dates for the top of such horizons to establish a minimal duration for phases of local talus slope stability at individual sections, they do not necessarily indicate phases of widespread talus stability.

7.3.2 Synchronous reworking of talus at study sites

To determine the synchroneity or otherwise of reworking of relict talus accumulations on Trotternish and at the study sites in NW Scotland, maximal calendar ages for the burial of former talus surfaces by debris flow and slope wash deposition are plotted in Figure 7.4. As previously noted, there is evidence of at least broadly synchronous local reworking of talus on Trotternish at *c.* 5.9-5.6 cal ka BP, *c.* 2.3-1.7 cal ka BP and *c.* 0.7-0.5 cal ka BP (section 7.3.1). With the exception of the last-mentioned, these periods correspond to possible episodes of apparently synchronous reworking activity on talus in NW Scotland at *c.* 6.3-5.6 cal ka BP and *c.* 2.7 to 1.6 cal ka BP, though the validity of the earlier of these is

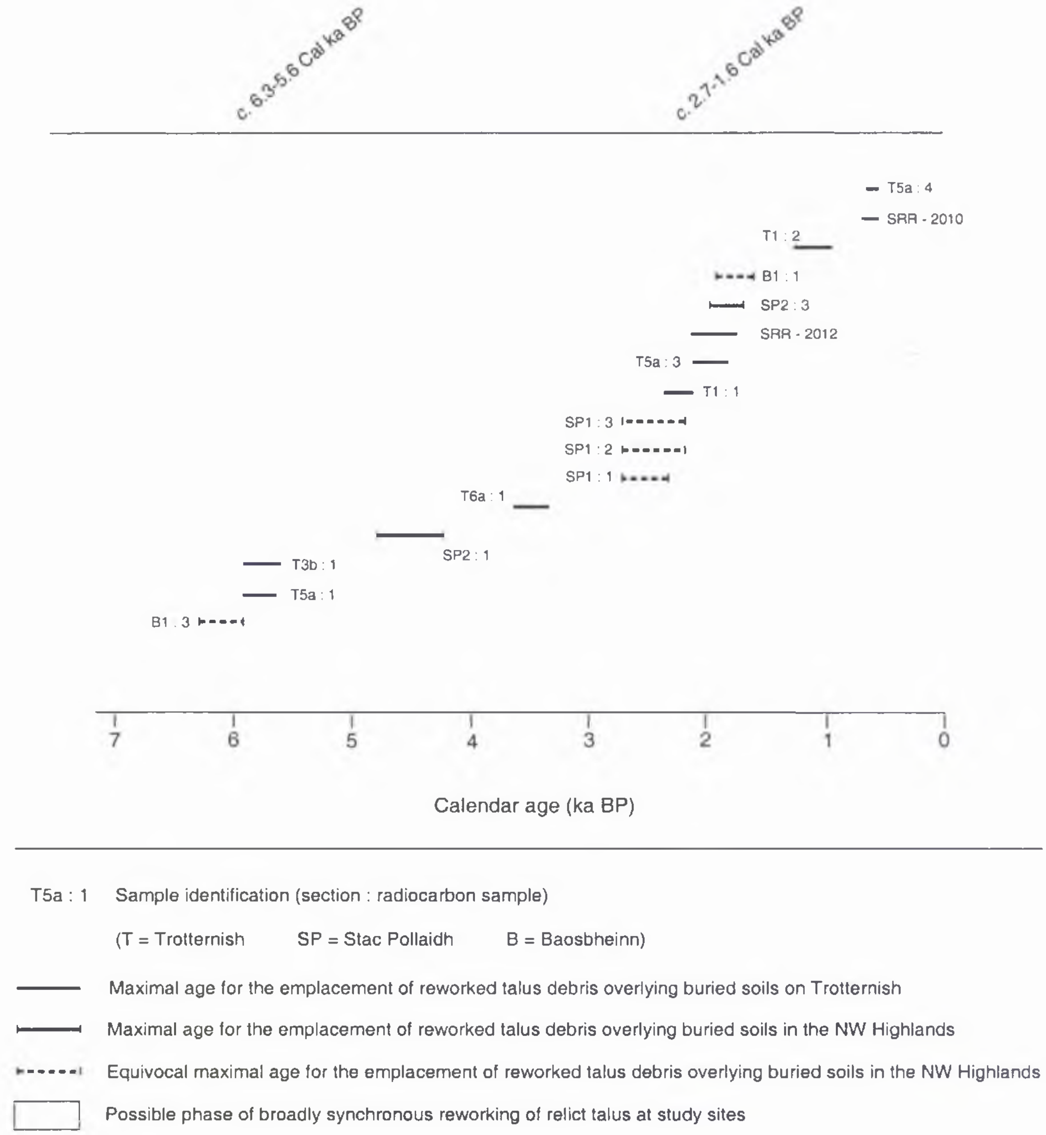


Figure 7.4. A comparison of maximal calendar ages for the emplacement of debris flow and surface wash deposits immediately overlying buried soils evident at excavated sections cut through relict talus slopes at Trotternish and the NW study sites. Conventional ^{14}C radiocarbon dates were transformed to calendar years using the CALIB 3.0 conversion programme of Stuiver and Reimer (1993) and the calibration data of Stuiver and Becker (1993). The calibrated age range is given at the 2σ level.

uncertain due to the inversion of radiocarbon dates obtained for buried soils at Baosbheinn.

A cluster of calendar ages for the burial of former ground surfaces at Trotternish, Stac Pollaidh and Baosbheinn at *c*. 2.7 to 1.6 cal ka BP presents a stronger argument for broadly synchronous and widespread reworking of talus debris in the Scottish Highlands. In sum, the data thus suggest non-random intermittent reworking of relict talus slopes over the past *c*. 6 cal ka BP. It should be noted, however, that five contributing dates on Figure 7.4 for buried soils at the NW study sites are of uncertain validity, and thus the suggested reconstruction of the timing of talus reworking is based upon a fairly limited number of reliable calibrated radiocarbon dates. On balance therefore, the findings reported above must be regarded as provisional pending further research. The data regarding the timing of talus slope instability will ultimately contribute to a joint research project undertaken in collaboration with C.K. Ballantyne and A. Curry at the University of St Andrews, intended to determine the timing and possible causes of apparent mid to late Holocene slope instability in the Scottish Highlands.

7.3.3 Recent erosion: Trotternish

Talus slopes on Trotternish, unlike those studied elsewhere in the Scottish Highlands, exhibit widespread evidence of recent intermittent erosion and downslope mass transport. Active gullies are superimposed on a palimpsest of vegetated relict slope failures of variable size and age (chapter 4). Consequently the upper surface of such slopes often comprises both stable, vegetated sectors and fresh discrete gullies. This bipartite classification of talus micro-relief reflects the juxtaposition of two distinctive geomorphic environments, the former characterised by quiescence and stability of form, the latter undergoing rapid rates of change. Several active gullies are located within broad, vegetated, relict slope failures, suggesting stabilisation of erosion scars prior to the onset of more recent talus reworking. Moreover, the rarity of youthful gullies and the relatively large size of most forms suggests that they are of a similar maturity

The onset of currently active reworking appears to have been relatively rapid given the similar inferred age of many gullies. The maximal age of such features is, however, unclear. Examination of aerial photographs of Trotternish from 1959, 1988, 1991 and 1995 indicates that the extent of gully erosion of talus has remained broadly similar over the intervening 36 years, and that gullying was already widespread prior to 1959. Using lichenometry and observations of surface lowering at gully sides, Innes (1982) speculated that recent gullying postdates the early 1930s. This estimate is, however, prone to error as younger debris flows may override older deposits, thus introducing a bias favouring lichenometric dating of the former (Innes, 1983b; Ballantyne, 1991b; Luckmann, 1992; Kotarba, 1997). In sum, aerial photographs and the findings of Innes (1982), indicate that the current phase of gullying of relict talus on Trotternish has a long history, a finding consistent with the large size of most gullies.

7.3.4 Summary

The principal conclusions regarding the timing of reworking of relict talus slopes in the Scottish mountains are as follows.

1. The onset of the modification of talus accumulations on Trotternish by erosion and mass transport locally predates *c.* 6 cal ka BP. Reworking of rockfall sediment may also predate *c.* 6 cal ka BP in the NW Highlands, though the validity of this date (obtained for a buried organic layer at Baosbheinn) is uncertain.

2. The bulk of the reworked talus sediments at all study sites apparently represents localised, intermittent late Holocene accumulation. Sediment accumulation appears to result from either the rapid emplacement of thick debris flow diamictons, or the deposition of slope wash sediment and small, fine-grained debris flows over periods of up to 3 ka.

3. Six radiocarbon dates obtained for palaeosols underlying relict talus slopes at the NW study sites yield ages that are difficult to interpret in terms of depositional history. The reasons for the inconsistencies are unclear; however, they may reflect contamination of palaeosols by down-washing of particulate organic carbon or rootlet penetration from stratigraphically higher soils, inwashing of organic-rich sediment from eroded soils upslope, or during collection, cold storage or transit.

4. Broad coincidences of timing are evident for the burial of different sectors of a relict talus slope on Trotternish at *c.* 5.9-5.6 cal ka BP, *c.* 2.3-1.7 cal ka BP and *c.* 0.7-0.5 cal ka BP. There is evidence for two episodes of more widespread talus slope instability across NW Scotland at *c.* 6.3-5.6 cal ka BP and *c.* 2.7-1.6 cal ka BP. The validity of the former of these is, however, uncertain.

5. The timing of the onset of recent gully incision on Trotternish is unknown. Consultation of aerial photographs, however, indicates gully maturation prior to 1959, a finding consistent with the observations of Innes (1982) who suggested that gully evolution began in the early 1930s. The possibility that the origins of such features are much older cannot, however, be excluded.

7.4 The possible causes of reworking

The evidence for possible causes of erosion and downslope mass transport of talus debris on Scottish mountains is reviewed in the following sections. In section 7.4.1 the extent to which reworking of the upper levels of talus is conditioned by the physical characteristics of such deposits, in particular the surface gradient and abundance of internal fine-grained sediment, is examined. Section 7.4.2 reports the results of testing the hypothesis that anthropogenic disturbance of local vegetation cover has been responsible for erosion and reworking of talus sediments. Finally, in section 4.7.3, the evidence for climate-induced (*sensu* Eybergen and Imeson, 1989) talus slope instability is reviewed.

7.4.1 Talus characteristics

The following discussion evaluates the possibility that the surface relief and the internal composition of relict talus accumulations have contributed to the subsequent failure and reworking of such deposits. In total, 43 transects were surveyed up talus accumulations at field sites to test the hypothesis that the steep inclination of relict talus slopes in the Scottish Highlands may be partly responsible for erosion and reworking of such features. The results demonstrate that the upper slope gradients of ungullied relict talus range from 32.8° to 47.1°, with a mean value of 37.5°±0.44°, where the range is expressed as one standard error of the mean value. Significantly, all surveyed upper rectilinear slope gradients are in excess of the suggested 30° minimum gradient for debris flow initiation on drift-mantled slopes in the Scottish Highlands (Ballantyne, 1981; Innes, 1983a). Thus the steep surface gradient of the upper slopes of relict talus accumulations at study sites represent an important precondition for reworking of such deposits by debris flows.

Several authors have observed that the internal sedimentary characteristics of hillslope sediments may facilitate the failure of such deposits (Rapp, 1987; Nyberg and Lindh, 1990; Jonasson, 1993). Others have suggested that the fine-grained products of sub-surface weathering may infill internal voids, ultimately facilitating the build-up of positive porewater pressures during rainstorms and thus subsequent failure and mass transport (e.g. Costa and Jarret, 1981; Florsheim and Kellor, 1987; Bovis and Dagg, 1987; Zicheng and Jing, 1987; Wohl and Pearthree, 1991). Statham and Francis (1986) suggested that such internal weathering of coarse rockfall debris may be partly responsible for the erosion of the upper slopes of mature talus accumulations. Analyses of samples of talus sediments from Trotternish, however, failed to substantiate this hypothesis. Instead, it has been argued above (chapter 6) that granular weathering of rockwalls upslope represents the dominant source of internal fine-grained sediment at this location, with fine particles falling on to and being washed into the accumulating talus. The net result of the enrichment of talus debris by inwashing of fines is inferred to be a potential lowering of the factor of safety of such deposits, and thus potential progressive reduction of the intrinsic geomorphic threshold for the initiation of sliding failure and debris flow activity. This effect may partly explain the apparent concentration of mass movement activity within the latter half of the Holocene. The rate of decline of the potential internal threshold for reworking of talus deposits is, however, unknown. Furthermore, current findings cannot exclude the possibility that confinement of talus reworking to the past *c.* 6 cal ka simply reflects a climatic or anthropogenic signal.

7.4.2 Anthropogenic disturbance

Destabilisation of drift-mantled hillsides in upland Britain has, in some instances, been attributed to anthropogenic interference with natural vegetation covers. For example, accelerated rates of late Holocene lacustrine sedimentation at

Braeroddach Loch in the Scottish Highlands (Edwards and Rowntree, 1980), Lough Catherine in Northern Ireland (Snowball and Thompson, 1990) and Llyn Geirionydd in north Wales (Snowball and Thompson, 1992), have been attributed to Neolithic woodland clearance and the subsequent diffusion of sedentary agriculture over the respective catchments. Deposition of Holocene terraced river valley-fills (e.g. Macklin and Lewin, 1986) and alluvial fans (e.g. Crampton, 1969) in the Welsh uplands has been interpreted as a likely consequence of accelerated slope erosion up-stream, and has been equated with catchment deforestation and subsequent local expansion of Iron Age farms.

Slope-foot debris cone accumulation in the Bowland fells of Cumbria appears to have occurred between approximately 4680±80 yr BP (5594-5053 cal yr BP) and 1780±70 yr BP (1874-1528 cal yr BP), followed by a more widespread phase of aggradation postdating *c.* 1200±70 yr BP.(1286-954 cal yr BP). Harvey and Renwick (1987) related the earlier phase of debris cone accumulation to disturbance of woodland, apparently coincident with Bronze Age or Iron Age settlement expansion in NW England. However, the extent to which cone formation also reflects a possible increase in rainfall at around 2.5 ka BP (*c.* 2.7-2.3 cal ka BP) with the onset of the sub-Atlantic chronozone (Lamb, 1977, 1982) is uncertain. The later aggradational phase (*c.* 1.1 ka BP) was attributed by Harvey and Renwick to clearance or disturbance of local woodland and the introduction of extensive sheep farming associated with local expansion of Viking settlement in the tenth century AD.

Overriding of stable alluvial terraces in the Howgill Fells of Cumbria by debris flows at around 940±95 yr BP (1053-668 cal yr BP), has also been associated with the introduction of sheep farming by Viking settlers (Harvey *et al.*, 1981). More recently, Harvey (1996) has published ages for multiple buried soils in the Howgill Fells developed on former ground surfaces and overlain by colluvium. The humic fraction of the lowermost soil in the sequence yielded a maximal date of 1210±50 yr BP (1263-968 cal yr BP) for burial, and thus represents further evidence of gully erosion and fan deposition in the Howgills originating in the ninth and tenth centuries AD. The formation of late Holocene slope-foot debris cones in The Black Mountain of south Wales may also have been triggered by sheep grazing upslope (Statham, 1976b). The possible links between overgrazing (particularly by sheep) and hillslope erosion are, however, imperfectly understood (*cf.* Pye and Paine, 1983; Innes, 1983c; Ballantyne and Whittington, 1987; Wilson, 1989; Ballantyne, 1991b), and thus remain conjectural.

Moorland fires are known to have initiated erosion of drift-mantled slopes in the Scottish Highlands (McVean and Lockie, 1967; Innes, 1983b). Innes (1982, 1983b, 1997) dismissed progressive weathering of drift and climate change as probable causes of an apparent recent intensification of debris flow activity in the Scottish Highlands, citing instead burning of moorland for improvement of sheep and deer grazings on Highland estates during the late nineteenth and early twentieth centuries AD as possible causal factors. Innes's arguments seem less applicable, however, where debris flows have originated in rock gullies, upslope beyond the likely influence of fire (Ballantyne, 1993). A stronger argument for the effects of burning in triggering sediment reworking are presented by Brazier *et al.,* (1988) who demonstrated a probable causal relationship between burning and clearance of woodland for agriculture and fluvial reworking of a debris cone in Glen Etive after *c.* 550±50 yr BP (650-508 cal yr BP).

Possible anthropogenic causes of slope instability are not, however, confined to land use changes. Several authors (e.g. Flower and Battarbee, 1983; Battarbee *et al.*, 1985) have suggested that increased acidification of upland water bodies in the nineteenth and early twentieth centuries AD represents the effects of deposition of air-borne industrial pollutants. Innes (1997 and in Ballantyne, 1991b) suggested that upland mosses are sensitive to acidification, and that any reduction in moss cover may have enhanced infiltration rates and thus had a detrimental effect on the factor of safety of affected slopes during rainstorms.

The hypothesis that anthropogenic interference with upland vegetation cover is responsible for triggering erosion and reworking of relict talus debris is tested below using palaeoecological data derived from analyses of palynomorph and charcoal deposits from buried soils within relict talus accumulations on Trotternish.

Palynological analyses

Using the methods outlined in section 7.2, three pollen diagrams (Figure 7.5-7.7) were produced for buried soils within talus accumulations on Trotternish. Analysis of soil pollen diagrams requires different techniques to those traditionally adopted for the interpretation of sub-fossil pollen extracted from peat beds or lacustrine gyttjas. According to Dimbleby (1985), recently deposited palynomorphs are apparently locked into a soil in some form of aggregate, possibly humic, and are thus immobile. Redistribution of individual pollen grains is, however, inferred following breakdown of soil aggregates, though down-profile displacement of individual grains is thought to be slow (*c.* 100 mm in 300 years for a studied podzol; Dimbleby, 1985). The crude distribution of constituent soil palynomorphs was modelled by Dimbleby (1985). In terms of the percentage frequency of total land pollen the model predicts high values for upper and lower levels of a soil. The former reflects addition of fresh palynomorphs at the surface, and the latter represents down-profile translocation and accumulation of older pollen grains resistant to decomposition. A significant implication of this model is that palynomorphs of variable derivation and age may potentially be resident at any given stratigraphic level in the soil.

Some buried soils studied on Trotternish (e.g. section T1, unit 2, and section T5.a, unit 5; Figures 7.5 and 7.6) exhibit relatively high percentages (and concentrations) of Pteropsida (monolete) indet. spores near the base. This spore is extremely resistant to erosion and its concentration in the lower levels of soils is consistent with the predicted distribution of resilient grains advanced by Dimbleby (1985). Furthermore, within individual palaeosols the highest frequencies of heavily degraded unidentifiable pollen grains are often recorded near the lower contact (eg. section T1, unit 2; and, section T6.a, unit 5; Figures 7.5 and 7.7 respectively). This result possibly represents mechanical damage of palynomorphs associated with down-washing and relocation, and is thus in general conformity with the Dimbleby model. These findings suggest that organic-rich layers overridden by talus debris represent undisturbed buried soils for which valid palynological examination may be undertaken.

Pollen diagrams for buried palaeosols at sections T1, T5.a and T6.a (Figures 7.5-7.7 respectively) exhibit little variation in pollen taxa with depth. All exhibit high frequencies of Poaceae (14-51%) and, with the exception of soil units 2 and 7 at section T6.a, *Calluna* (10-60%). The high representation of these taxa is interpreted as suggestive of a similar habitat to that currently evident on Trotternish, with herbaceous swards containing a component of low heath on free-draining talus slopes. The extent to which high palynomorph representation of *Calluna* represents inblown grains from adjacent *Calluna*-dominated lowland is, however, open to conjecture. With only one exception, pollen assemblages for individual buried soils exhibit a significant component of *Plantago lanceolata,* a taxon traditionally associated with colonisation of disturbed mineral substrates, and thus suggestive of talus slope reworking. Consequently, relatively low frequencies of *Calluna* palynomorphs (<2-14%) and relatively high levels of *Plantago lanceolata* pollen grains (9-28%) counted for buried soils 2 and 7 at section T6.a, may be inferred to represent erosion of formerly stable open-heath vegetation cover and subsequent colonisation of disturbed ground by the latter taxon.

Arboreal taxa are poorly represented (Figures 7.5-7.7). Recorded frequencies of *Betula* and *Pinus* palynomorphs (generally < 3% for each taxon) are sufficiently low to suggest inblowing from outside the immediate vicinity of studied palaeosols. However, slightly higher levels of *Alnus* palynomorphs (2-7%) counted for soil units 5 and 7 in section T5.a, and the base of soil unit 2 at section T1, may possibly indicate the localised establishment of alder carrs after *c*. 3.5 cal ka BP and prior to *c*. 2.2 cal ka BP. Possible expansion of alder at this time, probably in wet-land sites adjacent to sheltered stream courses, is approximately coincident with proposed climatic wettening following the onset of the sub-Atlantic chronozone (Lamb, 1977, 1982), and may indicate increased amounts of precipitation for NW Scotland at this time, the implications of which are examined below. The recorded frequency of *Corylus* palynomorphs is relatively high for buried soils at sections T1 (<2-14%) and T5.a (<2-15%), but low for those investigated at section T6.a (<2-3%), possibly representing localised Holocene growth of this shrub. The upward decline in percentage frequencies of *Corylus* exhibited in soil unit 2 of section T1, from 14% in a basal sample to <2% near the upper contact, may be interpreted as representing a progressive decline of this taxon prior to *c*. 2.2 cal ka BP, a trend previously documented in cores of mid to late Holocene age extracted from lowland sites on Trotternish (Vasari and Vasari, 1968; Birks, 1973; Birks and Williams, 1983; Lowe and Walker, 1991). Translocation of *Corylus* palynomorphs to the base of soil unit 2 in section T1 may, however, be partly responsible for an apparent increase in the frequency of this taxon with depth, giving rise to over-representation in basal layers (*cf.* Dimbleby, 1985). In general, however, the paucity of arboreal and shrub pollen recorded for buried soils strongly suggests that pedogenesis, and therefore emplacement of overlying sediments, is likely to postdate the main phase of anthropogenic woodland clearance.

Charcoal analysis

Examination of constituent soil charcoal particles has the potential to furnish useful data regarding the ecological development of landscapes (Tolonen, 1986; Patterson *et al.*, 1987; Edwards *et al.*, 1995; Tipping, 1996). Evidence of burning has traditionally been associated with either 'natural' or climate-induced fires (e.g. Swain, 1973, 1978; Singh *et al.*, 1981; Green, 1981, 1982; Clark, 1988), or anthropogenic burning of vegetation covers (e.g. Simmons and Innes, 1981; Edwards, 1988, 1989; Morrison, 1994; Whittington and Edwards, 1993, 1996), though the exclusivity of causal factors is questioned by Tipping (1996). The possible contribution of fire to erosion of hillslope regoliths has been acknowledged by several authors (e.g. Innes, 1983b; Parret, 1987; Brazier *et al.*, 1988; Wohl and Pearthree, 1991). Burning of vegetation appears to increase the probability of subsequent erosion of substrates by increasing infiltration rates, and by down-washing of particulate charcoal into the soil where, according to Wells (1987) it coats individual soil particles creating a water-repellent layer. Wells argued that the formation of a hydrophobic soil layer at shallow depth may, in some situations, create high near-surface postitive porewater pressures during intense rainstorms, facilitating failure and downslope flow of the soil. Though widespread reworking of talus debris on Trotternish apparently post-dates woodland clearance, it is possible that subsequent destabilisation of talus slopes may be related to burning of vegetation. The results of testing of this hypothesis are as follows.

Analyses of modern soils and those overridden by talus debris failed to detect any visible fragments of charcoal. Further analyses were undertaken to test for the presence of microscopic charcoal particles resident in buried soils. With the notable exception of soil unit 3 in section T5.a, the results indicate very low charcoal concentrations of 0.11-2.56 cm^2 cm^{-3} (Figure 7.5-7.7). These values appear sufficiently small to exclude local burning of vegetation during the period of soil formation (Whittington, personnel communication, 1997). Minor fluctuations in charcoal concentration with depth, confirmed by the charcoal to pollen ration (*cf.* Swain, 1973), may therefore reflect inblowing of charcoal particles from fires elsewhere. The lowermost soil (unit 3) at section T5.a, however, exhibits a significantly higher microscopic charcoal concentration of 14.54-28.64 cm^2 cm^{-3}. This value is not sufficiently large to suggest local burning of vegetation, an interpretation confirmed by the absence of constituent macrofossil charcoal and charred rootlets, and is thus interpreted as reflecting long distance, wind-blown transport. The relatively high charcoal concentration at this level may therefore reflect a change in the dominant wind direction or an increased incidence of regional fires or both.

7.4.3 Climate

Several workers have conjectured that late Holocene slope instability is related to phases of climate deterioration, in particular those that occurred following the onset of the sub-Atlantic period at *c*. 2.5 ka BP (*c*. 2.7-2.3 cal ka BP), and also during the 'Little Ice Age' of the sixteenth to nineteenth centuries AD (Taylor, 1975; Lamb, 1977). This view is founded upon apparent coincidences in timing and also the assumption that climatic deterioration is automatically related to enhanced levels of hillslope instability (Ballantyne, 1991b). The timing argument is, however, problematic as it does not necessarily imply a causal relationship between climate and hillslope modification. Furthermore, in view of the limited palaeoclimatological data available, it is often difficult to establish the changes in former weather patterns that may have been potentially responsible for the triggering of mass movements. Moreover, annual average temperatures during the 'Little Ice Age' in lowland

Britain appear to have been no more than 0.6° lower than at present (Lamb, 1977), and mean annual precipitation in eastern Scotland was *c.* 7% less than current levels (Thom and Ledger, 1976). Assuming that initial slope failure reflects increased infiltration rates, it is not immediately apparent why such minor average climatic changes should have initiated widespread erosion of hillslopes.

One possible solution is that the sub-Atlantic and the 'Little Ice Age' were both characterised by an increase in the frequency and ferocity of high-magnitude storms tracking across the British Isles (Lamb, 1977, 1979, 1984; Whittington, 1985; Ballantyne , 1991b). Infiltration of precipitation during intense rainstorms often produces a rapid rise in positive porewater pressures, reduction in effective normal stress, and thus increased propensity for hillslope failure and downslope movement of sediment. Initiation of widespread failure and erosion of steep sediment-mantled slopes in upland Britain by violent rainstorms is attested by several authors (e.g. Common, 1954; Baird and Lewis, 1957; Bevan *et al.*, 1978; Acreman, 1983, 1989, 1991; Harvey, 1986, 1991; Addison, 1987; Carling, 1987; Jenkins *et al.*, 1988; Coxon *et al.*, 1989; Collinge *et al.*, 1992; Evans, 1996). Therefore, increased storminess rather than average climate changes may be responsible for initiation of periods of enhanced hillslope instability during episodes of Holocene climate deterioration (Ballantyne and Brazier, 1989; Ballantyne, 1991b, 1993). The importance of antecedent soil moisture conditions prior to intense storms cannot be excluded however (Church and Miles, 1987; Kotarba *et al.*, 1987). The following discussion evaluates the evidence for possible climatic causes of talus slope instability in the Holocene and historic period. The research reported above is examined in the context of previously published work regarding mass movement frequency and causation.

Holocene reworking of talus debris

Evidence for possible climate-induced Holocene mass movement in the British uplands is scant. Brazier and Ballantyne (1989) reported a maximal age of 2020±50 yr BP (2115-1829 cal yr BP) for the overriding of a former soil by a debris flow diamicton in upper Glen Feshie, which may reflect climatic deterioration at the onset of the sub-Atlantic chronozone at *c.* 2.5 ka BP (*c.* 2.7-2.3 cal ka BP). Initial debris cone accumulation at this location may, however, be much older than this date suggests, as the evidence for earlier cone aggradation could have been destroyed or obscured by lateral erosion by the migrating River Feshie and overriding by more recent (post fifteenth century AD) debris flow diamictons (Brazier and Ballantyne, 1989). Sub-Atlantic climatic deterioration cannot be excluded as a possible cause of debris cone aggradation in the Bowland Fells of Cumbria between *c.* 5.3 and 1.7 cal ka BP, though the extent to which such activity corresponds to the diffusion of Bronze Age or Iron Age settlement over the region is debatable (Harvey and Renwick, 1987). Organic layers underlying relict talus immediately south of The Storr on Trotternish (Innes, 1983d), are here reinterpreted as being overlain by debris flow diamictons (section 7.3.1), one of which was emplaced at around 1.9 cal ka BP and thus exhibits a possible correspondence of timing with sub-Atlantic climatic changes. In the Cairngorms, burial of a former soil by soliflucted mountain-top detritus at around 2680±120 yr BP (3135-2363 cal yr BP) has also been interpreted as a possible reflection of climate deterioration during the sub-Atlantic (Sugden, 1971). Significantly, an increased occurrence of hillslope failures at *c.* 2.5 ka BP is also predicted by numerical modelling of landslide formation for different soil types in the Scottish Highlands (Brooks *et al.*, 1993a).

There is therefore some (admittedly limited) evidence that the timing of Holocene drift-slope erosion and reworking in upland Britain reflects accelerated activity early in the sub-Atlantic. Studies elsewhere in Western Europe suggest a similar time frame for an increase in rates of solifluction on Norwegian, Alpine and Icelandic slopes (e.g. Worsley and Harris, 1974; Nesje *et al.*, 1989; Nesje, 1993; Worsley, 1993; Veit, 1993; Sharp and Dugmore, 1985), debris flow activity on Scandanavian mountains (e.g. Rapp and Nyberg, 1981; Jonasson, 1993; Blikra, 1994), surface wash in Norway (e.g. Matthews *et al.*, 1986; Blikra and Nemec, 1993a, 1993b; Blikra and Nesje, 1997) and large-scale sliding failure in lowland Britain (e.g. Jones and Lee, 1993; Ibsen and Brunsden, 1997). In sum, there is a growing body of evidence for a general coincidence in timing between intensified mass movement activity and climatic deterioration at around 2.5 ka BP (*c.* 2.7-2.3 cal ka BP) in Western Europe, possibly due to increased storminess at this time.

The occurrence of exceptionally high-magnitude rainstorms may not, however, be exclusive to phases of Holocene climate deterioration (Ballantyne, 1991b). The possible effect of such a storm on relict talus debris may be a rapid attainment of high positive porewater pressure and consequent reduction of the factor of safety of the deposit, potentially resulting in slope failure and mass movement. Translational failures and debris flows resulting from such a storm are liable to erode extensive areas of vegetation and thus lower the threshold for subsequent failure or reworking of hillslope drift (Brazier and Ballantyne, 1989), possibly initiating a prolonged phase of localised hillslope instability. Therefore, in terms of climatic causes of Holocene mass movement in upland Britain there are two possibilities. Firstly, failure and reworking of drift may reflect increased storminess associated with episodes of climatic deterioration. Secondly, such activity may be triggered by infrequent high-magnitude storms of random occurrence. The extent to which these competing hypotheses provide a valid model for the interpretation of current data regarding the timing of erosion and reworking of relict talus slopes in the Scottish Highlands is examined below.

The distribution of approximate maximal ages for the burial of former talus surfaces by debris eroded and redeposited from upslope is illustrated in Figure 7.4. Hypothetically, a general deterioration in regional climate, possibly associated with a marked increase in the frequency of destructive local storms, may be represented by clustering of calibrated radiocarbon ages for burial of former talus surfaces at different sites. Infrequent violent rainstorms of random occurrence may be more likely to trigger mass movements on individual talus slopes. Consequently, such storms may be represented by apparently unrelated reworking events at different field locations. As noted previously (section 7.3.2), there is evidence for a non-random distribution of calibrated radiocarbon ages for episodes of talus reworking over the past *c.* 6 cal ka BP (Figure 7.4). Two phases of broadly synchronous reworking of talus debris in the Scottish Highlands may be identified, the first at around 6.3-5.6 cal ka BP, and the more recent at approximately 2.7-1.6 cal ka BP. The period *c.* 6.3-5.6 cal ka BP exhibits a correspondence in timing with a proposed increased incidence of north Atlantic depressions tracking across Britain during the 'wet' Atlantic period (Lamb, 1977). However, apparently coeval reworking of talus debris at different study sites during this period relies heavily on a potentially unreliable radiocarbon date, and subsequent inference of a causal relationship between climate and mass movement at this time may be premature. The latter period (*c.* 2.7-1.6 cal ka BP) exhibits a correspondence in timing with proposed climatic deterioration at around 2.5 ka BP (*c.* 2.7-2.3 cal ka BP) with the onset of the sub-Atlantic chronozone, and represents a stronger argument for a possible link between a phase climate deterioration and talus slope reworking. Significantly, this finding is consistent with the results of previous investigations of mass movement histories that have suggested a similar time frame for erosion and reworking of hillslope diamictons elsewhere in the Scottish Highlands, and also in Western Europe (see above). The possibility that the distribution of calendar ages evident in Figure 7.4, however, simply reflects severe local rainstorms apparently unrelated to long-term Holocene climate change cannot, given the small number of reliable calibrated radiocarbon dates plotted, be dismissed. This alternative interpretation is supported by dates for the burial of former talus surfaces (radiocarbon samples SRR-2010, T1: 2, T5.a: 4, T6.a: 1 and SP1: 1) that do not exhibit a correspondence in timing with proposed periods of increased wetness or storminess during the Atlantic and sub-Atlantic chronozones.

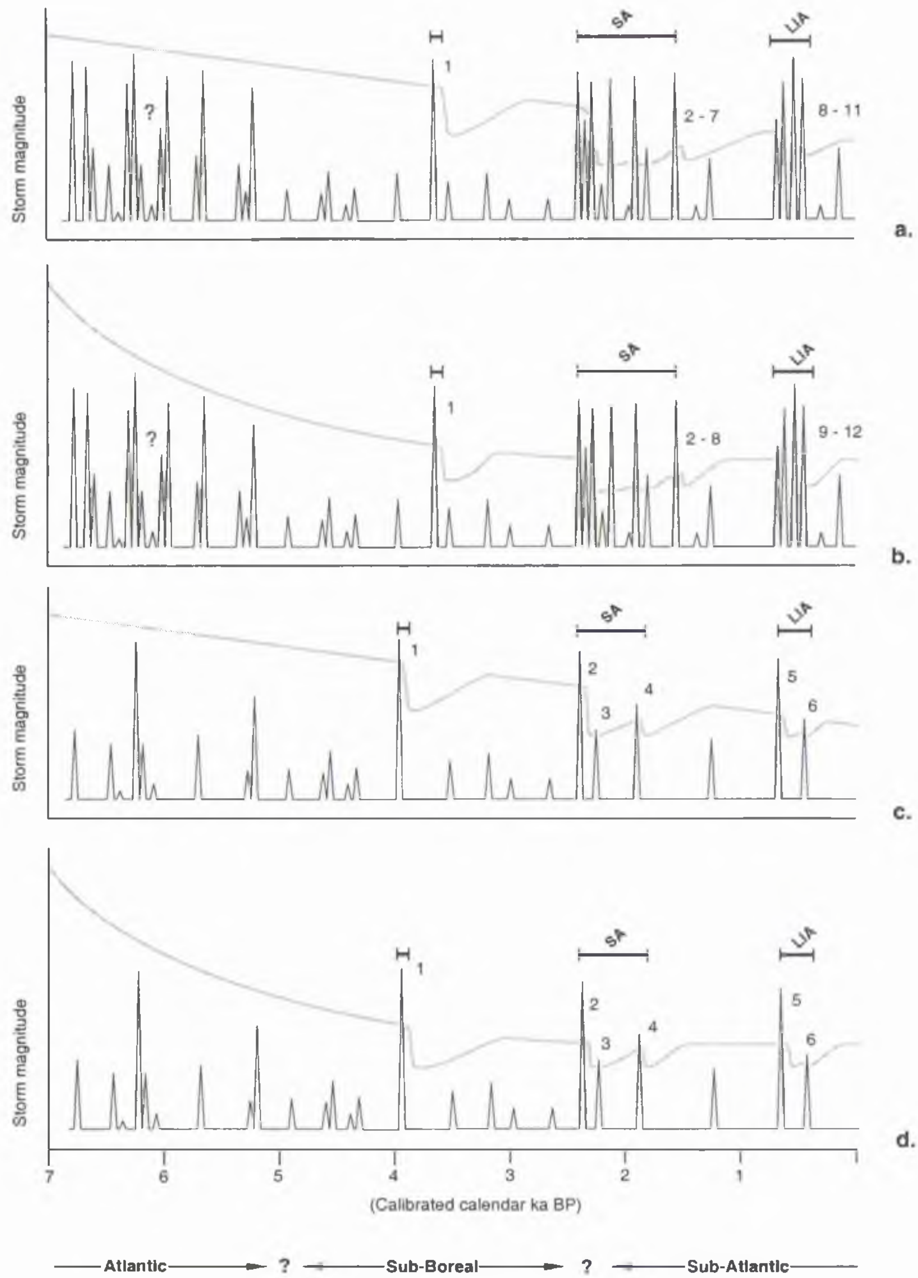
Historic reworking of talus debris

The age of currently active gully incision of relict talus on Trotternish and the most recent phase of gullying of mainland talus slopes is unknown, and it is thus difficult to suggest underlying causes. It is possible, however, that a general intensification of debris flow activity in the Scottish Highlands occurred in association with increased storminess during the 'Little Ice Age' of the sixteenth to nineteenth centuries AD (Ballantyne, 1991b, 1993). Radiocarbon dating of buried soils and plant rootlets underlying three coalescing debris cones in upper Glen Feshie indicated that the bulk of the current deposit has accumulated since the fifteenth century AD (Brazier and Ballantyne, 1989). This finding may indicate a local increase in mass movement activity associated with the 'Little Ice Age'. Five radiocarbon dates obtained by Ballantyne (1986c) for an *in situ* soil horizon overridden by a solifluction lobe on the Fannich Mountains of NW Scotland, yielded ages of between 890±120 yr BP (1053-568 cal yr BP) and 530±90 yr BP (664-327 cal yr BP), that are statistically indistinguishable from a date of 660±70 yr BP (693-527 cal yr BP) acquired from the same soil horizon immediately downslope of the lobe front. These ages were interpreted by Ballantyne as indicating the AMRT of the soil, and consequently that lobe advance over the soil was both rapid and recent. As noted by Ballantyne (1991b) "...it is tempting to relate the evidence for accelerated solifluction on the Fannichs to the onset or possibly the termination of more severe conditions during the Little Ice Age"; however, the extent to which accelerated solifluction reflects overgrazing following the introduction of sheep within the last 200 years is uncertain (Ballantyne, 1986c, 1991b, 1993).

Studies undertaken elsewhere in Western Europe have also suggested that the 'Little Ice Age' may be associated with an increased occurrence of hillslope instability. For example, Veit (1988) and Gamper and Suter (1982) identified periods of enhanced solifluction activity in the Alps that broadly equate to a episode of severe climate during the sixteenth to nineteenth centuries AD. Research in Scandanavia has also revealed phases of enhanced solifluction (e.g. Matthews *et al.*, 1986; Nesje *et al.*, 1989), and an increased frequency of sliding failures and debris flows (e.g. Grove, 1972; Grove and Battagel, 1981, 1983; Innes, 1985b; Jonasson, 1991, 1993), that may reflect climatic changes during the 'Little Ice Age'. Furthermore, lichenometric measurement of debris flows on talus in the High Tatra Mountains of Poland indicates mobilisation in the latter half of the 'Little Ice Age' (Kotarba, 1992, 1997). Therefore, severe weather associated with 'Little Ice Age' climatic changes may be invoked as a possible cause of currently active gully erosion of relict talus on Trotternish, and the most recent phase of hillslope debris flow activity at mainland field sites. The possibility that such activity was initiated by destructive storms of random occurrence cannot be discounted, however.

7.4.4 Synthesis

The possible causes of Holocene talus reworking are summarised using four conceptual threshold models in Figure 7.8. The steep upper slope gradient of talus is interpreted as facilitating mass movement. Representation of storm frequency is, however, both highly simplified and generalised. Moreover, the rate of lowering of the internal threshold for initiation of rapid mass movement on talus (due to progressive enrichment by fines) is unknown; though two possibilities are presented. Diagrams 'a' and 'c' indicate a possible uniform reduction of the factor



2	- Individual erosional event		- Phase of talus slope instability
	- Threshold for initiation of rapid mass movement on talus	SA	- Early sub-Atlantic chronozone
	- Generalised frequency of high-magnitude rainstorms	LIA	- Little Ice Age (Western Europe)

Figure 7.8. Possible causes of rapid mass movements on relict talus in the Scottish Highlands. Diagrams a. and b. respectively represent uniform and non-uniform lowering of the internal threshold for initiation of debris flows on talus and discrete periods of increased storminess during phases of Holocene climatic deterioration (Atlantic, sub-Atlantic and Little Ice Age). Diagrams c. and d. respectively represent uniform and non-uniform lowering of the internal threshold for initiation of debris flows on talus and infreqent high-magnitude Holocene rainstorms of random ocurrance. Note the short-term threshold reduction following individual storms reflecting tempory distruption of vegetation cover as suggested by Brazier and Ballantyne (1989).

of safety of talus slopes during the Holocene, whilst 'b' and 'd' represent an initial rapid lowering followed by a more gradual reduction. These latter two models assume that the threshold for initiation of failure of talus debris tends towards uniformity as internal voids are progressively infilled. Both scenarios are, however, hypothetical pending further research. Short-term lowering of the threshold for subsequent debris flow initiation due to disruption of vegetation cover by destructive storms is incorporated for all diagrams (*cf.* Brazier and Ballantyne, 1989).

Plots 'a' and 'b' on Figure 7.8 represent the possible effects of a falling internal stability threshold and discrete phases of increased storminess associated with general climatic deterioration during the Atlantic and sub-Atlantic chronozones, and the 'Little Ice Age'. The generalised frequency of high-magnitude storms for each of these periods is, however, highly speculative. Nevertheless, diagrams 'a' and 'b' offer a possible explanation of the apparent concentration of talus reworking in the past *c.* 6 cal ka, and also for the clustering of calendar ages for slope failure between *c.* 2.7-1.6 cal ka BP (Figure 7.8). An alternative interpretation of the available data for the timing of talus reworking at field sites (Table 7.1) is given in plots 'c' and 'd'. Significantly, it is shown that a similar pattern of talus slope instability to that observed for plots 'a' and 'b' can be generated by modelling the possible effects of infrequent high-magnitude storms of random occurrence, combined with a short-term lowering of the threshold for subsequent slope failure (*sensu* Brazier and Ballantyne, 1989). Evidence for a recent phase of enhanced hillslope instability in the Scottish Highlands during the 'Little Ice Age', however, is scant, and thus any suggestion of reworking of talus debris at this time is highly speculative. Furthermore, pending further research, it is difficult to evaluate the possible impact of nineteenth and early twentieth century AD deposition of air borne industrial pollutants on upland moss covers, and thus the possible effects on the hydrology and the stability of upland talus slopes.

7.4.5 Summary

The following summary synthesises the available evidence for possible causes of widespread erosion and reworking of relict talus accumulations on Scottish mountains.

1. The results of analyses of constituent soil pollen underlying relict talus on Trotternish appear to indicate that most erosion and mass movement postdates the main phase of local woodland clearance. The absence of macroscopic charcoal from modern and buried soils, and the paucity of microscopic charcoal in the latter, suggests that talus slope instability and burning of vegetation, either natural or anthropogenic in origin, are unrelated at this site.

2. The inclination of the upper slopes of relict talus accumulations investigated (32.8° to 47.1°) exceeds the minimum 30° gradient suggested for the initiation of debris flows on drift-mantled slopes on Scottish mountains (Ballantyne, 1981; Innes, 1983a). Thus the steep gradient of the upper slopes of relict talus may facilitate slope failure and reworking of sediment.

3. Holocene enrichment of talus accumulations by inwashing of fines derived from rockwalls (chapter 6) is inferred to be responsible for a long-term reduction of the stability of such slopes, and as a result, lowering of the internal threshold for the initiation of sliding failure and debris flow activity. The apparent concentration of talus reworking events in the latter half of the Holocene may therefore reflect the progressive addition of fine sediment to the talus accumulation.

4. Evidence for a possible phase of apparently synchronous reworking of talus on Trotternish and the mainland of NW Scotland at around 2.7-1.6 cal ka BP displays a coincidence in timing with proposed climatic deterioration at the onset of the sub-Atlantic chronozone at *c.* 2.7-2.3 cal ka BP. Such correspondence of timing may suggest a climatic explanation for enhanced slope failure and sediment movement on talus at this time, possibly due to increased storminess. Pending further research, however, the possible links between climate change and slope instability remain conjectural. Moreover, it is currently impossible to exclude the possibility that the periodicity of talus reworking reflects infrequent high magnitude storms of no obvious long-term climatic significance.

5. The possible cause of the most recent phase of gully erosion of talus is unknown. The extent to which such activity reflects overgrazing, primarily by sheep, or degradation of moss cover associated with deposition of air-borne industrial pollutants in the nineteenth and early twentieth centuries AD remains hypothetical and awaits further research (Innes in Ballantyne, 1991b; Innes, 1997). Alternatively, gully formation may have been triggered by intense rainstorms during the 'Little Ice Age' of the sixteenth to nineteenth century AD. At present, however, evaluation of the validity of these competing explanations is impossible.

7.5 Conclusions

Findings regarding the history of relict talus slopes on Scottish mountains are summarised below.

Calibrated radiocarbon dates for the burial of former talus surfaces indicate that modification of talus by mass transport has been intermittent throughout the latter half of the Holocene. Such behaviour suggests that the evolution of relict talus slopes at study sites has not progressed at a steady pace, but that phases of locally important talus modification are separated by intervening periods of relative slope stability. The late Holocene modification of relict talus slopes by slope failure, debris flows and wash may be inferred as representing a transitional phase as talus accumulations progressively evolve from a rockfall- to a debris flow-dominated state. If so, relict talus slopes in the Scottish Highlands may ultimately stabilise through modification by repeated debris flows, the effects of which are considered to be lowering of the upper rectilinear slope gradient and extension of the basal concavity (e.g. Statham, 1976b; Luckman, 1992; Ballantyne and Harris, 1994, p.230; *cf.* chapter 4), and thus the progressive development of a mass-movement-dominated form.

Another outcome of the current research is that external environmental controls may influence the evolution of talus surface relief and internal structure, a finding that is inconsistent with existing models of talus slope formation that regard talus development as reflecting internal controls within the slope system (Statham, 1973a, 1976a; Kirkby and Statham, 1975; Francou and Manté, 1990; Francou (1991). Thus existing models of talus evolution are inferred to offer only a partial explanation of the formation of such features.

Current findings suggest that relict talus slopes in the Scottish Highlands are highly sensitive to disturbance, possibly resulting from changing climate. Consequently, further analyses of buried palaeosols and depositional structures underlying talus slopes may ultimately yield a useful proxy record for reconstructing former climatic changes (*cf.* Matthews, *et al.*, 1993; Berrisford and Matthews, 1997). Furthermore, the strong morphological and sedimentological affinity exhibited by diamictic talus detritus and steep valley-side till deposits (chapter 6), suggests that future research into talus slope evolution may potentially be used in support of parallel theories of the evolution of other drift-mantled hillslopes in formerly glaciated uplands.

In sum, the research reported in this chapter provides a valuable new insight into the hitherto investigated behaviour of relict talus accumulations on Scottish mountains during the Holocene. The results are considered further in the next chapter, which presents a schematic model of Holocene talus evolution pertinent to talus slopes investigated at field sites, and, by inference, those elsewhere that support evidence of surface debris flow activity.

Chapter 8

A model of talus evolution: gully incision and debris cone formation

8.1 Introduction

The research reported in previous chapters has furnished a considerable body of new information regarding the characteristics and formation of relict talus slopes in NW Scotland. Some aspects of the evolution of relict talus at study sites, however, are clearly incompatible with existing theories of talus formation, namely the 'discrete particle rockfall model' (Statham, 1973a, 1976a; Kirkby and Statham, 1975) and the 'two facet model' (Francou and Manté, 1990; Francou, 1991). The former model predicts that increasing talus maturity is accompanied by an increase in the gradient of the upper slope and a reduction in overall slope concavity, but analyses of talus form (Chapter 4) failed to substantiate either of these predictions, a result interpreted as reflecting the modification of talus accumulations at the study sites by repeated debris flows. The 'two facet model' of talus evolution allows for downslope translocation of rockfall debris and envisages both the formation of a consistent transitional gradient (33-34°) between the transport-dominated upper slope and the accumulation-dominated basal concavity, and an increase in overall talus slope concavity with maturation. However, the model assumes a continuing supply of rockfall debris on the upper slope; such debris replaces that lost by downslope transport, which is not the case for relict talus slopes in NW Scotland. Thus existing models appear to provide only a partial explanation of the evolution of relict talus slopes at the field sites, a result which suggests that there is scope for a new or modified model of talus formation appropriate to upland Britain. The following sections report respectively the parameters (section 8.2) and the inferred stages of evolution (section 8.3) of a proposed new model of talus formation.

8.2 Parameters

The conclusions reached in previous chapters are here used as the basis for modelling the sequence of talus development. In terms of surface morphology, transects up ungullied sectors of relict talus slopes at study sites exhibit a steep upper rectilinear slope and basal concavity, features hitherto interpreted as being indicative of the deposition of falling particles from rockwalls. Talus surface relief, however, is dominated by gully incision and associated slope-foot debris cone formation. On Trotternish there is evidence for multiple phases of talus modification by debris flows. Furthermore, the loci of such reworking activity appear to have changed through time. The morphological evidence therefore suggests that modelling of the evolution of relict talus accumulations needs to consider both the formation and subsequent modification, primarily by repeated downslope mass transport, of a steep upper rectilinear slope and basal concavity

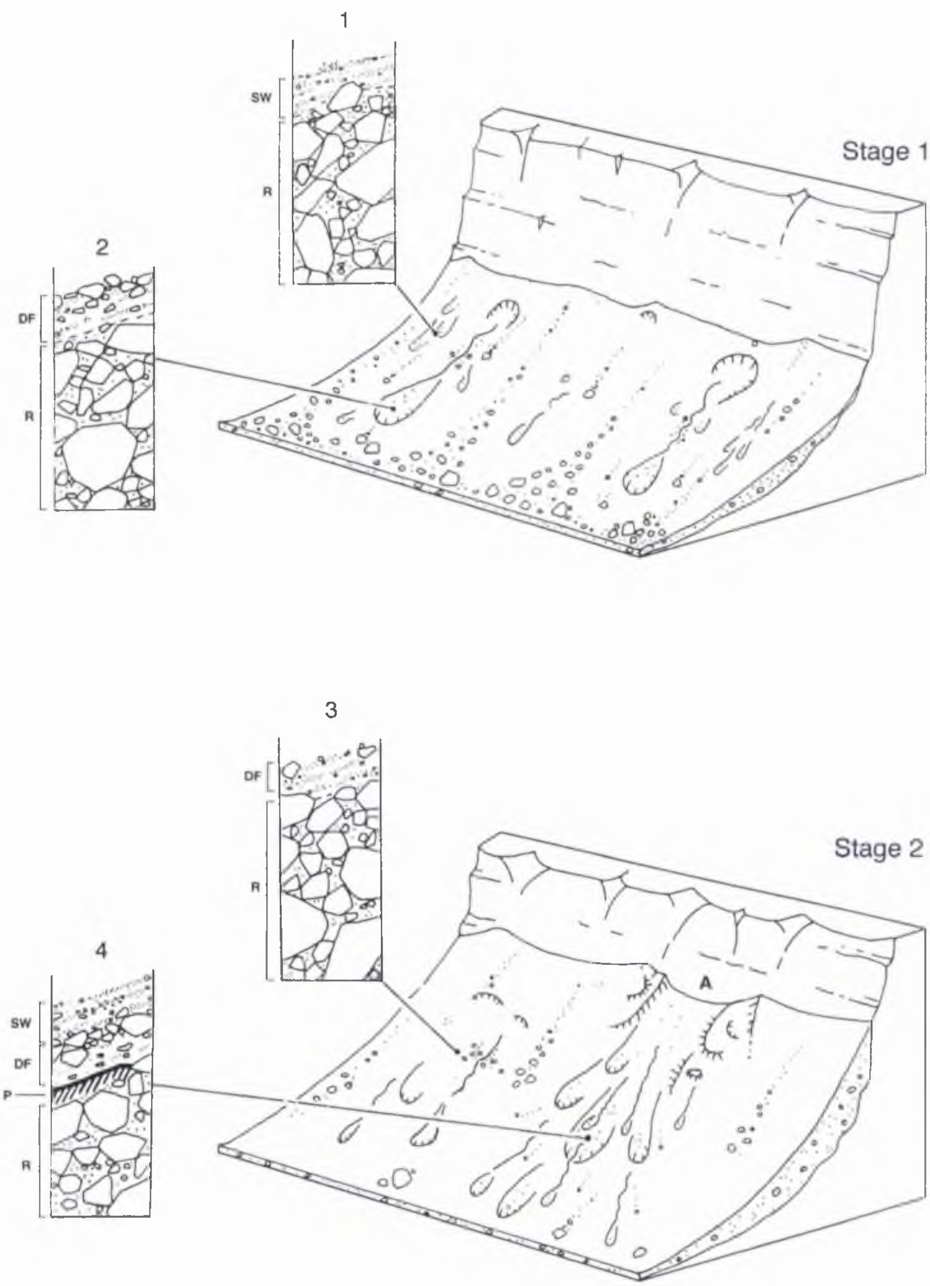
The results of analyses of the composition of sub-surface sediment units (Chapter 6) suggested the syndepositional accumulation of both coarse and fine particles from rockwalls, presumably during the interval between ice-sheet deglaciation and the end of the Loch Lomond Stade at *c.* 11.5 cal ka BP. Granular weathering of rockwalls, however, has also persisted during the Holocene. Analyses of sub-surface depositional structures (Chapter 5) demonstrated that the upper levels of talus at the field sites have been extensively reworked by debris flows and slope wash, a result consistent with the interpretation of talus surface relief. Buried soils developed on the tops of individual sediment units indicate periods of local slope stability prior to renewed downslope mass transport. Consequently, an appropriate model of talus evolution also needs to take into account a long history of intermittent modification of talus sediments by downslope mass movement.

8.3 Possible stages of talus evolution

The research reported in this thesis has focused primarily on the structure and evolution of relict talus slopes in the Scottish Highlands. Therefore, current findings are of only limited use in terms of modelling the formation of active rockfall talus slopes. In the following discussion, the evolution of talus surface relief and internal structure are divided into eight stages that represent a generalised sequence of talus formation. However, it is important to note that identification of discrete phases of talus development is somewhat artificial, as investigations of internal structure and the age of buried soils have shown that the evolution of relict talus slopes has been locally variable. Moreover, the development of some talus slopes may conceivably by-pass one or more of the phases of evolution suggested below. The model of talus development outlined here may therefore be considered as a generalised conceptual framework for the evolution of relict talus slopes in upland Britain, rather than a definitive history of individual cases.

Stage 1: Active, rockfall-dominated talus

Stage 1 (Figure 8.1a) depicts an early phase of talus development by rockfall accumulation. It is characterised by an immature talus slope with a relatively low overall gradient overlooked by a high rockwall. The accumulation of fines, derived from granular weathering of the rockwall, within inter-clast interstices may promote the development of high porewater pressures and possibly localised superficial failure of the upper slope and downslope flow of debris during extreme rainstorms. Thus, even during the early stages of talus development, it is possible that surface wash (section 1; Figure 8.1a) and unconfined debris flows (section 2; Figure 8.1a) may have been responsible for limited reworking of recently-deposited rockfall sediments. Snow avalanches may also have transported



R - In situ rockfall talus

SW - Surface wash sediments

DF - Debris flow diamicton

P - Buried palaeosol

Figure 8.1a. Stages 1 and 2 of talus slope evolution in the Scottish Highlands. Key for sections as in Figures 5.3 and 5.5.

sediment downslope under the periglacial conditions of the Late Devensian Lateglacial

Stage 2: Initial failure of mature talus

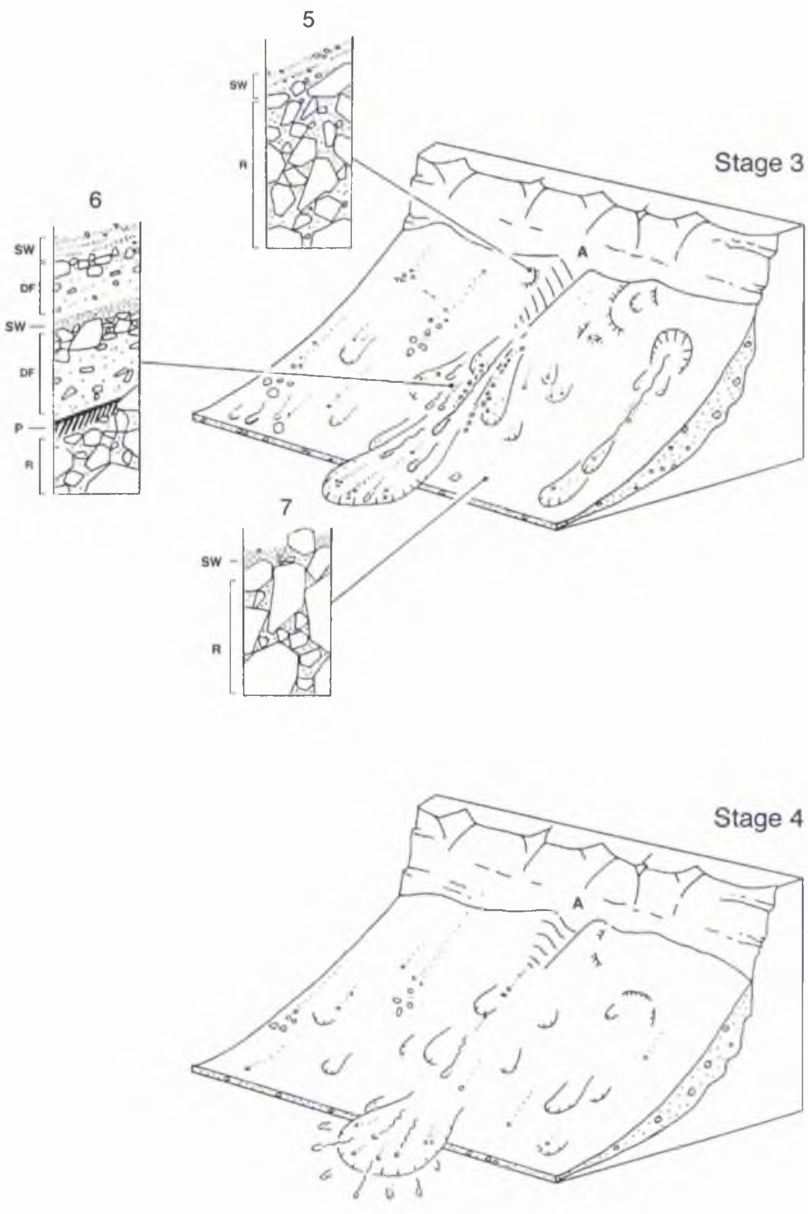
Stage 2 represents the onset of significant modification of mature talus slopes by downslope mass transport (Figure 8.1a). In upland Britain this transition may have occurred following a reduction in the rate of clast accumulation (possibly due to the onset of milder conditions at the beginning of the Holocene), and consequently the failure of rockfall accumulation to keep pace with downslope mass transport.

Shallow translational failure of upper slopes during extreme rainstorms probably initiated talus modification by downslope sediment movement. Such failures would be facilitated by the steep upper slope gradients characteristic of mature talus accumulations, and progressive reduction of infiltration rates due to the occupation of sub-surface interstitial cavities by fine sediment. The location of initial failures may have been determined by the spacing of rockwall gullies that focused the delivery of runoff to the talus downslope. The model envisages the remoulding and liquefaction of failed debris moving down steep slopes, producing unconfined debris flows that deposit sediment downslope in a broad, ill-defined runout zone. The exposure of unvegetated failure scars and debris flow lobes probably facilitated the subsequent reworking of finer sediment by slopewash. In terms of sub-surface depositional structures, deposition of reworked sediments is inferred to result in the burial of organic soils that developed on talus surfaces under the milder conditions of the Holocene (section 4; Figure 8.1a).

Stage 3: Gully development

Disruption of vegetation due to initial talus slope failure is envisaged as resulting in localised lowering of the geomorphic threshold for subsequent modification of talus by landslides and debris flows (*cf.* Brazier and Ballantyne, 1989), and the development of rills or gullies in unvegetated erosion scars probably facilitated the progressive channelling of surface wash and mass flows. Repeated downslope removal of sediment along lines of drainage concentration is envisaged as leading to progressive gully enlargement. Downcutting during the early stages of gully formation would have caused the development of potentially unstable, steep-sided incisions, with undermining and collapse of gully walls providing regular delivery of sediment to gully floors (*cf.* Statham, 1976b). Thus sediment availability is unlikely to have limited, at least initially, the frequency of individual debris flows down gullies. The pace of sediment evacuation from gullies at this stage therefore probably reflected the frequency of rainstorms of sufficiently high magnitude to mobilise sediment located on gully floors.

Progressive downslope gully enlargement at this stage may have resulted in the exposure of older (stage 2) depositional facies at gully sides. Stage 3 depositional landforms are envisaged to include parallel levées emanating from the downslope ends of gullies, low coalescing runout lobes on the mid-slope zone, and broad debris lobes or immature debris cones at the talus foot. Mid-slope and slope foot deposits at this stage are inferred to comprise stacked debris flow diamictons, slope wash sediments and occasional buried soil horizons (section 6; Figure 8.1b). Sequences of thin, relatively fine-grained sediments may also underlie slope foot debris lobes or cones, representing intermittent post-depositional reworking of the unvegetated surfaces of recently reworked deposits upslope by slopewash during rainstorms. Nonetheless, large sections of talus may have remained largely



R - In situ rockfall talus	SW - Surface wash sediments
DF - Debris flow diamicton	P - Buried palaeosol

Figure 8.1b. Stages 3 and 4 of talus slope evolution in the Scottish Highlands. Key for sections as in Figures 5.3 and 5.5.

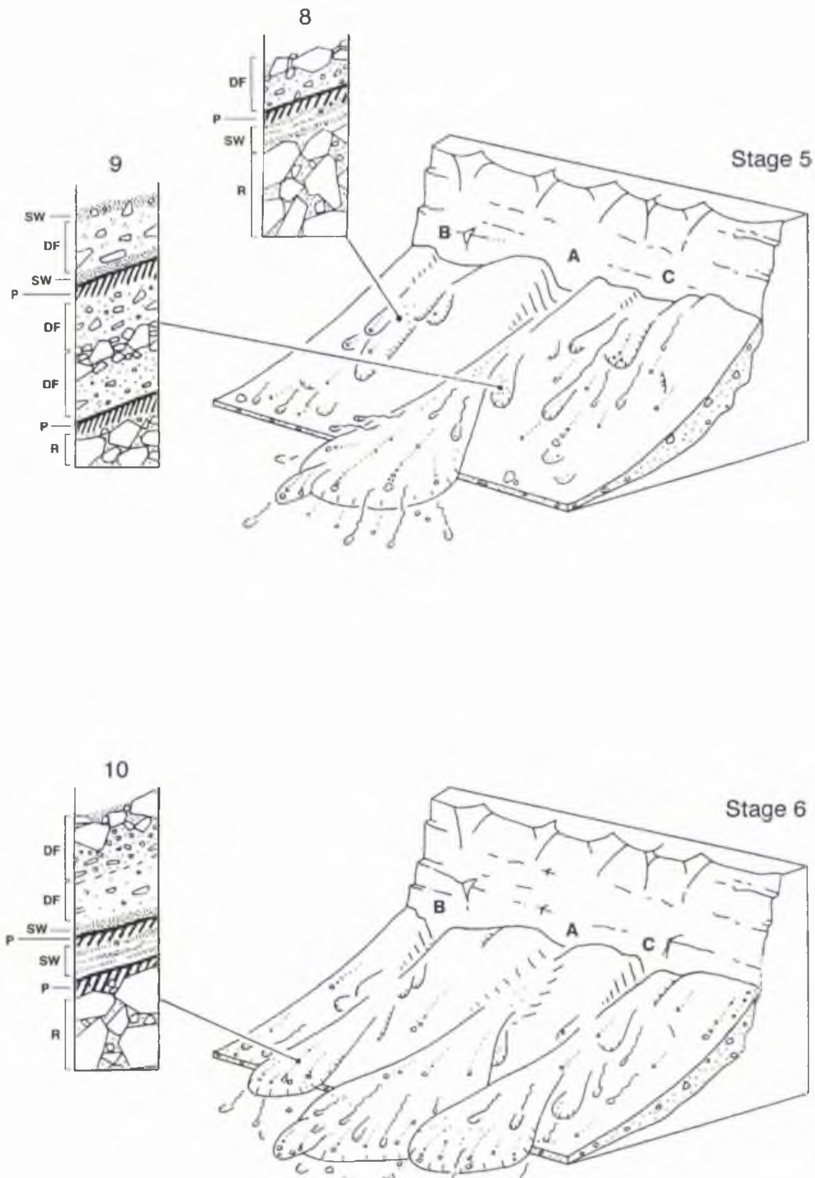
unaffected by erosion and mass transport at this stage (sections 5 and 7; Figure 8.1b).

Stage 4: Local stability

Buried soils underlying relict talus slopes in NW Scotland are interpreted as representing phases of local talus slope stability conducive to plant growth and soil development. One such episode is illustrated by stage 4 of talus evolution (Figure 8.1b). During this period, talus reworking may be confined to the accumulation of sediment on gully floors, degrading of older erosion scars and very limited reworking of debris flow and slope wash deposits.

Stage 5: Renewed gully initiation and reactivation

Stage 5 of talus development (Figure 8.1c) represents a phase of renewed gully initiation and rejuvenation of previous stabilised gully systems. The formation of new translational failures on hitherto unmodified sectors of the slope (represented by shallow landslides 'B' and 'C') is envisaged as being broadly synchronous with reactivation of older gullies (gully 'A'). The initial evolution of talus slope failures 'B' and 'C' may be similar to that of earlier landslides during stage 2 of talus evolution. Sub-surface depositional structures underlying the middle and lower portions of repeatedly-reworked sections of the slope are likely to have become increasingly complex following the renewal of debris flow activity (section 9; Figure 8.1d). Sections excavated through the deposit may, for example, comprise stacked debris flow diamictons that correspond to different phases of talus slope modification, and multiple buried soils of different ages.



R - In situ rockfall talus

DF - Debris flow diamicton

SW - Surface wash sediments

P - Buried palaeosol

Figure 8.1c. Stages 5 and 6 of talus slope evolution in the Scottish Highlands. Key for sections as in Figures 5.3 and 5.5.

Stage 6: Widespread gullying

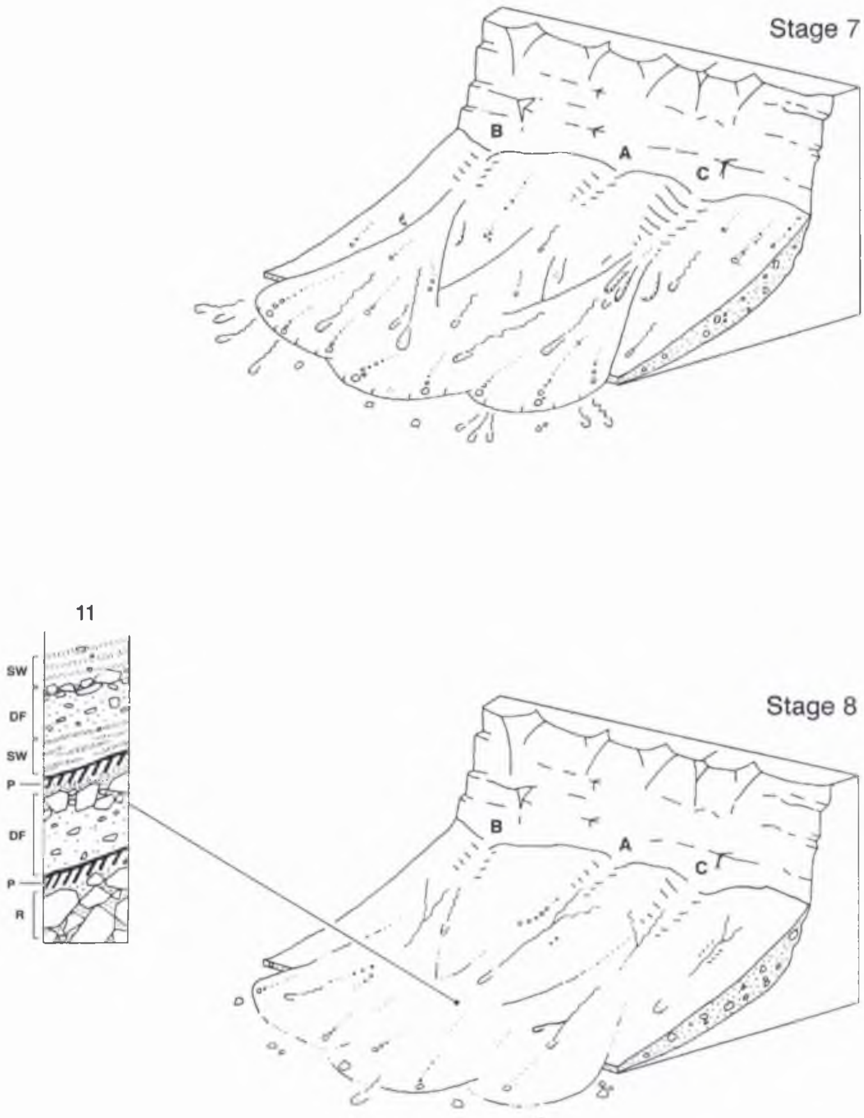
Stage 6 of talus development (Figure 8.1c) is characterised by an increase in the extent of gully erosion of talus. Upslope extension of developing debris cones into the lower portions of some mature gullies ('back-filling'), however, may limit the further enlargement of such features. During this period, former translational failures 'B' and 'C' may evolve into discrete, steep-sided gullies that provide a source of sediment for debris flows that terminate on the surfaces of small, immature debris cones downslope. Although youthful, these cones may contain multiple stacked debris flow diamictons, surface wash sediments and buried soils (section 10; Figure 8.1c). Furthermore, the close spacing of adjacent debris cones may result in the superimposition of sediment units that originated in neighbouring source gullies upslope.

Stage 7: Backfilling and degrading

During the penultimate phase of talus development (stage 7; Figure 8.1d), 'back-filling' of mature gullies may be widespread. Such activity is inferred to inhibit the subsequent removal of debris (derived from gravitational collapse of side-walls) from gully floors. Infilling of gullies is considered to lead to a reduction in the size and relief of such features, possibly promoting vegetation recolonisation and thus stability. Cone surfaces, however, may continue to support evidence of limited intermittent reworking of redeposited talus debris.

Stage 8: Debris flow-dominated talus

In the final stage of evolution (stage 8; Figure 8.1d), talus form may largely reflect the action of repeated debris flows, rather than the deposition of falling particles from a rockwall. In terms of surface morphology, debris flow-dominated talus slopes may exhibit a generally lower upper slope gradient and a larger basal



R - In situ rockfall talus	SW - Surface wash sediments
DF - Debris flow diamicton	P - Buried palaeosol

Figure 8.1d. Stages 7 and 8 of talus slope evolution in the Scottish Highlands. Key for sections as in Figures 5.3 and 5.5.

concavity than active rockfall-dominated talus. Furthermore, the surface of debris flow-modified talus, unlike that of unmodified rockfall-dominated slopes, may support shallow depressions (representing the degraded remnants of infilled former gullies) and ill-defined coalescing debris cones at the slope foot. In terms of internal structure, the upper levels of extensively reworked talus accumulations, rather than comprising coarse, clast-supported rockfall diamictons, consist of stacked debris flow diamictons, surface wash deposits and buried soils. During stage 8 of talus evolution, geomorphological activity may be confined to localised surface wash activity and limited fluvial erosion of infilled gully floors. Vegetation cover may be virtually complete.

Summary

In sum, the eight schematic stages of talus evolution outlined above describe the progressive modification of talus surface relief and internal structure by repeated downslope mass transport. The principal effects of repeated reworking of talus sediments are lowering of the height and gradient of the upper slope (primarily by translational failure and gully incision), deposition of sediment in levées and low debris lobes downslope of gullies, enlargement of the basal concavity (due largely to the formation of slope foot debris cones), and reorganisation of sub-surface talus sediments into superimposed, discrete units by debris flows and surface wash. This general model thus offers an explanation of both the characteristics of talus surface morphology and internal structure as revealed by the research reported in Chapters 4-6. The wider applicability of the model to relict talus accumulations in other environments remains to be tested.

Chapter 9

Conclusions: principal findings and future prospects

9.1 Introduction

The principal objective of the research undertaken in this thesis was to determine the nature of talus evolution in the Highlands of Scotland. The project focused on three particular aspects of talus development: first, the modification of surface morphology and internal structure by postdepositional reworking; second, the textural characteristics and origin of sub-surface sediments; and thirdly, the timing and possible causes of erosion and downslope sediment transport. The scope of this research is thus rather wider than that of most previous studies of talus evolution, which tend to have focused only on the surface characteristics of such slopes. The principle findings are summarised below, and potential avenues for further research are then explored.

9.2 Principal findings

The following conclusions are organised into three sections that summarise respectively the main findings pertinent to the postdepositional modification, sub-surface sedimentary characteristics and history of reworking of relict talus slopes.

9.2.1 Reworking of relict talus slopes

In terms of surface morphology, relict talus slopes on Trotternish and at field sites on the Scottish mainland exhibit a steep rectilinear (or near-rectilinear) upper slope and a distinct basal concavity, features hitherto interpreted as indicative of mature, unmodified rockfall talus accumulations. On closer investigation, however, aspects of the surface relief of these slopes, such as the large range of upper slope gradients of 32.8° to 47.1° and the variable level of overall slope concavity, appear inconsistent with a purely rockfall origin. In terms of sub-surface structure, the upper levels of talus on Trotternish and at the field sites in the NW Highlands comprise multiple stacked clast- and matrix-supported diamictons (either massive or stratified), and thin beds of poorly-sorted sand and gravel. The sediment units underlying relict talus slopes in the Highlands of Scotland thus clearly represent emplacement by processes other than discrete particle rockfalls.

The surfaces of talus slopes at the field sites support numerous deep gullies that terminate in slope-foot debris cones. Furthermore, 'ungullied' sectors of the talus slopes on Trotternish support shallow depressions and low runout lobes, which have been interpreted here as the degraded remnants of older slope failures. Ungullied sectors of the mainland taluses, however, support only limited evidence of former erosion and downslope mass transport, suggesting that the Trotternish taluses have been more extensively reworked than their mainland counterparts. Regarding internal characteristics, the structure of subsurface deposits and eigenvector analysis of subsurface clast fabrics suggest redeposition of talus sediments by debris flows. Thin beds of finer grades of granular sediment appear to represent buried wash deposits, probably derived from reworking of unvegetated debris flow deposits and failure scars during rainstorms. Comparative analyses of the sub-surface structure of talus at the study sites indicate a greater depth of sediment reworking on Trotternish than in the NW Highlands, a result that appears consistent with the differences in talus surface relief summarised above.

Collectively, these findings indicate that the essentially relict taluses investigated represent mature forms modified to varying degrees by downslope mass transport of coarse diamictic sediment, primarily by gully incision and intermittent debris flow activity. More generally, they imply not only that the combination of a steep upper rectilinear slope and a basal concavity fails to provide a reliable indication of truly 'unmodified' rockfall talus, but also that downslope transport and subsequent redeposition of talus debris at the slope-foot is at least partly responsible for the formation of the basal concavity. By way of a cautionary note, however, valley-side drift in upper Glen Feshie, though morphologically similar to the talus slopes at the other sites, has been shown to comprise largely glacigenic sediments that have been buried by a thin veneer of Lateglacial and Holocene rockfall detritus. This finding suggests that a continuum of steep hillslope sediment accumulations exists, all morphologically similar, but ranging from those consisting almost entirely of reworked till to 'true' talus slopes composed entirely of debris derived from rockwalls upslope.

Existing theories of talus formation, notably the 'discrete particle rockfall model' (Statham, 1973a, 1976a; Kirkby and Statham, 1975) and the 'two facet model' (Francou and Manté, 1990; Francou, 1991), appear to be incompatible with the results of analyses of slope surface morphology and internal structure. The former model fails to accommodate the effects of downslope transfer of rockfall debris by processes other than rockfall impact. The 'two facet model' makes allowance for mass transport down the upper slope of talus accumulations, and is thus consistent with observations of widespread reworking of taluses in the Scottish Highlands. However, the model assumes that a constant supply of fresh rockfall sediment replenishes that lost by downslope removal, which is not the case for the relict taluses in the study areas. Thus, existing models of talus formation offer at best an incomplete explanation of the nature and evolution of relict talus slopes in the Scottish Highlands.

9.2.2 Talus sediments

In terms of the textural characteristics of relict talus deposits on Trotternish, the overall proportion of fine-grained (<2 mm) particles present is in the order of 27-30 % by weight. The abundance of fines within the Trotternish talus accumulations (and, by inference, those elsewhere in the Scottish Highlands) suggests that it is unrealistic to model the evolution of such deposits in terms of free-draining openwork accumulations of coarse-grained debris. The textural properties of the relict talus accumulations have greater affinities with those of other diamictons, such as tills, in which build-up of pore-water pressures during rainstorms may trigger shallow translational failure and subsequent downslope flow of debris. Consequently, models that treat talus slopes simply as accumulations of coarse clasts (notably Statham, 1973a, 1976a; Kirkby and Statham, 1975) have very limited value in explaining their evolution and behaviour.

The aggregate clast characteristics, fine (<8 mm) sediment granulometry and mineral magnetic properties of bulk sediment samples collected from relict talus accumulations on Trotternish confirm that both the coarse and fine fractions of these deposits are derived from the rockwall upslope, with no evidence for a component of glacigenic origin. This finding permits the calculation of approximate rockwall retreat rates based on the volume of the talus deposit downslope. An average of *c.* 5 m of rockwall recession since deglaciation (*c.* 17 cal ka BP) was calculated for a 480 m long stretch of cliff face immediately south of The Storr, implying an average retreat rate of *c.* 0.3 mm yr^{-1} during this period, of which *c.* 0.08-0.09 mm yr^{-1} is attributable to weathering-out of fines rather than fall of clast-sized particles. Much of the coarse component of the talus deposit probably accumulated under periglacial conditions during the Late Devensian Lateglacial (i.e. prior to *c.* 11.5 cal ka BP), though granular weathering of the cliff face appears to have persisted during the Holocene (*cf.* Ballantyne, 1998).

9.2.3 The timing and causes of talus reworking

Radiocarbon dating of soils intercalated within talus sediments suggests that erosion and downslope redistribution of relict talus debris at the study sites in Trotternish and the NW Highlands locally predates *c.* 6 cal ka BP, though the bulk of sediment reworking apparently occurred during the late Holocene. There is evidence for two phases of broadly synchronous reworking of talus at Trotternish and the NW Highlands, at *c.* 6.3-5.6 cal ka BP and at *c.* 2.7-1.6 cal ka BP, though the validity of the earlier of these is uncertain because of inversion of radiocarbon ages at one of the mainland sites (Baosbheinn). Moreover, these findings are based on a rather limited number of reliable radiocarbon dates, and thus interpretations must be regarded as provisional. The age of the onset of currently active gully incision of talus on Trotternish, and of the most recent phase of gullying of talus slopes at the mainland field sites, is unknown. Aerial photographs of Trotternish, however, indicate gully maturation prior to 1959, and Innes (1982) suggested initiation of gullying at this location in the early 1930s. Gully age may, however, be markedly greater that these sources suggest.

Modification of the talus accumulations, primarily by slope failures and debris flows, appears to be facilitated by the steep gradients of upper slopes. Moreover, the inferred progressive infilling of interstitial cavities by inwashing of fine particles derived from rockwalls upslope may have resulted in a progressive increase in the likelihood of slope failure caused by build-up of porewater pressures during rainstorms. Thus the internal evolution of talus deposits may have caused a gradual increase in the sensitivity of talus slopes to extreme storm events.

An apparent phase of enhanced talus reworking at Trotternish and at the field sites in the NW Highlands at *c.* 2.7-1.6 cal ka BP is coincident with a well-established period of general climatic deterioration and increased wetness at the beginning of the Sub-Atlantic chronozone at around 2.5 ka BP (*c.* 2.7-2.3 cal ka BP). Such correspondence of timing suggests that changing climate, possibly associated with an increased incidence of violent rainstorms, may have triggered this particular episode of talus slope instability. Pending further research, however, the possible links between secular climate change and erosion of upland talus slopes remain conjectural. Moreover, it is not possible at present to exclude the possibility that the timing of talus erosion in the Scottish Highlands reflects the infrequent occurrence of random high magnitude storms rather than longer-term cycles of climate change.

9.3 Future research

The research reported in this thesis has furnished valuable new data regarding the physical characteristics and evolution of relict talus slopes on Scottish mountains. Brief summaries of potential avenues for further research in this field are explored below.

Debris flows have frequently been observed on talus slopes in mountainous terrain in Europe, continental North America and the Himalayas, indicating that reworking of the upper levels of talus is widespread, and raising the possibility that the sediments underlying these slopes are of similar (diamictic) composition to those investigated in this thesis, and contain a significant infill of fines at shallow depths. However, few studies have hitherto investigated in detail the internal composition and structure of talus slopes, and only two studies (Salt and Ballantyne, 1997; and the current research) have reported the results of textural analyses of subsurface talus sediments. Consequently, there is potential for further research to establish the generality of the sedimentological findings reported here, particularly with regard to currently-accumulating (active) taluses and those developed on other lithologies and in other climatic environments.

Structural analyses employed during the current research have focused on depositional facies underlying the upper rectilinear slopes of talus. The results suggest widespread modification of talus accumulations, mainly by debris flows. Fluvial reworking of talus sediments, however, tends to redistribute finer grades of sediment to the talus foot. Thus the results of structural analyses of sections excavated at the steep upper slopes of talus deposits may lead to under-representation of the role of surface wash and in particular fluvial transport down gullies in reworking talus sediments.

In this context it is notable that recently-emplaced surface wash sediments have been observed overlying peat deposits downslope of talus-foot debris cones both at Trotternish and at the field sites in NW Scotland. This suggests that peat beds immediately downslope of reworked talus accumulations may contain intercalated layers of fine-grained sediment derived from the talus. If so, such layers may provide a datable record of colluvial deposits reflecting intermittent modification of talus slopes (*cf.* Matthews *et al.*, 1997). Similarly, Lochan a' Bhealaich Bhig and its smaller neighbour, both located in small enclosed basins behind glacially-moulded landslip blocks immediately south of The Storr on Trotternish, provide traps for occasional inputs of fluvially-transported sediment from the adjacent talus. At these and similar locations, lacustrine sediments may yield a record of intermittent colluvial deposition, possibly related to the occurrence of debris flow events on adjacent slopes. Radiocarbon dating of organic-rich sediment intercalated with minerogenic slopewash deposits within slope-foot peat beds and lake basins may permit reconstruction of a complete chronology of inwashing of debris, and thus of talus reworking upslope.

The findings reported in this thesis concerning the history of erosion and reworking of talus sediments are based on only a limited number of reliable radiocarbon dates, and are thus provisional. More generally, there is a paucity of published information regarding the age, frequency and causes of phases of drift slope instability in the Scottish Highlands and elsewhere in upland Britain. Future research on the chronology of debris flow activity on talus and other slope deposits in upland Britain would thus be valuable. The radiocarbon ages for talus reworking reported in this thesis form part of a wider database relating to Holocene hillslope instability in the Scottish Highlands (C.K. Ballantyne, A. Curry and S. Hinchliffe, unpublished data). These data are currently under investigation to determine whether hillslope failure and consequent reworking of debris exhibits random timing throughout the mid to late Holocene, or whether there is significant temporal clustering that may reflect general climate deterioration, periodic increases in extreme events, or possible anthropogenic influences on slope stability.

The radiocarbon dating and pollen evidence discussed in this thesis suggest that the timing of late Holocene reworking of relict talus slopes in the Scottish Highlands may reflect a climatic signal, either associated with general climate deterioration or the occurrence of random high-magnitude storms. However, this finding is based largely on negative evidence that appears to exclude anthropogenic interference with vegetation as a possible cause of erosion and reworking of relict talus slopes. Continued research in this field is therefore necessary to test further the hypothesis that Holocene talus slope instability may be triggered by extreme climatic events. Moreover, the causes of currently active gully incision of talus on Trotternish and the most recent phase of gullying of mainland talus slopes remain elusive. Several authors have suggested that such activity may relate to increased storminess during the 'Little Ice Age' of the sixteenth to nineteenth centuries AD, land management practices on Highland estates, or the effects of deposition of air-borne industrial pollutants in the nineteenth and early twentieth centuries AD. Testing of the validity of these competing hypotheses represents a potentially important direction for further research, the results of which may have far-reaching implications for the evolution of sensitive upland areas in Britain and further afield.

The conclusion reached here, that the history of talus slope instability probably reflects the timing of extreme weather events, implies that future investigations of depositional structures and organic sediments underlying talus slopes may ultimately yield a proxy record of Holocene climate change, and in particular the frequency of extreme storm events. Moreover, the strong sedimentological and morphological affinities between talus accumulations and steep, valley-side glacigenic deposits suggests that investigations of talus slope history may also contribute to advancement of general theories of the evolution of steep, drift-mantled hillslopes in formerly glaciated uplands. The research reported in this thesis thus represents not only an advance in our understanding of the long-term evolution of talus accumulations, but has also demonstrated how study of such accumulations may contribute to our understanding of past environmental changes and how such changes have affected the stability and morphology of steep valley-side sediment accumulations in formerly-glaciated environments.

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Figure 7.5. Percentage pollen diagram.
Section T1, area 2, Trotternish, northern Skye.

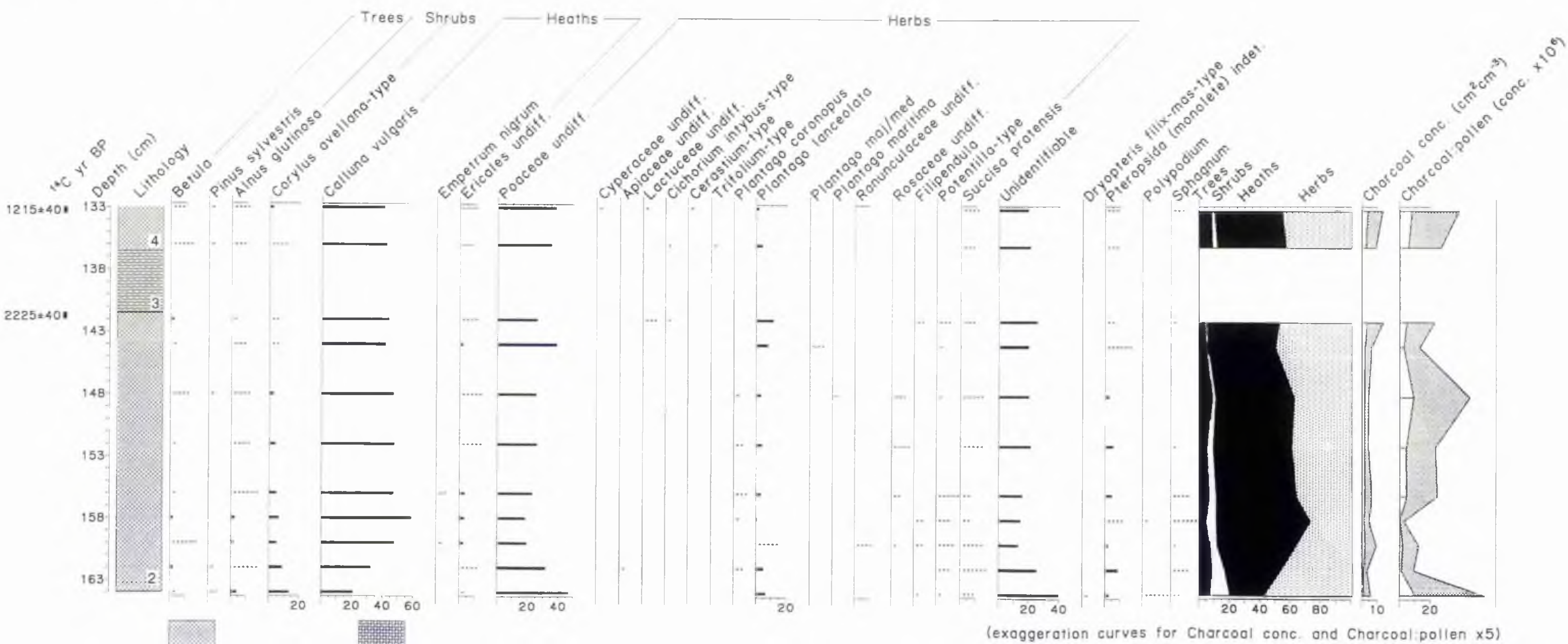
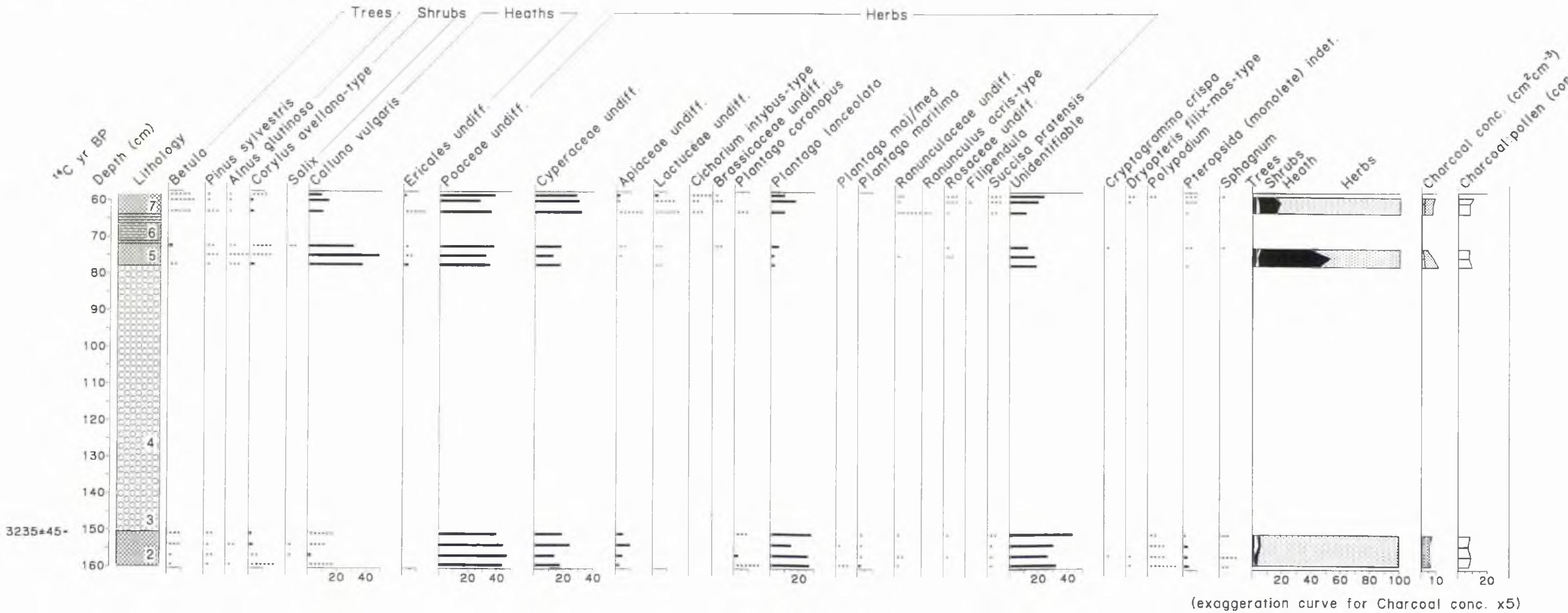


Figure 7.7. Percentage pollen diagram.
Section T6.a, area 2, Trotternish, northern Skye.



6. Percentage pollen diagram.
T5.a, area 2, Trotternish, northern Skye.