LATE QUATERNARY ALLUVIAL FANS, DEBRIS CONES AND TALUS CONES IN THE GRAMPIAN HIGHLANDS, SCOTLAND

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**A Thesis Submitted for the Degree of PhD
at the
University of St. Andrews**

1988

LATE QUATERNARY ALLUVIAL FANS, DEBRIS CONES AND TALUS CONES IN THE GRAMPIAN HIGHLANDS, SCOTLAND.

by

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Thesis presented for Degree of
Philosophae Doctor.
University of St. Andrews.

September 1987

A CONTINUUM OF FAN AND CONE LANDFORMS, GLENCOE.

I VANESSA..BRAZIER hereby certify that this thesis has been composed by myself, that it is a record of my own work, and that it has not been accepted in partial or complete fulfilment of any other degree of professional qualification.

Signed. Date..8.-.9.-.1987

I was admitted to the Faculty of Science of the University of St. Andrews under Ordinance No 12 on .1st.OCTOBER.1983... and as a candidate for the degree of Ph.D. on ....FEBRUARY.1985..

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I hereby certify that the candidate has fulfilled conditions of the Resolution and Regulations appropriate to the Degree of Ph.D.

Signature of Supervisors .. ..

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A. UNRESTRICTED

Tha mi a'coisrigeadh an tràchdas seo
do na smuaintean àlainn a dhrùidh
Weasdale orm agus do ghrinneas nan
dealbhan a dh'fhàg "Alligin Shuas"
nam chom.

ABSTRACT

Alluvial fans, debris cones and rockfall talus cones are widespread in upland Britain, but remarkably little is known about their characteristics, development and significance. This research project has three main objectives:

1. to establish the morphological and surface sedimentary characteristics of alluvial fans, debris cones and talus cones in the Grampian Highlands of Scotland;
2. to identify the factors that have controlled their formation and distribution; and
3. to determine the timing, nature and rate of fan- and cone-forming processes.

On the basis of previous literature, an *a priori* model that describes a continuum of fan and cone morphological and surface sedimentary properties was devised. The applicability of this model was tested using data for six variables (long profile gradient, slope form, downslope changes in clast size, roundness and form, and a scale ratio of maximum clast size to total fan or cone length) obtained for fans and cones in the Grampian Highlands and the Lyngen Peninsula in Northern Norway. The results of these tests were then used to produce a modified model appropriate to fans and cones in upland Britain.

Using a combination of map, field and aerial photograph data, several environmental and morphometric controls on the distribution and type of fan and cone development were investigated. The dimensions of different types of fan and cone are shown to be determined by basin morphometry, lithology and glacial history. Discriminant analysis identified basin gradient, basin width and basin height as the principal catchment properties that influence the dominant type of fan- or cone-forming process.

Stratigraphic and radiocarbon evidence suggests that many debris cones are essentially paraglacial landforms that formed in the earlier part of the Flandrian. Many of these cones have subsequently been modified in the late Flandrian by fluvial processes, in some cases in response to anthropogenic interference. However, evidence from one site has also revealed that substantial debris cone aggradation has occurred since *c* 300 BP, implying high rates of gully denudation in the recent past at this site. The volumes of other debris cones imply that as much as 1-3m of surface lowering has occurred in gullies upslope since deglaciation. Much lower values of surface lowering are associated with alluvial fan development, suggesting that, locally at least, denudation by fluvial processes has been less significant than denudation resulting from debris flow.

ACKNOWLEDGMENTS.

Financial support for the research project was provided primarily by a Natural Environment Research Council studentship. Additional funding for fieldwork was provided by the Bill Bishop Trust. A grant was also provided by the Natural Environment Research Council to meet the cost of the radiocarbon analyses. The work was undertaken at the Department of Geography at the University of St. Andrews. I am especially grateful to my supervisors Drs. Alan Werritty and Colin Ballantyne, who have given advice and encouragement throughout the course of the project and provided many useful comments on earlier drafts of this dissertation. I would also like to thank Dr. G. Whittington (Chairman of the Department) for his advice and encouragement.

Many students, friends and family have helped with the fieldwork including Cat Stretton, Norma Stewart, Sara Creswell, Janet Johnson, Stuart Purves, Janet Tompson, Martin Kirkbride, Gillian Law, Jackie Skeldon and friend Emma, Emma Armitage, Mary-Ann Smyth, Dr. Jack Jarvis, Schiona Campbell, Bill Reed, Kay Young, Barry Cullimore, and Shirley Martin, Mark Gunn and Jill Tate and other members of the 1985 St. Andrews Lyngen Expedition. I would particularly like to thank four stalwart individuals who helped on several occassions and were evidently unperturbed by the incessant rain and midges: Liz Kuisnik, Kitta Campbell, Rachel Roland and last but by no means least, Ali Kirkbride.

Many people have offered useful advice and assistance during the course of the research. I wish to thank Drs. R. Dyckhoff, H. Wier, J. Henderson and Ms. L. Innocent for invaluable help with computing problems and Dr. A. Gordon for advice on the use of multivariate statistics. I would also like to thank Drs. A.M. Harvey J. Innes, P.A. Carling, J. Jarvis and Mr. Moray (Highland Regional Council) for disscussions on particular field work related problems. Laboratory assistance was given by Colin Cameron, and the pollen counting by Mrs. Lois Wood. Dr. G. Whittington provided an interpretation of the pollen diagram in chapter 7. The radiocarbon analyses were conducted under the guidance of Dr. D.D. Harkness at the Scottish Universities Research and Reactor Centre, East Kilbride. Dr. D.D. Harkness also provided useful comments that aided interpretation of the radiocarbon dates. In particular, I would like to thank Dr. Melanie Robertson-Rintoul for her advice, encouragement and enthusiastic discussions on numerous aspects Flandrian geomporphology.

Finally, I am especially grateful to "the team" who helped me produce this dissertaion: Mary, Ali and Martin Kirkbride, Kay Young, Veena O'Halloran, Alison McLean, Bill Reed, Florence McAndie, and Mary, Clare, Polly and Yoko Toms.

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CHAPTER 1

INTRODUCTION

1.1 SCOPE AND DEFINITION.

Alluvial fans, debris cones and talus cones are planimetrically-similar accumulations of predominantly coarse sediment that occur on valley-side slopes in mountain environments throughout the world. Collectively, these landforms have been described as comprising part of a theoretical continuum of debris slope features (Rapp, 1960; Rapp and Fairbridge, 1968; Bull, 1968, 1977; Church *et al*, 1979; Selby, 1982). However, the interrelationships between different types of fan and cone landforms have received only limited investigation (Kostaschuk *et al*, 1986). In particular, there has been a failure in much previous research to discriminate between fans and cones composed predominantly of waterlaid deposits and those comprising mainly debris flow deposits.

The research described in this thesis explores several attributes of the continuum of fan and cone landforms, including the recognition of composite cones on which process thresholds have been crossed such that more than one depositional process has occurred at a single site. The research was based on a study of fan and cone landforms in the Highlands of Scotland, an area in which such features have received little previous study.

1.2 AIMS AND APPROACH.

In essence, the objective of this study is to determine the nature and significance of fan and cone landform development in the Grampian Highlands of Scotland. This objective can be subdivided into three component parts, as follows:

1. Establishment of the morphological and surface sedimentary characteristics of alluvial fans, debris cones and talus cones;

2. Identification of the factors that have controlled the formation and distribution of fan and cone landforms; and

3. Determination of the timing, nature and rate of fan- and cone-forming processes.

One of the characteristics of this study is that it has had to consider many questions concerning different types of fan and cone development over a large study area, largely without the benefit of a conceptual framework developed by earlier research. A variety of different approaches has therefore been employed in order to consider many of the factors that may have influenced the nature of fan and cone evolution in the Grampian Highlands. To overcome problems posed by the large size of the study area, the research was carried out at three different scales of investigation, a device that has enabled the advantages of studying a large sample of landforms to be combined with those that accrue from detailed investigations of single features or groups of features.

1.3 STRUCTURE OF THE THESIS.

The structure of the thesis has been organised so that most relevant background information is covered in the early chapters, but inevitably a certain amount of cross referencing and restatement has been necessary. Chapters 2 and 3 aim to set the scene with regard to environmental changes that have occurred in the Scottish Highlands since ice sheet wastage. The former reviews the literature on the timing, nature and significance of environmental and climatic changes in the Scottish Highlands and elsewhere in upland Britain; the latter provides detailed background information on the topography, climate, geology, geomorphology, vegetation history and landuse of each of the mesoscale study areas, within which more detailed investigations were carried out. Such information is necessary for proper evaluation of the effect of different environmental and topographic controls on the distribution and type of fan and cone landform development.

As a consequence of the pioneering nature of this study, many of the implications of environmental changes for fan and cone development suggested in chapters 2 and 3 are speculative, often being drawn from evidence concerning the development of other landforms. Such speculations nonetheless provide several useful and testable hypotheses regarding fan and cone development, hypotheses that to some extent guided the collection of field data and the approach adopted in later chapters.

Chapter 4 provides a detailed review of the literature on alluvial fans, debris flow dominated cones, and talus sheets and cones. Attention is primarily focused on literature concerned with tectonically-stable mountain environments similar to those of the Scottish Highlands. The literature base made possible the formulation of an *a priori* model of the morphological and surface sedimentary properties of different parts of the fan and cone continuum, as distinguished by dominant depositional process. Furthermore, the literature provided the necessary information that enabled differentiation in the field of genetically-dissimilar types of fan and cone landform through identification of specific diagnostic features. The environmental controls of different fan- and cone-forming processes are also reviewed in chapter 4; previous work on this topic suggested various possible effective controls on the distribution, type, chronology and evolution of different fans and cones in the Scottish Highlands.

The fifth chapter considers landform classification, and assesses the appropriateness of the *a priori* model developed at the end of chapter 4 with regard to the characteristics of fan and cone landforms in the Grampian Highlands. The findings of the Scottish research are then compared with data from a number of sites examined on the Lyngen Peninsula, Northern Norway, to establish the generality of the conclusions reached. The results from this part of the research provide a test of the concept of a continuum of fan and cone landforms, and the findings reported here were used as a basis for introducing several refinements to the *a priori* model of chapter 4.

Chapter 6 examines the role of various environmental and morphometric controls on the distribution and nature of different types of fan and cone landforms. The approach adopted develops from an examination of bivariate relationships to multivariate analysis of morphometric controls of dominant process. The model developed provides a starting point for further assessment of different process thresholds and controls.

Chapter 7, on chronology and evolution, provides a time framework for the development of fan and cone landforms in the Grampian Highlands. Several hypotheses relating to environmental changes (chapters 2 and 3) are examined with reference to a number of case studies of debris cone chronology and evolution during the Flandrian. Data from these and other sites are then used to evaluate the geomorphological impact of fan and cone accumulation and associated source area denudation in the Grampian Highlands in the 10,000 to 13,000 years since deglaciation. Finally, the age of recent fluvial and debris flow activity on fans and cones in Glencoe is examined.

The final chapter in the thesis (chapter 8, conclusion), brings together the principal findings of the research and attempts to present overall conclusions regarding the nature, significance and chronology of fan and cone landform development in the Grampian Highlands.

CHAPTER 2

ENVIRONMENTAL CHANGE IN UPLAND SCOTLAND FROM THE LATE DEVENSIAN TO THE PRESENT.

2.1 INTRODUCTION

The aim of this review is to examine the literature on Late Devensian and Flandrian environmental change in Scotland, and to consider the implications for fan and cone development in the Scottish Highlands over the last c 18,000 years.

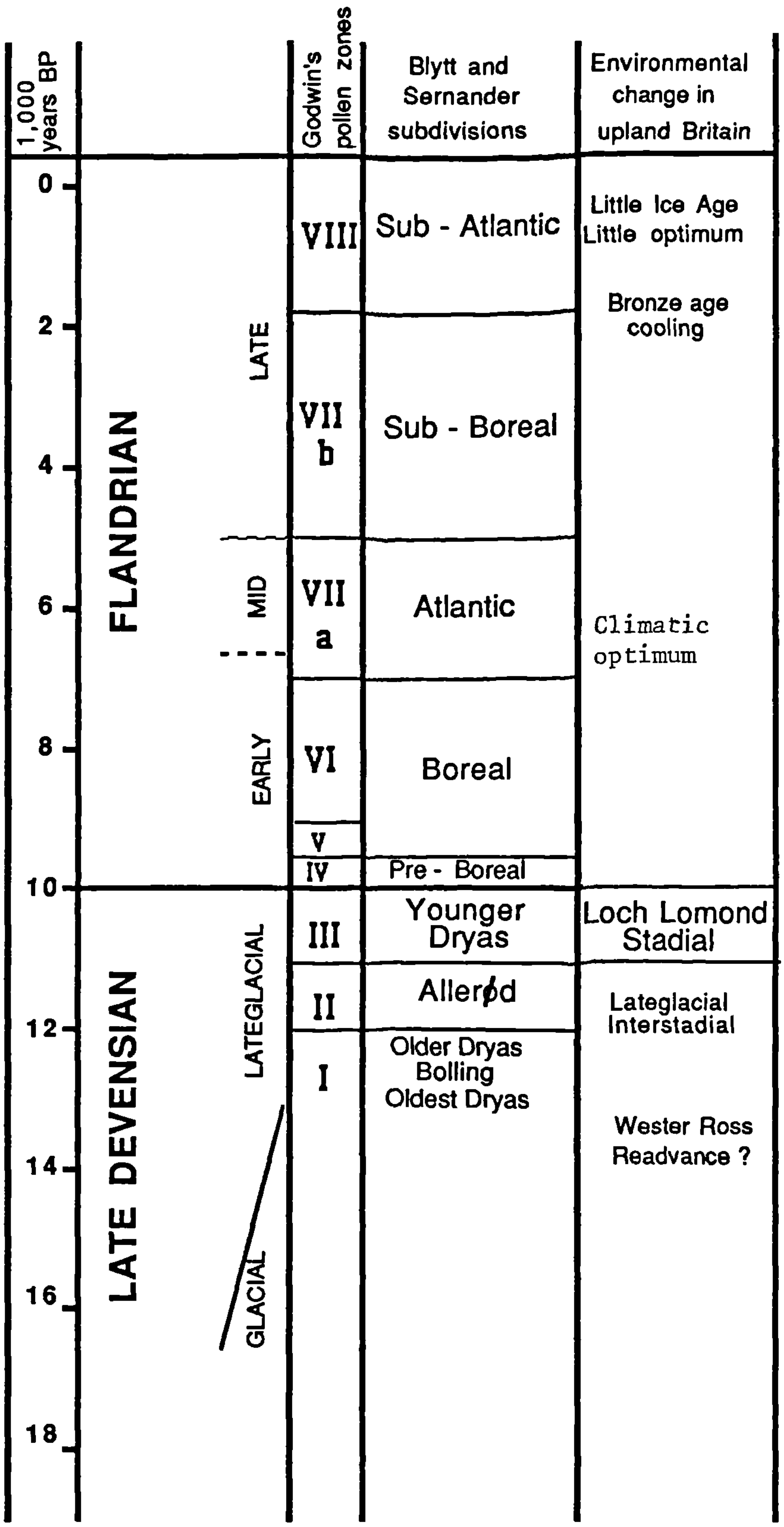
Certain assumptions have been adopted when considering the implications for fan and cone activity. Independent factors such as climate, geology, and topography have controlled where, when, and how alluvial fans, debris cones, and rockfall talus cones form. For the purposes of this review it is assumed that solid geology and regional patterns of topography have not undergone any significant change since deglaciation. It is therefore assumed that climate has, directly or indirectly, formed the major variable affecting the nature and rate of fan and cone formation during much of the Late Devensian and Flandrian in areas where geology and relief were favourable. The last c 18,000 years have been characterised by extreme climatic and environmental changes, including two periods of stadial conditions, as well as more minor climatic oscillations during the Flandrian. The possible implications of changing environmental conditions for fan and cone development will be considered at the end of each section, and thus provide the background for later chapters.

The period since c 18,000 BP has conventionally been subdivided into two major chronozones, the Late Devensian and the Flandrian (figure 2.1). The internationally recognised Devensian/Flandrian (Pleistocene/Holocene) boundary of 10,000 BP (Fairbridge, 1983) will be adopted in this review. The chronostratigraphic term Dimlington Stadial, recently proposed by Rose (1985), has been adopted for the last period of Devensian ice sheet cover in Britain, that is from c 26,000 to c 13,000 BP. The subsequent Lateglacial Interstadial and Loch Lomond Stadial are conventionally dated c 13,000 to 11,000 BP and c 11,000 to 10,000 BP respectively (Gray and Lowe, 1977).

2.2 LATE DEVENSIAN ENVIRONMENTAL CHANGE

Quaternary research in Scotland over the last few decades has resulted in a great wealth of literature on various aspects of environmental change during the Dimlington Stadial, the Lateglacial Interstadial and the Loch Lomond Stadial. The essence of present knowledge concerning these three periods of Late Devensian environmental change will be reviewed separately.

Figure 2·1
Chronology of environmental
change in upland Britain



(after Ballantyne, 1981)

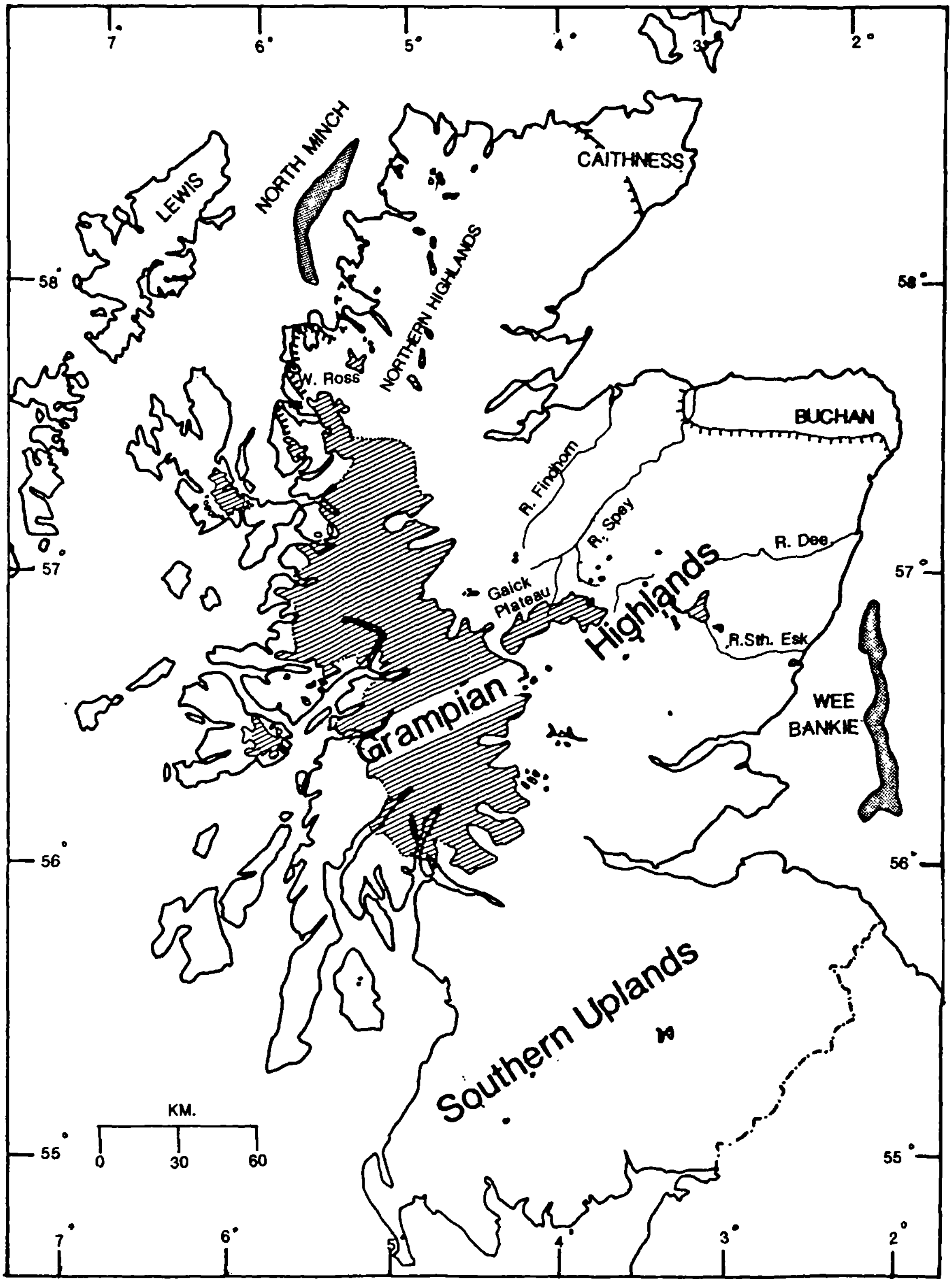
2.2.1 The Dimlington Stadial.

Deep sea cores from the Atlantic Ocean have provided evidence that ice sheets may have developed in Britain as many as 17 times during the Quaternary (Gribbin, 1978; Ruddiman et al, 1980). The last ice sheet in Britain is thought to have reached its southern maximum extent in England c 18,000 BP (Gray and Lowe, 1977; Wintle and Catt, 1985), and perhaps rather earlier in Scotland, (Sissons, 1983; Sutherland, 1984; Sutherland and Walker, 1984).

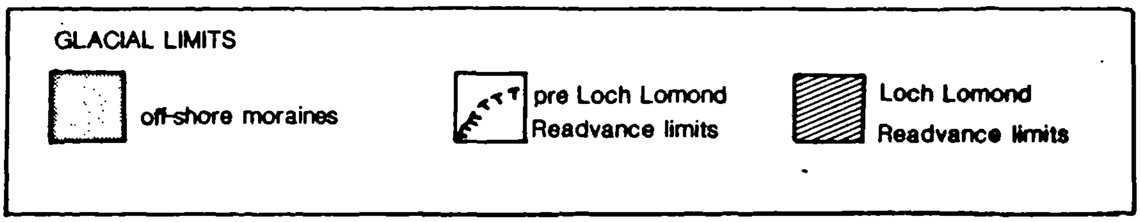
Much of the literature regarding the lateral extent of the last ice sheet in Scotland remains speculative. There has been much debate in particular over the possibility that some parts of the present land surface remained glacier-free at this time. Considering first the ice sheet limits to the north and west of the Scottish mainland, it was traditionally accepted that the last ice sheet reached its maximal extent well beyond the Outer Hebrides, possibly as far west as the continental shelf. This view has been adopted in a number of reconstructions of ice sheet dimensions (eg Boulton et al 1977; Gordon, 1979). However, recent research has shown that the last ice sheet did not reach St.Kilda (Sutherland et al, 1984) and that during the Late Devensian an independent ice cap was nourished in the Outer Hebrides (Coward, 1977; Flinn, 1978; Peacock and Ross, 1978). Furthermore, Sutherland and Walker (1984) have established that the northernmost tip of Lewis remained glacier-free throughout the Late Devensian. This implies that during the Dimlington Stadial the last Scottish ice sheet did not extend farther than the Minches in the west, where its limit may be marked by the North Minch Moraine (figure 2.2) identified by Sutherland (1984). Moreover, Sissons (1983) has suggested that for much of the Dimlington Stadial the margin of the ice sheet was normally situated amid the Inner Hebrides, where its approximate position may be identified from the distribution of supposedly contemporaneous high rock platform fragments formed under severe periglacial conditions. The maximum westernmost extent of the last Scottish ice sheet has therefore been radically reinterpreted in recent years. Similarly, in the east (in Caithness and Buchan) the hypothesis of ice free enclaves during the Late Devensian (Charlesworth, 1955; Synge, 1956) has also received renewed support (eg Sissons, 1981 , 1983; Hall, 1984; Connel et al, 1985).

There is,however, no consensus of opinion regarding much of the evidence for a Late Devensian ice-free zone in Buchan (Hall, 1984). Clapperton and Sugden (1977) believed that Buchan was the site of confluent Moray Firth Ice, Central Highland Ice and Cairngorm and Strathmore Ice Masses. They suggested that deglaciation was early in Buchan (before c 16,000 BP) thus accounting for the evidence of intensive periglacial activity in the area (FitzPatrick, 1956). Indeed Holmes (1977) noted considerable similarity between the coastal tills of Buchan and the till-like material associated with the offshore Wee Bankie Beds that

Figure 2.2 Late Devensian glacial limits in Scotland.



(Sources; Robinson and Ballantyne, 1979; Sissons, 1981; Sutherland, 1984; Ballantyne, pers. comm.)



have been interpreted as representing the easternmost extent of the last Scottish ice sheet off the coast of Fife and Angus (Figure 2.2). Farther north-east in the Central North Sea the Hills deposits and associated Scandinavian ice sheet moraines imply that glacier ice from Norway was not confluent with the last Scottish ice sheet during the Dimlington Stadial. Sutherland (1984) has suggested on the basis of the North Sea evidence that a Late Devensian ice limit may be defined in Caithness at the western margin of the shelly till that occurs extensively across this region (figure 2.2).

In summary, despite the inconclusive nature of some of the evidence, the last Scottish ice sheet appears to have been much less extensive than previously believed. One of the implications of this is that nunataks are likely to have existed above the ice in some parts of Scotland. The distribution of certain types of in situ mountain-top detritus may therefore yield further information concerning the dimensions of the last Scottish ice sheet (Ballantyne, 1984). Nonetheless, it seems very likely that all Highland glens were totally ice-covered at the time of the last ice-sheet maximum, so that accumulations of fan and cone sediments found on many valley floors cannot pre-date Late Devensian ice sheet deglaciation in the Scottish Highlands.

It is thought that the last Scottish ice sheet initially began to decay due to increasing aridity caused by the southerly migration of the oceanic polar front (Ruddiman et al, 1977), so that Britain was surrounded by cold polar waters (Lamb, 1977; Sissons, 1981 , 1983). This raises the possibility that temporary increases in precipitation during subsequent northward migration of the oceanic polar front may have led to limited readvances of the decaying ice sheet (Sissons, 1981). Robinson and Ballantyne (1979) have identified in Wester Ross several moraines marking the limit of one such readvance (the Wester Ross Readvance). These have been tentatively correlated with a Lateglacial shoreline and with moraines near Achnasheen (Sissons and Dawson, 1981). No age has been ascribed to the Wester Ross Readvance, though a radiocarbon date of 12,810 +/- 155 BP for deposits near Loch Droma in Ross-shire (Kirk and Godwin, 1963) provides a minimal age for this event. Similarly, Hinxman and Anderson (1915) have noted several moraine-like landforms in the Strath Spey and Strathdearn areas, but the significance of these remains uncertain.

Deglaciation of much of the Grampian Highlands had probably occurred by about 13,000 BP. Indeed, Sissons and Walker (1974) recorded a basal radiocarbon date of 13,150 +/- 390 BP at Loch Ettridge, which implies that the upper Spey valley was deglaciated by this date. It is therefore possible that fan and cone landforms began to accumulate in some glacier-free upland areas fairly early during deglaciation, under periglacial conditions, and continued to develop under the milder conditions that marked the beginning of the Lateglacial Interstadial. Rapid fan and cone aggradation during ice sheet deglaciation is likely to have been favoured by periglacial conditions characterised by high rates of frost shattering of rock, abundant unconsolidated glacial sediments, open vegetation cover (Walker, 1984), slopewash, and a nival runoff regime with high magnitude spring floods.

2.2.2 The Lateglacial Interstadial

The magnitude of climatic amelioration at the start of the interstadial (Coope, 1977a, 1977b; Bishop and Coope, 1977) suggests little chance of glacier survival, except possibly on high ground. Sugden (1970) argued that part of the ice sheet may have survived throughout the interstadial in the Cairngorms and adjacent Spey valley, but this has been disputed by Sissons and Walker (1974), who obtained a minimal radiocarbon date of 13,150 +/- 390 BP on basal organic sediments in Loch Etteridge in the Spey valley and by Sissons (1979b), who found that glacier ice cover in the Cairngorms during the subsequent Loch Lomond Stadial was of very limited extent. If glacier ice did survive the interstadial in Scotland then the most plausible location would have been in the west; Peacock _et al_ (1977) and Sutherland (1984) have suggested that a relatively large ice mass could have survived the thermal maximum of the early Lateglacial Interstadial on high ground in the Western

Highlands. At present, however, there is no conclusive evidence either in favour or against this proposition.

Environmental conditions during the interstadial have been reconstructed from palynological evidence and from the environmental implications of contemporaneous coleoptera. The latter have provided a particularly sensitive thermometer of climatic fluctuations at this time on account of their swift response to environmental change (Bishop and Coope, 1977; Coope, 1977a, 1977b; Coope et al, 1977). The identification of a rapid succession of thermophilous coleoptera found at sites in SW Scotland led Bishop and Coope (1977) to postulate sudden climatic amelioration with mean July temperatures reaching c 15°C (similar to that of the present) near the onset of the Interstadial c 13,000 BP, and Coope (1977a) has suggested rapid climatic amelioration of the order of 1°C per decade in North Wales. Coleoptera assemblages relating to later in the interstadial are more mixed, implying a decline from the thermal maximum that had marked the start of the interstadial to mean July temperatures of c 12°C in SW Scotland (Bishop and Coope, 1977). Coope (1977b) argued that a rather more severe climate may have existed in Highland Scotland throughout the interstadial, in view of the steep northward decline of the contemporaneous climatic gradient as identified from coleoptera studies throughout Britain.

Numerous pollen studies have yielded a relatively detailed picture of changes in plant assemblages in Highland Scotland during the Lateglacial Interstadial. Pioneer vegetation was characterised by open habitat taxa such as Rumex and Artemisia, with sparse shrub colonization and possibly some tree cover, though the presence of arboreal pollen must be interpreted with caution as these may reflect long distance transfer (Lowe and Walker, 1977; Cundill and Whittington, 1983). Various regional vegetation patterns developed after the pioneer stage. Near the west coast open grassland persisted with localized juniper and Betula stands, whilst on high ground heathland communities developed (Pennington, 1977; Gray and Lowe, 1977; Walker and Lowe, 1982). In the Grampians, the most widespread vegetation cover for much of the Lateglacial Interstadial was shrub tundra dominated by Empetrum (Birks and Mathewes, 1978), whilst in the SE Grampians moss heaths and poor grassland communities were to be found on the hills and closed grassland with some juniper, dwarf birch and willow stands in sheltered valleys (Walker, 1975b; Lowe and Walker, 1977; Godwin, 1977; Caseldine, 1980).

Palynological evidence from a number of sites in northern Britain suggests that a brief climatic reversal took place during the interstadial between c12,000 and c11,000 BP. This reversal may be equivalent to the Older Dryas chronozone of Northern Europe, which was characterised by the break up of vegetation cover and with a consequent increase in rates of soil erosion (eg Oldfield, 1960; Pennington _et al_, 1972; Walker, 1977; Caseldine, 1980). However, this climatic oscillation has not been identified in studies of coleoptera assemblages (eg Coope, 1970, 1977a, 1977b; Coope and Brophy, 1972; Bishop and Coope, 1977) or at many other Lateglacial Interstadial pollen sites (Lowe and Walker, 1977; Walker, 1984), so its significance in upland Scotland remains uncertain. Evidence from lake deposits suggests that minerogenic sedimentation was insignificant during the interstadial (Pennington, 1977).

In sum, the evidence discussed above suggests that the environment in the Scottish Highlands during the Lateglacial Interstadial was apparently not as temperate as elsewhere in Britain and probably cooler than at present. Fan and cone development may have been favoured by sediment availability following deglaciation, but the stabilising effect on sediment sources of increasing vegetation cover may have led to a decline in aggradation rates throughout the interstadial, a proposition that finds support in the decline in minerogenic sedimentation in lakes at this time (Pennington _et al_, 1972; Pennington, 1977).

2.2.3 The Loch Lomond Stadial

The existence of a distinct period of valley glaciation following the retreat of the last ice sheet in Scotland has been recognised for over a century (eg Chambers, 1855; MacLaren, 1855). This period of renewed glaciation was termed the Loch Lomond Readvance by Simpson (1933) and assigned to Godwin's pollen zone III (ie c 10,750 to 10,250 BP) by Donner's (1957) palynological investigations both inside and outside associated glacial limits. Controversy still surrounds the precise timing and duration of the the Loch Lomond Readvance and the associated cold episode, the Loch Lomond Stadial. During the last 15 years, however, much research has been devoted to the reconstruction of the limits of Loch Lomond Readvance glaciers, and this has, together with palynological evidence and evidence provided by certain relict periglacial features, contributed markedly to our present understanding of environmental conditions during this final glacial episode in Scotland.

It is thought that the Lateglacial Interstadial drew to a close with the renewed southerly incursion of polar waters into the Atlantic (Binns et al, 1974; Ruddiman et al, 1977; Sissons, 1983). A marked change c 11,000 BP from thermophilous to arctic coleoptera assemblages implies a sudden and dramatic climatic change from the already deteriorating conditions of the later interstadial to glacial conditions of the stadial (Coope, 1977b). Dramatic climatic deterioration has also been clearly identified in the pollen-stratigraphic record (Walker, 1984), but uncertainty remains over the precise timing of this environmental change in the Grampian Highlands. Some radiocarbon dates, from a number of palynological sites, imply that severe climatic conditions had been established well before c 10,700 BP (eg Vasari, 1977; Walker and Lowe, 1982). Outside the areas where glacier ice developed the tundra vegetation cover was generally open and dominated by herbaceous taxa characteristic of disturbed ground, including Artemisia and Rumex. Such species have been interpreted as indicating widespread erosion of interstadial soils (Pennington, 1977). Furthermore, there is evidence for an increased influx of minerogenic sediment into lochs at this time (Pennington, 1977).

Marine shells found in Loch Lomond Readvance moraines have been radiocarbon dated and at one standard error give an age range of 10,780-11,050 to 12,110-12,410 BP (Sutherland, 1984, p 214). These dates are maximal for entrainment by advancing glacier ice (Sissons, 1976a). Glacier accumulation during the stadial is thought to have been rapid, with the development of a large ice field in the Western Grampian Highlands (Thorp, 1986), and smaller ice caps or ice fields on the Gaick Plateau, in the SE Grampians, and elsewhere (eg Sissons and Grant, 1972; Gray and Brooks, 1972; Sissons, 1972, 1974). Throughout the Highlands many smaller individual glaciers also formed at this time, particularly in the corries and valleys of the north and west (figure 2.2).

The reconstruction of Loch Lomond Stadial glaciers and their associated equilibrium firn line altitudes (Sissons and Sutherland, 1976; Sissons, 1979c, 1980; Thorp, 1986), along with evidence provided by the distribution of

Artemisia (Walker, 1975; Birks and Mathewes, 1978; McPherson, 1980; Pennington, 1980), and diagnostic periglacial landforms (Ballantyne, 1984; Ballantyne and Kirkbride, 1986) has enabled detailed interpretation of stadial precipitation patterns. Regional patterns in the altitudinal distribution of reconstructed equilibrium firn line altitudes across the Scottish Highlands have been interpreted by Sissons (1979c, 1980) in terms of extreme regional contrasts in stadial precipitation, with annual values as high as 3,000 to 4,000 mm in the SW Grampians, but only 500-600 mm on high ground in the northern Cairngorms, and possibly as little as 200-300 mm in the Spey valley. More localized differences may have also occurred due to factors such as snow shadow (Thorp, 1981). However the extreme aridity implied by Sissons' (1979c, 1980) estimates of stadial precipitation in the Cairngorms area have been challenged by Ballantyne (1984), who has suggested that rock glaciers in the Cairngorms thought to be Loch Lomond Stadial in age may imply precipitation of the order of 1,000-1,200mm/year, although the general pattern of precipitation decline proposed by Sissons is substantiated by the altitudinal distribution of stadial protalus ramparts (Ballantyne and Kirkbride, 1986). Further evidence for a marked eastward or north-eastward decline in stadial precipitation has been consistently found in the palynological record. It has been shown by research in present-day cold environments that *Artemisia* thrives in arid areas, becoming more sparse with increasing snow cover

(Pennington, 1980). The spatial variability and concentration of _Artemisia_ pollen have been used to reconstruct the Loch Lomond Stadial pattern of snowfall (MacPherson, 1980; Walker, 1984) and such evidence from the pollen-stratigraphic record complements palaeoclimatic inferences made from glacier reconstructions in suggesting that the most important snow-bearing winds came from the SW and to a lesser extent the SE. This seems to imply a stormy climate with frequent depressions associated with a more southerly position of the oceanic polar front relative to the west coast of Britain than at present (Sissons and Sutherland, 1976; Ruddiman _et al_, 1977; Sissons, 1980; Duplessy _et al_ 1981). Variations in the concentrations of _Artemisia_ through single pollen-stratigraphic profiles of Loch Lomond age may reflect changing levels of precipitation during the stadial, and appear to reflect the progressive southward migration of the oceanic polar front (Caseldine, 1980).

Reconstructions of palaeotemperatures from evidence provided by certain fossil periglacial phenomena of supposed Loch Lomond Stadial age have provided a measure of the severity of the climate at this time. Sissons (1976a, 1977) reported three ice-wedge casts in low altitude sediments of Loch Lomond Stadial age; if correctly interpreted, these imply continuous permafrost down to sea level at this time. If this was the case , it seems likely that stadial mean annual air temperatures were no higher than about -5°C, and possibly no higher than -8°C to -10°C (Ballantyne, 1984). For lowland Britain, Coope _et al_ (1977) estimated (on the basis of evidence provided by coleoptera) a mean July Stadial temperature of _c_ 10°C with a marked northward decline to _c_ 8°-9°C in SW Scotland (Bishop and Coope, 1977). Reconstructed equilibrium firn line altitudes have provided estimates of mean summer sea-level temperatures of _c_ 7°C for the Western Grampians (Sissons, 1979a, 1980) and _c_ 6°C in the SE Grampians (Sissons and Sutherland, 1976). On the basis of these summer temperature estimates, and on the assumption that the supposed ice-wedge casts have not been misinterpreted, Ballantyne (1984) estimated that mean January sea-level temperatures were no higher than _c_ -17°C, and possibly no higher than -23°C to -27°C.

The severity and large seasonal range of the stadial climate, the probable presence of continuous permafrost and open vegetation cover are likely to have provided favourable conditions for accelerated geomorphic activity during the Loch Lomond Stadial. Evidence that rockfall was extremely active at this time includes now-relict talus slopes, rock glaciers and protalus ramparts (Sissons, 1975; Dawson, 1977; Ballantyne, 1984; Ballantyne and Eckford, 1984; Ballantyne and Kirkbride, 1987). Ballantyne and Kirkbride's (1987) calculations for protalus rampart accumulation during the Loch Lomond Stadial imply an average stadial rockwall retreat of 1.14-1.61m, giving estimated average rockwall retreat rates within the range 1.5 to 4.0 mm/year. On the basis of these values they suggested that during the stadial upland Britain may have experienced a high frequency of effective freeze-thaw cycles similar to that typical of present-day high alpine environments, although rock slope instability following earlier ice sheet deglaciation is also likely to have favoured high rockfall rates.

Stratigraphic evidence for enhanced slope instability during the stadial takes the form of a layer of minerogenic in-wash in peat bogs and lakes. This is very distinct from the primarily organic deposition characteristic of the Lateglacial Interstadial and the Early Flandrian, and is manifest in a triple sequence of organic/minerogenic/organic deposits (eg Sissons and Walker, 1974; Pennington, 1977; Oldfield and Robinson, 1983).

The development of alluvial fans during the stadial has been identified at a number of locations in Scotland, for example at Corstophine Loch and along the foot of the Ochil escarpment (Sissons, 1976a). In Glen Roy, extremely large fans may have accumulated whilst the valley was intermittently flooded by ice-dammed lakes (Sissons and Cornish, 1983) and thus may provide an indication of very high sedimentation rates during the stadial. They have also suggested that much of the coarse gravel lying below the 261m lake level in Glen Roy was deposited by torrential snowmelt floods that declined in magnitude towards the end of the stadial. However, Peacock (1986) has argued that the Turret fan in Glen Roy dates from the period of ice sheet wastage, and that the other alluvial fans were deposited subsequent to ice sheet deglaciation but before the flooding of the glen during the Loch Lomond Readvance. The Glen Roy fans may, therefore, indicate either extremely high rates of sedimentation during the Loch Lomond Stadial, or paraglacial sedimentation (cf chapter 4, section 4.2.1) following ice sheet deglaciation. If the former interpretaion is correct then similarly high rates of sedimentation may be expected to have occurred on other fans and cones that developed during this period. Regional differences in precipitation levels may, however, have affected the rate of contemporaneous fan and cone development, with more rapid aggradation in the west, though any clear relationship is likely to have been masked where glacier ice contributed meltwater to a fan or cone catchment.

2.3 THE FLANDRIAN

In marked contrast to the Late Devensian period, surprisingly little research has been concerned with the geomorphological development of the Flandrian landscape in upland Britain, although much work has been carried out on Flandrian pollen stratigraphy in lakes and peat bogs. It is known that a number of relatively minor climatic fluctuations occurred during the Flandrian, although none was of the same magnitude as those that characterised the Late Devensian. Nor is there any convincing evidence to suggest the return of glacier ice in Scotland at any time during the Flandrian (cf Rapson, 1985), despite occasional claims to the contrary (eg Sugden, 1977).

In this section the general character of the vegetation cover, the principal climatic oscillations, and present information on geomorphological activity in upland Britain during the Flandrian will be reviewed. It is acknowledged that serious limitations are associated with climatic reconstructions and inferred changing rates of geomorphic activity based on palynological evidence due to the time-transgressive nature of plant species adaption to climatic change, and it cannot be assumed that any climatic change identified in the pollen-stratigraphic record implies a concomitant increase or decrease in geomorphic activity, or that evidence for former soil erosion at a particular site implies anything more than local and temporary instability.

Rapid climatic amelioration over a timescale of 500 years or less during the Preboreal marked the end of the Loch Lomond Stadial and the beginning of the Flandrian (Bishop and Coope, 1977). Drier conditions with temperatures rising to mean July values of 15°C are evident from thermophilous insect assemblages indicating relatively warm summers by c 9,500 BP in SW Scotland, and from palynological evidence indicating associated rapid vegetation colonization (eg Coope et al, 1971; Lamb, 1977; Lowe and Walker, 1981). Pioneer plant communities in many upland areas were dominated by Betula, Juniperus and Empetrum (Pennington et al, 1972; Godwin, 1977; Birks and

Mathewes, 1978; Lowe and Walker, 1981; Walker, 1984). However, the pattern and timing of plant succession varied regionally. For example, the replacement of park tundra by juniper scrub was established in the Grampians by c 10,000 BP, but rather later (c 9,700-9,500 BP) in the Spey valley (Birks and Mathewes, 1978). The conspicuous absence of open habitat species such as Rumex during the succession of birch, hazel and then pine forests indicates that slope erosion was probably not pronounced on low ground at this time. This is also suggested by the abrupt cessation of minerogenic sedimentation in bogs and lakes in the early Flandrian (eg O'Sullivan, 1975; Sissons and Walker, 1975; Pennington, 1977). Such evidence suggests that the magnitude of slope activity was significantly reduced at this time. It is possible that contemporaneous fan and cone aggradation may have ceased or diminished because of the stabilization of unconsolidated sediments by vegetation. In areas deglaciated during the retreat of the Loch Lomond Readvance glaciers, however, slopes are liable to have remained unstable for some time, and associated slope failure and rockfall may have promoted debris slope development and the formation of talus cones, debris cones and alluvial fans. On a larger scale, Holmes (1984) has suggested that many rock slope failures in Scotland occurred during the Early Flandrian. Holmes considered that high and fluctuating cleft water pressures induced by the presence of glacier ice and possibly permafrost during the stadial would have promoted progressive rock slope failures both during and after deglaciation.

During the Atlantic period of c 8,000-6,000 BP, climatic amelioration continued until temperatures were at least c 1.3° to 1.6°C warmer, and mean annual precipitation was c 10 to 15% wetter, than at present (Lamb, 1977). Such oceanic conditions favoured the growth of ombrogenous blanket peat, which may have resulted in change in the hydrological systems of many upland environments (Pennington, 1977; Godwin, 1977). The evidence for widespread woodland clearance by Mesolithic man in the Scottish Highlands during the Boreal and Early Atlantic is equivocal. Although charcoal layers (suggesting forest fires) have been found in peats at sites in NE Scotland (Knox, 1954) and Wester Ross (Durno and McVean, 1959), and despite the discovery of Mesolithic artifacts in the peat beneath the charcoal layers, it has not been possible to establish whether the fires were anthropogenic in origin. Similarly, the possibility of slight human interference on the vegetation adjacent to the Loch of Park (Aberdeenshire) during the Atlantic period has only been tentatively inferred by Vasari and Vasari (1968).

The climate in upland Britain is thought to have became cooler and drier at the beginning of the Sub-Boreal, c 5,000 BP (Pennington et al, 1972; Lamb, 1977). During this time some bog surfaces apparantly dried out sufficiently for tree colonization (Pears, 1977). Forest clearance by Neolithic man has been recorded in many pollen stratigraphic records, and it is particularly evident in a decline in arboreal pollen, particularly Ulmus, c 5,000 BP (Birks, 1972; Smith and Pilcher, 1973), and in the influx of open habitat taxa including pastoral "weeds" (Walker, 1984). There have been problems, however, in detecting a clear elm decline in some Highland pollen-stratigraphic records because of the small amount of Ulmus ever recorded in such areas (O'Sullivan, 1977). Pennington et al (1972) have suggested that the decline in elm pollen evident at sites in NW Scotland probably reflects forest clearance farther south in Britain. Furthermore, Pennington (1977) has suggested that edaphic factors were primarily responsible for incomplete forest cover in parts of the Northern Highlands at this time, and that leached soils were equally unattractive for cultivation. O'Sullivan (1975) has argued that there is evidence for deforestation in the Cairngorm area from this time.

Knowledge of slope activity during the Sub-Boreal (c 5,000-2,000 BP) is limited, although some radiocarbon dates have been obtained from organic material buried by the advance of solifluction lobes in the Highlands. A total of four dates between 5,440 +/- 50 BP and 3,985 +/- 50 BP were obtained from organic material buried by and incorporated within an advancing solifluction sheet on Ben Arkle (Mottershead, 1978). Mottershead believed that human interference was unlikely at such a high altitude above the estimated natural treeline at that time. Vegetation buried by a solifluction lobe in the Cairngorms has yielded dates of 4,880 +/- 135 and 2,680 +/- 120 BP (Sugden, 1971). These dates coincide with the relatively wet period of the Atlantic and the cooler and stormier climate that marked the end of the Sub-Boreal. Stormier conditions may have also favoured renewed fan and cone aggradation, or reworking of existing fan and cone deposits where the supply of sediment from upslope had been exhausted.

The Sub-Boreal period ended with renewed growth of acid peat bogs. This is clearly evident in the pollen-stratigraphic record from England and on the continent, but is less clear or absent in cores sampled from the more maritime environments of Ireland and the west coast area of Scotland (Lamb, 1977). The beginning of woodland decline (c 5,000 BP) is thought to have culminated in large areas of treeless landscape in Scotland by c 2,000 BP (Walker, 1984). Between c2,950 and c 2,250 BP temperatures in Britain may have dropped by as much as 2°C below the mean annual temperature of the Climatic Optimum, with associated increased storminess and cooler summers (Lamb, 1966, 1977). Soil erosion exacerbated by human interference has been identified during this time and may be illustrated by a number of examples from around Britain. Anthropogenically-induced soil erosion has been identified in a catchment of the Dee at Loch Braeroddoch by Edwards and Rowntree (1980). An attempt has been made to date landslides by a comparison of regional pollen diagrams with fragmentary pollen evidence in buried peats in Derbyshire by Tallis and Johnson (1980), who maintained that a significant period of slope activity occurred between c4,000 and c2,000 BP. The significance of these results, however, may be questionable, because Tallis and Johnson (1980) assumed that peat growth began immediatly after the cessation of mass movement, and that the pollen record of these peat fragments would be comparable with full pollen-stratigraphic records from other sites in Northern England. Innes (1983d) reported renewed "alluvial talus" activity on Skye dated at c 2000 BP. However, he conceded that anthropogenically induced slope activity was unlikely on such a steep slopes, yet remained cautious about associating such geomorphic activity with climatic change because of moderating maritime influences. Harvey et al (1981) suggested that gully development in the Howgill fells of NW England may have been initiated by vegetation change giving rise to increased runoff during Iron Age and Romano-British times. However, debris cone development in the Howgill Fells apparently did not take place until 940 +/- 95 BP and is thought to be associated with Viking settlement and widespread introduction of sheep grazing into the area.

Two further climatic oscillations have occurred during the Sub-Atlantic, each involving minor temperature fluctuations. These have been labelled "Little Optimum" of c 1100-1300 A.D. and the "Little Ice Age" of the 16th-19th centuries A.D. (figure 2.1). In Britain, mean annual temperatures fell by between 1.5°C and 2°C, during the coldest part of the Little Ice Age, and reports of sea ice around the coasts of Scotland are indicative of much cooler seas than at present (Lamb, 1977). The contemporaneous southerly migration of polar water has been well documented in the accounts of the Faeroe fishing industry, which did not land or trade any cod in the years between 1675 and 1704, indicating that winter sea temperatures were less than 2°C (Lamb, 1977). In Europe and North America Little Ice Age glacier advances have been well documented (eg Bradley, 1972; Matthews, 1976; Grove, 1979, 1983; Matthews and Shakesby, 1984). There are reports of perennial snow cover on some Scottish mountains at this time (Manley, 1949; Sugden, 1971; Lamb, 1977), and the survival of a perennial snow patch may have led to the development of a protalus rampart on the northern side of Ben Nevis (Gatty, 1906). Sugden (1977) argued that glaciers may have developed in the Highlands during the Little Ice Age, on the basis of lichenometric evidence for the age of corrie moraines, but Rapson (1985) has recently demonstrated that glacier ice has not occupied Cairngorm corries since the Early Flandrian or earlier.

It seems likely that disruption of protective upland vegetation cover and consequent soil erosion increased under the cooler stormier climate of the "Little Ice Age", as well as under increased landuse pressure in some parts of upland Britain. This is borne out by evidence of enhanced slope activity and valley floor alluviation dating from this period. However, given the paucity of research on Flandrian geomorphic activity in general, it is difficult to evaluate the relative importance of these more recent events compared with as yet unresearched slope and valley floor activity which may have occurred earlier in the Flandrian.

Ballantyne and Whittington (1987) identified Early Flandrian wind erosion and concomitant niveo-aeolian sand accumulation on An Teallach in Wester Ross and argued that such activity was progressively reduced by vegetation colonisation throughout much of the later Flandrian. They believed that a recent phase of renewed niveo-aeolian sand accumulation on lee slopes on An Teallach may reflect the destruction of the protective vegetation mat on the plateau upwind, possibly resulting from overgrazing by sheep in the late 18th and early 19th centuries, and not necessarily solely as a result of climatic deterioration. In the neighbouring Fannich Mountains five radiocarbon dates ranging from 890 +/- 120 BP to 530 +/- 90 BP have been obtained from a podzol buried by an advancing solifluction lobe by Ballantyne (1986a). These dates appear to suggest extremely rapid, recent solifluction, possibly initiated by cooler stormier conditions of the Little Ice Age, or by vegetation destruction resulting from increased grazing pressure (Ballantyne, 1986a).

Similarly, Innes (1983a) suggested that the majority of hillslope debris flows in the Scottish Highlands have occurred within the last 500 years, primarily as a result of vegetation disruption caused by poor land use practices, such as heather burning (Imeson, 1971) and overgrazing (Innes, 1983b). The evidence for considerable hillslope debris flow activity during the recent past seems indisputable, but Innes' assertion that comparatively little activity occurred earlier in the Flandrian is less certain. Innes' inferences rely mainly on lichenometric dating, which suffers from a number of problems in its application to the dating of debris flow activity. First, because of the limited life-cycle of lichens, the use of lichenometry is restricted to dating deposits laid down in the recent late Flandrian in Scotland. Second, it is possible that lichens growing on a substrate today may not reflect the true age of the deposit. This could arise due to a number of reasons, including substrate surface rejuvenation by prolonged burial by snow (cf Rapson, 1985), the removal of an overlying vegetation cover (A. Dugmore pers. comm.), or by scorching. Third, the possibility of the burial of older debris flow deposits by more flow events cannot be ignored, especially where the density of debris flows is high, as in the Lairig Ghru in the Cairngorms. Innes (1982) believed that the source area would be exhausted by a single event, rendering burial by future events unlikely, but this assumption is perhaps unrealistic in the case of multiple hillslope debris flows, and certainly in the case of flows that have formed slope-foot debris cones.

The present-day climate in the Scottish Highlands is characteristically cyclonic, but temperatures are rarely extreme owing to the moderating influence of the North Atlantic Drift. Ballantyne (1987) has suggested that the climatic regime on British mountain tops is "maritime periglacial", and typified by extreme wetness, prolonged snow cover and frequent strong winds rather than severe cold. The high degree of exposure and extreme wetness mean that upland areas are particularly vulnerable to vegetation destruction and possible soil erosion caused by land use pressure and poor management practices.

The pattern of precipitation exhibits a marked decline from west to east, with values of over 3,600mm/year estimated for the summit of Ben Nevis in the west, but as low as 1,600mm / year for Mount Keen in the SE Grampians (Meteorological Office, 1977; see also chapter 3). Annual precipitation levels in the Highlands are high, compared with lowland Britain, but mean annual precipitation values are rather poor indicators of levels of geomorphic activity; slope processes are much more likely to be influenced by short duration intense precipitation events. Extreme rainfall events have been recorded in the Highlands, and the resulting floods have occasionally been exacerbated by snowmelt (Reynolds, 1985). For example, in September 1981 c 140mm of rainfall was recorded over a 24 hour period at Dundonnell, Wester Ross (Acreman, 1983). The resulting flood caused severe localized bank erosion and an estimated deposition of 1,800 tonnes of sediment downstream. Short-duration intense storms and subsequent floods are also important intitiators of geomorphic activity in upland areas. For example, in June 1982 an intense convectional rainstorm caused a flash flood in catchments in the Howgill Fells, where more than 70mm of rain fell in 2.5 hrs (Harvey, 1986). Harvey identified three types of geomorphic response to the storm, including the reactivation of previously-stable gully systems and the deposition of large debris cones. Further examples of the geomorphic impact of recent and historical storms events will be reported in chapter 3, in relation to the study areas (eg Lauder, 1830; Common, 1954; Baird and Lewis, 1957; Green, 1958, 1971; McEwen, 1986).

At two sites in Scotland measured present-day rockwall retreat rates average 0.015mm/year, values that are two orders of magnitude lower than estimates for the Loch Lomond Stadial (Ballantyne and Eckford, 1984; Ballantyne and Kirkbride, 1987). Furthermore, it has been observed that talus slopes are generally less well developed inside the Loch Lomond Stadial glacial limits compared with those outside, which suggests that Flandrian rates of rockfall accumulation have been low (Ballantyne and Eckford, 1984). Slope failures, gullying, debris flows and soil creep appear to be the dominant modes of geomorphic activity operating on many vegetation-covered talus slopes at present, indicating that current aggradation from rockfall is often negligible (Ballantyne and Eckford, 1984). A similar pattern of reworking activity may be expected for debris cones and alluvial fans where rockfall was at one time an important supplier of sediment in the source area. However, this effect may have been masked at many sites where sediment has been supplied from alternative sources, such as reworking of glacial deposits.

The Flandrian has been characterised by low magnitude climatic oscillations since rapid climatic amelioration marked the end of the Loch Lomond Stadial. There is some evidence to suggest that extreme storm events may have been important initiators of geomorphic activity on slopes and adjacent valley floors. Indeed, several periods of increased storminess with greater probability of initiating slope instability have been identified during the Flandrian, including the end of the Sub-Boreal and during the "Little Ice Age". It is not realistic, however, to infer any strong causal relationship between periods of climatic deterioration and, for example, debris cone accumulation because as yet insufficient is known about the timing of Flandrian landform development in upland Britain. Furthermore, there is rarely a clear-cut distinction between anthropogenic and environmental causes of enhanced upland erosion in the few studies hitherto made of late Flandrian geomorphic activity. What little we do know about Flandrian geomorphic activity in upland Britain tends to suggest that mass-movement processes in particular have occurred throughout most of the Flandrian, and that the once widely-held assumption that most upland slopes are essentially relict seems over-simplified. The question of Flandrian slope and valley floor process activity will be examined in greater detail in later chapters, along with the proposition that there have been changes in both the magnitude and type of geomorphic processes operating on upland slopes since the time of ice-sheet deglaciation.

CHAPTER 3

THE STUDY AREAS

3.1 INTRODUCTION

Fan and cone landforms are found in a variety of differing environments throughout the Scottish Highlands. Environmental controls of landform development, such as climate, relief and to some extent geology exhibit certain west-east trends across the Highlands. Three scales of investigation were employed restricting the spatial extent but not the range of environments encompassed by the project. At the macroscale, a wedge-shaped transect was defined between Glen Etive in the west, Strathdearn in the northeast, and Glen Clova in the east (figure 3.1). At this scale the aim of the project is to examine the role of morphometric and environmental controls on different types of fan and cone development (chapter 6). Seven glens were selected from within the transect in order that more detailed research could be carried out into the morphological and sedimentological characteristics and evolution of different types of fan and cone. Each of the seven glens exhibits slight and sometimes striking differences in one or several environmental factors, including geology, relief, climate, hydrology, vegetation cover, and environmental history. From south west to north east the glens are Glen Etive, Glencoe, Glen Tromie, Glen Feshie, Glen Clunie, Glen Clova and Strathdearn. Approximately 40 fans and cones were included in the mesoscale study, and

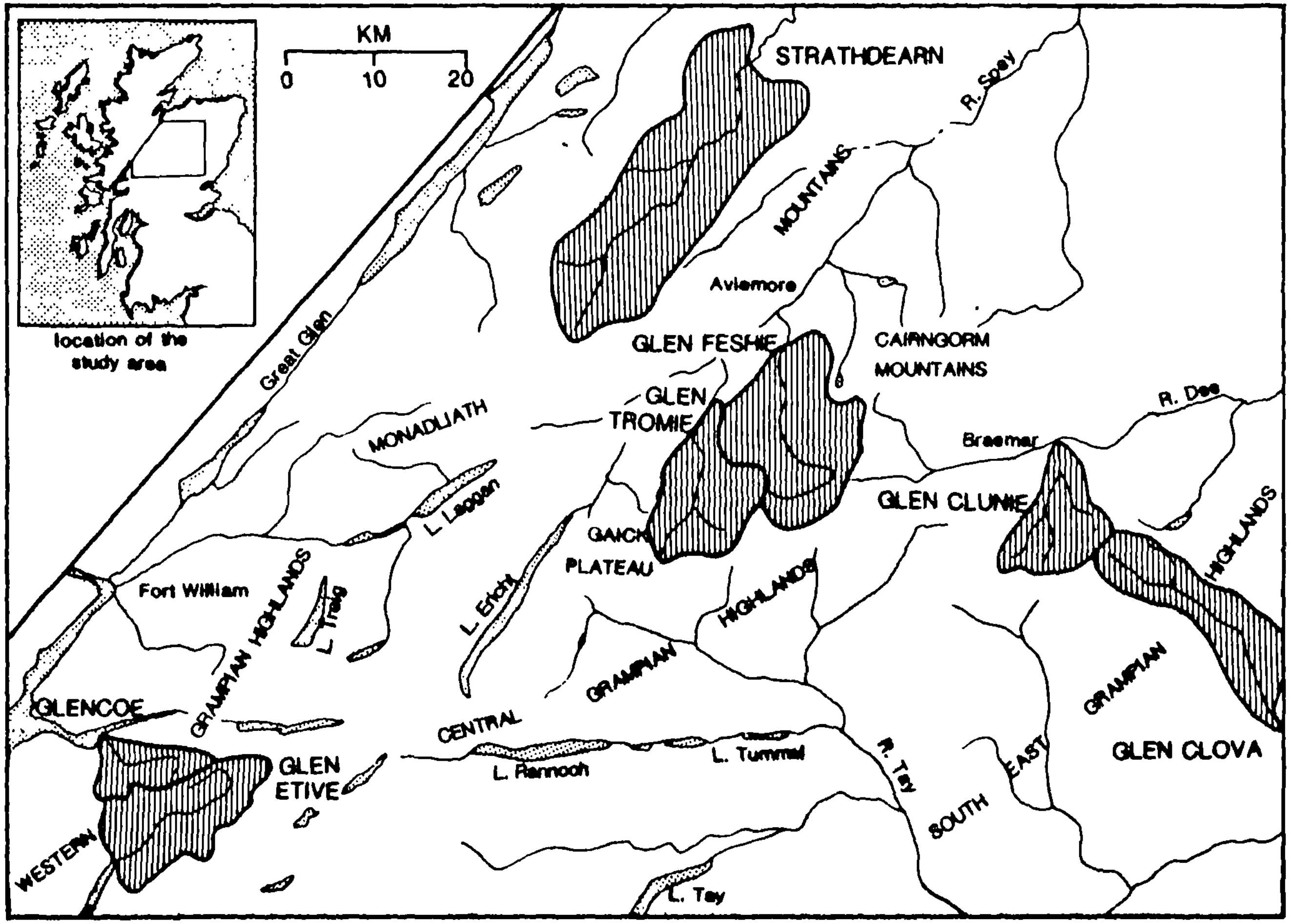


Figure 3.1 The maximum extent of the macroscale study area, and location of the seven study glens.

from these a smaller subsample of sites was selected for more detailed study.

3.2 THE MACROSCALE STUDY AREA.

At the macroscale the study area comprises a large wedge-shaped transect across the Grampian Highlands. The area contains some striking west-east contrasts in terms of climate, geology and relief. These environmental characteristics may be regarded as being fixed in "steady" time when considering landform development during the recent past. However, dramatic climatic changes including two glacial episodes have occurred within the timespan of c 18,000 years that is considered in this project (chapter 2).

Present-day west-east contrasts in mean annual precipitation are summarised in the precipitation map (figure 3.2). Precipitation data were derived from the Meteorological Office (1977) average annual rainfall map for the standard period 1941-1970. In figure 3.2 precipitation values drop significantly between Loch Leven (A) and Streens (B), and Loch Leven (A) and Braemar (C). Individual mountain masses and stretches of upland, however, are often associated with localised higher levels of precipitation that may interrupt the general eastward and north-eastward decline in mean annual precipitation as, for example, in the transect between Loch Leven (A) and Glen Clova (D). Ballantyne (1983) has demonstrated that isohyetal map values in some areas underestimate true precipitation values on

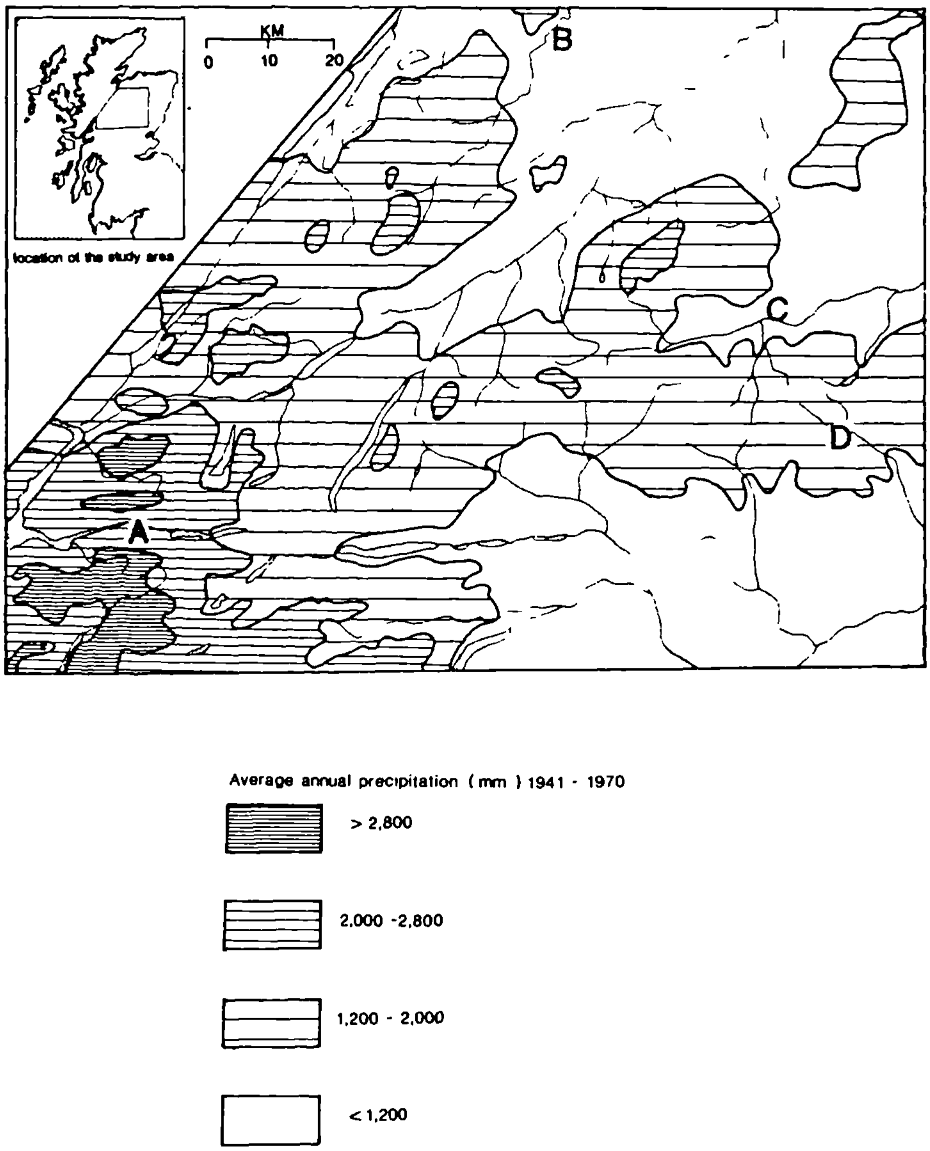


Figure 3.2 Average annual rainfall map for the standard period 1941-1970. (Source:Meteorological Office, 1977)

high ground in Scotland. Actual mean annual precipitation values in some mountain areas may, therefore, be greater than those depicted in figure 3.2. Figure 3.3 illustrates the contrast in the distribution pattern of reported maximum 2 hour (a) and maximum 24 hour (b) rainfall in the study area. Figure 3.3a shows that the highest recorded 2 hour rainfall has occurred in the area along the Highland Boundary fault between lower Glen Garry and lower Glen Clova. No recorded 2 hour rainstorms have exceeded 130 mm in the Western Grampians. Longer duration rainstorms give greater precipitation values in the west than they do in the east of the macroscale study area (figure 3.3b), with values as high as 350 mm in 24 hours recorded for areas such as Glencoe and Glen Etive. The geomorphological consequences of rainstorms will be considered in greater detail with reference to the mesoscale study areas, and later in chapter 4.

The Grampian Highlands comprise the highest land in Britain, with Ben Nevis reaching 1343m OD, and large areas of upland exceeding 900m OD. However, the Grampian Mountains do not consist entirely of impressive peaks, as much of the upland comprises dissected plateau surfaces (Linton 1951, 1959; Sissons, 1976). Such plateau surfaces are more extensive in the Eastern Grampians than in the Western Grampians, where the legacy of severe glacial erosion has left numerous corries and overdeepened rock basins separated by narrow ridges (figure 3.4).

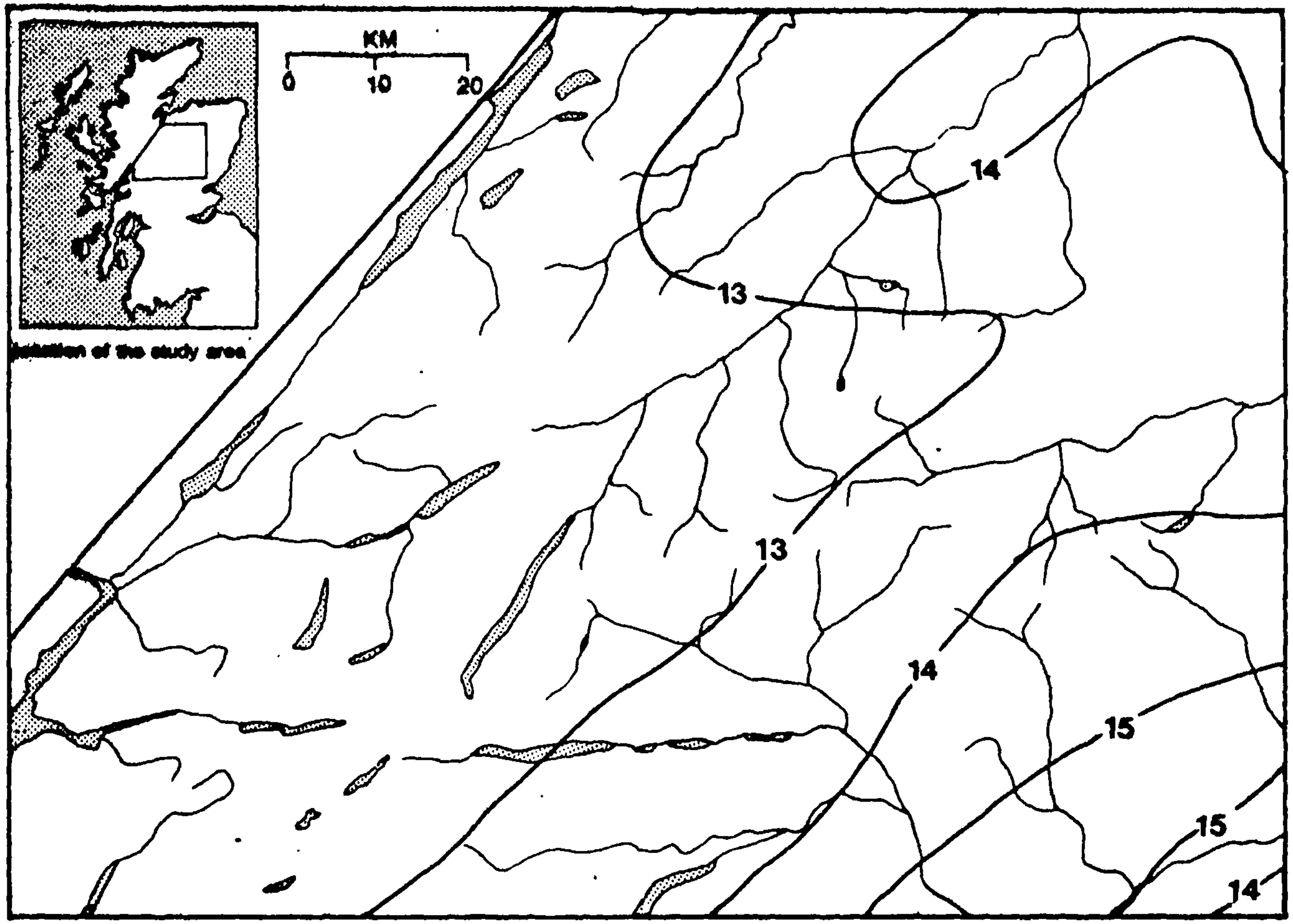


Figure 3.3a Estimated maximum 2 hour rainfall (cm)
(source: Natural Environment Research Council, 1975)

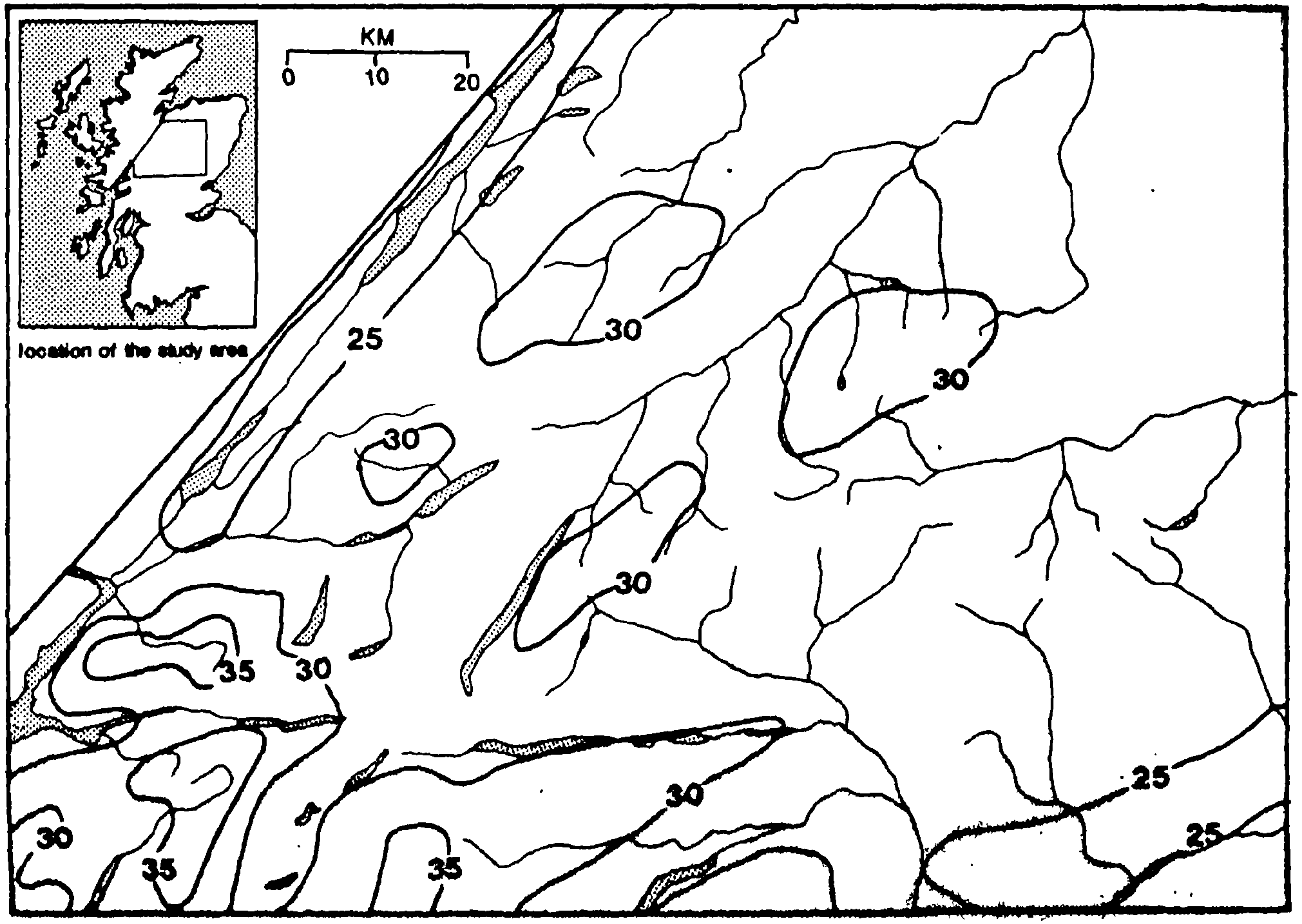


Figure 3.3b Estimated maximum 24 hour rainfall (cm).

(Source : Natural Environment Research Council, 1975)

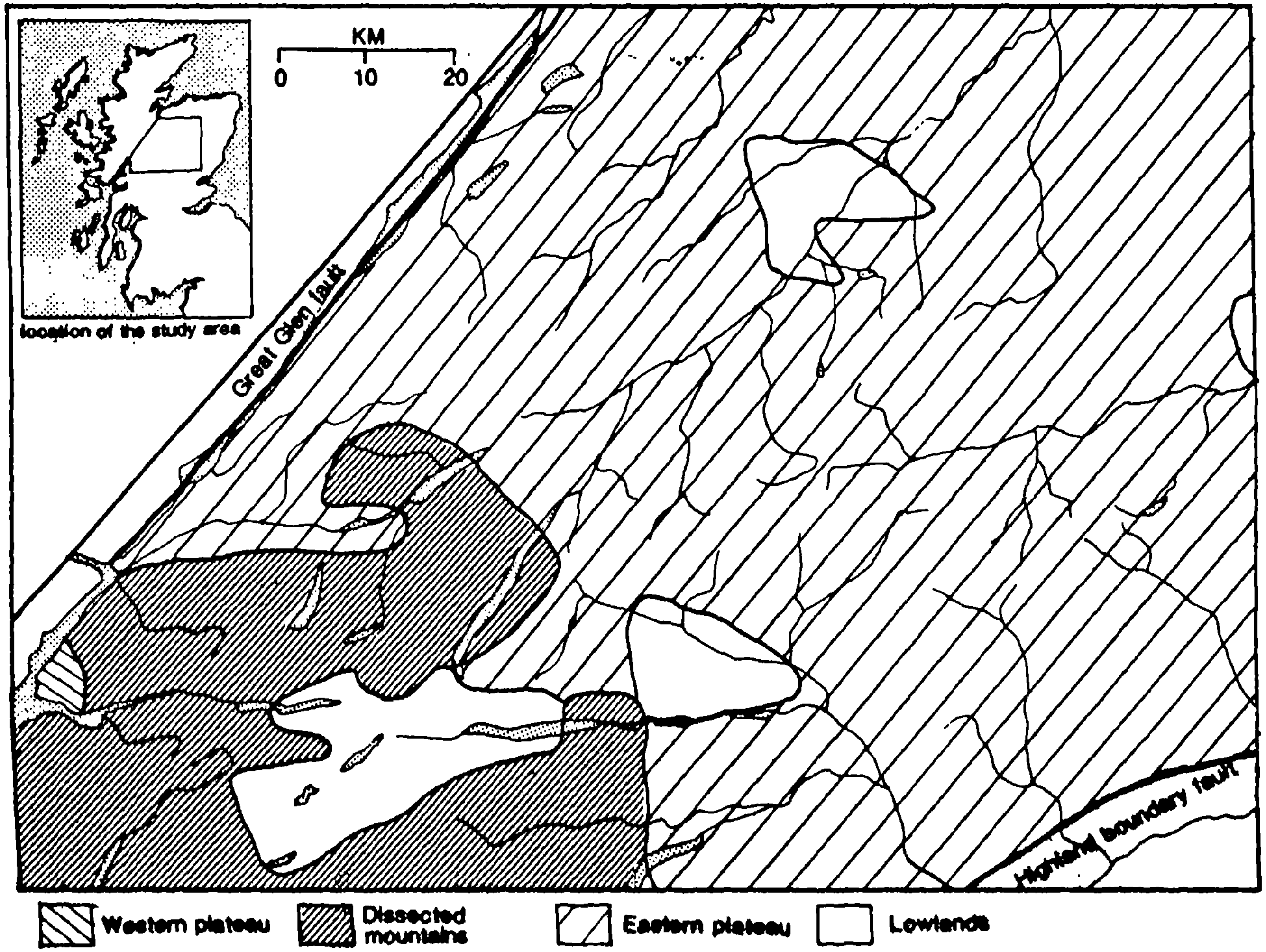


Figure 3.4 Morphological subdivisions of the Grampian Highlands.
(source : Sissons, 1976)

Consequently the Western Grampian glens are characterised by greater relief than the glens of the Central and Eastern Grampians. Fan and cone development may reflect these regional variations in topography with, for example, greater potential for talus and debris cone development at the foot of the steep slopes of the dissected western valleys. In contrast, the eastern glens with less relative relief between summits and valley floors tend to favour the development of alluvial fans.

Geology as well as glacial history has been instrumental in the evolution of the pattern of relief found throughout the Grampians between the Highland Boundary fault to the south and the Great Glen fault to the northwest (figure 3.5). Metamorphic rocks, especially schists, are the most widespread rock type, with Dalradian schists being common along the southern part of the study area, and Moine schists cropping out widely in the centre and north. The transect also incorporates mountainous areas composed of generally more resistant granite intrusions such as the Etive, Nevis and Cairngorm complexes (Brown, 1983). The highest concentration of intrusive dykes is found in the west of the transect; these dykes have markedly influenced local topography and subsequent landform development.

Part of the macroscale study area was glaciated during the Loch Lomond Stadial, whilst other areas remained glacier-ice free under severe periglacial conditions at this time (chapter 2). Thus the glacial history of different

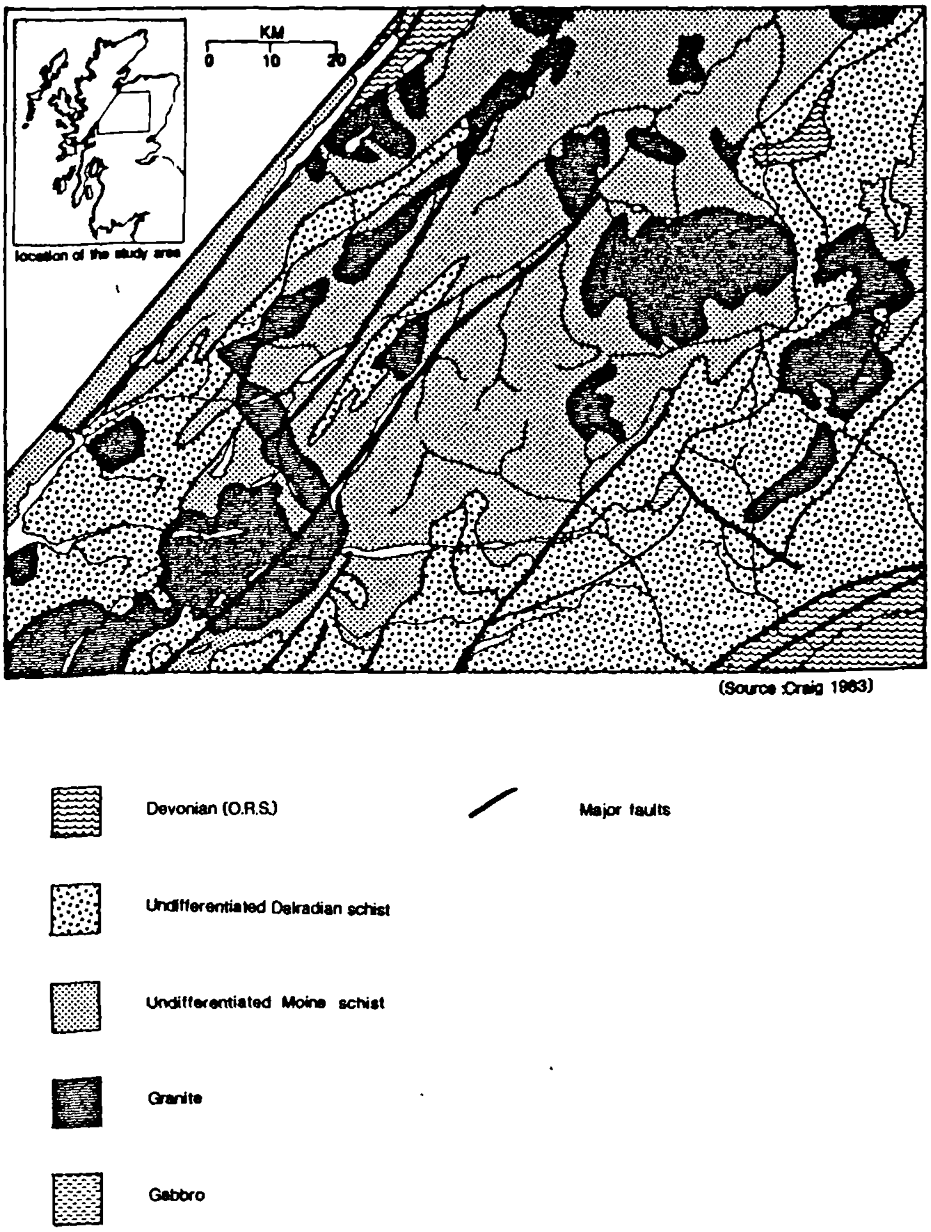


Figure 3.5 Solid geology of the macroscale study area.

parts of the macroscale study area determines the maximal potential age of fan and cone development.

3.3 THE MESOSCALE STUDY AREAS.

At the mesoscale the project comprises seven glens within the macroscale transect (figure 3.1). The areas have been defined by their watersheds as derived from 1:50,000 O.S. topographic maps. The study areas comprise Glencoe, Glen Etive, Glen Tromie, Glen Feshie, Glen Clunie, Glen Clova and Strathdearn; with the exception of Strathdearn, the glens have been grouped in pairs below in order to summarise their principal characteristics. Following suggestions outlined for palaeohydrological studies (Starkel and Thornes 1981), background information on each study area has been standardised to facilitate comparison. For each pair of study areas the following background information currently available from the literature will be summarised: catchment characteristics, climate and hydrology, geology, geomorphology, vegetation history and landuse. Catchment characteristics as summarised in table 3.1 were extracted from 1:50,000 Ordnance Survey maps. The parameters measured include drainage basin area (km^2), basin length (km), and basin relief (m). Basin relief is defined as the difference in metres between the highest summit in the basin and the altitude of the basin mouth. The relief ratio represents the basin relief divided by maximum basin length and is expressed in m/km. Average basin gradient (in degrees) is the inverse tangent of the relief ratio. Mean annual

TABLE 3.1

CATCHMENT CHARACTERISTICS

CATCHMENT	BASIN PARAMETERS						
	AREA KM^2	LENGTH KM	MAX. ALTITUDE M	MIN. ALTITUDE M	RELIEF M	RELIEF RATIO $M\ KM^{-1}$	MEAN GRADIENT degrees
GLENCOE	50.5	11.5	1150	0	1150	100	5.7
GLEN ETIVE	155	21.1	1150	0	1150	54.5	3.1
GLEN TROMIE	130	21.8	951	250	701	32.2	1.8
GLEN FESHIE	240	23.4	1265	229	1036	44.3	2.5
GLEN CLUNIE	128	15.7	1068	320	748	47.6	2.7
GLEN CLOVA	153.6	28	1010	137	873	31.2	1.8
STRATHDEARN	417	40	942	250	692	17.3	1

precipitation values for each of the study glens are presented in table 3.2, and were derived from the Meteorological Office (1977) average annual rainfall map for the period 1941-1971. Data on solid geology for each area were derived from the published 1:63,360 O.S. British Geological Survey maps and associated memoirs.

3.3.1 Glencoe and Glen Etive

3.3.1.1 Catchment characteristics.

Glencoe and Glen Etive are two striking glacially-overdeepened valleys whose rivers flow steeply down to sea lochs. The character of these glens is in marked contrast to the other five in the study, as illustrated in table 3.1. Relief is high throughout the Western Grampians in general, but especially so in Glencoe which has a mean relief ratio of 100 m/km and a mean gradient of 5.7. Much of the land in Glencoe consists of steep impressive rock buttresses and gullies (figure 3.6a), below which there is widespread talus and debris cone development. The Glen Etive basin embraces a variety of different landscapes from boggy wastes amid the moraines and lochs of Rannoch Moor, to the steep bare rock slopes of Ben Starav (figure 3.7a). Glen Etive has less extensive talus development because there are fewer suitable cliffs and gullies in comparison with Glencoe. However, the potential for alluvial fan development is greater in Glen Etive than in Glencoe, especially where tributary streams meet the main

Table 3·2

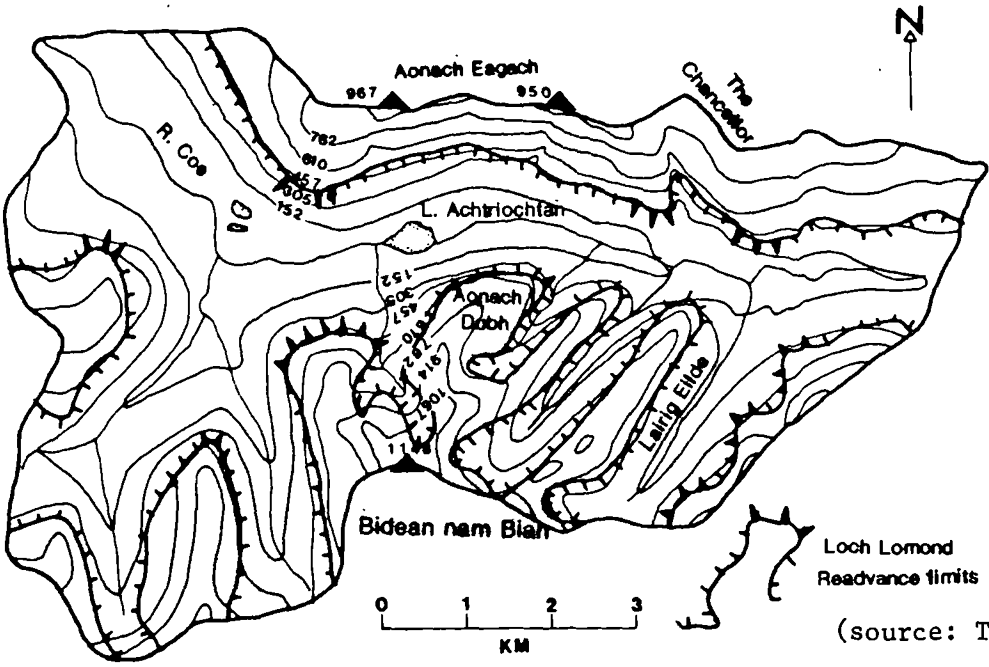
MEAN ANNUAL RAINFALL (mm)

	VALLEY	MOUNTAINS
GLENCOE	2,800	3,200
GLEN ETIVE	2,800	3,200
GLEN TROMIE	1,400 to 1,600	1,400 to 2,000
GLEN FESHIE	1,200	2,000
GLEN CLUNIE	1,400	1,600
GLEN CLOVA	1,400	1,600
STRATHDEARN	1,200 to 1,400	2,000

(source: Meteorological Office, 1977)

GLENCOE

A.



(source: Thorp, 1981)

contour interval c 50 m
height in metres

B. Solid Geology Key

Granite

Rhyolite and Andesite

Diorite and Tonalite

Gneiss

M Undifferentiated Moine Schist

D Undifferentiated Dalradian Schist

G Graphite Schist

Quartzite and Quartz Schist

Limestones and Calcareous Schist

Conglomerate

Alluvium

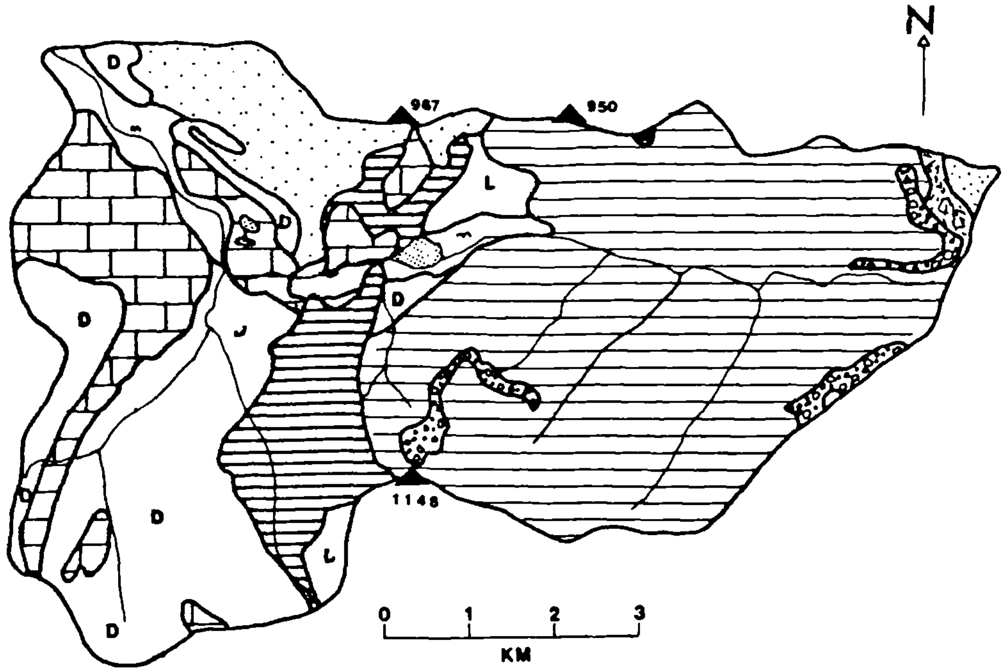


Figure 3.6 A: Topography and limits of the Loch Lomond Readvance.
B: Solid geology

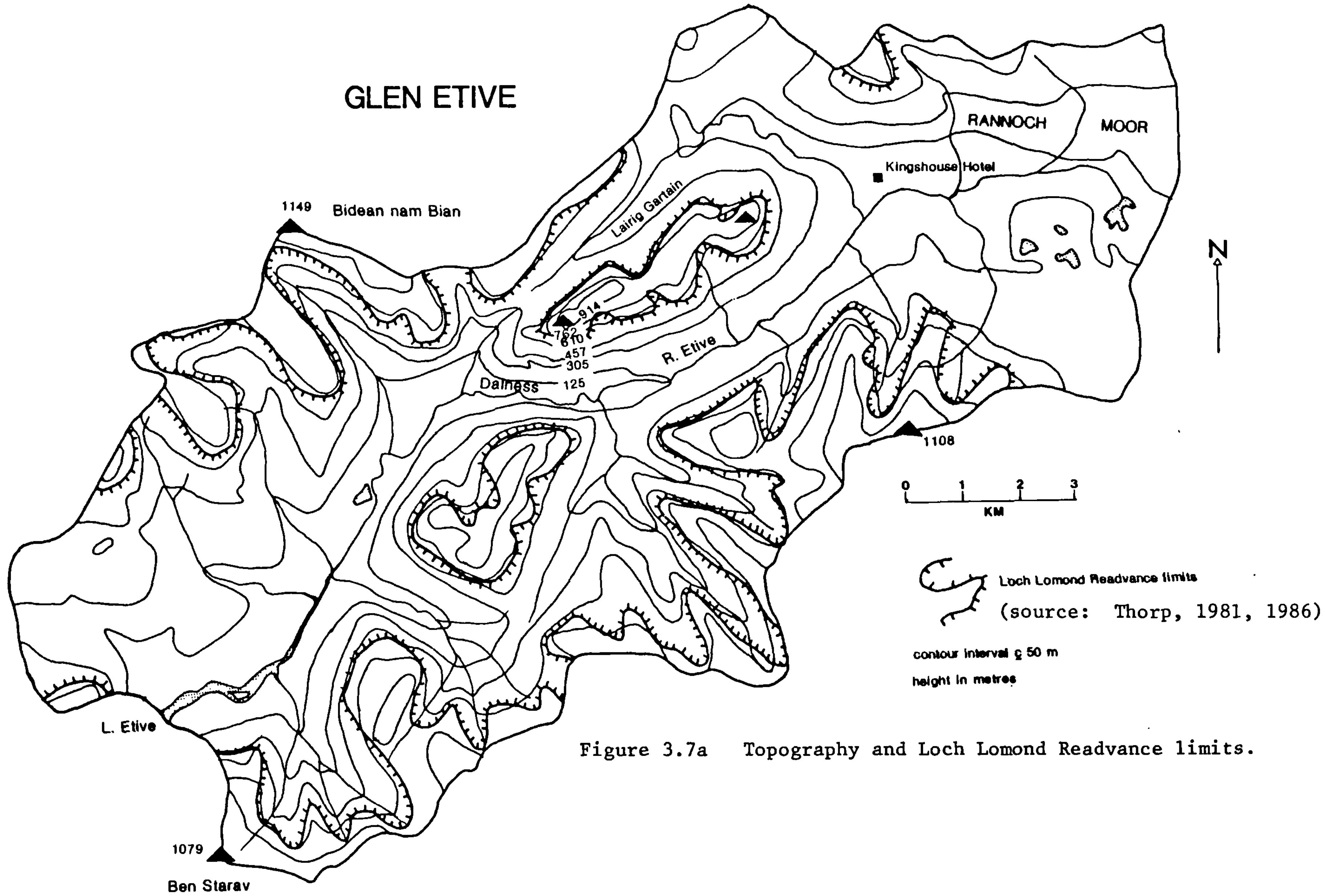
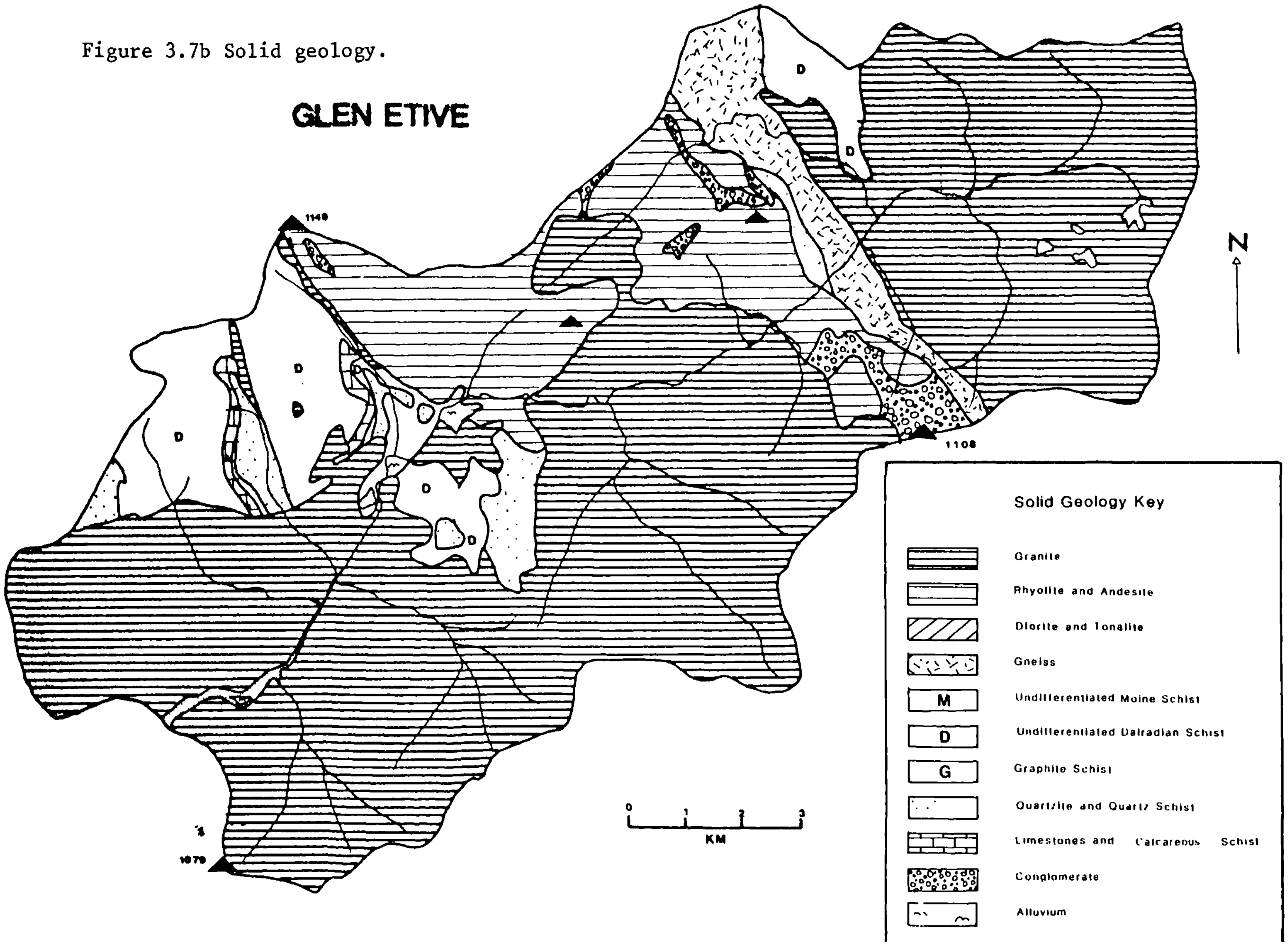


Figure 3.7a Topography and Loch Lomond Readvance limits.

Figure 3.7b Solid geology.



river in the wider parts of the glen. The two glens contain many major peaks over 900m, including Bidean nam Bian (1150m O.D.) which forms part of the watershed between them. The stream networks of the two glens also differ, with Glencoe exhibiting a more restricted rectilinear pattern than the dendritic pattern found in Glen Etive. The presence of cross-valley rock bars has locally influenced the pattern of valley floor sedimentation in both glens resulting in small areas of flat land, for example in Glencoe between two rockbars (NN 140567 and NN 158570) where the braided river is presently infilling Loch Achtriochtan.

3.3.1.2 Climate and hydrology.

The climate of the west coast area is distinctly oceanic compared with that of the interior. In general, west coast annual precipitation values are higher (table 3.2) and the annual temperature range is less extreme than in the east. Precipitation values and exposure, however, rapidly increase with altitude. Drainage density (>0.325 km/km^2) and stream frequency (>0.048 per km^2) are amongst the highest in the country in west coast catchments such as Glencoe and Glen Etive, whilst mean annual soil moisture deficit (<12 mm) and mean annual actual evapotranspiration (300-400 mm) are lower than in the Eastern Grampians (Ward, 1981). Consequently in coastal areas of the West Highlands the mean discharge ratio is >75%, compared with 50%-74% for most of the Grampian Highlands (Ward, 1981). This is clearly illustrated during wet conditions when short-lived streams flow down the steep rocky hillsides, giving rise to flash floods in the rivers and debris flows on drift covered slopes (Common, 1954). During a major flood that included a snowmelt contribution to runoff in December 1966, the highest rainfall-day total for the area was recorded at Dalness in Glen Etive (199 mm) (Reynolds, 1967).

3.3.1.3 Geology.

The area consists of both igneous and metamorphic rocks (figures 3.6b and 3.7b) associated with the Glencoe cauldron subsidence and the Etive ring faults. Ideas concerning geological evolution of this area have been modified since the original report by Clough *et al* (1909). The ring faults are now believed to be inward-dipping tensile fractures formed in response to the development of excess basal pressure and pressure release by magma escaping violently up fractures that led to subsidence of the central block forming a caldera in what is now Glencoe (Brown, 1983). The volcanic rocks include andesite and rhyolitic ignimbrites, seen for example in the step-like appearance of the face of Aonach Dubh, which has given rise to the development of "perched" talus that buries the lava treads. Geological evidence has suggested that at least four successive pulses of magma were associated with repeated ring fault subsidence in the Etive complex (Clough *et al*, 1909; Bailey, 1960), each of which resulted in the initiation of a remarkable number of dykes in the Etive swarm. These dykes are composed of porphyrite, microdiorite, lamprophyre, and porphyry (Bailey, 1960), and many have been selectively weathered to form deep river gorges and steep rock gullies. Thorp (1981) has suggested that abundant shatter planes in porphyrites and fault intrusions have given rise to a greater susceptibility to frost weathering relative to that of the more massive resistant igneous rocks such as rhyolite and andesite. Excellent examples of rock gully development include the Clachaig gully developed along the Glencoe ring fault, and Dalness Chasm, which is cut in a porphyritic dyke.

3.3.1.4 Geomorphology.

The glacial origin of much of the Glen Etive and Glencoe landscape has been described in detail by Bailey and Maufe (1916). The area was last glaciated during the Loch Lomond Readvance, when ice flowed down Glen Etive and Glencoe from an icefield centred over Rannoch Moor (McCann 1966; Gray 1972; Sissons 1979). Thorp (1981, 1986) has established the vertical limits of the glaciers in the Glencoe and Glen Etive area (figures 3.6a and 3.7a) by mapping in particular the lower limits of frost-weathered mountain-top detritus and the upper limits of glacially-modified rock surfaces. Thorp's results have revealed that all mountain summits in the area were nunataks above the maximum ice surface during the readvance. The ice surface, as reconstructed by Thorp, descends from an altitude of approximately 700m OD over west Rannoch Moor down to c.640-655m OD in Dalness (upper Glen Etive) and to c

475-525m OD in upper Glencoe. Dates obtained from shells within glacially-disturbed marine deposits near Loch Creran yielded ages of c 11,530 +/- 210 BP and 11,300 +/- 300 BP which are maximal for the last ice advance in the area (Peacock, 1971). Radiocarbon dates obtained for basal organic sediments in enclosed basins on Rannoch Moor imply that this area was deglaciated by c 10,000 BP (Lowe and Walker, 1976). Pre-Loch Lomond Stadial fans and cones would presumably have been removed by the stadial glaciers, so the maximum possible age for the commencement of fan and cone accumulation in this area would have been the end of the Lateglacial, c 10,000 BP or very slightly earlier.

In general there has been little documentation of postglacial landform development in the Highlands. Terraces near the confluence of Fionn Ghleann and Glencoe and the actively braided reach of the Coe River upstream of Loch Achtriochtan have, however, been described by Bailey and Maufe (1916), who also noted that excavation of sediment from rock gullies had led to the build-up of widespread "cones of scree" which sometimes encroached on the road during times of flood. The old hamlet of Achtriochtan was abandoned after partial burial by such "scree" or debris flow deposits. In recent times the excavation of a "scree" trap above the roadside aimed to eliminate this hazard. Further problems have emerged as a result of compaction of periodically-saturated debris flow deposits beneath bridge and culvert foundations (Highland Regional Council, pers.

comm.). Boreholes sunk through the toe area of debris cones suggest depths of debris flow deposits to be in excess of 15m at Achtriochtan (NN 157572). However, other borehole logs are less informative, with drillings through only the top 1-2m of sediment, for example 1.7m bored in the Chancellor debris cone (NN 163571) (Highland Regional Council, 1984). The geomorphological effects of a storm in May 1953 (Common, 1954), correspond with recent local reports of scree movements and debris flows that have been an annual occurrence between autumn 1983 and summer 1986 (W. Elliot, pers. comm.). Common (1954) gave a detailed report of extensive rainstorm-induced gullying, translational sliding, debris flow activity and debris cone development that disrupted road and rail connections in Lochaber, Appin and Benderloch in May 1953. He identified certain situations where debris flows occurred, including well-watered flushes and glacially-smoothed and oversteepened slopes on hillsides. Common also reported the damage caused to West Laroch reservoir by flood deposits; the event is still recalled by some of the local population.

Selected debris flow deposits at five sites in Glencoe and Dalness have recently been studied by Innes (1983a) (Glen Etive, NN 234510; Lairig Gartain, NN 188530; Beinn a'Chrulaiste, NN 245560; Aonach Eagach, NN 158573; Stob Dearg, NN 230547). Innes concluded from a survey throughout much of the Scottish Highlands that the majority of hillslope debris flows have occurred within the last 500 years. According to his data, at the Aonach Eagach, Stob Dearg and Lairig Gartain sites debris flow frequency dramatically increased in the 1970s, but declined from about 1950 onwards at the Glen Etive site. The oldest debris flow dated by lichenometry in the Glencoe and Glen Etive areas occurred at about AD 1780 in the Lairig Gartain, though the possibility of older buried deposits at the Aonach Eagach site was acknowledged (Innes, 1983a).

3.3.1.5 Vegetation history and landuse.

The postglacial vegetation history of neighbouring Rannoch Moor has been reconstructed from pollen-stratigraphic evidence based on cores taken from a number of enclosed hollows (Lowe and Walker 1976; Walker and Lowe 1977, 1979, 1981). Three of the enclosed basins studied by Walker and Lowe (1977) lie within the northeastern area of the Etive catchment, near the Kingshouse Hotel at NN 285555 (K1), NN 282555 (K2) and NN 288529 (K3). Walker and Lowe have suggested the following reconstruction of vegetation history:

1. Plant colonisation was rapid following Loch Lomond Stadial ice wastage. *Empetrum* heath and juniper scrub became well established prior to *c* 10,000 BP, and thereafter birch trees were present in large numbers.

2. The spread of woodland into the Rannoch Moor area proceeded uninterrupted, with closed birch and pine forests established well before *c* 6,000 BP, indicating fairly

favourable climatic conditions.

3. After the arrival of alder in the Mid Flandrian, major changes occurred in the vegetation cover, with the gradual decline in area of forest and its replacement by heather moor and blanket peat.

Walker and Lowe (1977) argued that these vegetation changes were natural and were unlikely to have been a result of Neolithic forest clearance. No published research is available on the nature and extent of human activity in this area during the Flandrian, although the results of pollen analysis of organic sediments from a site in Dalness may help to bridge this gap (chapter 7).

Acid peat bog development is common in poorly-drained areas, especially in upper Glen Etive on Rannoch Moor. The present-day vegetation cover comprises mostly grassland and heathland, but this becomes more sparse on steep slopes. On well-drained ground there are some patches of bracken. Natural growth of birch trees is restricted to rocky areas inaccessible to grazing animals, such as the rock ledges of Aonach Dubh in Glencoe. Local tradition maintains that much of the valley floor in Glencoe was forested well into the nineteenth century, when Glencoe was a recognised deer forest (Turnock, 1977). The extent of commercial deer forest is now restricted to Glen Etive and areas outside the National Trust boundary. Hill sheep farming is practised in both glens.

Vegetation colonisation during the Early Flandrian may have retarded fan and cone development by stabilising unconsolidated stadial sediments. Any interference by man or disruption of the vegetation cover by an extreme storm event may have resulted in the reworking of existing deposits at sites where the supply of new sediment had ceased in the source area (chapter 7). Some sites, however, particularly those issuing from steep rock gullies, may have been episodically active throughout the Flandrian.

3.3.2. Glen Tromie and Glen Feshie.

3.3.2.1 Catchment characteristics.

The River Tromie and the River Feshie are major right bank tributaries of the river Spey in the Central Grampians. Both rise from the Gaick plateau, though the eastern tributaries of the Feshie have their sources in the Cairngorm Mountains. The overall topographic character of these glens is far more gentle than that found in the Western Grampians (table 3.1). However, glacial breaches and troughs have resulted in locally high values of relative relief. There are subtle differences between the two catchments. Glen Tromie is surrounded by the regular surface of the Gaick plateau with summit heights up to 951m (figure 3.8a), and in the upper part of the glen the main rivers occupy steep-sided glacial troughs. The Feshie catchment (figure 3.9a) covers a much larger area, and has a higher relief ratio (44.3 m/km compared with 32.3 m/km in

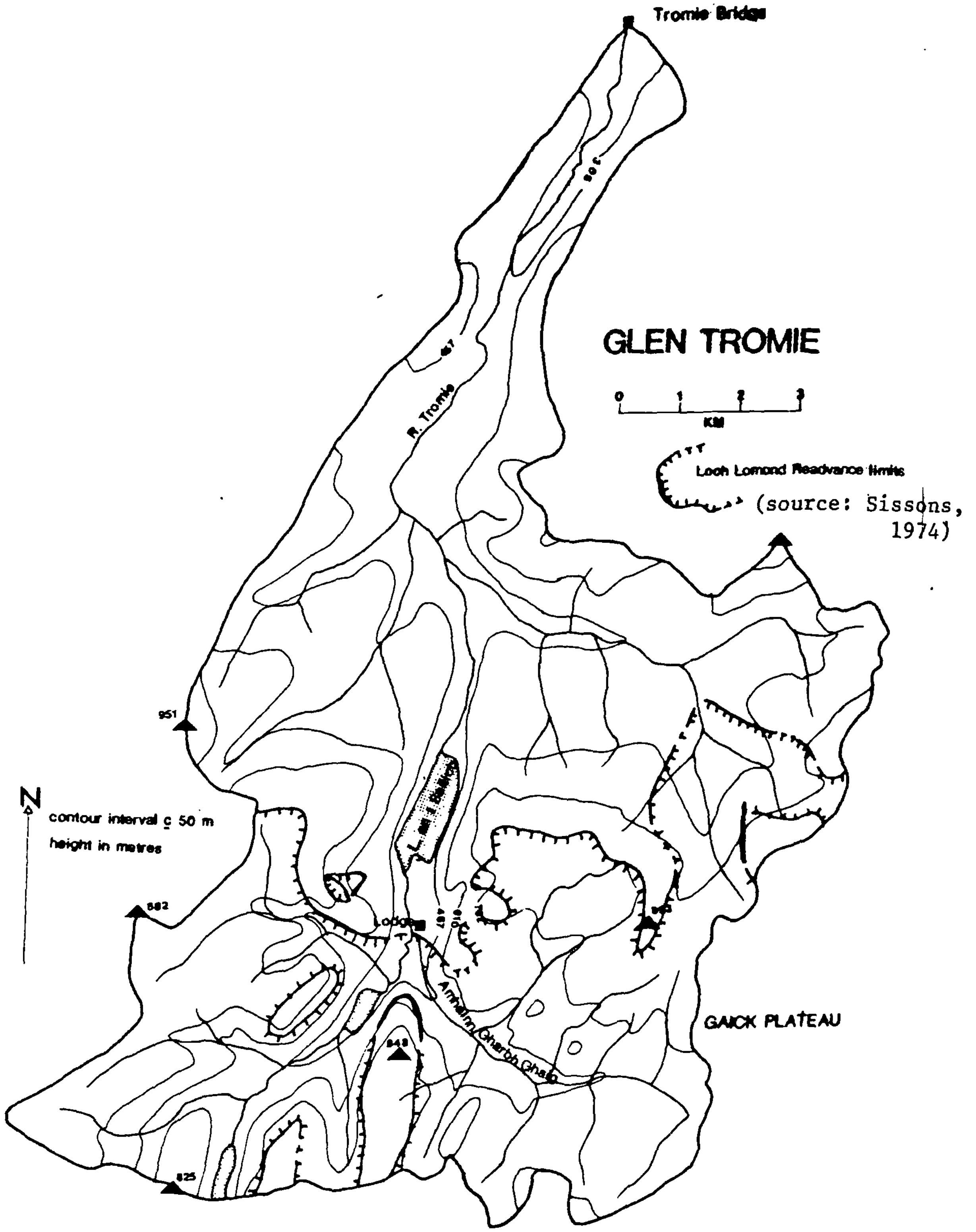


Figure 3.8a Topography and Loch Lomond Readvance limits.

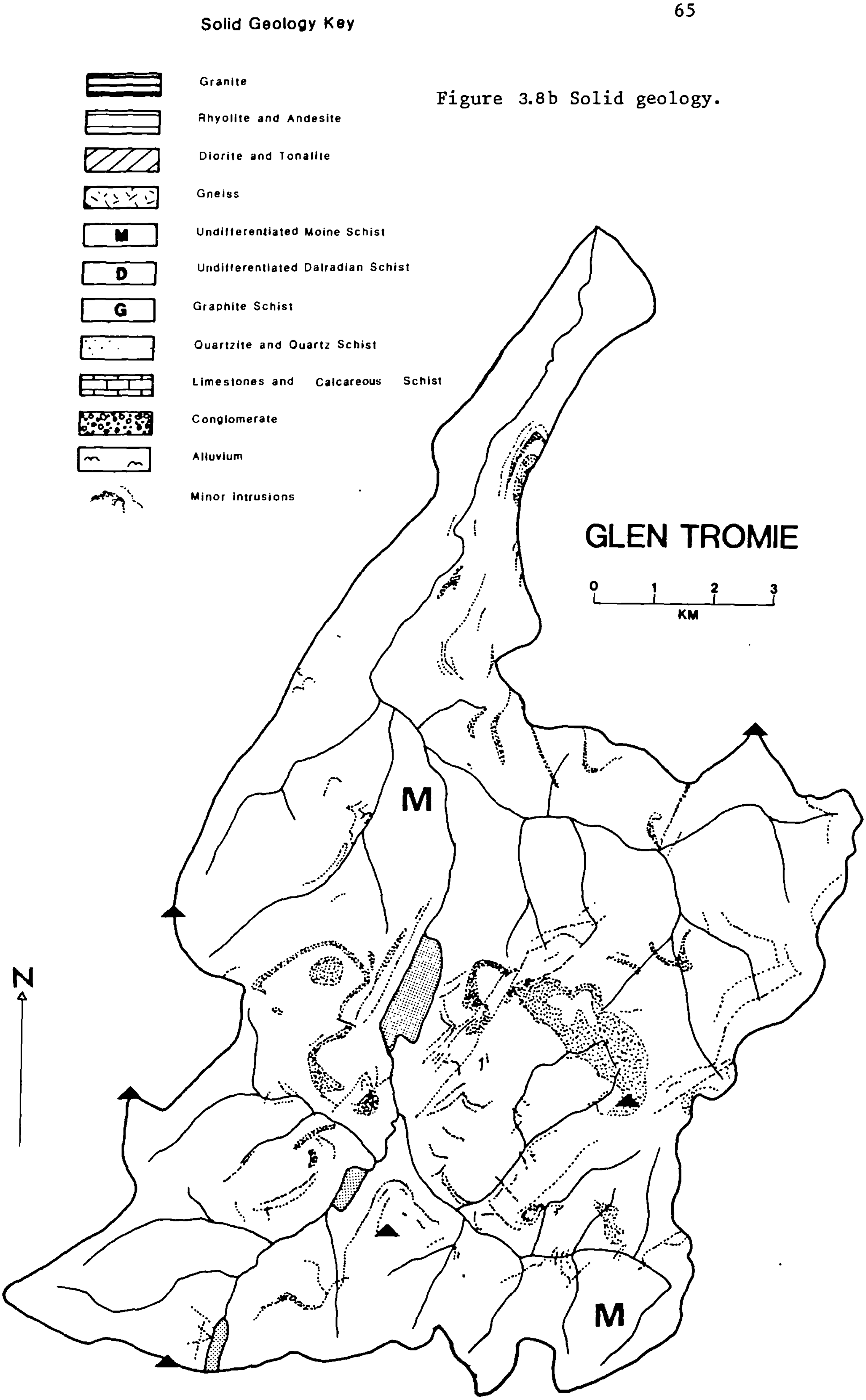


Figure 3.8b Solid geology.

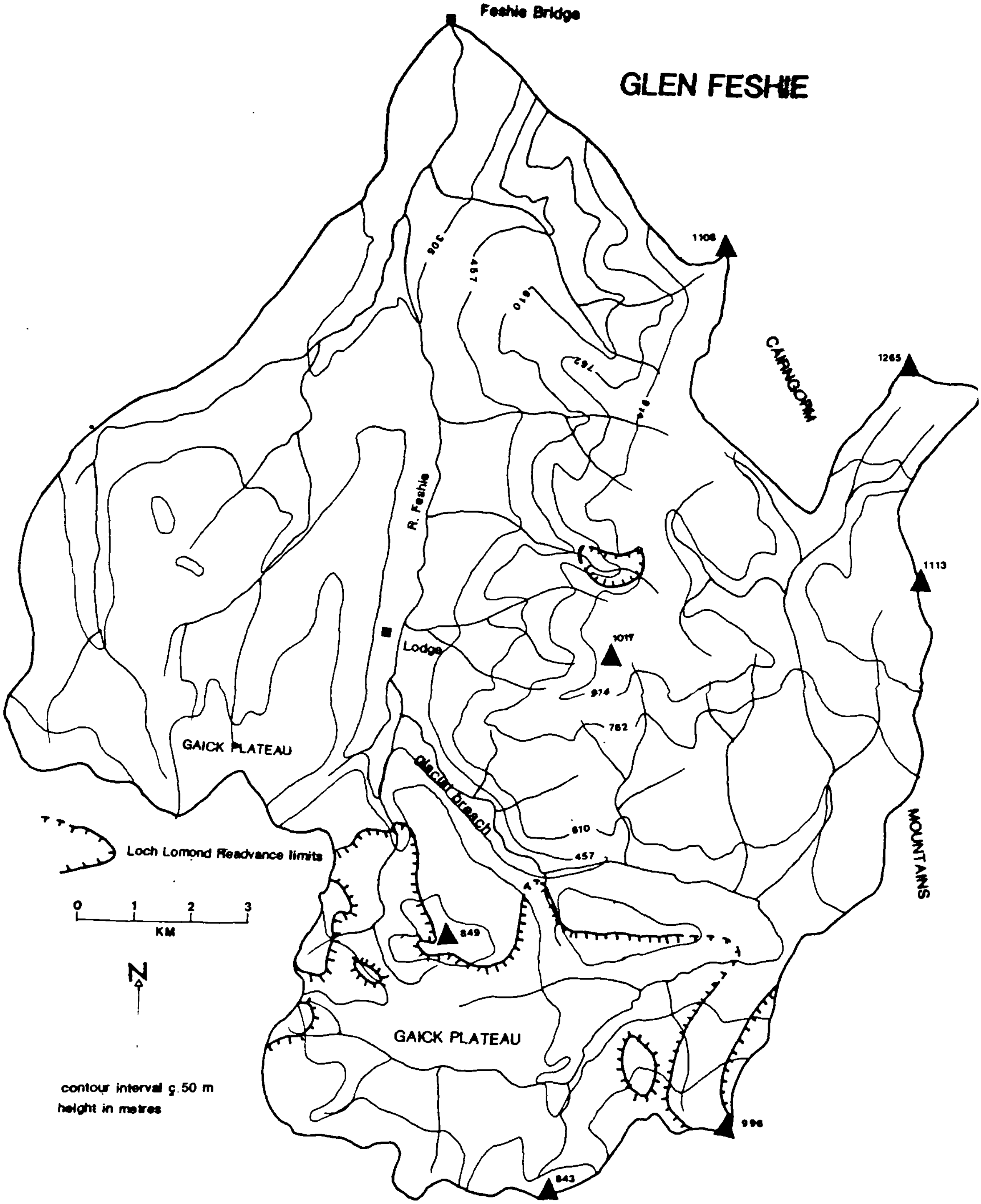


Figure 3.9a Topography and Loch Lomond Readvance limits.
(glacial limits after Sissons, 1974)

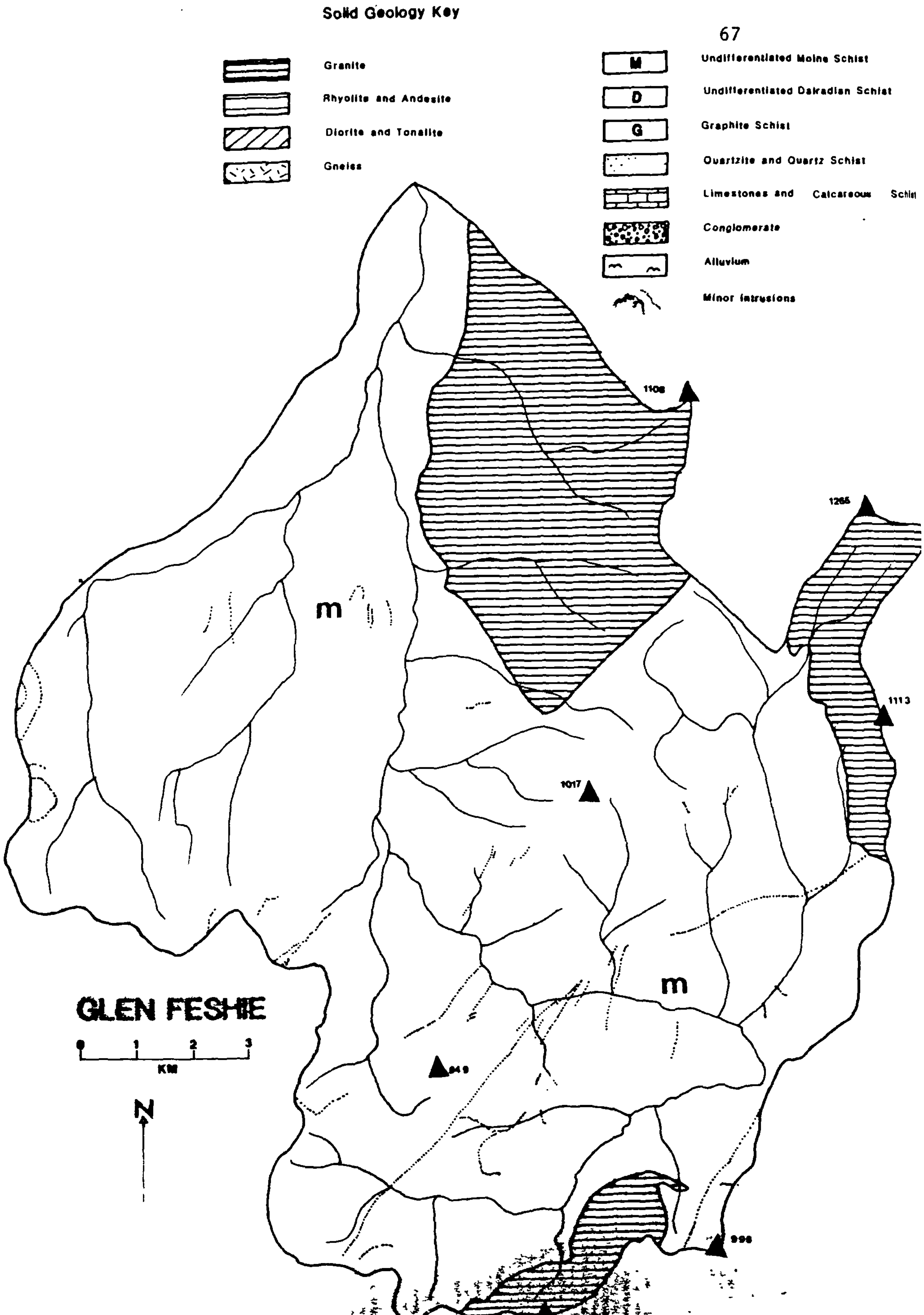


Figure 3.9 b Solid geology.

Glen Tromie) (table 3.1). The highest summit of 1265m in the Feshie catchment is in the Cairngorms. The upper River Feshie flows through a steep-sided glacial breach, excavation of which resulted in the capture of the headwaters of the River Geldie and the consequent anomalous drainage pattern of Glen Feshie (Linton, 1951). The glacial breach in Glen Feshie, and to a lesser extent the glacial troughs in the Upper Tromie, are favourable sites for talus and debris cone development. In Glen Tromie small tributary streams have given rise to the development of moderate-sized alluvial fans and composite cones. Barrow et al (1913) have suggested that geological control has resulted in marked parallelism of the lower course of the Tromie and the Feshie rivers.

3.3.2.2 Climate and hydrology.

Precipitation levels in Glen Tromie and Glen Feshie are predictably much lower than those near the west coast, averaging between 1200 and 1400 mm/year in the glens but as much as 2000 mm/year in the Cairngorms. Much of the precipitation in the Cairngorms falls as snow, which may be stored in late-lying snow patches until early summer. Ward (1985) has established that snow avalanches occur on average once in every five years at selected sites along the Cairngorm side of the lower Feshie catchment. Between March and June the snowmelt contribution to runoff results in marked diurnal oscillations in the River Feshie discharge (Ferguson, 1984). The flashy nature of the high energy

River Feshie has been described by Ferguson and Werritty (1983). Changes in the pattern of extreme rainfall and flooding events during the last c 180 years in the Upper Spey catchment have been identified by McEwen (1986), who has demonstrated that rainfall and runoff events were exceptional in both magnitude and frequency prior to AD 1900. For example, the exceptional regional storm of August 1829 affected this area (>95 mm rainfall in 24 hours at Huntly on the lower Findhorn), as did four subsequent winter cyclonic storms which locally resulted in flood damage equal to that of the 1829 event (McEwen, 1986). McEwen also identified an increase in more moderate flood flows during the 1870s and 1880s. More recently two major frontal storms occurred in 1956 and 1970. Neither, however, was comparable to the pre-1900 AD floods recorded on the Spey, or even within individual catchments where major flood events have occurred (McEwen, 1986).

3.3.2.3 Geology.

The bedrock of the Feshie and Tromie catchments consists predominantly of undifferentiated metamorphic rocks of Moinian age, especially schists (figures 3.8b and 3.9b). The eastern part of the Feshie catchment includes part of the major granitic batholith of the Cairngorm massif, but in Glen Tromie igneous rock outcrops are restricted to dyke intrusions of lamprophyre and porphyritic microgranite, with limited outcrops of pelitic gneiss in the north. Fewer dykes have been mapped in Glen Feshie, although abundant quartz veins intersect the fissile, densely-jointed metamorphic rock of the glacial breach. Such areas have been selectively weathered and are associated with cone development. The high density of shatter planes in the schists has locally given rise to a relatively small size range for the available clast-sized sediment (Chapter 5).

3.3.2.4 Geomorphology.

Barrow *et al* (1913) recognised ice sheet, valley and corrie glaciations in the area. The geomorphic impact of ice-sheet wastage in lower Glen Feshie has been discussed in detail by Young (1974, 1975a, 1975b, 1976), and Sissons (1974) has mapped the limits of small Loch Lomond Readvance outlet glaciers that descended from the Gaick ice cap into the upper valleys of the Tromie and the Feshie (figures 3.8a and 3.9a). Fluvioglacial landforms are widespread in the lower parts of both catchments, and some accumulations are remarkably thick (Sissons, 1976a). Young (1975a, 1976) has suggested three stages of terrace development in Glen Feshie, the first dating from the period of ice sheet wastage, the second associated with meltwater from the Gaick ice cap during the Loch Lomond Stadial, and the third, represented by the lower and more continuous Feshie terraces, he interpreted as Flandrian in age. Detailed research by Robinson-Rintoul (1986) has, however, revealed that at least five major terraces can be identified in the valley floor of Glen Feshie, and these have been tentatively dated to *c* 13,000, *c* 10,000, *c* 3,600, *c* 1,000 and *c* 80 BP.

Observations of channel pattern changes in the braided sections of the river Feshie have been made over three contrasting time scales of 1, 30, and 200 years by Werritty and Ferguson (1980), who suggested that channel switches may have been triggered by small-scale floods with recurrence intervals of less than once a year. In certain parts of the glen river channel changes across the valley floor have trimmed the distal deposits of fans and cones. Annual rates of bank erosion of 10m/year where the river is very active have been reported by Ferguson and Werritty (1983). It would appear, therefore, that in certain parts of Glen Feshie valley floor processes during the Flandrian have been considerably more active than implied by Young (1975a). However, less is known about Flandrian slope development in either of the glens, although it is probable that fluvially-controlled basal erosion has influenced slope development in parts of Glen Feshie for much of the Flandrian (chapter 7). Baird and Lewis (1956) recorded the geomorphological effects of the 1956 summer storms in the Cairngorms which resulted in numerous "summer solifluction flows" or hillslope debris flows initiated in neighbouring Glen Geusachan and in the Lairig Ghru; these storms may well have resulted in debris flow activity in upper Glen Feshie.

3.3.2.5 Vegetation history and landuse.

The following Flandrian plant succession in the central and eastern Grampians has been proposed by O'Sullivan (1975).

1. Soon after the end of the Loch Lomond Stadial, shrub tundra communities were succeeded initially by Juniper scrub and then by birch-hazel woodland prior to c 8,000 BP.

2. Pine cover expanded from c 8,000 BP to c 6,600 BP, especially in the Loch Garten area.

3. In Speyside, pine-birch forests were established between c 6,600 BP and 5,500 BP, followed by a major rise in *Alnus*. Pennington *et al* (1972) have suggested that this period was one of increased oceanicity, which resulted in a reduction of base status in waterlogged soils. Pears (1967, 1977) has suggested bioclimatic change during the Mid to Late Holocene from evidence of tree line fluctuations between 750m and 850m in the Cairngorms, and O'Sullivan (1976) identified a slight increase in the number of non-arboreal pollen, which suggests deforestation, possibly resulting from wetter soils in the area around Loch Pityoulish (Spey valley), during the period subsequent to the *Alnus* rise. The wetter conditions during this period may have affected the activity of alluvial fans debris cones and talus cones in Glen Feshie and Glen Tromie, but there is no direct evidence concerning sediment release in the source areas that would determine whether activity was primarily aggradational or involved erosion and reworking of existing

deposits. The lack of evidence for soil erosion during this time in cores taken from the Spey area may suggest that locally slopes were stable, but no inference can realistically be made from this for conditions on steep slopes of mixed resistant and vulnerable lithologies such as found in the glacial breach of upper Glen Feshie.

4. After c 3,800 BP, short-lived episodes of forest clearance of c 100 years duration have been identified in the Loch Pityoulish area, and at nearby Loch Garten forest clearance commenced at c 3635 BP and was associated with the activities in the Spey valley of secondary Neolithic cultures (O'Sullivan, 1976). Forest clearance, however, may not have been continuous. O'Sullivan (1976), for example, has identified significant periods of pine forest regeneration and soil stability c 1650 BP. At the Loch Pityoulish site, heathland pollen concentrations gradually increased whilst pine pollen concentrations remained high, implying the natural opening up of the forest canopy, until a renewal of human activity c 1,000 BP (O'Sullivan, 1976). As alluvial fans in particular may have offered well-drained sites for forest clearance and habitation, human activity may have influenced the stability of such sites and their susceptibility to incision and erosion.

The present-day cover of Caledonian forest is now restricted to the valley floor and lower slopes in Glen Feshie. The timber trade moved into Speyside during the end of the eighteenth century, and felling continued until the

Second World War (Stevens and Carlisle, 1959). Grazing deer have restricted the natural regeneration of the forest to steep and inaccessible parts of the glacial breach (D. Gowans, pers. comm.). Flood damage, such as that associated with the 1829 flood, has also been reported as destroying parts of the forest in the valley (Stevens and Carlisle, 1959). Peat bogs are sparse in the Feshie valley, but Glen Tromie is less well drained in places, and much of the Gaick plateau upland is blanketed in peat. Land management in the two glens is principally for deer forest but the Gaick estates also support large areas of grouse moor. The extensive patchwork pattern of the heather moor bears witness to periodic vegetation burning in the upper Tromie catchment, a factor which has been implicated as promoting increased soil erosion and debris flow activity (Imeson, 1971, 1974; Innes, 1983a).

3.3.3 Glen Clunie and Glen Clova.

3.3.3.1 Catchment characteristics.

Glen Clunie and Glen Clova are the easternmost glens studied in the transect, and represent the headwater catchments of the Dee and South Esk rivers respectively. They possess similar topographic characteristics, both being glacially-eroded troughs that dissect the regular plateau surface of the South East Grampians (figures 3.10a and 3.11a). The legacy of glacial erosion is especially marked in Glen Clova, where the valley sides rise steeply to nearly

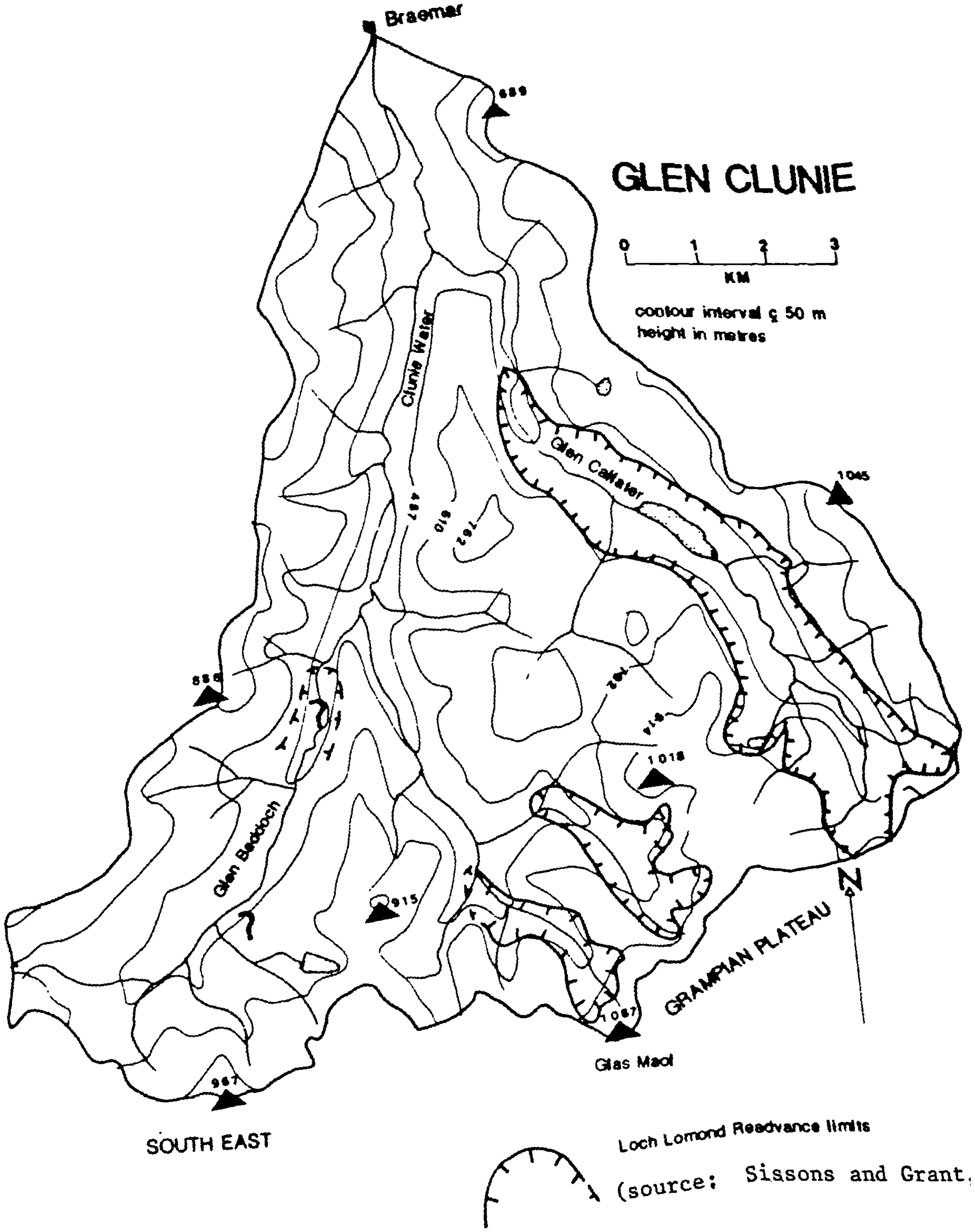
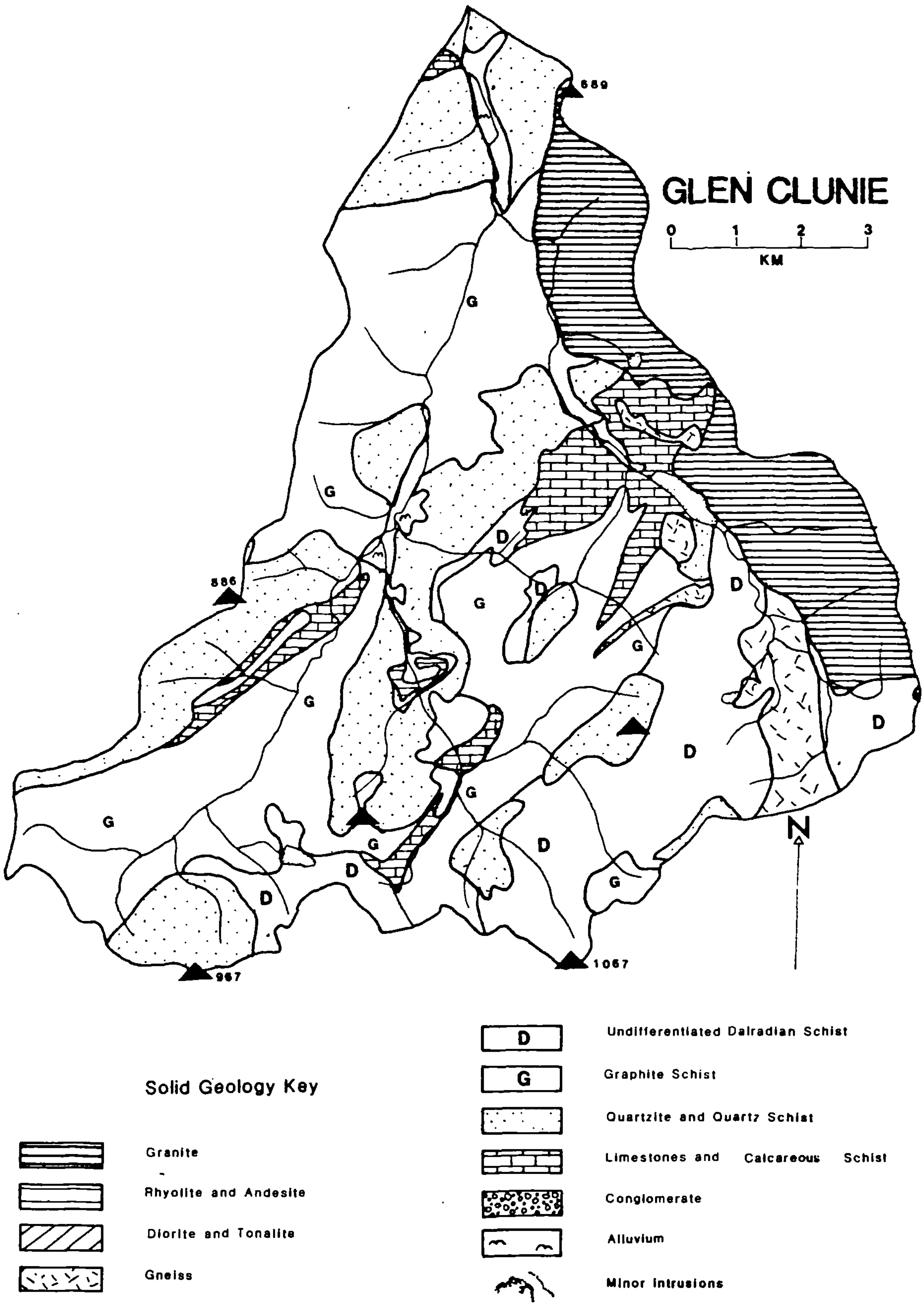


Figure 3.10a Topography and Loch Lomond Readvance limits.
(Glen Baddoch glacial limits discussed on page 80)

Figure 3.10b Solid geology.



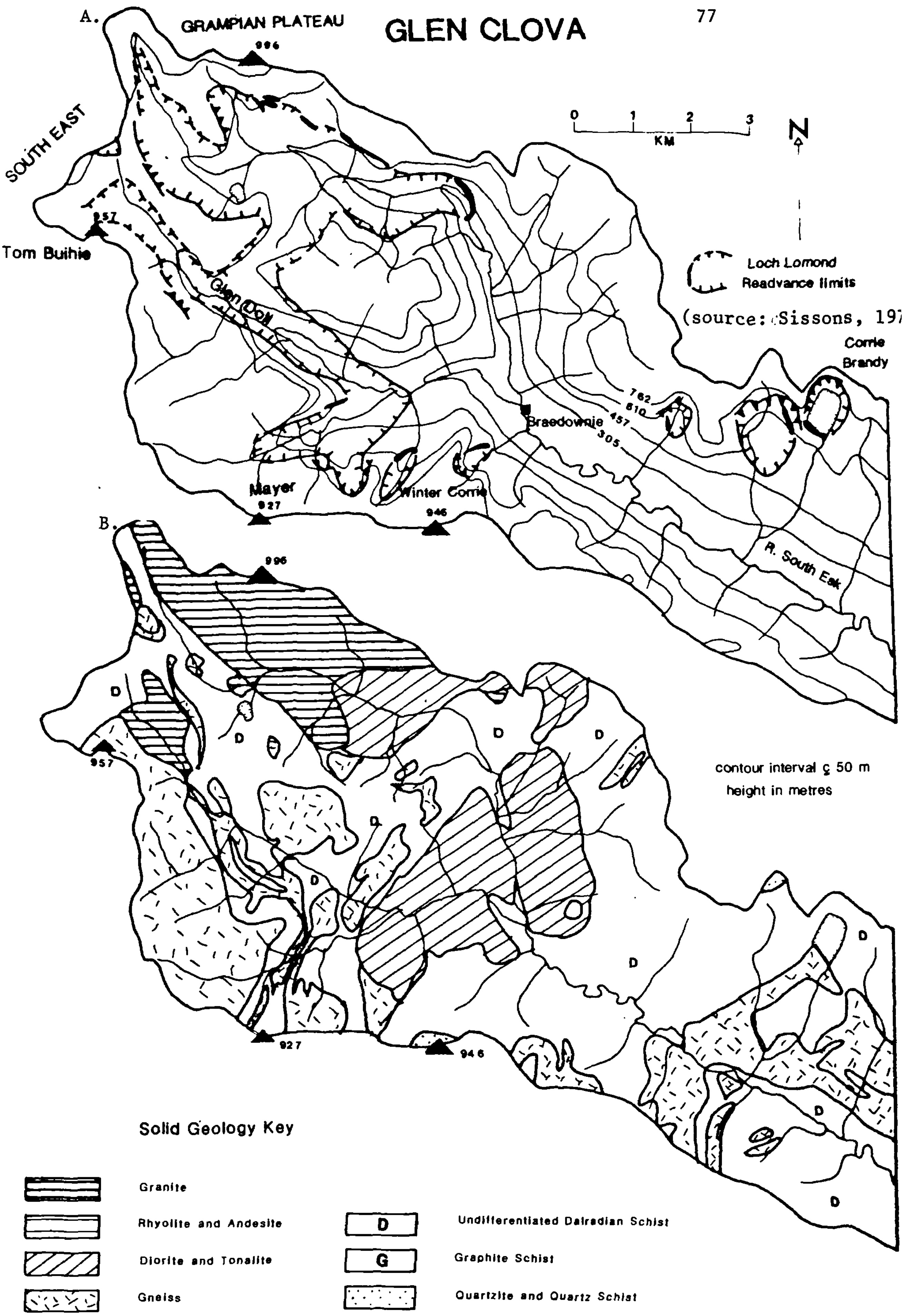


Figure 3.11a Topography and Loch Lomond Readvance limits.

Figure 3.11b Solid geology.

550m above the flat valley floor. The low average basin gradient of 1.8° characterises the gentle course of the River South Esk through the glacial trough in Glen Clova, but does not reflect cross valley amplitudes in relief (table 3.1). Glen Clunie is a much wider and shorter catchment than Glen Clova and consequently has a higher average basin gradient (2.7°) despite the lower value of basin relief compared with Glen Clova (748 m to 873 m respectively; table 3.1). Glen Clova has more steep rock faces and consequently more extensive talus development than Glen Clunie, where the gentler relief has given rise to block slopes, sparse talus development and small fans and cones.

3.3.3.2 Climate.

Precipitation values are similar to other eastern glens in the mesoscale part of the project, ranging from 1,400 mm/year at Braedownie in Glen Clova to c 1,600 mm/year falling on the surrounding hills (table 3.2). McEwen (1986) has reported that between the 1870s and 1880s there was an increase in the frequency of moderate to extreme rainfall events (of 24 to 48 hour duration) in Deeside. These rainfall events were often associated with summer frontal storms and resulted in an increased incidence of moderate to extreme floods. However, the regional storm of 1829 does not appear to have caused any extraordinary flooding in Glen Clunie, like that experienced in the Cairngorm tributaries of the Dee. McEwen cited several reports of very localised "water spouts" in Deeside such as that on 2nd August 1870 when 53.3mm of rain fell in 45 minutes at Braemar, and that on 12th August 1885 when 87.4mm fell in under 12 hours at Braemar, and another which caused slope failure on the hillside above the Linn of Dee in August 1884. Since 1900 AD minor climatic fluctuations have occurred, including a increased incidence of high magnitude rainfall events (McEwen, 1986). Flooding has been associated with exceptionally high antecedent rainfall in the Eastern Grampians (eg 340.6 mm precipitation was recorded in January 1937 at Braemar) and long duration (>48 hours) winter cyclonic storms (McEwen, 1986).

3.3.3.3 Geology.

Glen Clunie and Glen Baddoch are underlain by a diverse association of Dalradian metamorphic rocks, including quartz-graphite and calcarious schists (figure 3.10b). Granite outcrops occur on the eastern side of the Clunie catchment, with other minor intrusions of porphyritic microgranite, diorite, tonalite and lamprophyre trending SW-NE. Mapped minor intrusions are not so abundant in Glen Clova, but there are extensive areas underlain by diorite and tonalite. Granite outcrops in the north of the Clova catchment (figure 3.11b) form some of the higher land. In the north-west of the Clova catchment, Tom Buihie is underlain by oligoclase biotite, and muscovite gneiss and hornblende gneiss and schists crop out in Glen Doll and on Mayar.

3.3.3.4 Geomorphology.

Barrow et al (1912) gave detailed descriptions of glacial deposits and landforms in the South East Grampians. They identified three phases of glaciation, including one when ice covered the whole area, a period of valley glaciation and one of corrie glaciation. Deposits relating to the ice sheet glaciation may now be assigned to the Dimlington Stadial, whilst some of the evidence for valley and corrie glaciation in Glen Clova and Glen Clunie has been attributed to the Loch Lomond Readvance (Sissons 1972; Sissons and Grant 1972; Sissons and Sutherland 1976; figures 3.10a and 3.11a). Sissons (1972) mapped the limits of six small independent corrie glaciers in the Clova catchment. The main valley glaciers in Upper Glen Clova and Glen Doll descended from a thin ice-mass on the plateau. Within the Clunie catchment, Sissons and Grant (1972) mapped the limits of Readvance glaciers in Glen Callater, Glen Fionn and Gharbh Glen (figure 3.10a). The profusion of hummocky moraines and clear glacier limits in Glen Baddoch, however, have not received attention other than the description by Barrow et al (1912). It is suggested that such geomorphological evidence indicates that Glen Baddoch was occupied by a Loch Lomond Readvance glacier of similar proportions to the one in Glen Callater. Glen Clunie and Glen Clova, therefore, have lower reaches that remained glacier-free during the Loch Lomond Stadial. All fans and cones that are found within the Loch Lomond Readvance glacial limits must be Flandrian in age.

McEwen (1986) argued that the palaeochannels visible adjacent to the lower Clunie Water were present at the time of Roy's map (c 1750), and that part of the upper Clunie Water subsequently changed its channel pattern from "sinuous" to "wandering" with occasional "new" islands identified from changes on the second and third edition Ordnance Survey maps (c.1900 and 1970).

3.3.3.5 Vegetation history and landuse.

Walker (1975b) has described the pollen stratigraphy of a core taken from an enclosed hollow in Glen Clova at Roineach Mhor (NO 331728), and from this interpreted the triple basal sequence of organic / minerogenic / organic sediments as representing Lateglacial Interstadial, Loch Lomond Stadial and postglacial sedimentation respectively. The interstadial pollen indicate that the area was colonised by open habitat taxa and then by grassland with willow, juniper and dwarf birch. The return to cold conditions during the Loch Lomond Stadial caused the break-up of existing plant communities, and the proliferation of chionophilous tundra vegetation. The Flandrian began with rapid climatic amelioration, and a succession of grassland, heathland and eventually birch forest over large areas of the South East Grampians (Walker 1975b).

Today very little natural woodland survives, with grassland and heather moorland common in both catchments. Thick blanket peat deposits are found on poorly-drained areas of the plateau.

3.3.4 The Upper Findhorn (Strathdearn).

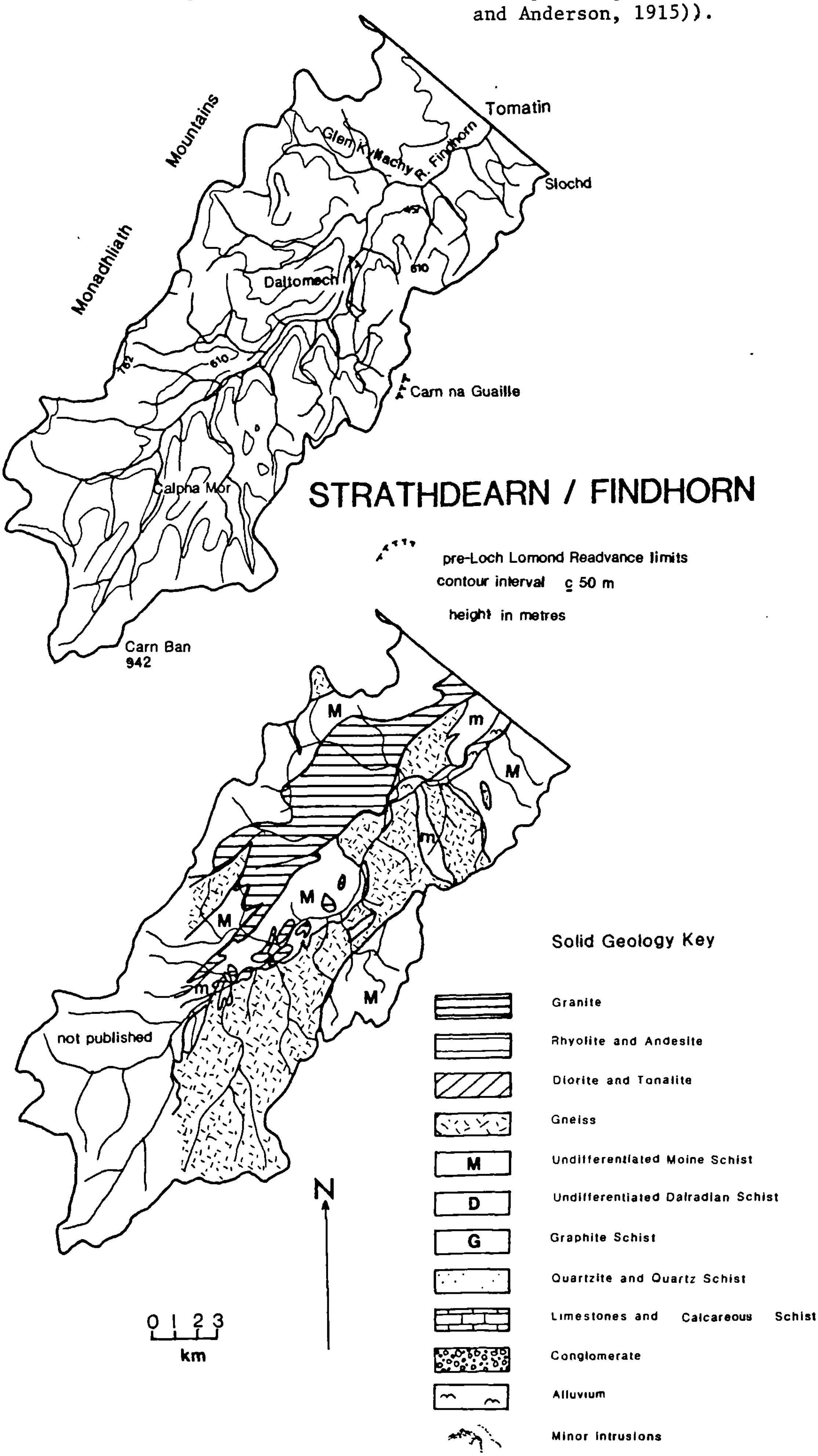
3.3.4.1 Catchment characteristics.

The Findhorn valley is the northernmost study area in the macroscale transect. The Findhorn river flows northeastward, roughly parallel to the Nairn, Dulnain, and Spey rivers. The monotonous plateau topography of the Monadhliath Mountains has been glacially dissected along the main course of the upper Findhorn river (figure 3.12a), although the glacial trough is not as deep as in other eastern glens such as Glen Clova. The highest ground is in the southeast of the catchment where the land rises to 941m OD. Overall basin relief is 692m, with an average basin gradient of 1°, the lowest of all the study areas. The steep valley slopes in the certain parts of the glacial trough have favoured localised talus and gully development, and large alluvial fans have built up at the confluence of many tributary streams with the main river.

3.3.4.2 Climate and hydrology.

Mean annual precipitation ranges between 1,200 mm and 1,400 mm in the main part of the valley (table 3.2), but up to 2,000 mm on the surrounding hills. Intense rainstorms

Figure 3.12a Topography and pre Loch Lomond Readvance moraines, (glacial limits based on descriptions given by Hinxman and Anderson, 1915)).



over the Monadhliath Mountains have resulted in devastating flash floods. An eye witness account described how the river Findhorn rose a record 15m at Randolph's Leap (south of Forres) during the 1829 flood (Lauder, 1830). Maximum annual discharge data for the Findhorn at Shenachie over a 22 year period reflects the flashy nature of the river (Acreman, 1986). Rating curves established for a flood in 1981 have been used to estimate the maximum discharge of the Findhorn during the 1829 flood giving a very large value of 1,000 m^3/sec (equivalent to 2.2518 m^3/sec/km^2) at Shenachie (Werritty pers. comm.). Both the 1829 and 1981 storms resulted in reworking of alluvial fans in Strathdearn. Green (1958, 1971) described two strikingly similar storms that resulted in flood damage in the Moray area, including damage caused to bridges, some of which crossed streams on alluvial fans in Strathdearn. Green (1971) has suggested that during these storms, orographic influences intensified the frontal rainfall in the area with falls exceeding 150 mm in 72 hours.

3.3.4.3 Geology.

Metamorphic rocks of Moinian age are widespread in the upper Findhorn catchment and include pelitic gneisses and schists and silicious schists and granulites with some quartzite outcrops (figure 3.12b). The schists have given rise to distinctive platy clasts where they have been frost shattered as seen, for example, in talus deposits near Daltomach. Outcrops of younger intrusive igneous rocks occur in the north western part of the catchment and include granites and granodiorites. Minor intrusions of felsite, porphyritic microgranite, and granophyre also occur, and many of these have been selectively weathered giving rise to rock gullies.

3.3.4.4 Geomorphology.

A remarkable sinuous moraine running along the watershed on Carn na Guaille was described by Hinxman and Anderson (1915), who noted that the Dulnain side of the moraine was steeper than the western side, and that some of its erratics are of an unusual feldspar porphyry similar to that found in Glen Tromie to the south. On the basis of this evidence they suggested that the moraine was deposited by ice moving northwards from the Spey basin. Two other moraines relating to the last ice sheet were also identified by Hinxman and Anderson (1915), on Calpha Mor and crossing the valley at Daltomach. Hinxman and Anderson argued that the position of the Daltomach moraine implies that ice spilled from the Great Glen area down Glen Kyllachy and deposited debris in the Findhorn valley. Despite the recent interest in defining the limits of the last Scottish ice sheet and associated readvances (chapter 2), no further research has been undertaken to explain the origin or significance of the Findhorn moraines.

Numerous meltwater channels have been mapped cutting across the Strathdearn watershed (eg Slochd Summit) (Hinxman and Anderson, 1915), and on the valley sides (Young, 1980). Downstream of the Daltomach moraine (see above) numerous high outwash terrace fragments have survived, with fluvioglacial sediments overlying thick clayey till deposits (Young, 1980). Near Tomatin, nine test boreholes were sunk for preliminary site investigations for the construction of the Findhorn viaduct, and these revealed that the valley fill consisted of silts, sands, gravels and boulders with some glacial till, with total recorded thicknesses of between 13.8 m and 33.6 m (Scottish Development Department, 1983). The borehole data show that the valley fill comprises a complex sequence of granular materials that have been tentatively interpreted as interbedded fluvioglacial sands and gravels and glacial tills (Scottish Development Department, 1983). These data could imply that several glacial sequences are recorded in the valley fill near Tomatin, as well as illustrating the large amount of fluvioglacial material deposited during ice sheet wastage. It is possible that alluvial fan development in this area was initiated during or shortly after the final period of fluvioglacial sedimentation whilst part of the upper catchment still supported glacier ice, and when periglacial conditions favoured rapid sediment release from unconsolidated glacial deposits and localised rockfall from rockfaces in parts of the glacial trough. Strathdearn was glacier-ice free under the cold climatic conditions of the Loch Lomond Stadial, when periglacial conditions would again have influenced the nature and rate of alluvial fan, debris cone and talus cone development.

On the valley floor a series of low terraces have been identified that post-date the fluvioglacial deposits (Hinxman and Anderson, 1915; Young, 1980). Little evidence is available from which any reliable estimate of fan and cone development during the Flandrian can be inferred, but it is probable that the rate of development was reduced as a result of vegetation colonisation. Locally, and under special circumstances arising from poor landuse practices, rapid gully erosion has been reported in the Drynachan area, north of Tomatin, by Fairbairn (1966) who estimated that one gully had enlarged by as much as 45.4% in 16 years.

3.4.4.5 Vegetation history and landuse.

No pollen-stratigraphic data are currently available for Strathdearn, although the vegetation history of this glen may well have been similar to that established for the neighbouring Spey valley (see section 3.3.2.5 above).

Several large estates control present-day landuse in upper Strathdearn, where the land is managed primarily for deer forest and grouse moor. The potential exists, therefore, for localised anthropogenically-induced debris flow activity and soil erosion, which may have also influenced past fan and cone development. In the valley there is some sheep pasture and there are limited areas of conifer forest. Areas of natural birch forest are restricted to steep hillsides.

3.4 SUMMARY

From a transect across the Grampian Highlands, seven glens were selected with the aim of representing the variety of different environments found in this area. The following *a priori* chronological implications for fan and cone chronology and evolution in these areas are suggested, based on the information presented in both this chapter and in the preceding chapter.

Dimlington Stadial

It is possible that rapid fan and cone development followed ice sheet deglaciation in all areas where relief and sediment supply were suitable. Such fan and cone development may have taken place initially under periglacial conditions in areas that were deglaciated relatively early.

Lateglacial Interstadial

The interstadial seems likely to have witnessed a reduction in the rate of fan and cone formation associated with increasing slope stability brought about by vegetation colonisation under warmer conditions. Such mild climatic conditions, however, declined toward the end of the interstadial.

Loch Lomond Stadial

During this period fan and cone landforms are likely to have been obliterated by glacier ice in all of Glencoe and Glen Etive, and parts of Glens Tromie, Feshie, Clunie and Clova. Outside the limits of glaciation, however, in Strathdearn, most of Glen Feshie and parts of Glens Tromie, Clunie and Clova there may have been increased accumulation of fan and cone landforms under the periglacial conditions of the time.

Early Flandrian

In areas that lie within the Loch Lomond Stadial limits there may have been initially rapid fan and cone formation resulting from reworking of unconsolidated glacial and other deposits, especially in the short interval before complete vegetation colonisation. In areas outwith the Loch Lomond Stadial limits, however, there seems likely to have been a reduction in the magnitude of (or possibly complete cessation of) fan and cone accumulation as a result of vegetation colonisation and possibly depletion of sediment supply.

Early, Mid and Late Flandrian.

It is difficult speculate on the possible nature of fan and cone development during the Flandrian when so little is known of Flandrian geomorphological activity in general, other than to suggest that fan or cone deposition was probably no more than intermittent during most of the Flandrian (chapter 2). Certain local factors may have promoted continued fan or cone aggradation, such as the presence of fissile, easily erodible lithologies in contributing areas. Short term factors that could have triggered or promoted episodic fan and cone accumulation or erosion during the Flandrian are likely to have included stormy weather conditions and poor landuse practices by man (particularly burning and overgrazing).

CHAPTER 4

ALLUVIAL FANS, DEBRIS CONES AND TALUS CONES: REVIEW OF LITERATURE

4.1 INTRODUCTION

The principal aim of this review is to summarise and discuss the main themes in the literature on alluvial fans, debris cones and talus cones, and to provide an appropriate background for later chapters. The second aim is to establish an *a priori* classification for the field identification of genetically-distinct fan and cone landforms based on findings reported in the literature.

The environmental setting and morphological and sedimentological characteristics of fan and cone landforms will be discussed separately in the following three sections. The use of inappropriate or ambiguous terminology in some of the literature has been misleading and has sometimes limited the generality of the findings of research. In this context Luckman (1971, 1978b) has suggested that, prior to field investigation, talus slopes should be classified in terms of the dominant process operating on them. In this review such a procedure has been adopted and a system of *genetic* terms has been developed to designate fan and cone landforms arising from either one process (ie alluvial fans, debris cones resulting from debris flow accumlation and rockfall talus cones) or more than one process (ie composite cones such as fluvially-modified debris cones and debris flow modified talus cones). Attention is focused on fan and cone development in deglaciated mountain environments and in arctic areas, as such environments provide the closest analogues to both present day and past conditions in the Scottish Highlands.

4.2 ALLUVIAL FANS

4.2.1 Environmental controls of alluvial fan development.

Alluvial fans are accumulations of predominantly water-laid deposits that have spread out at the junction of tributary valleys with main valley or basin floors. Alluvial fans are known to develop in both tectonically-active and tectonically-stable environments. Much research during the 1950s and 1960s was centred on alluvial fan development in arid and semi-arid areas (eg Blissenbach, 1954; Beaty, 1963; Bluck, 1964; Denny, 1965; Melton, 1965). More recent research, however, has drawn attention to alluvial fan development in other regions of the world, such as humid temperate environments (Rachocki, 1981; Kesel and Spicer, 1985; Harvey, 1986), deglaciated mountain environments (Ryder, 1971a, 1971b; McPherson and Hirst, 1972; Roed and Wasylyk, 1973; Desloges and Gardner, 1981; Jackson *et al*, 1982; Kostaschuk *et al*, 1986), and arctic environments (Anderson and Hussey, 1962; Hoppe and Ekman 1964; Leggett *et al*, 1966). Alluvial fans have been found in many parts of the world, thus calling into question the suggestion made by Bull (1977) that semi-arid conditions are the most favourable for alluvial fan formation.

Alluvial fan development often comprises distinct periods of alternating aggradation and incision. It has been claimed that the type of fan activity alters in response to changes in the environmental conditions that influence water discharge and the supply of sediment to the fan (eg Ryder, 1971b; Wasson, 1977; Jackson et al, 1982; Saito, 1983). Two themes in the literature on such environmental conditions are relevant to this study. The first consists of a number of observations recorded in the literature that may conveniently be grouped under the title of the periglacial hypothesis, and the second comprises the hypothesis of paraglacial sedimentation.

Alluvial fan activity in periglacial areas is generally controlled by seasonal patterns of runoff and by the rate of weathering and the supply of sediment (Anderson and Hussey, 1962; Hoppe and Ekman, 1964; Leggett et al, 1966; Theakstone, 1982; chapter 2). For example, Wasson (1977) argued that a periglacial and nivational regime with its associated lack of vegetation had resulted in alluvial fan aggradation in Tasmania, whereas subsequent climatic amelioration had resulted in the dissection of such fans. High rates of periglacial weathering during stadial conditions, however, may not necessarily lead to a concomitant increase in alluvial fan sedimentation. Thus

Saito (1983) has argued that significant periods of alluvial fan aggradation occurred under temperate conditions in those areas of the Japanese Alps that had been subject to periglacial weathering during preceding cold climatic conditions. No evidence of increased aggradation was observed for those fans whose contributing areas had not experienced periglacial weathering. This suggestion implies that alluvial fan aggradation may be enhanced either by contemporaneous periglacial conditions or by the legacy of periglacial weathering in the catchment. As such this periglacial hypothesis, unlike the paraglacial hypothesis, does not require fan catchments to have undergone glaciation during cold periods, such as the Loch Lomond Stadial in Scotland.

The hypothesis of paraglacial sedimentation has been given considerable attention in the literature on alluvial fan development. The term "paraglacial" implies an environment conditioned by glaciation, and as such may include a transition period from glacial to nonglacial conditions (Church and Ryder, 1972; Jackson et al, 1982). Such environments may have large amounts of unconsolidated glacial sediment mobilised by mass movement processes (P.G. Johnson, 1984) or by fluvial processes (Church and Ryder, 1972). Paraglacial sedimentation has been estimated as having been in excess of 2,500t / km^2 /year for parts of the north west of the United States of America, values that are probably matched only by present-day rates in high mountain proglacial environments (Church and Ryder, 1972). The period of paraglacial sedimentation is, however, thought to be relatively short-lived and dependent on the total amount of sediment available. Thus, once sediment sources are depleted, the nature of the associated landform development may change from a dominantly-aggradational to a dominantly-erosional regime (Ryder, 1971b; Roed and Wasylyk, 1973; Jackson et al, 1982).

This general pattern of paraglacial fan development is confirmed by several studies in Western Canada. Thus studies carried out in the area of the Bow River, Alberta have revealed the chronology and evolution of paraglacial river terrace and alluvial fan sedimentation for this area. Radiocarbon dates imply that the Bow River valley was deglaciated by c 13,000 BP, with forest cover established by c 10,000 BP (Jackson et al, 1982). Mazama tephra dated at c 6,600 BP has been found either overlying final sediments or in the near-surface deposits of both alluvial fans and river terraces (Roed and Wasylyk, 1973; Jackson et al, 1982). Such stratigraphic evidence implies that there was a dramatic reduction in the rate of sediment accumulation around or before 6,600 BP, and therefore that the bulk of the fan sediments must have been deposited during a period between deglaciation and the mid Holocene. Furthermore, the sedimentological evidence also implies that there was a change from debris flow to fluvial deposition as the dominant process on certain alluvial fans at this time (Roed and Wasylyk, 1973). The lack of clear stratigraphic divisions between debris flow units together with the absence of organic matter led Jackson _et al_ (1982) to suggest that early fan aggradation by debris flow was very rapid but short lived, possibly occurring after deglaciation but prior to the establishment of forest cover _c_ 10,000 BP.

A similar chronology for alluvial fan and composite cone formation in British Columbia has been documented by Ryder (1971b) who also found Mazama tephra in near-surface fan deposits. Farther northeast in the Upper Saskatchewan river basin in Alberta, McPherson and Hirst (1972) have however recorded fan sedimentation as late as _c_ 2,000 BP using tephrachronology. Desloges and Gardner (1981) have reported even more recent surface deposits on the Mt Rae Glacier Creek alluvial fan, also in Alberta. They detected a complex set of responses relating fan development to specific basin properties. One of the most important factors determining the magnitude and frequency of depositional events at this site is the presence of glacial ice in the catchment. Rapid ice wastage between the time of the Little Ice Age maximum and about 1920 AD is thought to have reduced glacier volume by as much as 75%, and past fan aggradation is thought to have been associated with glacier wastage. More recent glacier recession rates, however, are thought to have been insufficient to have caused meltwater flooding on the Glacier Creek fan. Desloges and Gardner (1981) interpreted several flood deposits as the consequences of meteorological events that are known to have caused flooding elsewhere in the neighbourhood, and they also suggested that small-scale jokulhlaups may have temporarily exacerbated discharge levels. A possible change in sediment provenance was also noted, with recent angular deposits implying a change from a glacial to a frost-shattered origin for debris supplied to the fan.

It seems probable that paraglacial alluvial fan development in the Scottish Highlands may have occurred during and immediately after deglaciation. Several points that emerge from the literature on paraglacial fans suggest, however, that the hypothesis should not be too narrowly defined, either in terms of the processes involved, or of the high magnitude of sediment delivery. First, it is clear that the duration of paraglacial slope instability and supply of sediment may vary considerably across neighbouring regions, by as much as several thousand years. Second, a change in dominant process has been recorded at some, but not all, alluvial fan sites. Third, aggradational activity may still continue after the main period of paraglacial aggradation, and the transition from a paraglacial to non-paraglacial regime may be difficult to detect simply in terms of process magnitude, as other factors such as changes in sediment source may occur (cf Desloges and Gardner, 1981). Despite these reservations about the rather simplistic notion of paraglacial sedimentation, the hypothesis remains viable in the Scottish context, as does the closely related periglacial hypothesis, and both will be examined later in this thesis.

Morphometric relationships between alluvial fans and their contributing basin areas have been studied by several authors. Ryder (1971a) observed that fan gradients may be statistically related to such basin variables as relative relief, height, area and slope, but also noted that the degree of correlation was lower than that observed for fans in semi-arid regions (eg Melton, 1965) reflecting different depositional histories. The strength of such relationships also varies considerably between neighbouring areas of British Columbia, which Ryder (1971a) argued might reflect differences in the timing of deglaciation, catchment lithology or precipitation. These differences, however, may equally have resulted from the lack of differentiation of fans formed predominantly by fluvial deposition and those resulting, at least in part, from debris flow accumulation. Kostaschuk _et al_ (1986) noted that different morphometric relationships occur between fan slope and basin ruggedness depending upon dominant process, with lower-angled fluvial features associated with less rugged catchments, and generally steeper debris cones below more rugged source areas. Their results, however, were not statistically significant owing to the small sample size employed. Clearly, potential exists for further examination of fan or cone properties in relation to source area characteristics. Care must, however, be taken in the choice of morphometric variables and the method of analysis if any meaningful advance is to be made in our understanding of the nature of these relationships. Recent research by Wells and Harvey (1987) provides perhaps the most encouraging advance in tackling this problem. An intense rainstorm in the Howgill Fells, Northern England, resulted in fluvial, transitional and debris flow deposits on associated fans and cones in the flood affected area. Catchment properties such as geomorphology, sediment type and supply, together with both the spatial pattern of rainfall intensity around the locus of the storm and changing rainfall intensities during the storm determined the type of depositional events generated on each fan or cone. Wells and Harvey (1987) observed that the catchments favouring debris flow deposition were relatively small, steep and cut into soliflucted till deposits. In contrast, fluvially-dominated fan catchments were larger, less steep and sometimes developed in bedrock as well as soliflucted till. Harvey (1984) also noted a similar morphometric and lithological relationship between contributing areas and consequent depositional processes on fans in Spain. Similar relationships between source area morphology and lithology and dominant process may also exist for fans and cones in the Scottish Highlands, thus raising the possibility of defining the nature of process control exerted by the contributing catchment on the nature of fan or cone development.

4.2.2 Alluvial fan morphology.

Alluvial fan planform may approximate a segment of a cone with distal widths ranging from very narrow to wide as determined by topographic conditions (eg Hooke, 1967). Total depth of sedimentation may be large for fans in tectonically-active areas, but it is unlikely that fans in stable areas can achieve great depths. For example, seismic profiles through an alluvial fan in Sweden indicated relatively shallow deposits with maximum values between about 10 and 20 m (Hoppe and Ekman, 1964). Long profiles radiate down-fan from a narrow apex, usually the highest part of the fan. Long profile form is generally concave (McPherson and Hirst, 1972; Hooke and Rohrer, 1979; Desloges and Gardner, 1981; Kesel and Spicer, 1985), resulting from selective deposition of larger clasts first with loss of stream competence down-fan. In tectonically-active areas long profile form may also be affected by the rate of uplift of the mountain front (Bull, 1977). Mean medial gradients of alluvial fans have been reported to range from less than 5^{o} to as much as 25^{o} (Nilsen and Moore, 1984). Bull (1977) has suggested that relatively small features with gradients in excess of 20° should be called "alluvial cones", rather than fans. Such taxonomic niceties, however, have tended to obscure rather than shed light on the problem of interpretation of a complex set of landforms that appear morphologically similar but may not have resulted from the same process. Hooke (1967) suggested that a predominance of debris flow deposition may result in steeper fan and cone development than that which would be achieved by fluvial processes alone. It is therefore probable that the mean gradients reported for landforms defined in the literature as alluvial fans overestimate the typical gradients associated with fluvial deposition alone. Fan gradients for sites where fluvial processes are known to dominate give a better indication of characteristic slopes for alluvial fans *sensu stricto* with values ranging from 1° to 10° (Eckis, 1928; Mammerickx, 1964; Ryder, 1971b; McPherson and Hirst, 1972; Wasson, 1977; Desloges and Gardner, 1981). A major control on fan slope is dominant discharge, as demonstrated by Hooke and Rohrer (1979) in their laboratory studies. They defined dominant discharge in perennial alluvial fan streams as that equalled or exceeded only 5% of the time that flow occurs in the channel, and demonstrated that effective dominant discharge is proportional to debris size. Medial fan gradients may be lower than lateral gradients on coarse sediment fans because the dominant fan-forming discharges are more likely to flow down the medial axis of the fan (Hooke and Rohrer, 1979).

Cross-profile form has been described by many authors as typically convex (Hoppe and Ekman, 1964; Ryder, 1971b; Hooke and Rohrer, 1979; Desloges and Gardner, 1981; Kesel and Spicer, 1985). Cross-profile form may, however, be irregular, especially where unequal aggradation and dissection have affected much of the fan surface.

Changes in channel direction may be caused by deflection of the stream course by boulder or debris dams deposited during floods (Desloges and Gardner, 1981), or by relatively sediment-free overbank flow that can rapidly erode a new channel and eventually capture the main stream flow. Hooke and Rohrer (1979) modelled alluvial fan sedimentation using a Markov model. They suggested that channel switching was a natural process by which low areas on fans could be infilled until they became topographic highs, thus deflecting the channel to other low areas and so smoothing the fan surface (cf Werritty and Ferguson, 1980). Paleochannels are therefore a common characteristic of fans dominated by fluvial deposition.

Stream incision or trenching may also cause irregularities in the form of alluvial fans. Several theories have been developed that purport to explain the origin and significance of fan dissection. Conflicting explanations of fan-head incision have been given for composite cones where both debris flow and fluvial processes operate. For example Bluck (1964) suggested that incision of existing debris flow deposits occurs through river incision, whereas Pierson (1980) observed deep fan-head trenching during a single debris flow event. Observations made during the experimental construction of a "wet" alluvial fan in the laboratory suggested that trenching was periodic (Schumm, 1977). The development of this alluvial fan started with fluvial deposition at the fan apex, and continued until a slope threshold was reached, at which point trenching occurred. Following the development of a trench at the fan apex the source area channel was rejuvenated, thus increasing the supply of sediment to the fan and infilling the trench. Such a model may, however, be inappropriate for relatively immature fans in areas with a complex history of environmental change.

Returning to theories of fan-head incision, Ryder (1971b) has suggested that such incision may be a response to a significant reduction in the supply of sediment or to a change in base level. Harvey (1984) has noted two major phases in alluvial fan development in Spain, namely an initial period of aggradation with some trenching, followed by a later phase of dissection accompanied by localised incision and infill. This pattern of development he interpreted as reflecting changes in the net amount of sediment available, with changes in dominant depositional process from debris flow and sheet flood to channelled fluvial activity. Harvey argued that the morphological changes recorded on the fan surfaces reflected a progressive adjustment of slope values in response to process changes. This was evident on many of the fans where slope angles decrease from fan surface to terrace to channel. Hence, the modern channel gradient may be lower in the upper trenched reaches than it is on the fan slope downstream of the intersection point where the main channel is the same level as the fan surface (Bowman, 1978). It is evident from the above discussion that there is a lack of consensus about the causes of fan incision. If fan development in the Scottish Highlands has been essentially paraglacial or periglacial, then morphological responses, such as fan incision, may be expected in response to reduction in sediment supply during the Flandrian.

4.2.3 Alluvial fan sediments.

In reviewing the sedimentary facies associated with alluvial fans, Nilsen and Moore (1984 p 19) suggested that "streamflow deposits are generally more characteristic of distal fan facies and humid climate fans and debris flow deposits more characteristic of proximal fan facies and arid climate fans". Indeed, on composite features involving both fluvial and debris flow deposition there may be a spatial relationship between concentrations of debris flow deposits nearer the apex and fluvial deposits farther downstream, although the assertion that debris flow deposits are more common in arid environments seems more dubious (cf Ryder, 1971b; Roed and Wasylyk, 1973; Pierson, 1980; Wells and Harvey, 1987). Furthermore, Nilsen and Moore (1984 p 19) have also claimed that "debris flows and related deposits on alluvial fans are one of the most important features that permits alluvial fan deposits to be recognised in the ancient stratigraphic record", an observation that is clearly at odds with the interpretation of alluvial fans as fluvial landforms *sensu stricto*. In this review of alluvial fan sediments only fluvial deposits will be considered; the characteristics of debris flow deposits are described in section 4.3.3.

Deposition of sediment occurs on alluvial fans when discharge levels are no longer sufficient to transport fluvially-entrained debris. Loss in competence can occur with changes in the channel geometry when the main channel bifurcates or rapidly enlarges, or through discharge loss by infiltration into underlying permeable fan deposits and bedrock. Both mechanisms may operate on any one fan, although the permeability of the fan deposits may be controlled by antecedent conditions and the level of the water table. Several distinct down-fan sedimentary properties have been observed on alluvial fans in various environments. These include a general decrease in maximum clast size, an increase in sorting, and changes in clast shape (eg Bluck, 1964; Melton, 1965; Bull, 1968; Ryder, 1971b; McPherson and Hirst, 1972; Wells, 1977).

McPherson and Hirst (1972) undertook detailed analysis of the surface sedimentary characteristics of two alluvial fans in the Canadian Rockies. Their results showed a clear decrease in clast size (based on mean intermediate axis values) down-fan and a corresponding increase in sorting and rounding. Such patterns for these sediment properties were similar for both stream channel deposits and fan surface sediments, which in turn led McPherson and Hirst (1972) to suggest that channelised flow was the dominant depositional process operating on the fans. Desloges and Gardner (1981), however, observed a difference between the sediment character of active channels and that of fan surface deposits. Channel deposits showed good down-fan sorting, size reduction and rounding. In contrast, fan surface deposits were relatively poorly sorted with no clear size reduction down-fan and there were no systematic changes in clast roundness. Indeed, they noted that fan surface sediment sorting and size reduction were only evident if the relatively coarse debris of the apex and the relatively fine deposits of the toe area were compared. Desloges and Gardner (1981) interpreted these differences as being indicative of rapid fan aggradation during short lived floods and sheet flows, while the better distance-related sediment properties of the channel deposits reflected longer term reworking. Similar variations in downstream decrease in clast size have been observed on sandar (eg Ballantyne, 1978). It is possible that some Scottish alluvial fans originated as outwash fans when glacier ice supplied them with meltwater during the Loch Lomond Stadial (chapter 2). Moreover, it has been suggested that alluvial fans and sandar are essentially similar sedimentary environments (Boothroyd and Nummedal, 1978).

Ryder (1971b) observed that alluvial fan sediments in general are more angular than active channel facies. The subangular shape noted by Desloges and Gardner (1981) was interpreted as reflecting the relatively short travel distances over which clast shape had been modified. Indeed, fan size may be an important factor in determining the effectiveness of down-fan sedimentary patterns. Boothroyd and Nummedal (1978) have proposed a flexible sedimentological model for humid alluvial fan deposits. The model basically divides the typical fan or sandur proximal, medial and distal core facies, correspond to average (major axis) clast sizes greater than 100mm, between 100 and 2mm and sand-sized material respectively. Boothroyd and Nummedal observed that the rate of downstream change in clast size with distance was similar for all sites studied, which ranged in length from 2.4 km to 30.5 km. The model implies, therefore, that small fans may support only proximal facies, medium-sized fans proximal and medial facies and large fans all three core facies.

Waterlain sediments may show a variety of depositional characteristics, depending on whether they are laid down as sheets of sand and gravel, as individual bar units, as infillings of stream channels or in lobate forms called sieve deposits (Hooke, 1967; Bull, 1977). Sheets of sediment may be deposited by surges of sediment-laden water during flood conditions, giving well-stratified deposits, but bar sediments may give more lens-shaped beds, and stream infills are generally coarser, poorly-sorted and unstratified (Bull, 1977). Sedimentary beds may be of constant thickness in dip sections, but transverse sections may be more complex with both lensing and channel cut and fill sequences (Ryder, 1971b). On composite cones fluvial sediments may be distinguished from debris flow deposits by their better sorting, stratification and lack of matrix-supported clasts (eg Hooke, 1967; Wasson, 1977).

Individual sedimentary units have distinct characteristics. Sieve deposits, first reported by Hooke (1967) are probably the most controversial of the fan facies that have been described in the literature. Sieve deposition is thought to occur when the entire flow drains through the underlying deposits before reaching the fan toe. Hooke (1967) suggested that when this occurs a lobe of coarse debris is deposited that forms a "sieve" through which subsequent water may drain leaving finer debris and forming a flatter area behind the lobe front. Such deposits may exhibit weak stratification behind the coarse "sieve". The sedimentological characteristics of sieve deposits are similar to those of noncohesive gravity flows such as hyperconcentrated debris flows (eg Carling, 1986; Wells and Harvey, 1987), and as such may represent the product of a transitional process. Bull (1977, p235) claimed that repeated sieve deposition over the surface of an alluvial fan could give a distinctive hummocky surface, but the features shown in the photograph he used to illustrate this phenomenon very closely resemble the characteristics of debris flow deposition.

Other fluvial sedimentary units observed on alluvial fans include gravel spreads, bars and boulder berms. Gravel bars may be complex amalgamations of smaller depositional units, with coarser and generally more imbricate debris in the bar head area, and finer sediments in the tail (Bluck, 1982; Wells and Harvey, 1987). Boulder berms are massive accumulations of very coarse boulders and are thought to be deposited during extreme flood events (Costa, 1984).

In summarising a large number of studies on alluvial fan sedimentation it would appear that alluvial fans generally exhibit down-fan changes in clast size and sorting that vary in clarity depending upon depositional history (ie whether or not the deposit has been reworked) and fan size. Other complications to the general pattern of sedimentation may occur when the mode of fluvial deposition is mixed (eg sheet flood and channel deposits) or when other processes such as debris flow operate. Small-scale variations introduced by the deposition of features such as bars, may also mask overall down-fan trends.

4.3 DEBRIS CONES

4.3.1 Environmental controls of debris flow activity and debris cone development.

Debris flow processes have attracted considerable attention in the literature in recent years because in many mountain environments they pose a threat to human activity. There is, however, some dispute over what precisely constitutes a debris flow, a dispute exacerbated by inconsistent, and in some instances idiosyncratic, terminology. A broad definition of debris flow processes has been adopted here. This is based on that used by Costa (1984) and includes features previously referred to as mudflows, lahars, debris avalanches (eg Varnes, 1978) and till flows (eg Hartshorn, 1958), but does not include rock avalanches or sturzstroms (eg Hsu, 1975). There is evidence to suggest that "mud flows", such as those described by Hutchinson and Bhandari (1971), form a separate process type characterised by distinct velocity distributions through the moving mass, and that such flows may be periodically reactivated. This type of mud flow will not be considered further in this study. Debris flows have been described by Brunsden (1979, p 173) as "a transitional set of processes lying between streamflow or mass transport and the drier forms of mass movement". Thus the term "debris flow" may be used to describe part of a continuum of processes. The location of individual debris flow events along the continuum may be determined by the relative proportions of a poorly-sorted mix of granular solids, clay minerals, water and air (A.M. Johnson, 1984). Debris flow properties may vary considerably depending upon the source area environment. The various common characteristics of debris flows will be reviewed in relation to the environment of the Scottish Highlands, with particular emphasis on debris cone formation.

A distinction has been made in the literature between "valley confined" and "unconfined" or "hillslope" debris flows (Brunsden, 1979; Innes, 1982). However, the criteria for separating these two groups of debris flow are not well defined, and the two categories are not mutually exclusive. For example, Innes (1982) claimed that hillslope debris flows are "unconfined", but in fact many such flows emanate from shallow drift-cut gullies. Conversely, the tracks of debris flows that commence in gullies or valleys may travel considerable distances across an unconfined open fan or cone surface before they are deposited. The terms "unconfined debris flow" and "confined debris flow" have, therefore, only been employed in this review as and when specific reference has been made to them in the literature and not as an indication of mutually exclusive types of debris flow process. If any classification system is to be evolved to accommodate the range of debris flow characteristics it may be more meaningful to base it upon the sedimentological character and mass movement dynamics of flow, as advocated by Costa (1984), rather than on potentially ambiguous morphological criteria.

Debris cones typically consist of debris flow deposits that have accumulated along valley sides below drift- or rock-cut gullies or steep narrow tributary valleys. Little is known about the overall distribution or frequency of debris cones in the Scottish Highlands, due partly to a lack of research and partly as a result of failure to distinguish them from planimetrically-similar fluvially formed fans (Innes, 1982). It has been suggested that the distribution of "valley confined" debris flow deposits (including debris cones) is more limited than the distribution of hillslope debris flow deposits in the Scottish Highlands (Innes, 1982), but the validity of this suggestion is challenged in Chapter 6.

Debris cones generally develop as a result of deposition by episodic debris flows. These originate either as small landslides in the upper part of gullies, or from the mobilisation of sediment that has collected on gully floors (Statham, 1976a; Smith and Hart, 1982; A.M. Johnson, 1984). Conditions conducive to debris flow have been summarised by Innes (1983c) and include sufficient gradient, suitable regolith and high pore water pressures. Each of these preconditions for debris flows are examined in more detail below.

Minimum slope angles necessary for slope failure leading to debris flow have been reported to range from 15° to 30° (eg Williams and Guy, 1973; Owens, 1974; Brunsden, 1979; Ballantyne, 1981). Innes (1983c) has suggested that the majority of hillslope debris flows in the Scottish Highlands have their sources on slopes between 32° and 42°, with some on slopes as steep as 46°. It is questionable whether or not many slopes with gradients over 40° could retain sufficient sediment cover necessary for debris flow activity, however, especially in the Scottish Highlands where debris flow susceptible regolith has been described as predominantly sandy and non-cohesive (Innes, 1982), soil properties that would be potentially unstable on such steep gradients. Furthermore, many of the hillslope debris flows Innes (1982, 1983c) studied occur on relict talus, for example in the Lairig Ghru in the Central Cairngorms. In such cases it is probable that the angle of debris flow initiation has been determined by the angle of talus accumulation. For both these reasons it would be misleading to suggest that debris flow initiation in the Scottish Highlands requires a generally higher minimum slope angle than found elsewhere in the world. Indeed there is some evidence to suggest that debris flows starting in stream channels or in the base of gullies may be initiated at mean gradients as low as 15° (Innes, 1983c). Conversely, debris flow activity may be favoured in very steep gullies where large boulders provide temporary dams behind which sediment and water can build up (Takahashi, 1978).

Particle size analysis on debris flow susceptible regoliths in the Scottish Highlands indicated that clay contents were very low, accounting for only 0.01% to 3% of the samples by weight (Innes 1982). Innes also observed that regoliths susceptible to debris flow were significantly coarser and more poorly sorted than regoliths in otherwise similar locations where evidence of debris flow activity is absent.

High porewater pressure is probably the most crucial factor initiating debris flow events. Sources of excess moisture that have been reported as resulting in debris flow events include snowmelt (eg Sharp and Nobles, 1953; Owens, 1974; Theakstone, 1982); rapid snowmelt with heavy rain (eg Broscoe and Thompson, 1969; Rapp and Stromquist, 1976); intense rainfall (eg Jahn, 1976; Caine 1980) and "dam" bursts from either glacial lakes, volcanic crater lakes or small-scale ponding in gullies (Takahashi, 1981).

Where antecedent moisture conditions are high the following mechanisms have been used to explain the initiation of debris flows in a variety of different environments:

1. Undrained loading (Hutchinson and Bhandari, 1971; Ballantyne 1981).

2. Vibrations from thunderstorms (Winder 1965; Scott 1972) and also from other debris flows are known to initiate some flows (Okuda et al 1980).

In the Scottish Highlands the most common causes of debris flow activity are extreme rainstorm events, such as those described in chapter 3 (Common, 1954; Baird and Lewis, 1957). Caine (1980) compiled data on storm-related landslide and debris flow activity and found that there was a relationship between rainfall intensity and duration and slope failure that can be expressed in the form of a limiting curve:

$$I = 14.82\ D^{-0.39} \qquad (4.3.1)$$

where I is rainfall intensity (mm/hr) and D is duration of rainfall in hours. A similar limiting curve specifically for debris flow initiation, also based on data in the literature (Innes, 1983c) is expressed by

$$T = 4.9355\ D^{0.5041} \qquad (4.3.2)$$

where T is total rainfall (mm). Studies of the recurrence interval of debris flow events originating in channels and gullies, however, have shown that they are not entirely governed by the frequency of competent storm events, but may in fact reflect the time necessary for sufficient sediment accumulation in the source area (Broscoe and Thompson, 1968; Statham, 1976a). Also, the geomorphological effectiveness of intense storm events cannot be explained adequately by rainfall duration alone. Other factors that may enhance or temper storm impact include antecedent precipitation and soil moisture conditions, the extent and type of vegetation cover (eg Selby, 1976; Pierson, 1980; Larsson, 1982; Rapp, 1986), and in cold environments the presence of a permafrost table at shallow depth (Jahn, 1976; Larsson, 1982). For example, unusually wet conditions in Spitsbergen during August 1976 are thought to have enhanced the probability of slope failure and debris flow activity generated by an intense rainstorm (Larsson, 1982). Prior and Douglas (1971), however, noted that slope failure and consequent debris flow in Northern Ireland occurred during a rainstorm following relatively dry conditions. At these sites susceptibility to slope failure is thought to have been enhanced by the underlying slope configuration, which included a lithological discontinuity that gave rise to a temporary perched water table. High water table conditions caused by intense rainstorms and the presence of an impermeable layer beneath sediment infill have also been observed in gullies immediately prior to debris flow events (Okuda et al, 1980).

There are two ways in which debris flows may be mobilised, either as a result of landsliding or as a slurry of coarse and fine sediment that continues to entrain material until the concentration of granular solids approaches 80%to 90% by weight (A.M. Johnson, 1984). Two mechanisms have been proposed to explain the transition from a rigid sliding mass to a mobile viscous fluid. Liquifaction of a rigid slab of debris may occur when conditions of high porewater pressure and diminished shear strength cause soil particles to lose coherency, leading to the remoulding of debris (Costa, 1984). The second possible mechanism, dilatancy, involves an increase in the bulk volume of the moving mass by the incorporation of water (Costa, 1984). Johnson and Rahn (1970) proposed an idealised model where dilation is enhanced by progressive failure at the base of a moving landslide, which allows small blocks to rotate, incorporate more water and dilate until the remoulded sediment reaches the fluid transition.

4.3.2 Debris cone morphology.

Debris flow deposition has long been recognised as an important process operating on arid region alluvial fans (eg Beaty, 1963; Bluck, 1964; Hooke, 1967; Bull, 1977; Schumm, 1977), and has also been identified in debris cone aggradation in arctic, alpine and temperate areas (eg Statham, 1976a; Pierson, 1980; Rapp and Nyberg, 1981; Suwa and Okuda, 1983; Wells and Harvey, 1987). The morphological characteristics of debris flow erosion and deposition are here reviewed in relation to debris cone formation.

Reported debris cone mean gradients range from 12° to 35° (Campbell, 1974; Statham, 1976a; Pierson, 1980; Rapp and Nyberg, 1981). Variations in source area slope may partly explain this large range of debris cone gradients. For example, many steeper debris cones are developed at the foot of talus slopes (eg Statham, 1976a; Rapp and Nyberg, 1981) whereas less steep debris cones occur below tributary valleys (Campbell, 1974; Pierson, 1980). The morphological effect of fluvial reworking of debris cones may result in an overall lowering of gradient. Similarly, very fluid types of debris flow may themselves give rise to slope angles as low as 4° on the lowermost part of some cones (Pierson 1980).

Debris cones characteristically have a concave long profile as described, for example, by Statham (1976a). However, as individual debris flow lobes (see section 4.3.3 below) often thicken downslope, it is possible that locally more complex slope elements could be produced depending upon the dominant pattern and frequency of debris flow deposition on different parts of the debris cone. For example, a complex profile with a marked upper convexity could result from an increase in debris flows deposition near the apex at a rate exceeding that of sediment redistribution down-cone. Cross profiles of debris cones have been shown to be highly irregular with marked topographic changes occurring as a result of recent debris flow deposition (Suwa and Okuda, 1983).

Individual debris flows are known to pass through erosive, equilibrium and depositional phases (Campbell, 1975). It has been estimated that the shear stress exerted on a channel bed by the passage of debris flow may be as much as 6 times as great as that of water floods, and debris flows have been known to shear large quantities of bedrock during a single flow episode (Costa, 1984). Lateral and vertical erosion by the passage of debris flows on large-scale debris cones has been described by Pierson (1980) and observed during field experiments by Suwa and Okuda (1983). Fan head entrenchment of up to 10m occurred during short debris surges on cone gradients at or less than 10° on Mount Thomas, New Zealand (Pierson, 1980). However, Statham (1976a) noted that debris flow erosion was succeeded by deposition on small debris cones developed at the foot of talus on gradients as high as 16°. He speculated that on such slopes debris flows retained just sufficient pore-water pressure to maintain motion over turf without destroying it; episodic debris flow of this nature may lead to the successive burial of intact organic horizons (eg Rapp and Nyberg, 1981). Much higher gradients ranging from 24° to 28° have also been reported to mark the transition from erosion to deposition for a number of hillslope debris flows in North West Scotland (Ballantyne, 1981). By assuming that erosion was a product of undrained loading under the advancing debris flow, Ballantyne (1981) suggested that the variability in the gradient at which deposition replaces erosion reflects sediment supply and therefore the size (and weight) of the flow. In sum, reported gradients marking the transition from debris flow erosion to deposition range widely from as low as 10° to as high as 28°, and it is therefore uncertain whether or not a simple slope angle relationship can be used to predict this transitional phase of flow on debris cones, owing to the potential variability in the magnitude and nature of debris flows issuing from heterogenous catchments.

Studies of debris flow deposition on debris cones have revealed variations in the character and geomorphological significance of debris flow processes (Pierson, 1980; Suwa and Okuda, 1983; Wells and Harvey, 1987). Typically a single visco-plastic debris flow lobe comprises an arcuate and steep-fronted snout, behind which the flow surface is at a lower gradient and supports localised arcuate pressure ridges. The passage of a debris flow lobe is often marked by the deposition of two near parallel levees of sediment (Sharp, 1942). Debris flow deposition on cones has been described as digitate in planform, a pattern that results either from multiple surges during a single event (each surge reflecting release of sediment upslope) or multiple debris flow events (Suwa and Okuda, 1983). Debris flows may follow pre-existing drainage channels, but may be diverted by boulder dams or levees and may overtop the channel and consequently change direction.

Two principal types of debris flow were identified during research on the Kamikamihori fan in the Japanese Alps (Suwa and Okuda, 1984). In the area around the apex of the fan the debris flow snouts are typically swollen in form, with steep lobate fronts suggesting viscous flow. Farther down-fan debris flows become flatter and thinner, similar in form and sedimentology to alluvially-formed sieve deposits (cf Hooke, 1967). Suwa and Okuda (1984) suggested that these shallower debris flow deposits had resulted from the lateral (but not vertical) escape of water from the debris slurry causing the mass to stop. Similar deposits have been identified on the lower part of the Mount Thomas fan in New Zealand (Pierson, 1980), and have also been observed in the downstream dilution of lahar deposits (Harrison and Fritz, 1982; Pierson and Scott, 1985). Thus the morphology of individual debris flow deposits can vary considerably in response to the liquid state of the constituent mass during flow. At one end of the debris flow spectrum highly fluid hyperconcentrated debris flows are thought to mark the transition from cohesive debris flow to fluvial transport. Costa's (1984) classification of debris flow processes provided the first approximation for the identification of this important process threshold, which has subsequently been adopted in research by Carling (1986).

In sum, debris cone morphology may be locally highly irregular depending on the character of debris flow deposition. Overall, mean gradients are higher than those observed for alluvial fans and lower than mean gradients reported for talus cones (section 4.4.2).

4.3.3 Debris flow sediments.

The shear strength of debris flows is thought to be a function of the typically unsorted mixture of sediment including clays (providing cohesion) and larger clasts (determining the internal angle of friction) (Hampton, 1972; Rodine and Johnson, 1976; Pierson and Scott, 1985). Poor sorting allows relatively high sediment density, and the fact that clasts are typically matrix-supported implies the possibility of reduced effective normal stresses. This in turn implies reduction in the shear strength of the debris flow material, such that high density debris flows are capable of moving over relatively low-angled slopes (Rodine and Johnson, 1976). Reported clay contents are often low, usually less than 10% (Innes, 1983c; Costa, 1984), but Hampton (1975) has suggested that only very small quantities of clay are necessary to give some cohesive strength to otherwise silty and sandy matrix material.

Small changes in the water content of moving debris can dramatically alter the shear strength and nature of mass movement (Johnson, 1970). Several varieties of debris flow processes have been reported in the literature ranging from fluid hyperconcentrated flows to highly viscous debris flows (eg Pierson, 1980; Carling, 1986; Wells and Harvey, 1987). During a single event, viscous debris flow, hyperconcentrated flow and water flood can all occur in response to changes in the ratio of sediment to water input from the source area (eg Okuda et al, 1980; Pierson, 1980; Wells and Harvey, 1987). Viscous debris flow lobe snouts and levees are generally composed of the coarsest debris, with poorly-sorted clasts and a fine matrix forming the lobe deposits behind the snout; such deposits sometimes support very large boulders (eg Fisher, 1971; Wasson, 1978; A.M. Johnson, 1984; Wells and Harvey, 1987). Hyperconcentrated debris flow deposits are generally poorly-sorted but may show weak stratification when transitional to water flood deposits (Wells and Harvey, 1987).

The fabric of debris flow deposits may reflect the motion of flow and deposition. Clasts pushed aside by the passage of the debris flow show distinct preferred orientation (Innes, 1982). Pressure ridges consisting of concentric ridges of matrix-poor sediment containing characteristically sheared elongate clasts have been observed in viscous debris flow lobe deposits; fabric analyses of clasts in sections cut through these pressure ridges have shown a strong preferred orientation, with the principal axes dipping away from the lobe boundaries and into the deposit (Wells and Harvey, 1987). It is thought that pressure ridges in debris flows represent pulses of sediment released from the source area at intervals during a single debris flow event (Pierson, 1980; Wells and Harvey, 1987). According to Wells and Harvey (1987), such structures may however be absent or only weakly developed in the more fluid forms of debris flow.

The mechanisms responsible for the selective sorting and orientation of clasts in debris flows have received considerable interest. Bagnold (1954) demonstrated experimentally that in unconcentrated nonsorted granular mixtures shearing during flow would result in preferred movement of larger clasts upwards towards the surface. Bagnold described this process of dispersive stress as resulting from a "knock-on effect" of particles in collision during shearing. Because dispersive pressure is proportional to clast size, the largest clasts are preferentially moved the farthest from the base of the flow. Naylor (1980), however, disagreed with Bagnold's dispersive pressure model on the grounds that clast collisions are probably minimal when clasts are matrix-supported. He argued that shearing of densely-packed material requires dilation to allow grains to pass over one another, and suggested that this occurs most effectively in debris flows with a predominantly sandy matrix, such as those in Scotland (cf Innes 1983c).

Very large boulders are not thought to be carried in suspension during flow, but have been observed to roll and slide and intermittently bounce downstream (Lowe, 1982). It has been suggested by Hampton (1979) that the weight of a large clast can increase the pore water pressure in the underlying fine-grained matrix, from which water cannot rapidly dissipate. Thus the presence of large boulders on the surface of the moving mass may increase flow competence by reducing the shear strength of the debris. Costa (1984) identified five possible mechanisms for the freighting of large boulders, namely cohesion, buoyancy, dispersive pressure, turbulence and structural support. He suggested that the relative importance of each of these mechanisms would vary dependant upon the physical properties of the debris flow. However, only three of these mechanisms (cohesion, structural support and buoyancy) can operate immediately after immobilisation: the limitations of each will be considered in turn.

First, experimental observations have suggested that static clay-water slurries with densities of $1.17 g/cm^3$ can suspend medium-sized sand grains (Johnson, 1970; Hampton, 1975, 1979; Rodine and Johnson, 1976). However, the cohesive strength of the fluid phase is dependant on a clay content of at least 10% in order to support sand-sized grains, which implies that much higher clay concentrations than those reported in the literature would be necessary if cohesion alone is responsible for allowing boulders to remain on the surface of recently-immobilised debris flows.

Second, Pierson (1980) has suggested that under certain conditions grain-to-grain contact may be instrumental in supporting about one third of the weight of large boulders on new debris flow deposits. This implies that some other mechanism or mechanisms must assist in supporting the other two thirds of the weight of such boulders.

Third, the difference in density between large clasts and the debris flow deposits they displace may not be large (Johnson, 1970; Hampton, 1979). Buoyancy may, therefore, provide an adequate explanation for the rafting of large boulders by the mobile mass, and for continuing to support boulders on the surface of recently immobilised debris flows. Furthermore, as water escapes from immobilised debris flow deposits the compressive strength of the debris will increase, thus further enhancing the capability of the underlying sediment to support very large boulders.

In sum, debris flow deposits usually consist of varying proportions of poorly-sorted clasts within a matrix of sands, silts and clays, and large boulders may be supported on the surface of the deposit. The relative proportions of the constituent materials and the water:sediment ratio during deposition may give rise to distinct clast fabrics and pressure ridges on viscous debris flows, but such features may be absent from deposits laid down by more fluid hyperconcentrated debris flows. These characteristics suggest that surface deposits on debris cones may not show any discernable downslope sorting or fining patterns, and that locally sediment size and sorting may be extremely variable.

4.4 TALUS CONES.

4.4.1 The talus cone environment.

Talus cones are accumulations of rock rubble found below rock gullies, which localise material delivery (Church *et al*, 1979). Talus cones are found in a variety of different environments where the mechanical weathering of rock outcrops occurs, including hot arid regions (Albijar *et al*, 1979), temperate maritime areas such as Western Europe (eg Douglas, 1980), montane or alpine environments (eg Caine, 1969; Luckman, 1976; Gardner, 1983a, 1983b), subarctic areas (Thornes, 1971), and high arctic areas (eg Howarth and Bones, 1972). Various rates of rock wall retreat through rockfall have been identified in different climatic environments (Carson and Kirkby, 1972), long-term changes in rockfall rates may be associated with climatic change (Ballantyne and Kirkbride, 1987; chapter 2).

Rockfall may vary in frequency as well as magnitude. Luckman (1976) identified 2 main controls of rockfall activity, namely:

1. Climatic factors, which through their control of temperatures and the availability and phase of water, are primary controls of rockfall trigger mechanisms; and

2. Geologic factors, which via cliff form and character and availability of materials influence the type, distribution and intensity of rockfall activity.

Seasonal variations in observed rockfall activity have been identified by Douglas (1980) in County Antrim, Northern Ireland, where peak rockfall activity occurs in spring and autumn. Seasonal patterns are also evident in the Canadian Rockies (Luckman, 1976), and in the high arctic (Bones, 1973). Diurnal variations in rockfall frequency have also been reported. For example Gardner (1983a) found that the greatest frequency and probability of rockfalls in the Highway Pass area of the Canadian Rocky Mountains occurred in the mid-day hours on slopes of favourable aspect. At Mount Rae in the Canadian Rocky Mountains, annual rates of rockfall accretion on talus have been shown by Gardner (1983b) to be extremely variable, with maximum rates of 30-40 mm per year. Such high accretion rates on may, however, partly reflect extreme events such as debris flows and full depth snow avalanching, and not be explained solely by factors such as lithology and slope exposure. Talus cones resulting predominantly from rockfall share with rockfall talus sheets certain characteristics that distinguish them from related landforms such as avalanche talus or avalanche-modified talus. The principal morphological and sedimentological characteristics of rockfall and composite taluses will be discussed in the following two sections.

4.4.2 Talus cone form.

Rockfall talus sheets and cones have been described as typically possessing an upper rectilinear slope and a basal concavity (eg Thornes, 1971; Gardner, 1971; Howarth and Bones, 1972; Albijar et al, 1979; Church et al, 1979; White, 1981; Brunsden et al, 1984). Albijar et al (1979) suggested that convex segments are more commonly found on talus slopes in periglacial areas whereas talus slopes in semi-arid areas are usually concave. This suggestion, however, does not agree with substantial evidence in the literature for predominantly concave and concave-rectilinear talus profiles in periglacial areas. Basal erosion of talus by rivers, the sea or glacier ice may destroy basal concavity, and may lead to an overall slope steepening through dry avalanching(Thornes, 1971; Howarth and Bones, 1972).

Upper slope convexity has also been reported for some taluses (eg Thornes, 1971; Church et al 1979; Albijar et al, 1979; Akerman, 1984) and attributed to a lag in the redistribution of rockfall rubble above a shallow slip failure (Church et al 1979) or to accumulation of small clasts (Howarth and Bones, 1972). Basal convexity may also result from erosion at the foot of the talus (Howarth and Bones, 1972).

Mean gradients reported for rockfall talus cones lie between 25° and 35° (Church et al, 1979; Ballantyne, 1981), Unmodified rockfall talus slopes and cones have been widely reported as having an upper rectilinear slope with a gradient of 35° to 36°. This gradient was at one time interpreted as representing the "angle of repose" of constituent clasts (Andrews, 1961; Kotarba, 1976). The "angle of repose" (or, more correctly, the "angle of residual shear") has been described as the angle at which a sliding mass of non-cohesive granular debris will just come to rest after release from a low height of fall (Statham, 1976b). The validity of this concept as an explanation of talus slope form has, however, been questioned (Statham, 1975, 1976b, 1977; Carson, 1977). Three widely-reported characteristics of rockfall talus slopes are inconsistent with the requirements of the "angle of repose" model (Statham, 1976b). First, the model requires that the entire slope must be straight. Most rockfall talus slopes, however, comprise a basal concavity as well as an upper rectilinear slope, so that the talus debris cannot be at the "angle of repose" down the entire length of the slope. Second, engineering research into the strength of rockfill has suggested that the minimum angle of shearing resistance (approximately equal to the angle of residual shear) of talus material lies between 39° and 40° (Chandler, 1973), which is significantly steeper than the 35° to 36° typically reported for the upper rectilinear sections of the talus. Even the straight upper sections of talus slopes therefore lie below the true "angle of repose" of the constituent debris, although steeper talus gradients may occur as a result of basal erosion (Howarth and Bones, 1972). Third, the "angle of repose" concept implies that the talus debris must be close to failure with dry avalanching as the dominant process. Statham (1975, 1976b, 1977) has argued that both basal slope concavity and the downslope increase of sediment size characteristic of rockfall talus slopes (section 4.4.3) are inconsistent with the requirements of the "angle of repose" concept. Indeed, few slope facets were found that were close to failure even on active talus slopes in Baffin Island (Church et al, 1979).

An alternative model of talus slope development based on the input energy of falling clasts (rather than on the mechanical properties of the accumulated mass) has been proposed by Kirkby and Statham (1975) and tested by Statham (1976b). This model encompasses sequential development of talus profile form in response to decreasing rockfall height. According to this model, in the early stages of talus development a large range of clast travel distances occur because clasts fall from various heights on the cliff, and Statham (1976b) argued that this initial wide range of clast travel distances is responsible for producing an extensive basal concavity. As the headwall is progressively buried by the aggrading talus, however, the range of input velocities decreases and this, coupled with increasing talus length, ensures that clasts are more likely to be deposited higher upon the talus, thus reducing slope concavity at the expense of a growing upper rectilinear unit.

This model was tested in the field on Skye, where Statham (1976b) demonstrated that the proportion of the slope that was concave decreased, as predicted, with reduced cliff height. He also found that the angle of the upper straight segment is steeper than c 35° on talus slopes where the cliff has been buried by the talus (ie as clast input energy approaches zero). On such taluses the higher segment angle reflects accumulation of debris by processes other than rockfall. A number of authors have subsequently employed the implications of the rockfall talus model in interpreting the maturity of talus slopes. For example, Ballantyne and Eckford (1984) interpreted talus slopes on An Teallach in Wester Ross as probably more mature than those found on the Lomond Hills in Fife, partly on the basis of the relative proportion of upper rectilinear slope to the rest of the profile. Thus, the model appears to give a reasonable explanation of rockfall talus morphology and evolution that is applicable to the study of talus cones in Scotland. There are, however, certain limitations associated with the related fall-sorting mechanism which will be considered in the next section.

Sediment redistribution processes on talus include creep, dry avalanching, debris flows, and slush and snow avalanching. The capacity for these processes to modify talus morphology is dependant on the magnitude and frequency of such processes. Debris flow and slush and snow avalanching may lead to the modification of the upper rectilinear slope, and to the development of an overall slope concavity (eg Caine, 1969; Luckman, 1971, 1978a; Howarth and Bones, 1972; Brunsden et al, 1984).

Howarth and Bones (1972) described in detail the effects of "meltwater" on high arctic debris slopes. They defined "meltwater processes" as including erosion and redeposition of material by running water, and by meltwater-saturated debris or snow, giving debris flows and slush avalanches respectively. They suggested that the most effective erosion is likely to occur early in the short thaw season on sites where the permafrost table was at or near the surface of the debris slope. They described how slush avalanches give rise to distinct chutes, smooth surfaces and extensive boulder aprons, and reported that one slush avalanche had travelled nearly 100m over the ice pack at the base of a talus slope. Other researchers have described distinct stripes and lobate deposits resulting from snow and slush avalanche activity (eg White, 1981; Brunsden et al, 1984). It has also been observed that snow avalanching tends to reduce overall slope angles (eg Caine, 1969; Howarth and Bones, 1972; Luckman, 1978a). For example, Howarth and Bones (1972) reported gradients of 33.3° to 20.9° on talus slopes affected by "meltwater", and Caine (1969) gave a limiting slope angle of c 25° for effective redistribution of sediment by snow avalanching. Caine has also suggested that on some slopes snow or slush avalanching is the dominant deposition process, bringing rock debris down on to the slope from gullies and rock slopes. Luckman (1978a) described avalanche talus cones as distinct features from avalanche boulder tongues, the form of such features being dependent on the nature of the avalanche source area, whether constrained (such as by a gully), or from open slopes, slight hollows, or cornice locations. Avalanche boulder tongues generally have flatter cross profiles and a more lobate form than conical-shaped avalanche cones (Luckman, 1971). Avalanche cones have been called "debris cones" by Church et al (1979), but this latter term is used here to refer to features produced predominantly by debris flow.

In Spitsbergen, debris flow activity on talus has been related to aspect (Akerman, 1984) and extreme rainfall events, (Jahn, 1960, 1976; Rapp and Nyberg, 1981). Akerman discovered that the predominance of debris flow activity on Spitsbergen talus slopes is often restricted to the shaded sides of valleys, whilst the opposite slopes experienced low magnitude pebblefalls and rockfalls. Debris flows affecting talus slopes have been identified by their distinctive lobate form, and by tracks flanked by levees (eg Rapp 1960;

Whitehouse and McSaveney, 1983).

In sum, rockfall talus cone long profiles may vary from rectilinear to concave, with generally steeper mean gradients than those observed for debris cones. Talus modified by other processes however, may have lower gradients and possibly more irregular profiles.

4.4.3 Characteristics of talus sediments.

Talus deposits have been described as possessing an upper veneer of clasts with open-work packing, underlain by a poorly-sorted mixture of coarse material within a matrix of fines that have been derived from comminution of clasts during deposition (Church *et al*, 1979). Observations of surface sediment sorting suggest that rockfall talus slopes are characterised by distinct downslope increases in clast size, a feature commonly called "fall sorting" (eg. Tinkler, 1966; Gardner, 1971; Bones, 1973; Statham, 1973, 1975; Church *et al*, 1979). Constraints on the development of fall-sorting patterns on rockfall taluses include the lithology of the source area dictating the range in potential clast size, and talus size (Church *et al*, 1979). Comparison of the degree of fall sorting on talus slopes reported in the literature is hampered by differences in sampling procedure. Moreover, the number of sampling sites per downslope transect has often been insufficient to allow evaluation of the strength of the sorting-distance relationship (chapter 5, below). For several talus slopes in the Canadian Rockies, Gardner (1971) found that there was an inverse nonlinear relationship between mean particle size and distance from the talus crest. Church et al (1979) found four general patterns of clast-size variation, with type 1 showing good fall sorting with distance on small taluses, whilst type 2 demonstrated that large taluses may have less clear fall-sorting patterns. They also noted that three types of local sediment distribution occurred down a typical rockfall talus: material on upper slopes accords with Rosin's Law for crushed debris (ie skewed toward coarse material); intermediate slope material tends towards log-normal distributions resulting from rockfall and redistribution processes; and lower slopes tend to support bimodal size distributions that may result from a mix of past and more recent deposition.

Statham (1976b) argued that fall sorting of sediment was a product of both surface friction and the sieve-like action of clasts already on the surface at any point on the talus. Once initiated, fall sorting becomes a self-perpetuating mechanism on rockfall-dominated slopes as clasts tend to come to rest amongst material of similar size. Statham rejected the hypothesis that particle mass and hence kinetic energy was the fundamental cause of observed fall sorting as suggested by other authors (eg Rapp, 1960; Bones, 1973). However, one of the weaknesses of the rockfall talus model (Kirkby and Statham, 1975) is that it assumes that particle motion over the talus is essentially one of sliding, but particles travelling down talus slopes tend to do so by bouncing and rolling rather than sliding (eg White, 1981). Thus the "fall sorting" of particles down a talus slope may also be influenced by factors such as the direction they take when bouncing off other clasts on the talus surface.

Other processes operating on talus slopes tend to obscure, and in some cases reverse, the fall sorting pattern. Snow and slush avalanche deposits are typically both poorly sorted and unstable, and may be identified by very angular shattered rock fragments perched on boulders (Rapp, 1960; Luckman, 1971; Church et al, 1979; White, 1981). Debris flow modification of talus sediments is generally more localised than snow avalanching, and the deposits may have more fines either infilling the interstices or supporting the clasts (Church et al, 1979; White, 1981; Brunsden et al, 1984).

In summary, rockfall-dominated talus cones tend to exhibit some degree of fall-sorting, but this pattern may be weak on large cones and poor to non-existent where other processes operate.

4.5 CONCLUSION

Two aims were identified at the start of this chapter. The first was to summarise and discuss the main themes in the literature on alluvial fans, debris cones and talus cones, thus providing an appropriate background for the study of such features in the Scottish Highlands. The second aim was to establish an _a priori_ classification for the field identification of fan and cone landforms.

The environmental setting and morphological and sedimentological characteristics of fans and cones arising from the dominance of a single process (either fluvial, debris flow or rockfall) have been described in some detail in the preceding sections, and it would appear that in general these landforms may be distinguished from one another on the basis of their morphology and surface sedimentary characteristics.

4.5.1 The fan and cone environment.

Alluvial fans, debris cones and talus cones are found throughout the world in contrasting mountain environments. No distinction, therefore, can realistically be made between genetic type and, for example, regional climate. Indeed, alluvial fans, debris cones and talus cones may be found within the same valley. What factors, then, determine the nature of dominant process at individual sites? The limited research that has been carried out into this question suggests that a combination of factors within a contributing catchment leads to the development of a specific type of fan or cone. These factors may include lithology, glacial history, aspect, altitude, precipitation, vegetation cover, relief and gully or valley configuration. Further examination of the influence of these possible controls will be made in chapter 6.

However, the influences of such environmental controls may not be constant over time, and any changes within the contributing area character (eg depletion of sediment supply, climatic change or vegetation change) may lead to radical and possibly irreversible changes in the nature, magnitude and frequency of fan- or cone-forming processes. Natural adjustments during the course of landform development may also affect the nature of fan or cone development. In relation to this problem, several scenarios of fan and cone evolution have been discussed in chapters 2 and 3 and in the present chapter with the introduction of the periglacial and paraglacial hypotheses. The chronology and evolution of alluvial fans and debris cones in the Scottish Highlands will be considered in greater detail in chapter 7.

4.5.2 Fan and cone morphology

Evidence in the literature suggests that alluvial fans, debris cones and rockfall talus cones may be planemetrically similar, but have distinct slope gradients and form characteristics reflecting dominant process. Mean medial gradients range from 1° to 10° for alluvial fans, 12° to 35° for debris cones, and from 25° to 35° for talus cones. Medial profiles of undissected alluvial fans are generally smooth and concave, debris cones are normally concave but irregular, and talus cones are smooth and concave-rectilinear.

4.5.3 Fan and cone surface sedimentary properties.

In general the down-fan surface sedimentary characteristics of each of the three dominant process groups show considerable differences. Alluvial fans usually display some degree of down-fan fining and increased sorting and rounding, but debris cones often display very poor down-fan reduction in sediment size and very variable patterns of sorting, whilst rockfall talus cones exhibit some degree of fall sorting (downslope coarsening) of very angular sediment. The clarity of these down-fan or down-cone relationships, may, however, be masked by localised deposition associated with individual bars or debris flow lobes or in the case of talus cones by various modifying processes.

4.5.4 An 'a priori' classification of fan and cone landforms.

The morphological and sedimentological characteristics of alluvial fans, debris cones and rockfall talus cones therefore distinguish each type of fan and cone landform as do the diagnostic structures that independently indicate the dominant type of process (table 4.1). These characteristics, however, may not always be clearly defined especially on fans or cones where more than one process operates. Such landforms are composite features, and these may share some, but not all, of the characteristics of single process dominated fans or cones. For example, the

TALUS CONE	Debris flow modified talus cone	DEBRIS CONE	Fluvially-modified debris cone	ALLUVIAL FAN	
ROCKFALL		**DEBRIS FLOW**		**FLUVIAL**	Dominant process
Steep gradient 25°- 35°.		Moderate gradient 12°- 35°.		Low gradient 1°- 10°	Mean gradient
Rectilinear to concave long profile.		Concave and generally irregular long profile		Generally smooth and concave long profile.	Slope form
Angular clasts				Sub angular to sub rounded clasts	Average clast shape
Clear downslope increase in clast size		Poor and possibly irregular downslope decrease in clast size.		Generally good down-fan fining and increase in sorting and rounding of clasts.	Clast size and distance downslope

Table 4.1 An *a priori* model of fan and cone landforms.

gradient of a composite fluvially-modified debris cone may be slightly lower than that of an unmodified debris cone, but significantly steeper than that of an alluvial fan. Moreover, individual processes, such as debris flows, may show considerable variety, and this too may influence the general characteristics of the landform development. It is therefore proposed in this dissertation that a process continuum best describes the relationship between alluvial fans, debris cones and rockfall talus cones and their composite forms. The theory of a continuum of debris slope landforms is not new (Rapp, 1960; Rapp and Fairbridge, 1968; Bull, 1968, 1977; Church et al, 1979; Selby, 1982), but the the full range of features from rockfall talus cones to alluvial fans (and even sandar and deltas) has received little examination. This thesis will, therefore, focus attention on the development of planimetrically similar "fan"-shaped features as a subset of a much wider-ranging process continuum. The generality of the characteristics of the a priori classification presented here (table 4.1) will be examined in detail in the next chapter.

CHAPTER 5

CLASSIFICATION

5.1 INTRODUCTION

The previous chapter considered the sedimentary and morphological properties of fans and cones that have been reported in the literature. From this information an *a priori* model of fans and cones was developed. The aim of this chapter is to establish the applicability of this model for fan and cone development in the Scottish Highlands, and to compare the results from sites in Scotland with a small number of sites in arctic Norway.

The chapter is subdivided into three main parts. Section 5.2 considers methods of data collection, section 5.3 deals with analysis and discussion of results, and section 5.4 considers the implications of the research in both Scotland and Norway for the development of a system for classifying fan and cone landforms in deglaciated mountain environments.

5.2 DATA COLLECTION

Sites included in the Scottish study were selected from four of the glens described in chapter 3, namely Glencoe, Glen Etive, Glen Feshie and Strathdearn (figure 5.1). The general requirements governing site choice were that there should be surface sediment visible down the length of the feature, and that the course of the medial long profile

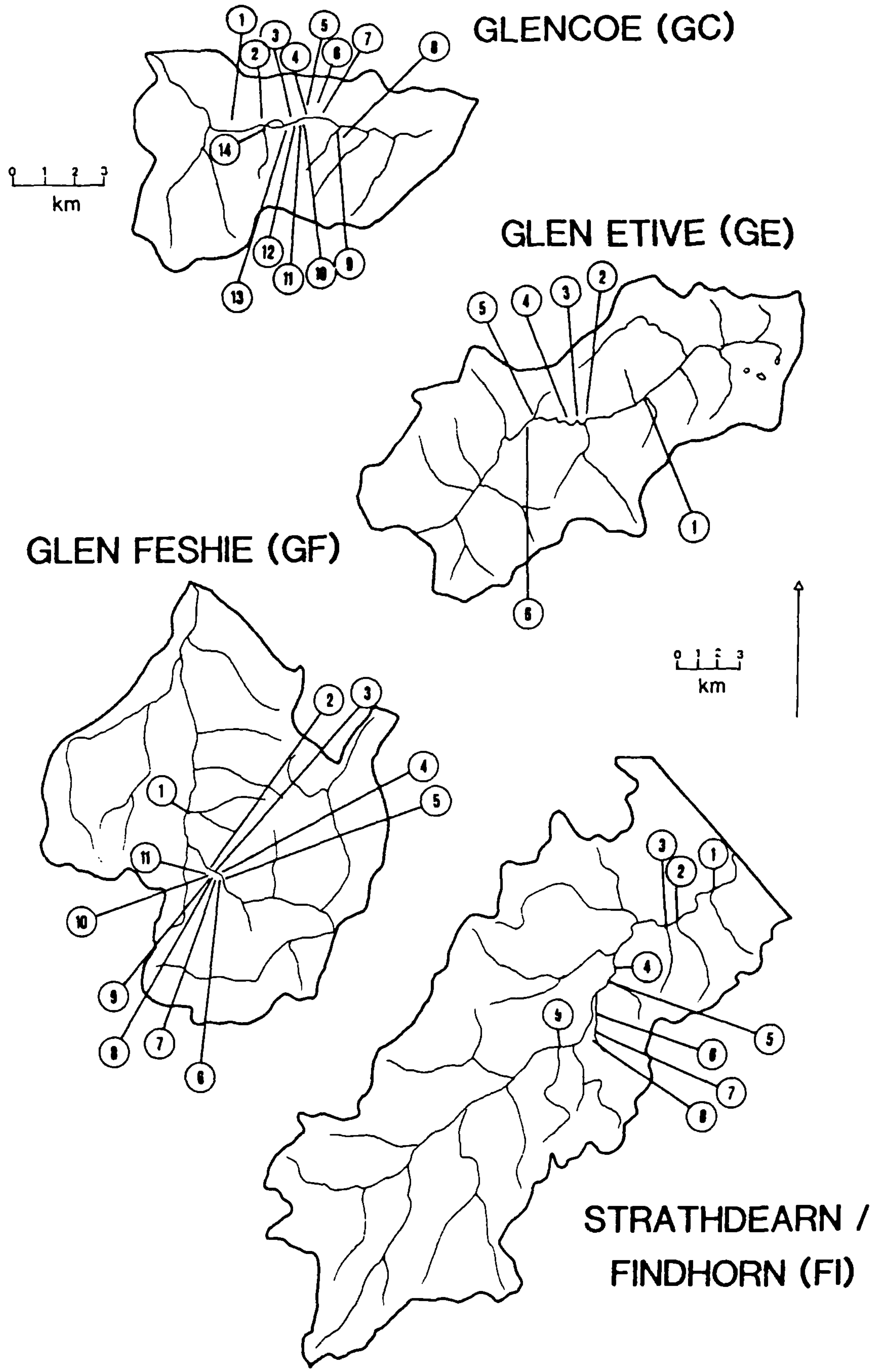


Figure 5.1a Location of the study sites discussed in chapter 5.

SITE	A	B	C	D	E	F	DOMINANT PROCESS rf	df	wf	Group
GC10	X						X			ROCKFALL TALUS CONES
GC12	X						X			
GC13	X						X			
GF07	X						X			
GF09	X						X			
GF10	X						X			
GF11	X			X			X			
GC11	X	X					X	X		DEBRIS CONES
GC07		X			X			X		
GC05		X			X			X		
GC06		X			X			X		
GF04		X						X		
GF06		X						X		
FI06		X						X		
GC04		X	X		X	X		X	X	FLUVIALLY-MODIFIED D. C.
GC08		X	X					X	X	
GC02		X	X					X	X	
GC03		X	X		X	X		X	X	
GC01		X	X		X	X		X	X	
GE04		X	X					X	X	
GE03		X	X		X	X		X	X	
GE02		X	X					X	X	
GF05		X	X					X	X	
GF02		X	X					X	X	
GF03		X	X					X	X	
FI04		X	X					X	X	
GC14			X			X			X	ALLUVIAL FANS
GC09			X						X	
GE01			X						X	
GE06			X						X	
GE05			X			X			X	
FI05			X			X			X	
FI07			X			X			X	
FI09			X						X	
FI08			X			X			X	
FI02			X			X			X	
FI03			X			X			X	

Figure 5.1b The allocation of individual sites to different catergories of fan or cone, using diagnos tic features and subsurface sedimentary characteristics described in table 5.1, page 145.

Dominant process: rf ROCKFALL
df DEBRIS FLOW
wf FLUVIAL

should not be severely disrupted by dissection. A number of representative fans and cones were selected from each of the glens, giving an overall total of 38 sites where both morphological and surface sedimentary data were collected, and 2 additional sites where it proved possible to carry out only a morphological survey. The criteria used to identify the dominant depositional processes at each site were based on the identification of diagnostic structures indicative of certain processes that have been well established in the literature (chapter 4, section 4.5, table 5.1).

At most sites a tacheometric survey was undertaken along the medial long profile of the fan or cone. A Sokkisha TM6 theodolite was used, with readings correct to the nearest 6 seconds of a degree. A small number of sites were surveyed using an Abney level, tape and ranging rods. The level of precision of the abney survey was checked at each siting by taking two or more readings; measurement was made to 0.5 of a degree. Siting was carried out at regular intervals along the profile, but extra positions were also used to mark breaks of slope such as terraces, lobe snouts or minor slope failures.

The two morphological variables derived from these survey data were FGRAD and FORM. FGRAD is the mean medial gradient (in degrees) between the apex and toe of the landform. Slope form may be assessed by comparison of the profile with an idealised curve, or by the calculation of appropriate indices. The former method was considered too

Table 5.1

Diagnostic features used to identify different processes in the field.

	PROCESS		
	ROCKFALL	DEBRIS FLOW	FLUVIAL
DIAGNOSTIC FEATURES	A Apron of coarse debris at the foot of the slope.	B Arcuate, and often steep lobe snouts. Pressure ridges may be visible on the lobe tread, characterised by the vertical orientation of elongate clasts, that also occur at the lobe snout. Levees may mark the passage of debris flows. Some of these parallel ridges may only survive as fragments, when they have been breached by later debris flows.	C One or more active stream channels. Channel pattern may be braided or sinuous. Depositional features range from individual linear bars to gravel sheets and boulder berms.
SUB SURFACE SEDIMENTARY CHARACTER	D Coarse openwork debris, with some finer infill.	E Clasts may be matrix supported, or show evidence of collapse where fines have been washed out. Deposits are characteristically poorly sorted, and are generally not stratified. However, weak stratification may be present in transitional types of debris flow deposit. Individual debris flow units may be visible.	F Clast supported sediment with some fine infill. Deposits may be stratified, and well sorted.

time-consuming and probably unrealistic, so a slope form index was used. Two such indices have been devised by Church _et al_ (1979) for the analysis of debris slope profiles, but these could not be employed because many fans and cones have complex small scale topographic irregularities that would make their calculation difficult. In this study, therefore, a somewhat cruder method of measuring form was adopted with the aim of assessing overall fan or cone long profile concavity, convexity or linearity. The index FORM was derived by dividing the gradient* of the uppermost third of the long profile by the gradient of the lowermost third. Thus, rectilinear slopes will have values at or near to 1.0, predominantly concave slopes values above 1.0, and predominantly convex slopes values below 1.0.

In the previous chapter, several contrasting patterns of sedimentation were described; these included down-fan fining on alluvial fans and down-cone coarsening (or fall sorting) on rockfall talus cones. One of the aims, therefore, in developing a classification of different types of fans and cones is to describe accurately the relationships between sediment size and distance downslope. Sample design therefore required that both sufficient and representative samples of surface sediments were measured on the fan or cone to allow identification and testing of such relationships. The sampling strategy employed in a number of previous studies has been extremely varied, a factor that has unfortunately limited the findings of such research.

*NB All gradients are measured in degrees.

For example, the number of sampling sites per downslope transect that have been used to determine the surface sedimentary characteristics of talus slopes are as follows: Akerman (1984) 3; Caine (1969) and Brunsden et al (1984) 5 or less; and Bones (1973) 6. Gardner (1971) reported only that 117 sampling sites were established on 20 debris slopes (ie an average of 5 or 6 samples per site). Related to this problem is the choice of sample size, which must be sufficient to reflect the sediment character at each sampling point. Small samples enable rapid assessment of average clast size at a large number of points on many fans or cones, but such sampling strategies may be at the expense of accuracy and objectivity. Alternatively, very large sample sizes may be unnecessarily time-consuming for relatively little gain in accuracy and detail. Previous research on talus cones has involved a range of sample sizes: Brunsden et al (1984) 20; Gardner (1971) 25 at a sampling site plus 12 clasts from around the site; Church et al (1979) 48; Bones (1973) 50; and Caine (1969) 100.

In this study samples of the surface sediment were measured along the medial long profile at 10 or more regularly-spaced intervals, though in a few cases, when the feature was small (<20m in length), less than 10 samples were measured. At each sampling point 50 clasts were sampled from the surface, which was defined as the depth not exceeded by the size of the largest clast. A larger sample size of 100 was used for the detailed case studies described later in the chapter. The extent of the sampling area at a point could not be realistically defined by the use of a quadrat because at some sites very large clast sizes would require extensive quadrats to allow the sampling of 50 of the surface clasts. Sampling area was therefore roughly defined by sediment that was "within reach" of the sampling point marker, at distances not usually exceeding two metres. At points where large boulders were very frequent the sampling area was extended laterally in order to preserve any clast size-distance relationship.

Several measurements were made on each clast. The A axis was measured as the length of the major axis in the maximum projection plane, the B axis was measured as the minor axis orthogonal to the A axis, and the C axis was measured as the shortest axis, perpendicular to the B axis. These three measurements were averaged ((A+B+C)/3) to give a measure of mean clast diameter. The median and not the mean value of clast size was used as the measure of central tendency at each sampling point because the frequency distributions were generally skew, reflecting the well known property that sediment sizes are often logarithmically distributed (cf Church et al, 1985). A minimum size of 35mm for the B axis was adopted so that only clast-sized sediment was measured. As a result of this limit, some small rod-shaped stones were unfortunately excluded from the survey, particularly on a few of the sites in upper Glen Feshie.

The *a priori* model of fans and cones suggests that there are distinct downslope sediment sorting patterns associated with the three single dominant process types (alluvial fans, debris cones and rockfall talus cones). However, the degree of down-fan changes in clast size may also be influenced by fan or cone size. Two variables, FINING and SCALE, were employed to assess such patterns. FINING is a crude estimate of gross down-fan changes in sediment size and is calculated by dividing the median clast size of the apex sampling point by the median clast size of the toe sampling point. Downslope increases in median clast size are recorded by values smaller than 1.0, and downslope fining by values greater than 1.0. SCALE provides a measure of the maximum change in clast size that can be achieved over the total length of the profile, and is calculated by dividing the maximum mean clast size (ie maximum (A+B+C)/3 value) measured on a fan or cone by the total distance downslope from apex to toe. If the *a priori* model is appropriate then, for example, values for FINING on larger alluvial fans will be lower than those on smaller alluvial fans.

The properties of both clast form and roundness have been used in analysing sediments that have been transported by fluvial, glacial, and periglacial processes (eg Briggs, 1977; Shakesby, 1980; Ballantyne, 1982; Matthews and Petch, 1982). Studies of clast form and roundness suggest that it is possible to use these properties to distinguish clasts that have been subject to different geomorphological processes. In this project, two variables describing the shape of clasts were used, the variable C/A (Ballantyne, 1982), and Matthews and Petch's (1982) angularity index (MP-ANG).

The variable C/A was calculated by dividing the shortest axis (C) by the longest axis (A) of each clast. The resultant values range from 1.0 for a perfectly equi-dimensional clast to values approaching 0.0 for very thin, long slab-shaped clasts. The percentage of clasts with C/A values less than or equal to 0.4 was then summed for each sampling point as an indication of aggregate clast form.

Clast roundness was assessed visually in the field by reference to a standard chart and each clast was assigned to one of six categories ranging from very angular to well rounded (figure 5.2). This method has been criticised as being subjective, but the advantages of rapid measurement are thought to outweigh this disadvantage especially as the data are used for comparison of "relative roundness" amongst a large number of samples or sites (Shakesby, 1980). In this project the six roundness classes were identified by the degree of sharpness of the facet edge and flatness of the facet face as illustrated in figure 5.2. Only one operator was used throughout the data collection to minimise operator variance. The data are considered to reflect accurately the relative differences in clast roundness

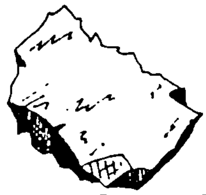
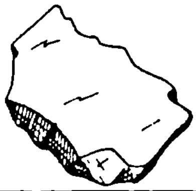
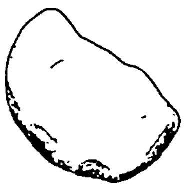
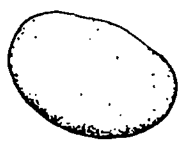
CLASS	CRITERIA	ILLUSTRATION
Very Angular 1	Flat facets, 'razor'-sharp facet edges	
Angular 2	Flat facets, well-defined facet edges	
Sub Angular 3	Flat facets, blunt edges	
Sub Rounded 4	Blunt and rounded edges to facets	
Rounded 5	Roughly-rounded clast, no distinct edges but facets still visible	
Well Rounded 6	Rounded, smooth surface, no facets or edges	

Figure 5.2 Clast roundness comparison chart, based on similar methods to those described by Briggs, 1977; Shakesby, 1980; Matthews and Petch, 1982: and advice from C.K. Ballantyne.

between individual sampling points on both fans and cones. Each roundness category was given a value, ranging from 1 for very angular to 6 for well rounded. These values were then summed and averaged for each sampling site, giving the variable MP-ANG.

5.3 DATA ANALYSIS AND DISCUSSION

5.3.1 An examination of the "a priori" model using Ward's method of cluster analysis.

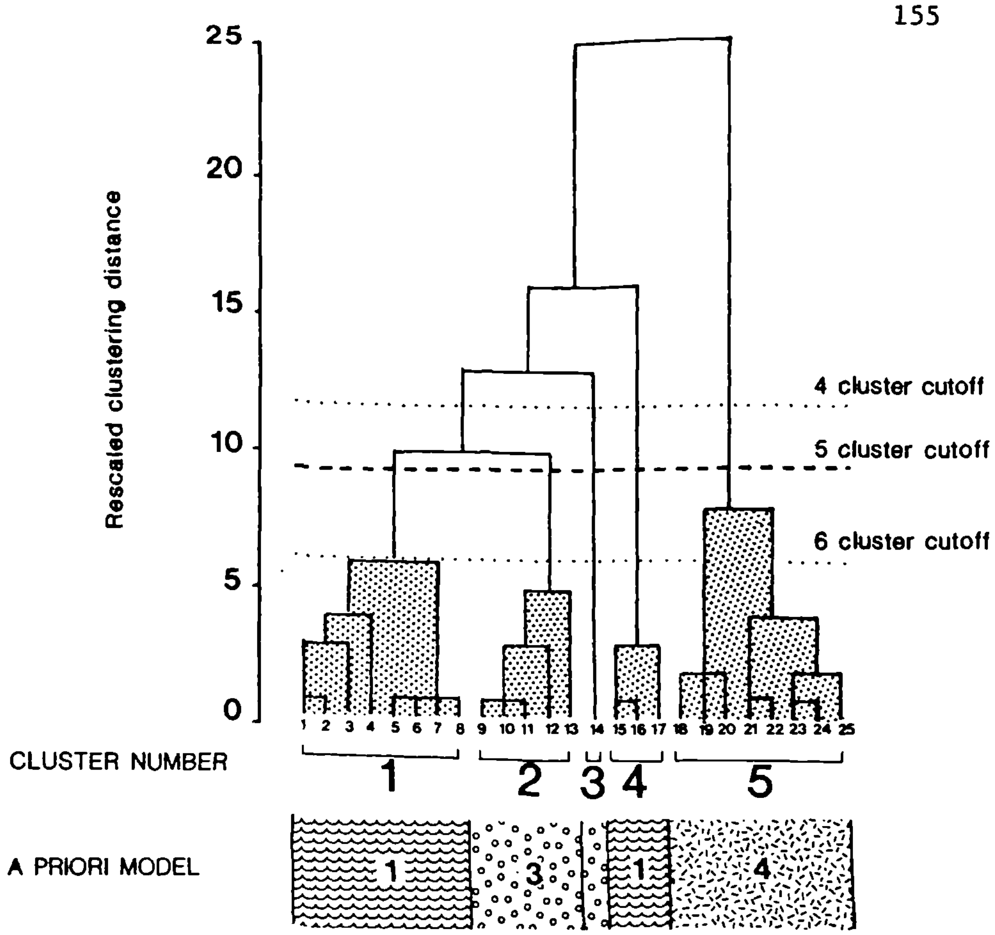
The main aim of this chapter is to test the representativeness and generality of the *a priori* model. The effectiveness of the combined variables FGRAD, FORM, SCALE, FINING, MP-ANG and C/A in differentiating alluvial fans, debris cones and talus cones will be discussed prior to more detailed comparison of the model with the morphological and surface sedimentary characteristics of the field sites (section 5.3.2).

Cluster analysis was used to evaluate how well the six different fan and cone properties combine to define alluvial fans, debris cones and talus cones. This analysis provides a preliminary test of the *a priori* model, and one that is independent of the field classification of sites.

Cluster analysis is a general term used to describe a variety of different statistical methods that seek to group similar individuals according to specified objective criteria. In this study, Ward's method of clustering cases was used in the SPSS-X2 procedure CLUSTER. Ward's method is an agglomerative algorithm that groups individuals one at a time in a hierarchical fashion. Initially all cases are regarded as separate. At the second stage the two closest samples are grouped together and are henceforth regarded as an individual, which in turn may be grouped with another similar individual at the next stage until ultimately all cases or groups become members of the same great cluster. At each stage in the analysis all variables are considered, unlike divisive methods which use only one criterion at a time. In Ward's clustering algorithm the only similarity measure used is Squared Euclidean Distance, which represents the shortest distance in multi-dimensional space between two samples, Squared Euclidean Distance being suitable for use with both interval-scale and ratio-scale data (Mather, 1976). This method seeks to minimize within-group variance of the distances between individuals and their group centroid, and also maximizes between-group variance, thus producing tight clusters (Johnston, 1976). However, the raw data are not suitable for the calculation of within and between-group variances because the variables are measured on different scales. It was therefore necessary to transform all values to z-scores giving each variable a mean of zero and a unit variance (Mather, 1976).

There are several characteristics of this method that make it preferable to the others. For example, Ward's clustering strategy does not lead to either chained or backward linkages between individuals or groups, which can make interpretation of cluster analysis difficult (Lance and Williams, 1967; Mather, 1976; Johnston, 1976; Young, 1986).

Fluvially-modified debris cones (composite cones) were omitted from the analysis because they form an intermediate group and their inclusion could make interpretation difficult, particularly in the absence of data for a similar intermediate group between debris cones and talus cones. The results of Ward's method of cluster analysis as employed for fans and cones where a single process is dominant are illustrated by the dendrogram in figure 5.3. The field classification of the sites into alluvial fans (1), debris cones (3) or talus cones (4) is indicated by the shaded column below the dendrogram, with fluvially-modified debris cones (group 2) having been omitted. The results of the cluster analysis illustrated in the dendrogram show that there is a major division separating alluvial fans and debris cones from talus cones. With decreasing distance more subdivisions are apparent within the alluvial fan and debris cone section of the dendrogram, but the talus cones remain fairly homogenous. Between four and six major groupings were obtained by the cluster analysis (figure 5.4). The middle cut-off described by this range will be described below by discussing each of the five clusters in turn.



number	site code	number	site code	number	site code
1	GE 1	8	FI 5	15	FI 7
2	GE 6	9	GC 5	16	FI 9
3	GE 5	10	GF 6	17	GC 14
4	GC 9	11	GC 6	18	GF 7
5	FI 8	12	GF 4	19	GF 10
6	FI 2'	13	GC 11	20	GF 8
7	FI 3	14	GC 7	21	GC 12
				22	GC 13
				23	GF 9
				24	GF 11
				25	GC 10

GE: Glen Etive GF: Glen Feshie

GC: Glencoe FI: Strathdearn / Findhorn

NB Fluvially-modified debris cones have been omitted.

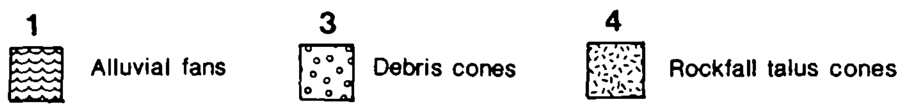


Figure 5.3 Dendrogram showing relationships between individual alluvial fans, debris cones and talus cones, revealed in cluster analysis (using Ward's method) of six morphological and surface sedimentary properties of fans and cones.

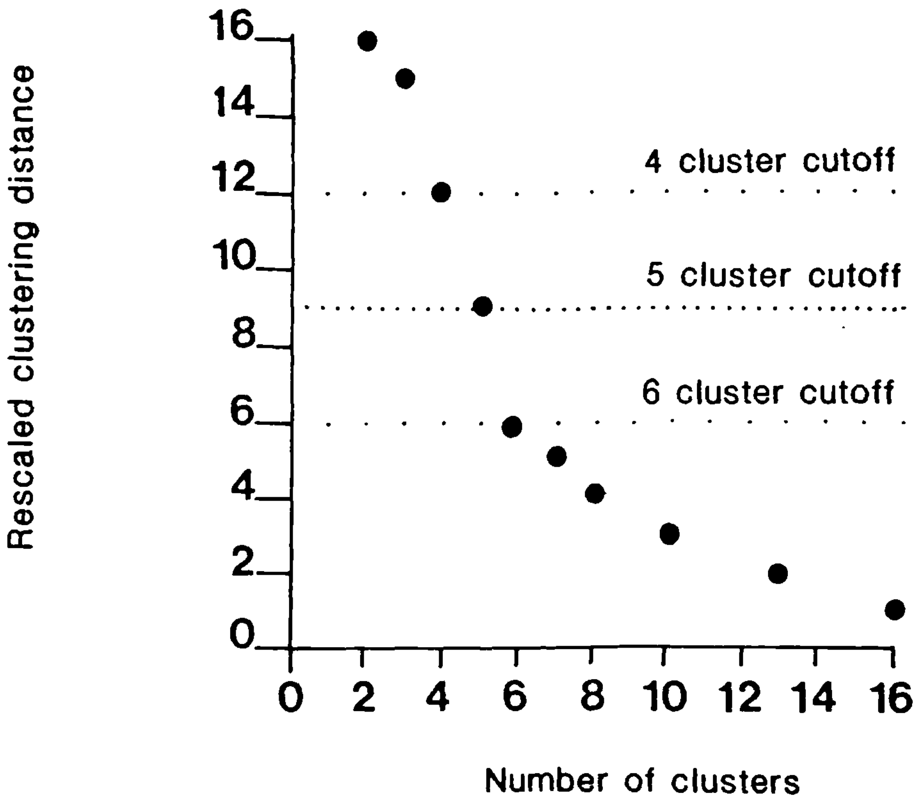


Figure 5.4 Choice of cluster cut off levels, determined by the relationship between increasing numbers of clusters and associated loss of between and within-group variance.

On the far left of the dendrogram the first cluster comprises 8 sites that were classified in the field as alluvial fans. Within this cluster two "sub-groups" occur. The first sub-group (working from left to right in figure 5.3) consists of fans from Glen Etive and Glencoe, and of these GE 1 and GE 6 show the greatest similarity (ie they link early in the dendrogram to form a new individual when the rescaled clustering distance is low) compared to GE 5 and GC 9, which display greater individuality (represented by a single line from rescaled distance from 0 to 3 or 4). The second sub-group contains 4 very similar sites (FI 8, FI 2, FI 3, FI 5) all from Strathdearn / Findhorn. The results from these two sub-groups suggest that regional variability may influence the degree of within-cluster homogeneity. Three other sites classified in the field as alluvial fans form cluster 4 farther over to the right of the dendrogram. These sites are FI 7, FI 9 and GC 14, and collectively they stand alone until high up in the linkage tree, implying that they are not closely related to either cluster 1 which contains the other alluvial fans or any of the other clusters (see section 5.3.2.3).

Cluster 2 comprises all the debris cones except GC 7 which alone forms the third cluster. The latter is the very large Chancellor debris cone which, for various reasons explained below, is a rather unusual feature. The other debris cones in cluster 2 comprise GC 5, GF 6, GC 6, GF 4 and GC 11, the latter two sites being less similar than the others. It is notable that GC 11 has an input of rockfall debris at the apex that may account for the slight difference in character.

The fifth cluster encompasses all the sites defined as rockfall talus cones. As with the first cluster of alluvial fans, cluster 5 may be considered to fall into two parts. The first "sub-group" consists of three very similar sites, namely GF 7, GF 10 and GF 8.

The results of the cluster analysis of sites where a single dominant process operates as described above suggest a number of points about the field classification and the generality of the *a priori* model. First, the combined variables FGRAD, FORM, SCALE, FINING, MP-ANG and C/A independently define 5 broad clusters that correspond reasonably well with the field classification. Other clustering algorithms (MEDIAN, CENTROID, BAVERAGE) in the SPSS-X2 package CLUSTER gave groupings similar to those reported above. Indeed when the fluvially-modified debris cones (composite cones) were included in the analysis a similar pattern of grouping emerged, but the similarities between some composite cones and either an alluvial fan or a debris cone made it more difficult to interpret grouping patterns in the sub-clusters. It should be noted, however, that the *a priori* classification is based on cut-off points for various properties, whereas cluster analysis uses continuously-scaled data.

Second, the pattern of clustering suggests that within a process group there may be strong similarities between sites from the same study area (particularly the alluvial fans in Strathdearn / Findhorn and talus cones in Glen Feshie). In extreme cases either small groups or individual sites form distinct clusters because the strength of regional influences, such as lithology or relief (see section 5.3.2.2), masks relationships with genetically-similar features in other areas.

Third, the overall association between process groups, as illustrated by cluster analysis, implies that alluvial fans and debris cones share more similarities than either does with talus cones. This could suggest that alluvial fans and debris cones are only distantly related to talus cones, or that the alluvial fan / debris cone transition has been less well defined in the field than the debris cone / talus cone transition. An alternative is that the variables chosen for this analysis are insensitive discriminators of differences between alluvial fans and debris cones. The latter possibility will be considered immediately below, whereas the other implications will be dealt with in the section devoted to more detailed analysis of the morphological and surface sedimentary characteristics of the study sites (section 5.3.2).

The ability of each variable to discriminate between different types of fan and cone was assessed by using Kruskall-Wallis nonparametric analysis of variance (table 5.2). This method compares the ranked distribution (not absolute values) of a variable between groups. For each variable the null hypothesis states that there is no significant difference between alluvial fans, fluvially-modified debris cones (composite cones), debris cones and talus cones.

Table 5.2 illustrates the mean rank values of each variable for the four groups of fan and cone, and also shows the chi square value and significance. The only variable that is not a significant discriminator between each of the four groups is C/A, which evaluates aggregate clast form. The mean rank values of C/A for each group reveal very similar values for groups 1, 2 and 3 but a greater value for group 4, the rockfall talus cones. This variable, therefore, is only capable of discriminating talus cones with their generally higher proportion of slab-shaped clasts from the rest of the fans and cones, which generally have a greater range of aggregate clast form values. This variable is also most likely to be influenced by contributing area lithology, as discussed below.

The best univariate discriminators are represented by the highest chi square values and lowest significance levels depicted in table 5.2. FGRAD and MP-ANG are good discriminators of all four groups as is illustrated by their

Table 5·2
Results of the Kruskall-Wallis nonparametric analysis of variance

VARIABLE NAME	MEAN RANK				CHI SQUARE	significance
	G 1 n=11	G 2 n=13	G 3 n=6	G 4 n=8		
FGRAD	6.2	17.9	27.6	34.4	33.7	<0.0001
FORM	19	27.8	13.3	12.2	11.8	0.008
SCALE	10.3	16.1	23.8	34.5	24.2	<0.0001
FINING	22.8	23.1	25.2	4.9	17.7	0.0005
MP-ANG	31.5	21.7	12.7	4.9	29.6	<0.0001
C / A	18.8	17.2	17.6	25.7	3.3	0.35

RANKED CHI SQUARE VALUE

1 FGRAD

2 MP-ANG

3 SCALE

4 FINING

5 FORM

6 * C/A N.B. not significant

GROUP MEMBERSHIP

G 1 = ALLUVIAL FANS G 4 = DEBRIS CONES

G 2 = COMPOSITE CONES G 3 = TALUS CONES

difference in mean ranks and high chi square values for each group. The other variables are less effective in discriminating between one or more of the groups. For example, the minimum and maximum values for SCALE (table 5.3) show there is some overlap in values between fluvially-modified debris cones and debris cones, but talus cones have much higher SCALE values reflecting the generally smaller downslope lengths of the eight features studied. As with C/A, both FINING and FORM have an imbalance in terms of their ability to discriminate (see the mean rank values in table 5.2), with no significant difference being found between the first three groups, but a clear differentiation registered for talus cones, thus helping to account for the distinct clustering the latter group. According to the FINING index used, alluvial fans, fluvially-modified debris cones and debris cones generally show some degree of overall downslope fining of sediment (with values greater than 1.0). This contrasts with talus cones which display a general downslope clast size increase (with values from 0.1 to 1.0). The values for FINING for groups 1, 2 and 3 are also widely distributed (eg 0.8 to 6.7 for 6 debris cones), suggesting considerable between-site variation in each group. The discriminating effectiveness of FORM is also weakened by a large range in values for the 13 fluvially-modified debris cones, as well as by the fact that the values show some degree of between group overlap. Indeed, it is not surprising that members of group 2 have the highest values for concave long profile form. Such sites generally have a

Table 5·3

Minimum and maximum values of the Scottish data describing fan and cone morphology and surface sediments.

CRITERIA	RANK	G 1 n=11		G 2 n=13		G 3 n=6		G 4 n=-8	
		MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
FGRAD	1	2°	10°	9°	17°	20°	25°	25°	33°
FORM	5	1	3	1.4	6.7	1	2.3	0.8	2.3
SCALE	3	1	3	1	4	2	9	9	23
FINING	4	0.9	3.5	0.8	5.6	0.8	6.7	0.1	1
MP-ANG	2	2.3	3.1	2.0	2.8	1.4	2.2	1.1	1.7

GROUP NAMES

G 1 = ALLUVIAL FANS

G 2 =FLUVIALLY-MODIFIED DEBRIS CONES

G 3 =DEBRIS CONES

G 4 =TALUS CONES

steeper upper third reflecting debris flow deposition, whilst the the lower third of their slope may, as their name suggests, reflect considerable fluvial modification giving rise to much lower gradients.

In sum, it appears that not all of the variables used in the cluster analysis provide effective differentiation between all groups of sites. Two reasons may account for this. First, the distribution of values for some individual variables overlap between-groups. This is consistent with the concept of a process continuum as expressed in the *a priori* model (chapter 4, section 4.5, figure 4.1). Second, the initial calculation of the indices required significant generalisation of site character, and may in some instances have been insufficient to reflect either the morphological character or the patterns of downslope sediment size and shape changes. These factors will be considered in greater depth in the next section.

5.3.2 Alluvial fans, composite cones, debris cones and rockfall talus cones: examples from the Scottish Highlands.

The variables used above to assess the model may not be sufficiently sensitive to describe the range of characteristics found on fan and cone landforms in the Scottish Highlands. We shall, therefore, return to the original data from which the generalised variables were derived. This part of chapter 5 will be subdivided according to the characteristic to be discussed, commencing with long profile form and then surface sedimentary characteristics. These findings will then be compared with data from a small number of sites in Lyngen, Northern Norway, to assess the generality of the conclusions reached.

5.3.2.1 Fan and cone long profile form.

5.3.2.1.1 Gradient.

The *a priori* model suggested that distinct medial profile gradients characterise alluvial fans, debris cones and rockfall talus cones. The predicted ranges in slope angles were 1° to 10° for alluvial fans, 12° to 35° for debris cones and 25° to 35° for talus cones. The results of the Kruskall-Wallis analysis of variance demonstrated that mean fan gradient (FGRAD) is an effective univariate discriminator of different types of fans and cones, and this may also be illustrated by a dispersion diagram (figure 5.5). The values for alluvial fans, debris cones and talus cones nearly all fall within their expected ranges, with composite cones forming an intermediate group between the alluvial fan and debris cone distributions.

5.3.2.1.2 Long profile form.

Figures 5.6 to 5.9 illustrate the surveyed long profiles of alluvial fans, composite cones, debris cones and rockfall talus cones respectively. The profiles have been standardised in terms of their length to facilitate visual comparison. However, total distance down-fan should be

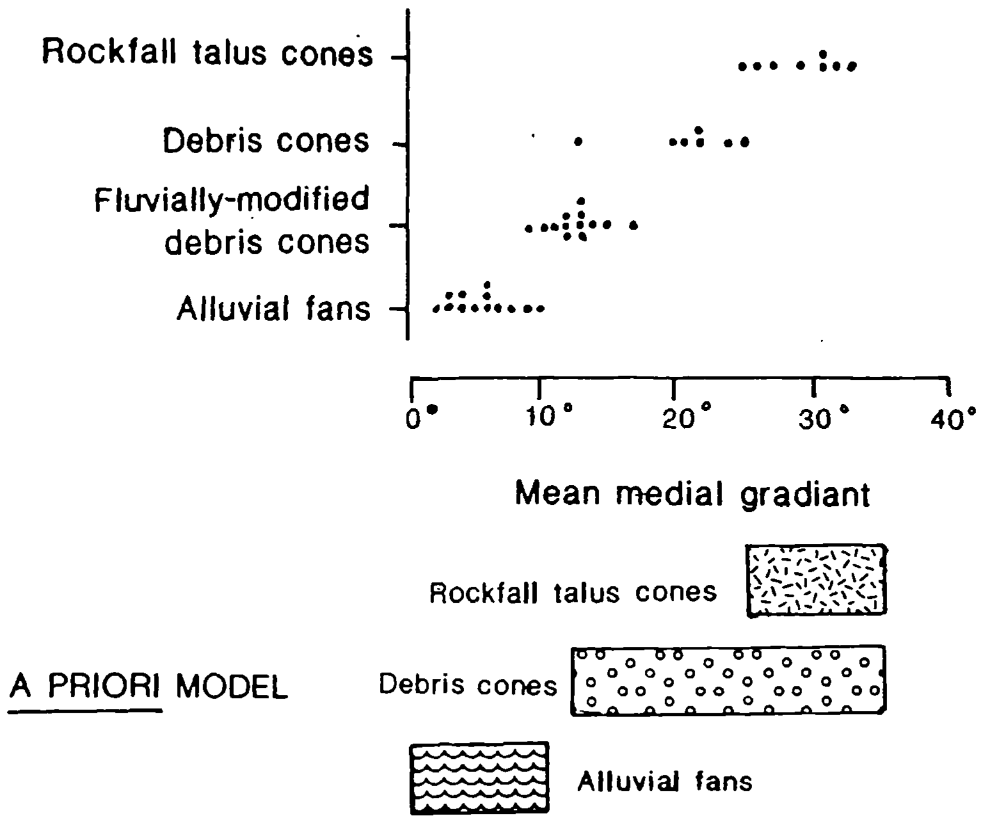


Figure 5.5 Comparison of actual and expected mean medial gradients of different types of fan and cone landform.

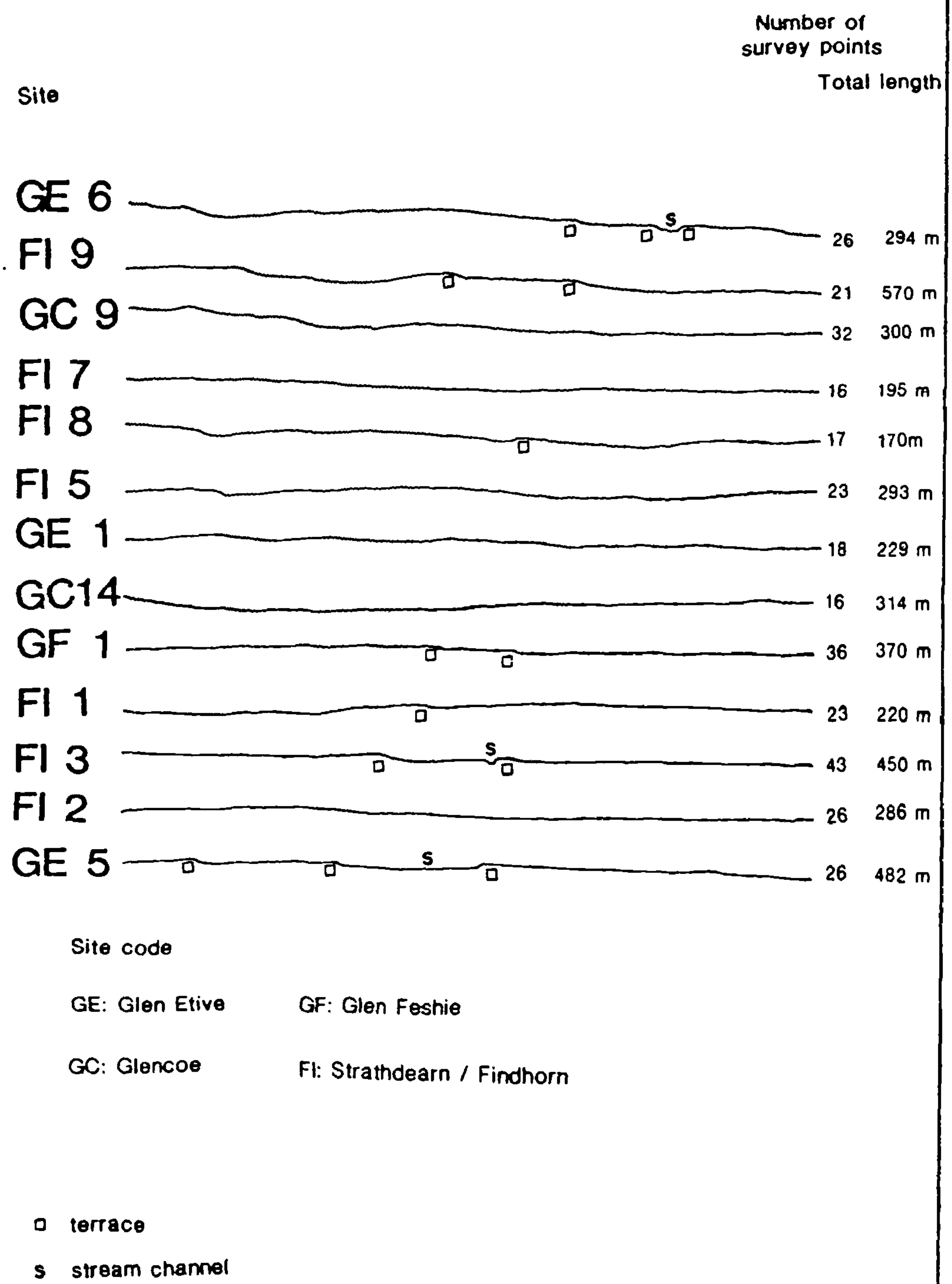
noted, as these features range in length from 10m to 570m (see lower numerals to the right of each profile). The total number of survey points have also been recorded on the right of each profile (upper numerals).

Alluvial fans.

As expected, the alluvial fans (figure 5.6) have profiles with the lowest overall gradient. The *a priori* model stated that profile form is characteristically smooth. Most alluvial fans illustrated in figure 5.6, however, do not have smooth profiles because of incision and terrace development. This is most clearly illustrated by the bottom profile in the diagram, that of GE 5. At this site the main stream channel meanders across the medial axis leaving two terrace risers, one facing down-fan, the other facing up-fan.

Two of the alluvial fans, GE 6 and GC 9, have steep (11° and 13°) upper third gradients. Fan GE 6 has lobate structures near the apex that have locally steepened the slope profile. These structures were difficult to interpret because they are considerably degraded and covered in vegetation. Furthermore, there were no available sections that could have determined whether or not debris flow deposition has occurred at this site; it is possible that the lobe-like structures are boulder berms similar to very coarse accumulations evident in the present-day channel. The Corrie nan Lochan burn alluvial fan (GC 9) has a complex

Figure 5.6 The morphological character of the long profile of Scottish alluvial fans.

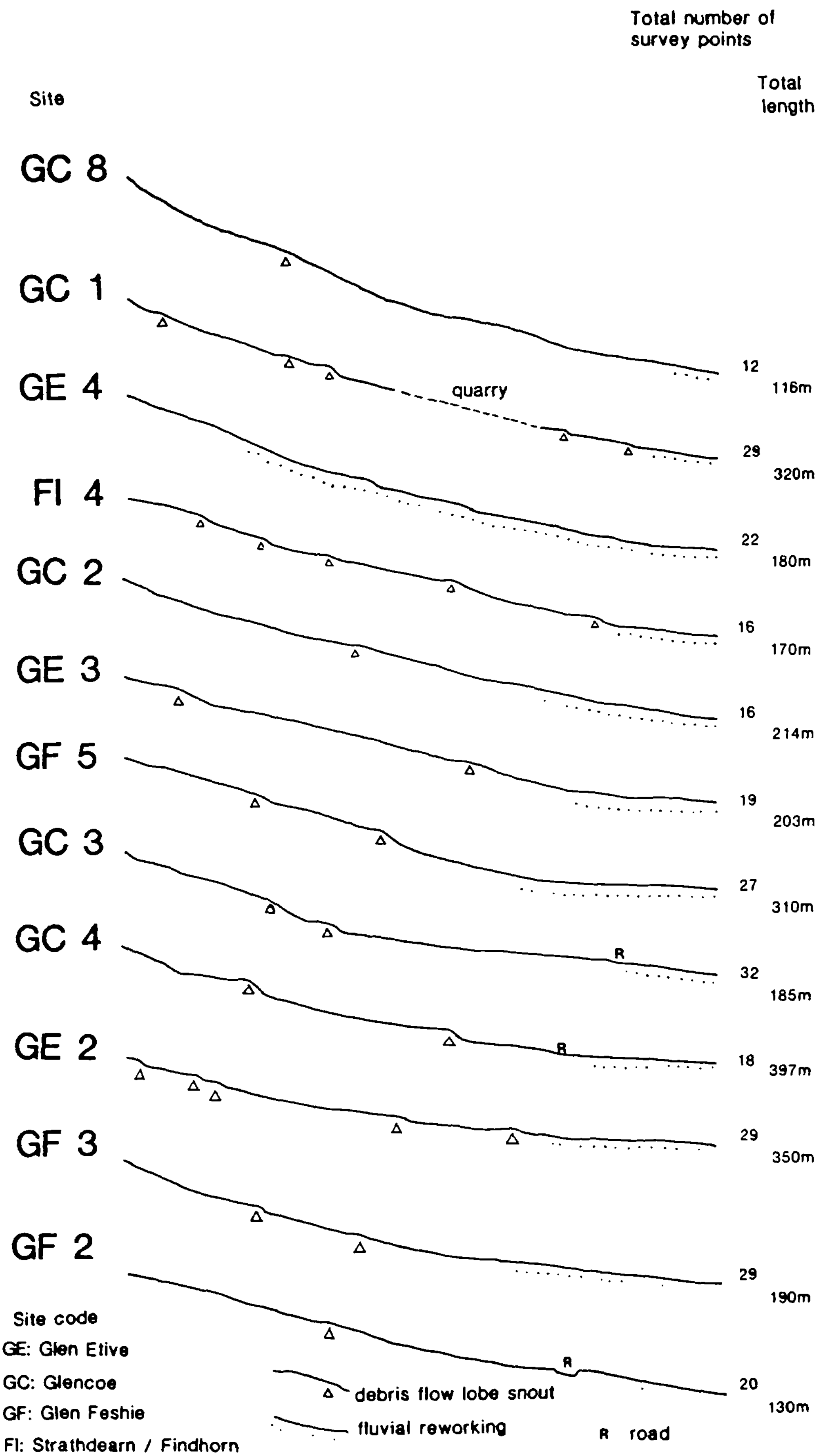


surface morphology, which together with lichen evidence suggests that most of its surface has been affected by both erosion and aggradation (chapter 7, section 7.4). Because of the extensive fluvial reworking of the near-surface deposits there is some difficulty in establishing whether or not debris flow deposition has occurred sometime in the past that would account for the steep upper third of the long profile at GC 9. In addition, there is some morphological evidence for debris flow lobes on the old fan surface at site FI 5 in Strathdearn. These sites show a greater degree of slope concavity as a result of their steeper apex areas. In view of the uncertainty of the genesis of such sites it would be misleading to suggest that the degree of slope concavity exhibited by them reflects only fluvial activity.

Composite cones or fluvially-modified debris cones.

Figure 5.7 illustrates the long profiles of 12 composite cones. The *a priori* model suggested that cones formed by more than one process share some, but not all, of the characteristics of related single process features. It has been demonstrated above that the mean gradients of this class of cone (10° to 18°) fall between and overlap the ranges for alluvial fans and debris cones. The relative importance of either fluvial activity or debris flow deposition probably determines the mean gradient and form of the cone. For example, many of the sites illustrated toward the top of figure 5.7 have only very small fluvial segments near the toe, and thus have steep but only slightly concave long

Figure 5.7 The morphological character of the long profile of Scottish flluvially-modified debris cones.



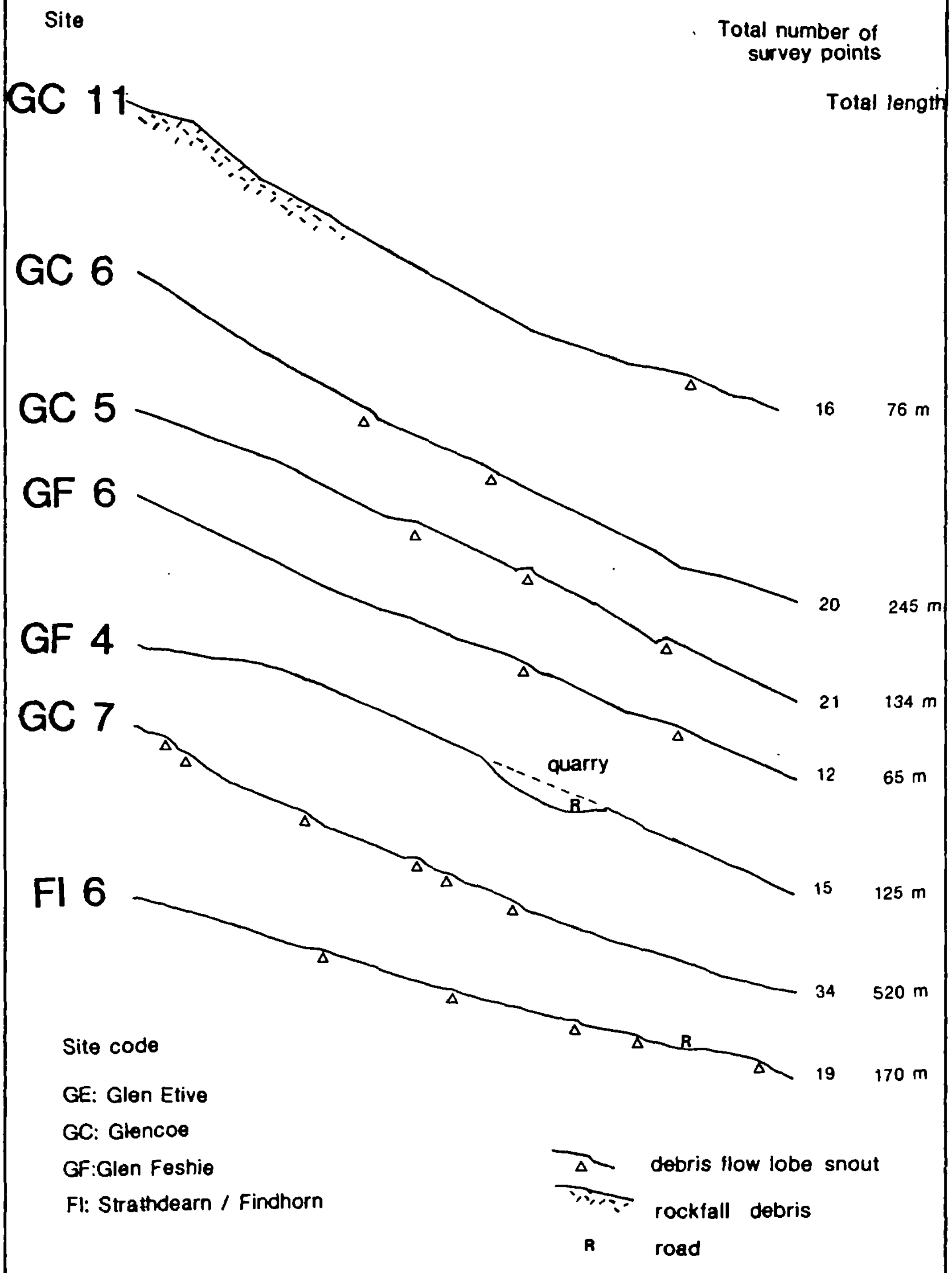
profiles. Other sites such as GF 5 have a steep upper half profile formed by debris flow deposition, and a lower half extensively modified by fluvial reworking producing a much reduced gradient, giving a marked concavity to the slope overall. Many of the sites show fluvial reworking of only part of the cone, but at site GE 4 (plate 5.1) the entire surface is actively being modified by streams issuing from a steep rock gully. The gully floor is packed with boulders, but debris flow activity appears to have ceased at this site. The stream power at this site also appears to be insufficient to mobilize the larger boulders and thus a simple lack of available sediment cannot explain the change in process regime. The probable causal factors responsible for changes in the type of dominant deposition process will be discussed in greater detail with reference to specific sites in chapter 7. Meanwhile, it is sufficient to note that debris cones that have been fluvially modified are more common composite features in Highland Scotland than composite cones formed by both fluvial and debris flow deposition during cone aggradation (giving a stratigraphy of alternating fluvial and debris flow deposits).

Debris cones.

Figure 5.8 shows the long profiles of 7 sites which field evidence suggested were formed by debris flow deposition; site GC 11 below Aonach Dubh, however, also has a rockfall input of sediment at the apex, giving it a steep upper slope. The *a priori* model predicts that debris cones

Plate 5.1 The fluvially reworked part of GE 4 is extensive, with only a small fragment of original debris cone visible in the top right of the photo (behind the pole).

Figure 5.8 The morphological character of the long profile of Scottish debris cones.



will have concave and irregular profiles.

The sites illustrated in figure 5.8 demonstrate that slope form is indeed irregular, but not always concave. Site GF 4, for example, shows a remarkable degree of upper profile convexity, reflecting incision of the apex area to a depth of several metres by the passage of debris flows which have deposited material some distance downslope.

The most concave profiles are GC 11, GC 6 and GC 7. The first of these sites, GC 11, has been oversteepened at its apex by the rockfall, this input consequently exaggerating the cone's overall long profile concavity. The other two sites are actively aggrading and are extremely large when compared with the other debris cones considered in this chapter. Indeed the Chancellor debris cone (GC 7; plate 5.2) is probably one of the largest debris cones in the Highlands, a conclusion supported by borehole data that records depths of debris flow deposits in excess of 15m near the toe (Highland Regional Council, 1984; chapter 3). On such large cones there may be a preferential accumulation of debris flow deposits in the upper part of the cone thus increasing long profile concavity, whilst smaller cones have a greater probability of debris flows reaching the toe and consequently have a less concave form. Furthermore, on the lower slopes of cones GC 7 and GC 6 very shallow lobate deposits with no strong clast fabric probably indicate hyperconcentrated debris flow deposition (cf Wells and Harvey, 1987) which may explain low gradients at the toes of

PLate 5.2 The Chancellor debris cone (GC 7), which is probably one of the largest of its kind in Scotland. The characteristic irregular morphology of the cone is the product of numerous debris flow events. The central axis of the cone is bounded by some very large levees, for example in the top left of the cone.

these cones. At these sites and others where both viscous debris flow deposition occurs near the apex and hyperconcentrated debris flow deposition occurs on the lower slopes, there will be a greater degree of profile concavity. The steep rocky catchments supplying these sites may have enhanced the probability of hyperconcentrated debris flow activity by promoting rapid runoff capable of diluting the sediment:water mix during a single depositional event, in a manner similar to that described by *Wells and Harvey (1987)*. Morphologically-similar "fluid-type" debris flow deposits have been identified on the lower parts of other sites, including fluvially-modified cones such as GC 1, GC 3 and GC 4 (also built out from the lower slopes of the Aonach Eagach). These sites in Glencoe show signs of considerable recent activity compared with vegetated cones in other areas such as Strathdearn. It is therefore possible that cones now relict may have also experienced hyperconcentrated debris flow deposition. However, it has not been possible to identify this at such sites because vegetation cover has obscured diagnostic structures, such as the shallow lobate forms characteristic of hyperconcentrated flows, and there is also a lack of suitable sections. Furthermore, where stratigraphic evidence is available it has not always been possible to separate clearly such "fluid" debris flow deposits from sediment-rich fluvial deposits, particularly at sites where debris flow deposits have provided the sediment source.

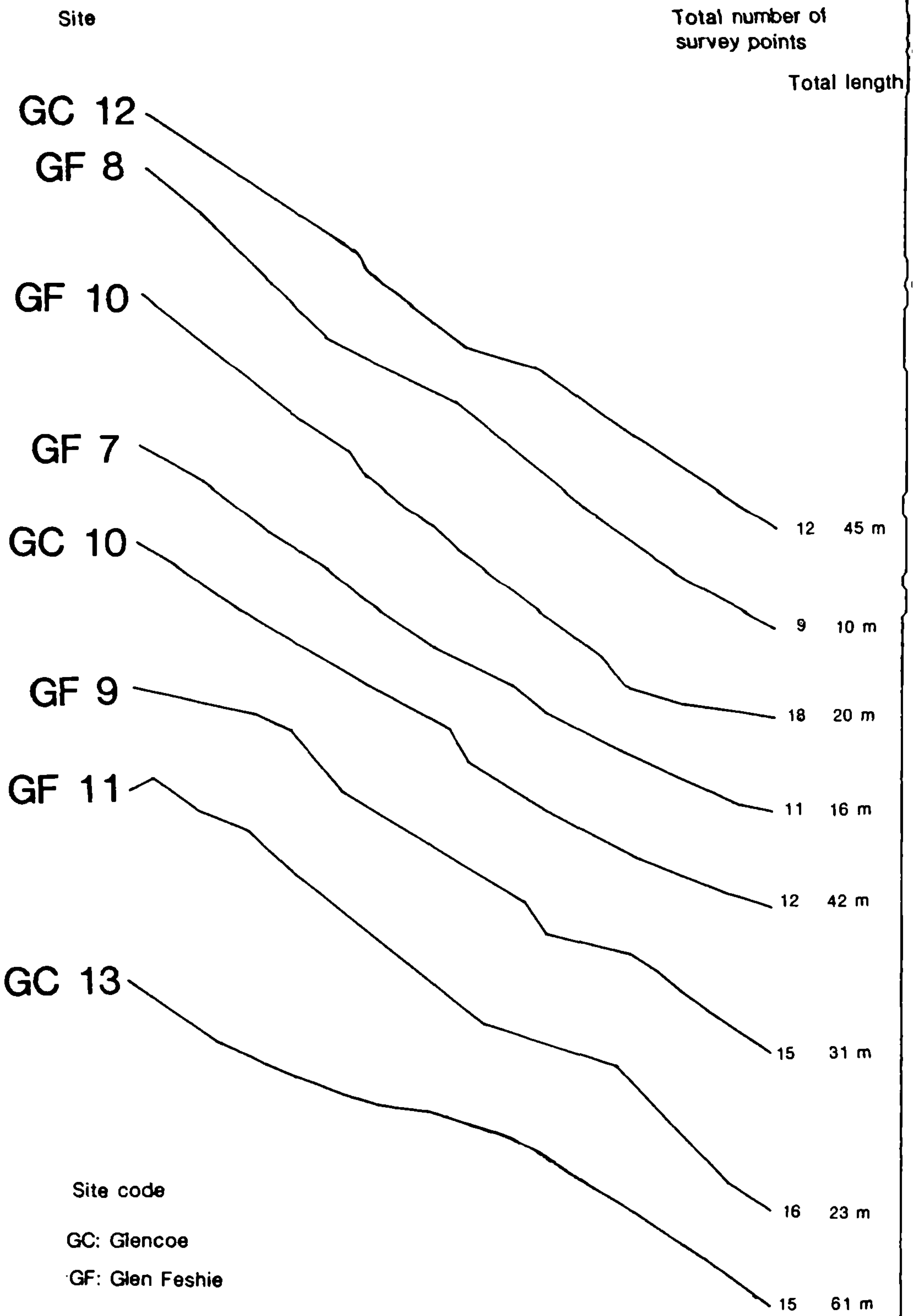
The site with the rockfall input, GC 11, has an upper slope facet of 40^{o} reflecting the angle of accumulation of rockfall debris. The upper part of the profile has a convex form, which has probably arisen because the rockwall overhangs the apex so that more debris is preferentially delivered farther downslope. Much of the rock rubble that arrives at this site has not been released from a rockface behind it, but has in fact spilled over the rock ledge from talus accumulating farther upslope.

Talus cones.

Figure 5.9 illustrates the long profiles of 8 talus cones. Most of these cones are small when compared with debris cones and alluvial fans. The *a priori* model implies that talus cones have steep rectilinear to concave smooth slope forms. The profiles illustrated in figure 5.9 are certainly steeper than debris cone profiles, but they exhibit a remarkable amount of slope irregularity, and at one site (GC 13) the form of the slope is the reverse of what was expected in terms of the *a priori* model. Reasons for the departure from expected mean gradient and form can, however, be identified for each of the "irregular" sites, the characteristics of which do not necessarily militate against *a priori* expectations.

An upper rectilinear slope of around 35^{o} is evident at sites GC 12, GF 8, GF 10, GF 11 and GC 13. Sites such as GC 10 and GF 7 have an upper rectilinear slope of less than 35^{o}.

Figure 5.9 The morphological character of the long profile of Scottish rockfall talus cones.



Only one site (GF 8) has an upper slope of 40°, which is extremely unstable, and probably reflects the limited height for rock fall, the steep configuration of the narrow rock gully below which the cone has accumulated and also the immaturity of the feature, which has a total length of only 10m.

Site GF 9 exhibits a strongly convex upper profile which appears to reflect a high concentration of small sized clasts, a phenomenon that has also been observed by Church _et al_ (1979). Schist outcrops in the source area are densely jointed so that a great proportion of the debris falling on to the cone is small sized and does not have sufficient energy to maintain motion after the first impact near the top of the slope. Consequently there is a piling up of small-sized debris giving localized slope convexity near the apex. It should be noted, therefore, that the upper slope convexity observed at GF 9 has a different explanation to that given for a similar morphological phenomenon found on the talus component of GC 11 (see above; overhanging rockwall) or GC 13 (see below).

Below the upper rectilinear segment of GC 13, the long profile gradient becomes shallower until approximately midway downslope, where the form of the profile becomes convex. The complex slope form of this cone implies that another mechanism as well as discrete rockfall has delivered rock debris to the cone. Possible explanations for the convex central segment include a single large rock release event (cf Ballantyne, 1981, figure 8.4), or debris flow modification. There is, however, none of the characteristic evidence of debris flow activity at this site, though debris flow modification of the talus may have happened in the past. Explanation of this in terms of a large scale rockfall is supported by a subtle change in the fall-sorting pattern, which suggests two discrete sediment distributions down cone (section 5.3.2.3, figure 5.18 below). Indeed, the convex segment has slightly coarser sediment than that immediately up or down cone.

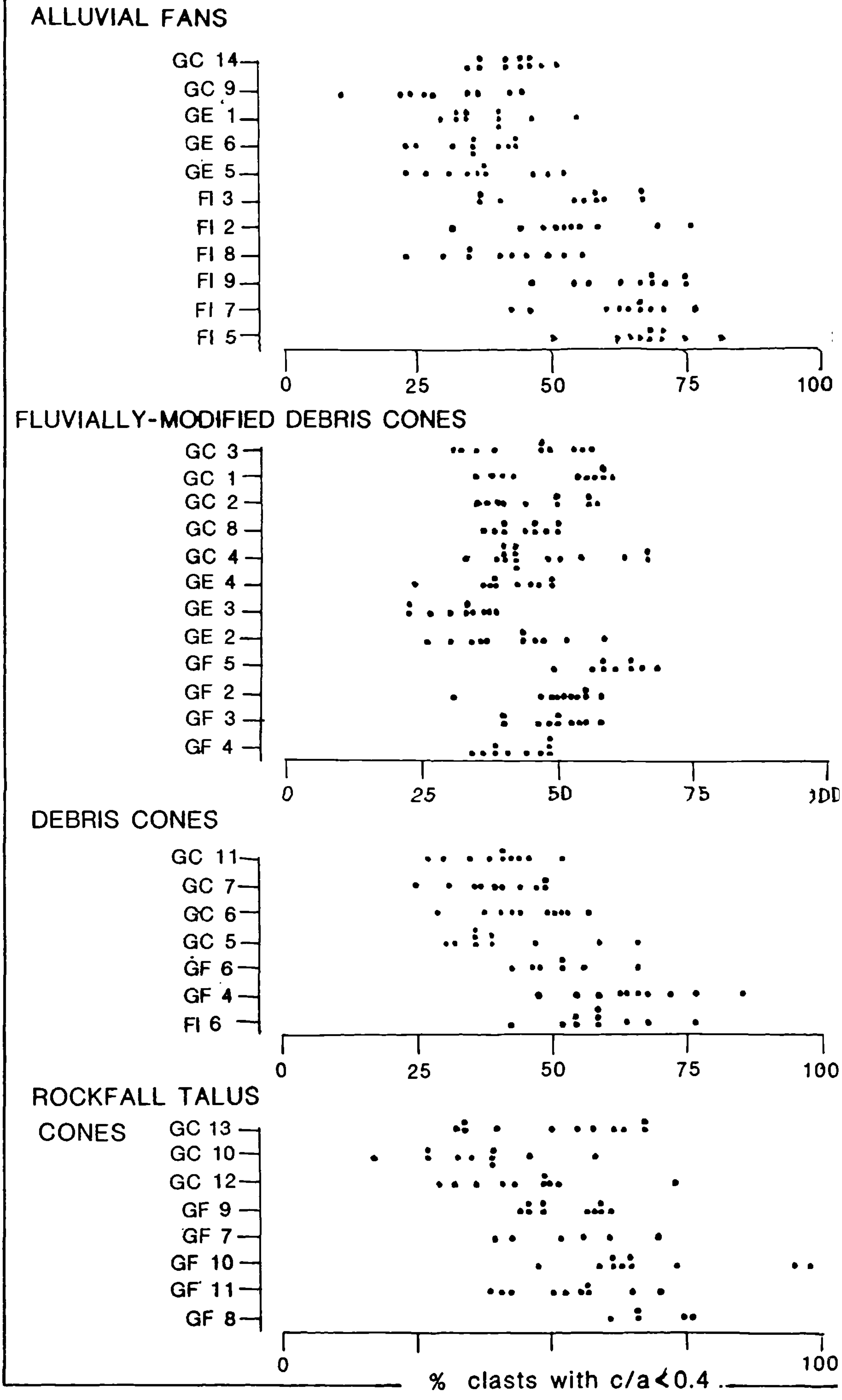
Basal erosion by rivers has led to slope readjustment at sites GC 12, GF 8, GF 10, GF 9, and GF 11. As a result these sites do not exhibit a concave basal fringe as seen at sites GF 7 and GC 10. Two of the most recent basally-eroded sites (GF 9 and GF 11) have the most complex, and in places unstable, long profile forms. Indeed, river undercutting of the lower part of cone GF 11 has exposed much smaller-sized sediment than that found in comparable positions on the flanks of the feature (figure 5.18). The concave basal fringe is absent from site GC 13 because this cone has prograded to the edge of a rock ledge.

5.3.2.2 Fan and cone sediment characteristics: clast shape.

Two measures of clast shape were assessed, namely C/A and MP-ANG. Both clast form and roundness have been used in research on a range of sediments with different weathering and transportational histories (Briggs, 1977; Shakesby, 1980; Ballantyne, 1982; Matthews and Petch, 1982). In view of differences in formative process, systematic differences in clast form and roundness might be expected between alluvial fans, debris cones and talus cones, with the most rounded and equidimensional clasts on alluvial fans and the most angular, least equidimensional clasts on talus cones. Kruskall-Wallis nonparametric analysis of variance demonstrated that average clast roundness (MP-ANG) does indeed vary between the different process groups; but the percentage of slab-shaped clasts with C/A values less than or equal to 0.4 was not an effective univariate discriminator between alluvial fans, composite cones and debris cones. The variable C/A was, however, more effective at discriminating talus cones from other fan and cone landforms.

Figure 5.10 illustrates the range in the distributions of the variable C/A values for all sampling points at each site. Considerable variation occurs within each landform group. This can be illustrated by two contrasting talus cone sites. At site GF 10 in Glen Feshie, sampling at two points revealed C/A values exceeding 90%, yet at another sampling point the C/A value does not exceed 50%. In contrast a second talus cone, in Glencoe (GC 10), has generally fewer slab-shaped clasts at each sampling point, and an overall range from 17% to 58% for variable C/A in the measured samples. The first of these sites occurs below an

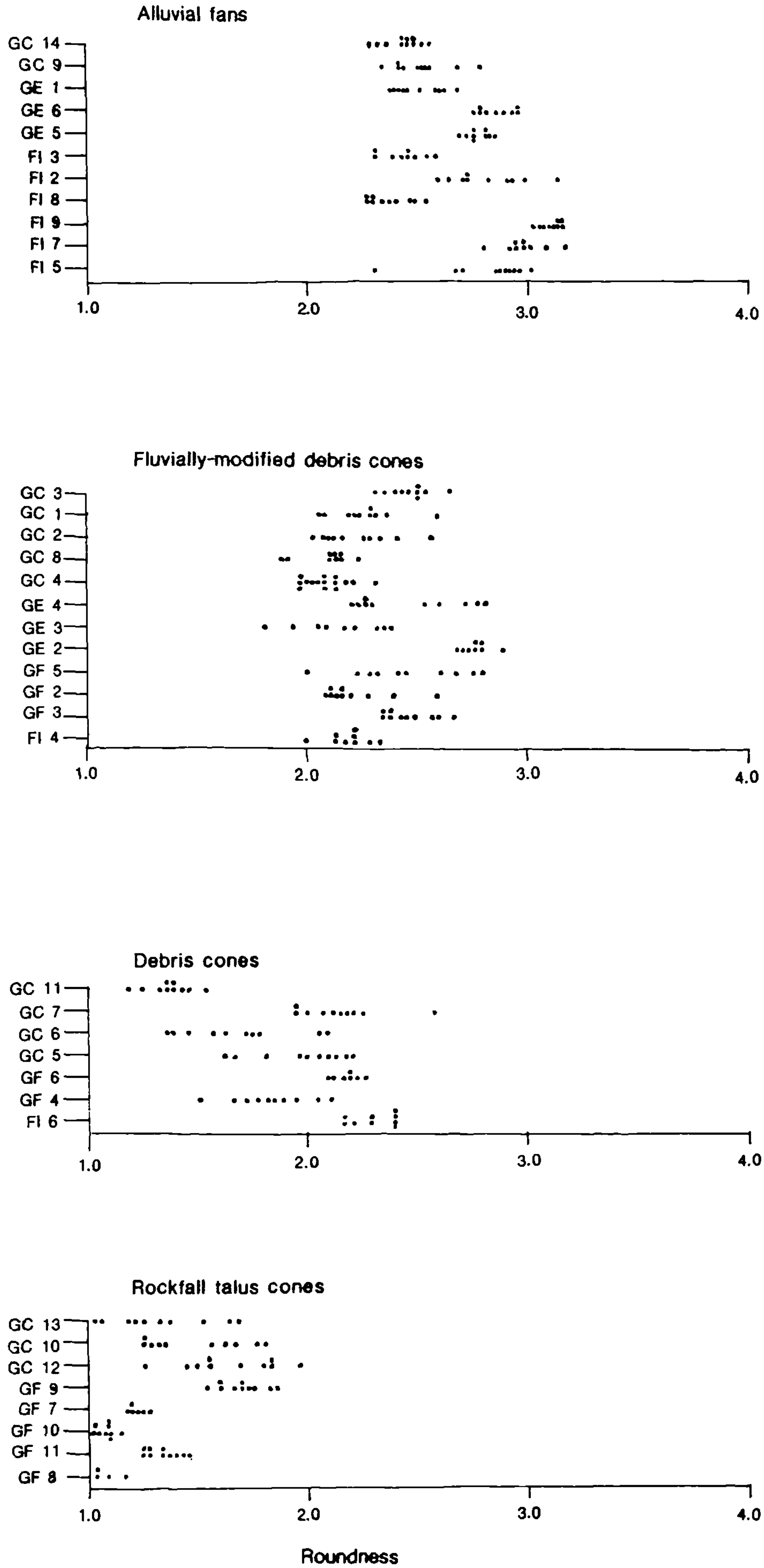
Figure 5.10 Median aggregate clast form characteristics of fan and cone surface sediments, assessed by percentage of clasts with C/A values greater than, or equal, to 0.4.



outcrop of very fissile and densely-jointed Moinian schist in upper Glen Feshie (similar to the outcrop illustrated in plate 5.4 above), whilst the other site has been built up by rockfalls from rhyolite and andesite lava outcrops, which generally give rise to more equidimensional fragments. The same patterns can be identified within other fan or cone groups suggesting that lithological control is more important than process in determining aggregate clast form. In general, both lavas and granites tend to give rise to more equidimensional clasts than schists and some gniesses. These patterns were not altered by changing the cut-off point of C/A from 0.4 to any value in the range 0.2 to 0.8. The effects of different source lithologies on aggregate clast form may therefore have been partly responsible for the development of sub-clusters in the cluster analysis results. In view of these findings measurement of the degree of clast slabiness was not undertaken in Lyngen nor at the detailed case study sites. It is suggested that without controlling for lithology (which was not practicable in this study owing to the variety of lithologies in the study areas) C/A is not a suitable criterion for classifying alluvial fans, composite cones, debris cones and rockfall talus cones. Other shape indices (including the Cailleux flatness index and Krumbien's sphericity index) were calculated from the A, B and C axes measurements, but the results of these analyses were equally unfruitful. Cluster analysis was not re-run without the variable C/A because this would have given an imbalance to the six variable data set and would call into question the objectivity of the analysis. The data set examined by the cluster analysis has two variables describing aspects of slope form, two measuring sediment sorting and distance and two refelecting dominant clast shape. If C/A was removed, this would downgrade the role of dominant clast shape. Substitution by another clast form index was not worthwhile for reasons discussed above.

In contrast, clast roundness provides a good discriminator of different types of fans and cones. However, lithological control again influences the degree of within-group homogeneity. The clearest example of this can be seen in the talus cone group in figure 5.11. With the exception of GF 9 all sites in Glen Feshie (fissile schists) have more uniform and slightly lower values of roundness in comparison with three sites from Glencoe (lavas) that have more varied and higher roundness values. In the alluvial fan group, sites in Strathdearn generally have the most rounded clasts, for example sites FI 5, FI 7 and FI 9. At these sites there is a large proportion of weathered granite clasts, which are vulnerable to rounding over relatively short travel distances down-fan. If we return to the dendrogram (figure 5.3) we see that FI 7 and FI 9 form cluster 4 (along with GC 14). The majority of sites did not show any appreciable change down-fan in degree of rounding, which probably reflects the small size of the individual fans and cones compared with those researched in other

Figure 5.11 Median clast roundness characteristics of fan and cone surface sediments, assessed by visual classification of the clasts into one of six roundness categories, and quantified using Matthews and Petch's (1982) roundness index.



mountain environments (chapter 4).

5.3.2.3 Fan and cone sediment characteristics: down-fan changes in clast size and sorting.

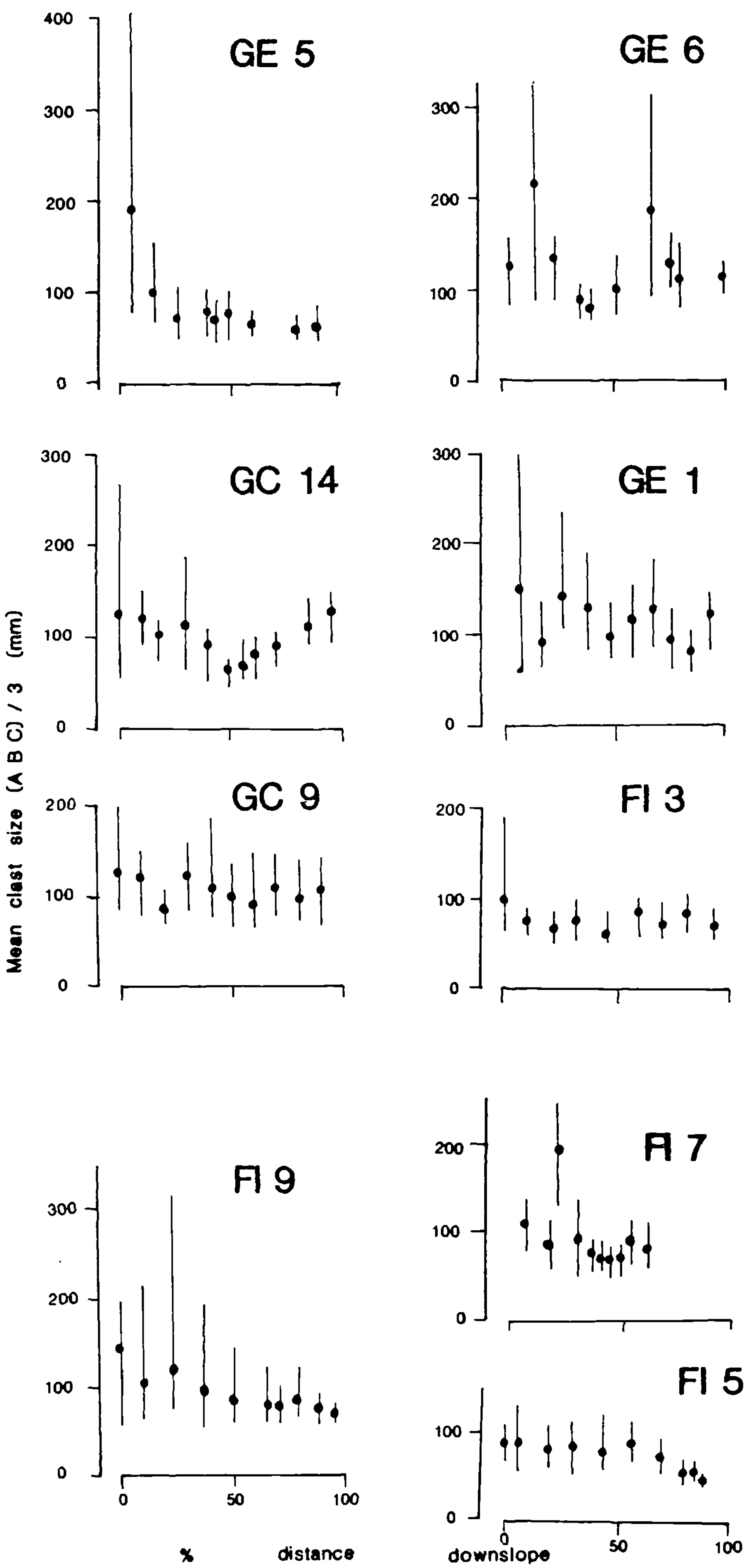
The median and inter-quartile range of clast size ((A+B+C)/3) have been plotted against percentage distance down-fan from the apex for alluvial fans, composite cones, debris cones and talus cones in figures 5.12 to 5.18. A brief glance at these plots shows that there is an enormous amount of within-group variation. One of the original intentions in this research project was to characterise statistically the down-fan pattern of sediment size and sorting changes. However, given the variability of the data this would not be meaningful. In the following section the general down-fan pattern of sediment sorting and size changes is summarised, with discussion of selected examples from sites where the expected patterns are poorly developed or absent.

Alluvial fans.

A general down-fan decline in clast size matched by an increase in sorting was expected, as expressed in the *a priori* model (chapter 4, section 4.5). Only at site GE 5 at Dalness House in Glen Etive was such a pattern clearly demonstrated (figure 5.12). Because GE 5 is vegetation covered, clasts were sampled from the fan channel, and may not be representative either of clast size sorting patterns associated with fan aggradation or patterns found over the

Figure 5.12 Median and interquartile range of mean clast size changes with distance downslope on Scottish alluvial fans.

A.



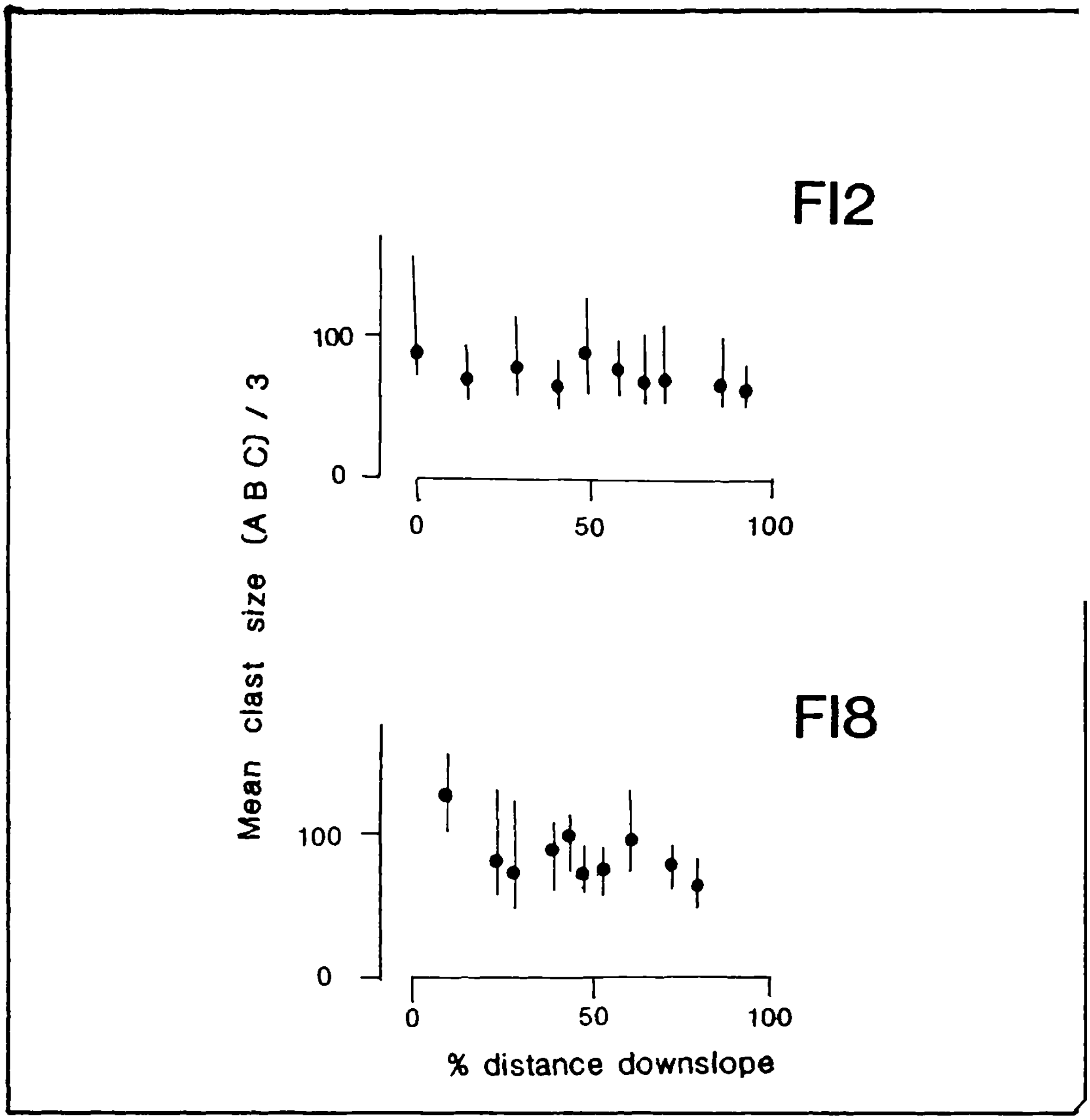


Figure 5.12b Median and interquartile range of mean clast size changes with distance downslope on Scottish alluvial fans.

entire fan surface. Indeed, the majority of alluvial fans have stable vegetated surfaces, with a narrow segment of active channelised stream erosion and reworking of fan sediments. Recent flood erosion and reworking on some fans, particularly FI 2, FI 3 and FI 5 in Strathdearn, has enlarged the lateral extent of these active segments (plate 5.3 above).

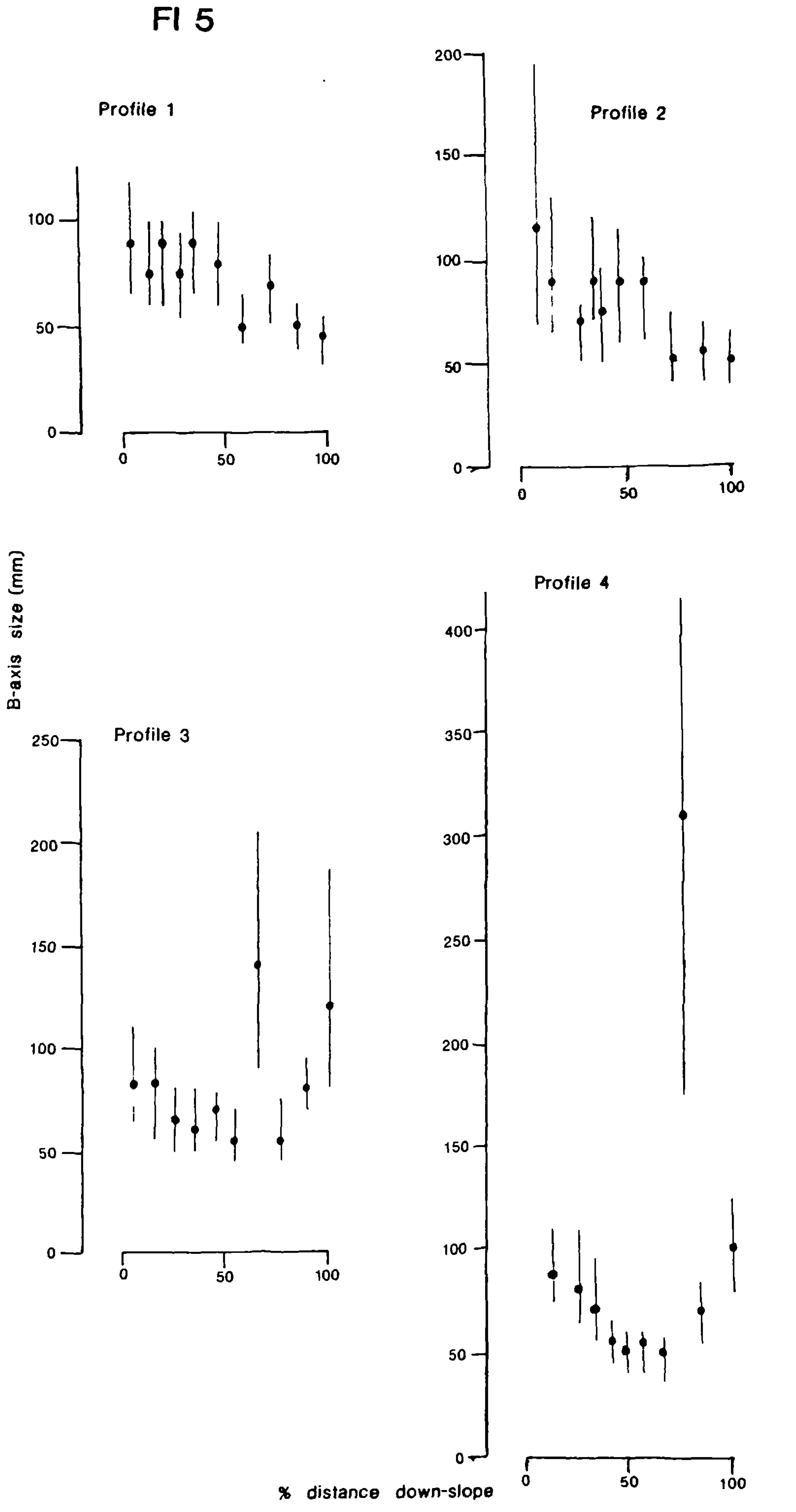
Down-fan changes in clast size and sorting illustrated in figures 5.12a and 5.12b apparently reflect a complex sequence of erosional and depositional events. For example, GC 14 is a large alluvial fan that has built out from the foot of Corrie nam Beithach into Loch Achtriochtan in Glencoe. The western segment of GC 14 shows a complex sequence of terrace development and channel abandonment. The most recent sediments (see also chapter 7) have been deposited in and around the present channel and also on top of adjacent terrace surfaces during times of flood. Thus down-fan patterns of clast size (and to a lesser extent sorting) show two contrasting trends. In the upper half of the fan median clast size declines, although at sampling point 4 the interquartile range increases showing that clasts here are more poorly sorted than at sampling points 2 and 3. Palaeochannel infill is significantly smaller than sediment upstream, seen in low median clast sizes and relatively good sorting at points 6 and 7. After these sampling points clast size steadily increases. The lowest sampling points (8 to 11) occur on a low terrace surface where considerable amounts of sediment have been deposited on the grass by overbank sheet floods, probably during a number of different events (cf Ferguson and Werritty, 1983).

Down-fan sedimentary patterns are also irregular on fans where the sampling sites were located on a single surface and where there is no appreciable incision. For example, FI 9 shows fluctuating median clast size down-fan reflecting individual bars that have discrete sorting patterns.

Total distance down-fan may influence the degree of clear down-fan changes in sediment size and sorting (Boothroyd and Nummedal, 1978). Scottish Highland alluvial fans have a high proportion of clasts larger than 100mm, a criterion that Boothroyd and Nummedal (1978) used to characterize proximal core fan facies. According to their model, "small" fans may have only proximal core fan facies present on them. It is suggested that the majority of Highland fans are immature features that attain only a crude level of down-fan fining because of their relatively short length. It is also suggested that rapid deposition of sediment (often derived from fan incision short distances upstream) during flood events has resulted in very poor grading of sediment in a similar manner to that described by Desloges and Gardner (1981). Indeed, their observations suggested that there may be considerable variability in sedimentary character across one fan surface. In order to assess this problem a study of sedimentary patterns across the active segment of FI 5 was undertaken (figure 5.13).

Four radial profiles were established down the active segment of FI 5 (plate 5.3) from the bridge down-stream of the fan apex. Measurements of the B axes of 100 clasts were made at ten regularly-spaced sampling points on each profile. The first and second profiles show an overall down-fan decline in median clast size. Local departures from this trend reflect the position of individual sedimentary units along the profile axis, particularly bars and to a lesser extent gravel sheets toward the toe. Profiles 3 and 4, however, show down-fan fining only in the upper half of the active segment. This general pattern is interrupted at the 7th point on profile 3, and at the 8th point of profile 4 by very coarse imbricate bouldery deposits. Many of the larger boulders show signs of lichen cover that has been scoured off on the upstream side, and also some of the boulders are clearly _in situ_ as they are embedded in vegetation-covered soil. These bouldery accumulations are interpreted as either marking the path of a former channel that was blocked during a major depositional event, or as a boulder berm deposited during a catastrophic flood event sometime in the past. Selective scour of lichens and trash entwined between the boulders was noted during summer 1984. This indicates that many of these boulders have been recently reworked by a flood, probably that which occurred in September 1981 when the bridge at this site was destroyed. Downstream of these bouldery

Figure 5.13 Median and interquartile range of mean clast size with distance downslope. Examples from four long profiles down the active segment of an alluvial fan.



PUate 5.3 A large incised alluvial fan in Strathdearn (FI 5). Several former surfaces of this fan indicate that it has been extensively reworked in the past, with present day activity confined to a small segment.

deposits, on the lowest parts of profiles 3 and 4, the final sampling points show an increase in sediment size which may reflect the presence of clasts originally deposited by floodwater from the River Findhorn, which flows around the toe of the fan and deposits trash on the fan surface during floods.

The sedimentary properties of accreting gravel bars have been investigated by Bluck (1982), who found that bars are composed of numerous small units that adhere to a parent bar. Coarse sediment in the bar head area is thought to increase the scale and intensity of turbulence enabling more fine material to be washed out of the fabric and redeposited down-bar, hence increasing the rate of migration of finer sediment towards the bar tail. The rate at which such activity occurs may be reduced when small unit bars have joined a bar, because greater discharges are needed to mobilize sediment from larger and topographically higher composite deposits. Once bar amalgamation has occurred, the sedimentary character becomes more unified. Bluck further suggests that a bar may "select" a certain size range of sediment, since only clasts large enough to withstand the high turbulence down-stream of the bar head can be deposited, a process that is determined by the clast size at the bar head. Bluck has observed that small unit bars are less mature where there is rapid sedimentation and also in braided channels (such as on sandar and alluvial fans) where channel changes may be so rapid that bars are abandoned early in their development.

If Bluck's (1982) explanation of gravel bar accretion is correct, one might expect very immature gravel bar development on alluvial fans for the reasons noted below. On such features the degree of bar maturity is dependant upon stream flow regime (some fan channels are dry for long periods of time), the length of time the stream channel itself is occupied, and the rate of sedimentation. Detailed investigations on a single fan bar illustrate the very poor degree of sorting present at such small scales on a typical coarse sediment alluvial segment of a cone.

Figure 5.14a shows down-stream changes on a 14m long gravel bar located at the upper end of the alluvial fan that has built out of a relict debris cone (GE 3, Dalness Chasm cone; see also chapter 7). There is an overall downstream increase in sediment size, with the smallest-sized clasts near the bar head (sampling points 2 and 3) but larger clasts of generally similar size at all the other points. The channel was dry at the time of the survey, and it is suggested that points 2 and 3 do not reflect the same stream discharges that were operative when the coarser bar sediments were deposited. Bluck (1982) observed that some small channel bars have poor downstream fining of sediment, indicating the relative immaturity of the deposit. Similarly, the channel bar studied at site GE 3 is thought to have been deposited rapidly and only slightly modified during a subsequent flow event that was capable only of

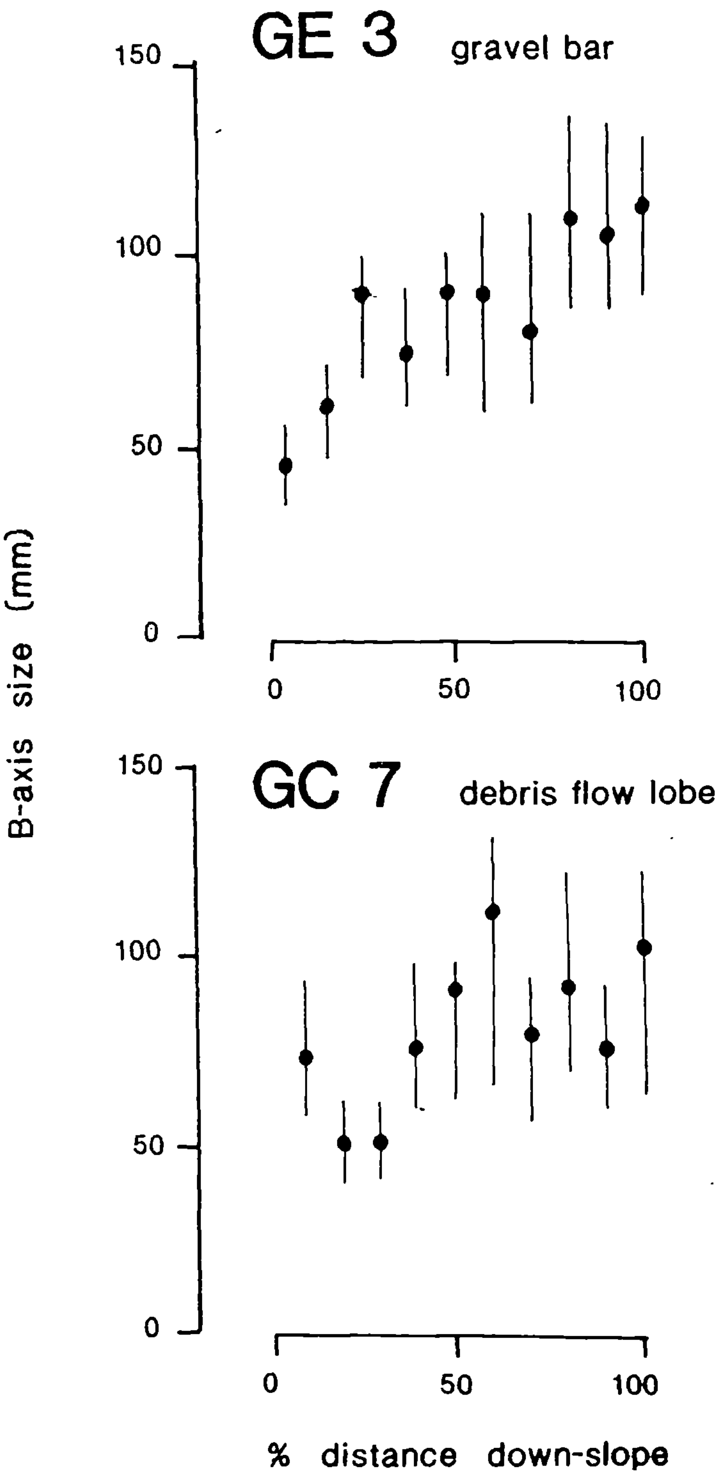


Figure 5.14 Median and interquartile range of mean clast size changes with distance downslope.

A. An example of a gravel bar. (14m long)

B. An example of a debris flow lobe. (19m long) depositing relatively small clasts near the bar head. Indeed, during the summer field seasons in 1984-1986 the channel configuration on this part of the cone underwent several substantial changes caused by episodes of incision immediately upstream that generated localised rapid sedimentation, including the formation of bars such as the one studied.

This site probably gives an extreme example of poor sediment sorting on an individual bar, as the channel at this site is steeper than on a single process alluvial fan. However, a similar lack of down-bar fining observed on other coarse-sediment alluvial fans in Scotland suggests that most bars on such fans are immature features, an interpretation that supports the proximal core facies explanation of small fan sedimentation suggested above. Indeed, the sedimentary characteristics of individual immature bars may most closely reflect different flood events that only affected parts of the active segment of any particular fan. Water flow on fans during wet conditions has been observed to follow several "old" channels as well as the main channel, and changes in the main channel alignment may occur when the main stream becomes diverted around new coarse bouldery deposits.

The poor degree of down-fan fining on alluvial fans in the Scottish Highlands (figure 5.12) is therefore thought to be a function of a combination of factors, including small fan size, long term depositional and erosional history, shorter term changes in the alignment of the main channel, and the magnitude and frequency of stream flow events that affect sorting across a range of scales. These results therefore show that the *a priori* model provides an inadequate indication of the "typical" sedimentary character of Scottish Highland alluvial fans.

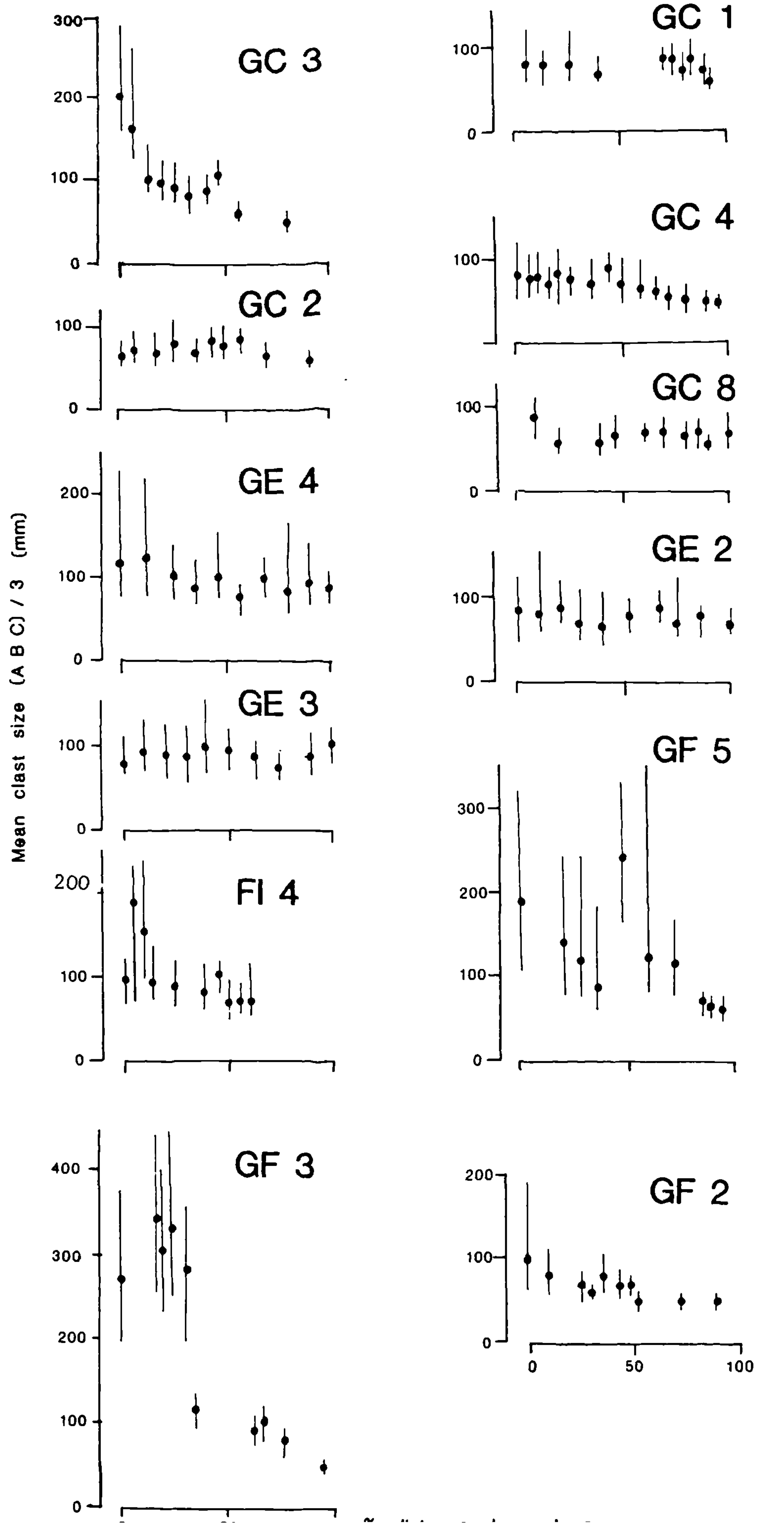
Composite cones or fluvially-modified debris cones.

Fluvially-modified debris cones were expected to share some of the characteristics of alluvial fans and debris cones. Figure 5.15 shows the down-fan changes in median and interquartile range of clast size for 13 debris cones which display varying degrees of fluvial modification.

The upper sampling points on all sites except GE 4 were located on debris flow deposits. Some of these locations (eg GF 5 and FI 4) have been scoured by stream flow so that only very coarse sediment remains near the cone apices. Other sites also have the coarsest sediment near the apex (eg GC 3), but usually in the form of unmodified debris flow lobes. The position of individual lobe fronts has influenced the down-fan pattern of fining, such that at some sites there is a temporary increase in average clast size (eg GC 3, GF 3).

The influence of fluvial reworking and redeposition of sediment can be clearly seen in the generally smaller size and better sorting of clasts measured at the distal sampling points. Many of these deposits have been laid down in

Figure 5.15 Median and interquartile range in clast size changes with distance downslope on Scottish fluvially-modified debris cones.



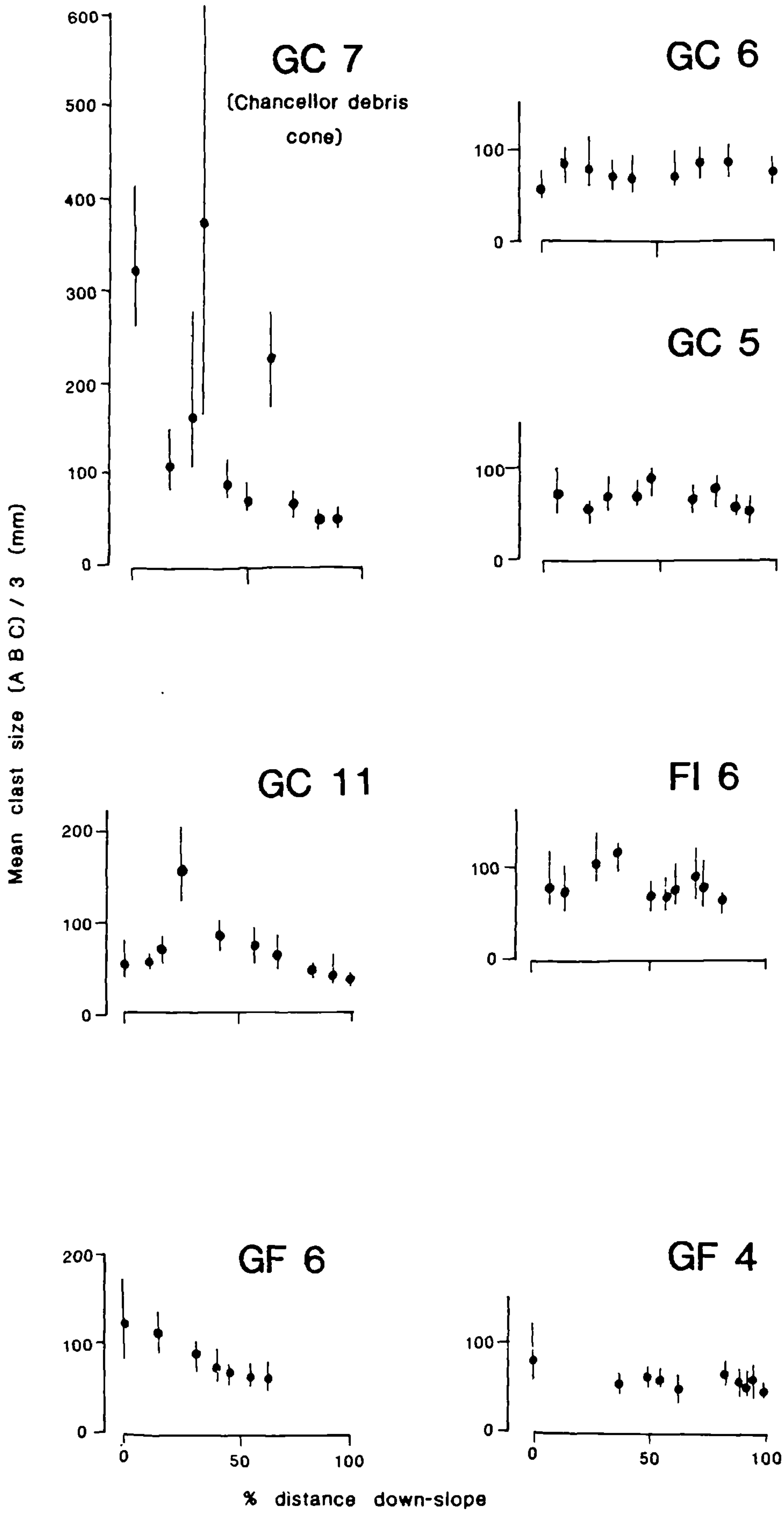
shallow sheets burying short vegetation, which implies overbank deposition during flood events (eg GF 5, GF 2, GF 3, GC 3, GC 1, GC 4).

Debris cones.

The a priori model suggests that typically the surface deposits of debris cones are poorly sorted, with an irregular reduction in clast size. Indeed, the characteristics of the 7 debris cones investigated show *considerable individuality* (figure 5.16). Irregularities in both clast size and sorting with distance downslope reflect the position of individual debris flow lobe snouts, which support generally coarser clasts. For example, the survey line on site GC 5 crossed 3 lobe snouts, marked by a temporary increase in clast size at sampling points 3, 5 and 7. Debris flow levees on site GC 7 (the large Chancellor cone; plate 5.2 below) are crossed by the survey line at sampling points 1 and 4 and yielded the largest clasts measured on any of the fans and cones. Indeed, some of the individual debris flow deposits characteristically support large clasts on their surfaces. Where such clasts are few, the resultant sediment distributions are markedly skewed (eg GC 6, points 3 and 6).

The surface sedimentary pattern on debris cones can also vary laterally, as illustrated by measurements made along four radial profiles on GC 6 (figure 5.17; chapter 7, section 7.5). This cone has built out of a steep gully cut

Figure 5.16 Median and interquartile range in mean clast size changes with distance downslope on Scottish debris cones.



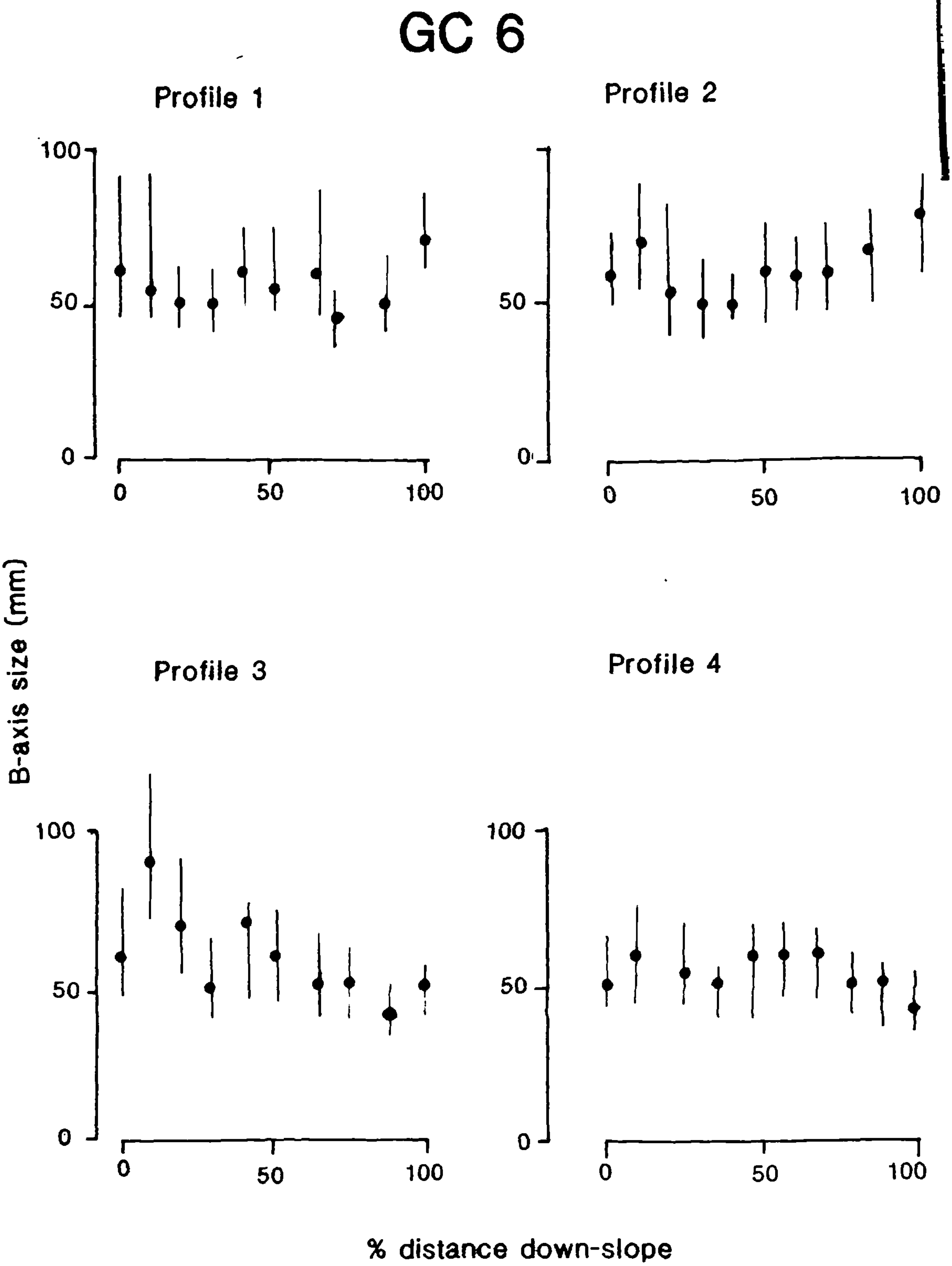


Figure 5.17 Median and interquartile range of mean clast size changes with distance downslope. Examples from four long profiles down an actively aggrading debris cone.

mostly through rock, but with the lower reach cut through glacial drift. At this site the overall clast size range is small, and reflects the homogeneity of the rock gully source area. There are, however, a small number of boulders that rest on the surface of the cone. Each profile has a slightly different down-fan pattern depending on the position and size of individual lobe snouts. The last three sampling points on profile 1 mark a miniature talus of downslope coarsening sediment at the front of one very steep lobe. Similar patterns in clast size sorting are associated with the position of individual lobe snouts on the other three profiles.

Figure 5.14b illustrates the pattern of sediment size increase down the middle of a single debris flow lobe on the Chancellor debris cone (GC 7). Median clast size range is smallest on the lobe tread (sampling point 1) where clast sizes are significantly smaller than they are at the lobe front. The fabric of the lobe sediment suggests that the coarser debris was pushed out toward the lobe margins during flow. Some of the looser debris had fallen from the steep snout face, and had formed a miniature talus around the base of the feature. Such sedimentary patterns have been seen on all Scottish debris cones in this study and have also been reported to occur on cones in the Howgill Fells in northwest England (Wells and Harvey, 1987).

The down-cone pattern of sediment size reduction on debris cones is indeed irregular and deposits are sometimes poorly sorted, as predicted by the *a priori* model. However, the gross pattern of downslope fining observed at GC 7 and GC 6 was not expected, and as illustrated in the figures is visually similar to some of the alluvial fan downslope sorting patterns discussed above. Such apparent similarities do not imply the same genesis for alluvial fans and debris cones but reflect the complex range in the properties and character of debris flows and their subsequent deposits. This can be illustrated by comparing the poorer degree of sorting found at sampling points nearer the apex some of debris cones (eg GC 7, GF 6, GF 4) compared with the marked downslope increase in sorting on the lower parts of others (eg GC 7, GC 6). Diagnostic features suggest that more fluid debris flow deposition has occurred at these distal sampling points. The small range in clast sizes found on such deposits probably reflects the greater fluid content, and consequently lower strength of the mobile debris, properties that would not have favoured the rafting of large clasts.

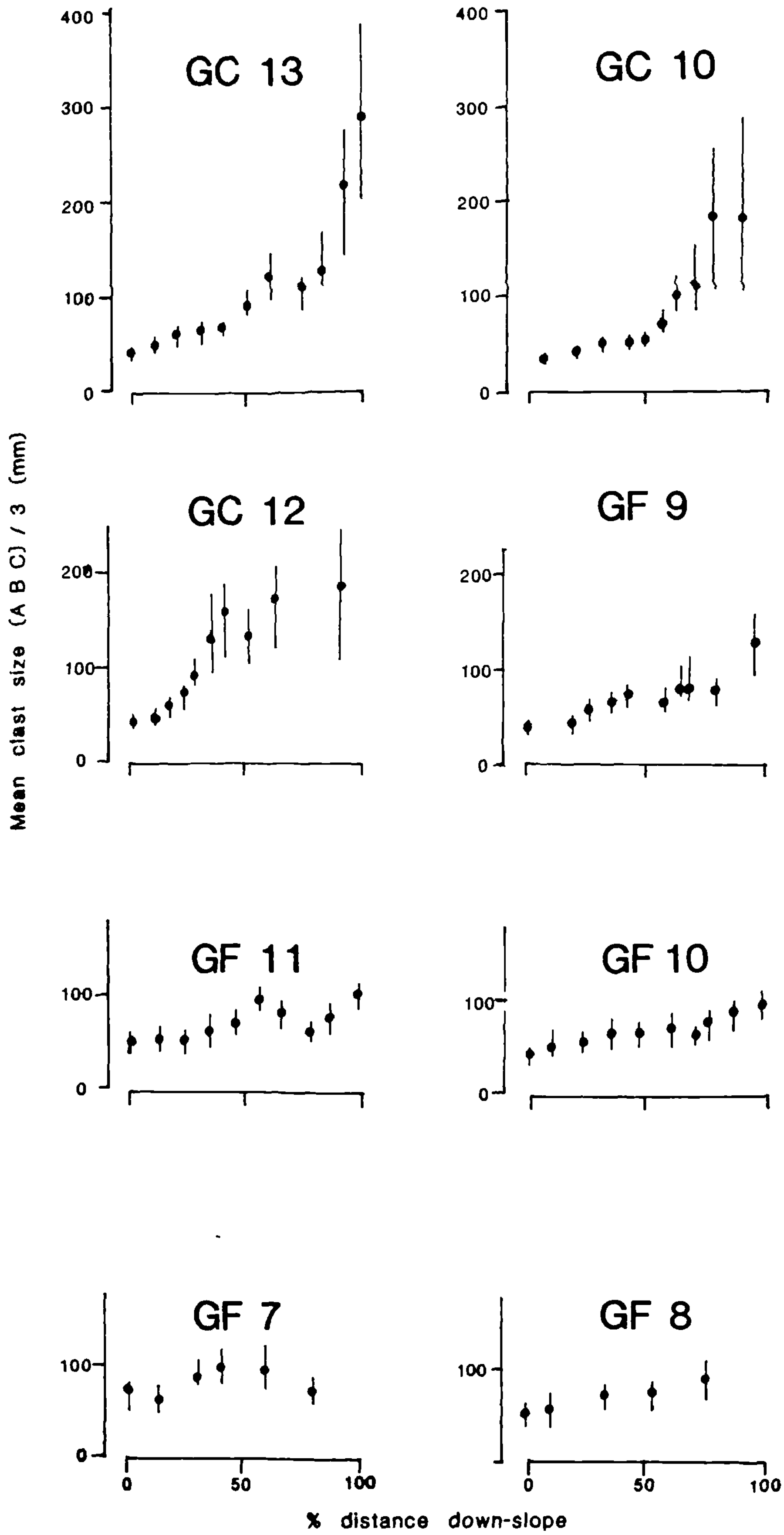
Rockfall talus cones.

The *a priori* model suggests that unmodified rockfall talus cones are generally characterised by downslope increases in clast size (fall sorting). Indeed, table 5.3 above demonstrated that the Scottish talus cones studied exhibit overall fall sorting. The clarity of this characteristic of rockfall talus cones, however, appears to vary in response to lithological control.

Figure 5.18 illustrates the sedimentary character of 8 talus cones from Glencoe and Glen Feshie. In general, sites from Glencoe have better developed fall-sorting patterns, particularly sites GC 13 and GC 14. The former has an unusual long profile form (figure 5.9), and it is suggested that this could have resulted from either a major rock release event or debris flow activity. The general downslope increase in clast size observed at this site, however, suggests that debris flow modification is unlikely. This pattern is interrupted at sampling point 7 where clast size is greater than at the next sampling point downslope, a phenomenon that corresponds with localised slope convexity. The coarser clasts at sampling point 7 are interpreted as the toe deposits of a major rockfall, and not a product of discrete rockfalls (cf Ballantyne, 1981).

Two factors have limited the development of consistent downslope increases in clast size. The first is illustrated by the contrast in overall clast size available at the sites in Glencoe and Glen Feshie. Many of the cones that have built up along the valley sides in the glacial breach of Glen Feshie are formed from very angular slab-shaped fissile schist fragments. Closely-spaced joints in the source areas in Glen Feshie (plate 5.4) have resulted in only a restricted size range of clasts on these cones and this is probably responsible for their poorer fall-sorting patterns

Figure 5.18 Median and interquartile range in mean clast size changes with distance downslope on Scottish rockfall talus cones.



PCate 5.4 Fissile schist outcrop in the glacial breach, upper Glen Feshie. The highly fracture nature of the rock has given rise to a small range in clast size on cones in this area.

compared with those on the Glencoe talus cones, where a wide range of clast sizes are present and which generally exhibit the clearest fall-sorting patterns.

Basal erosion by rivers has also modified the expected basal fringe of boulders at the foot of some of the talus cones (GC 10, GC 12, GF 11, GF 10.) For example, at GF 11 the expected clast size increase downslope of point 6 does not occur because basal erosion by the river has led to slumping on the lower part of the profile that has exposed finer sub-surface sediment (plate 5.5).

In general, therefore, expected fall-sorting patterns do occur on talus cones formed predominantly by rockfall. Exceptions to this pattern occur as a result of either basal erosion or lithological constraints on available clast sizes.

5.3.3 A comparative study based on sites from Lyngen, Northern Norway.

In order to assess the generality from the results of the Scottish Highlands on the characteristics of different types of fans and cones, a comparable but more restricted study was undertaken in Lyngen, Northern Norway (figure 5.19). The Lyngen Peninsula is located approximately 40km due east of Tromso, lying between latitudes 69° and 70° north, and longitudes 20° and 20° 30' east. The peninsula comprises a deeply dissected mountainous area with peaks of up to 1800m. Active glaciers are found in the upper parts of many

Plate 5.5 Basal erosion by the River Feshie has exposed much finer sediment at the toe of GF 11, and has also given rise to a much steeper lower slope segment than would otherwise have occurred if the characteristic concave basal fringe of boulders had been intact on this rockfall talus cone site.

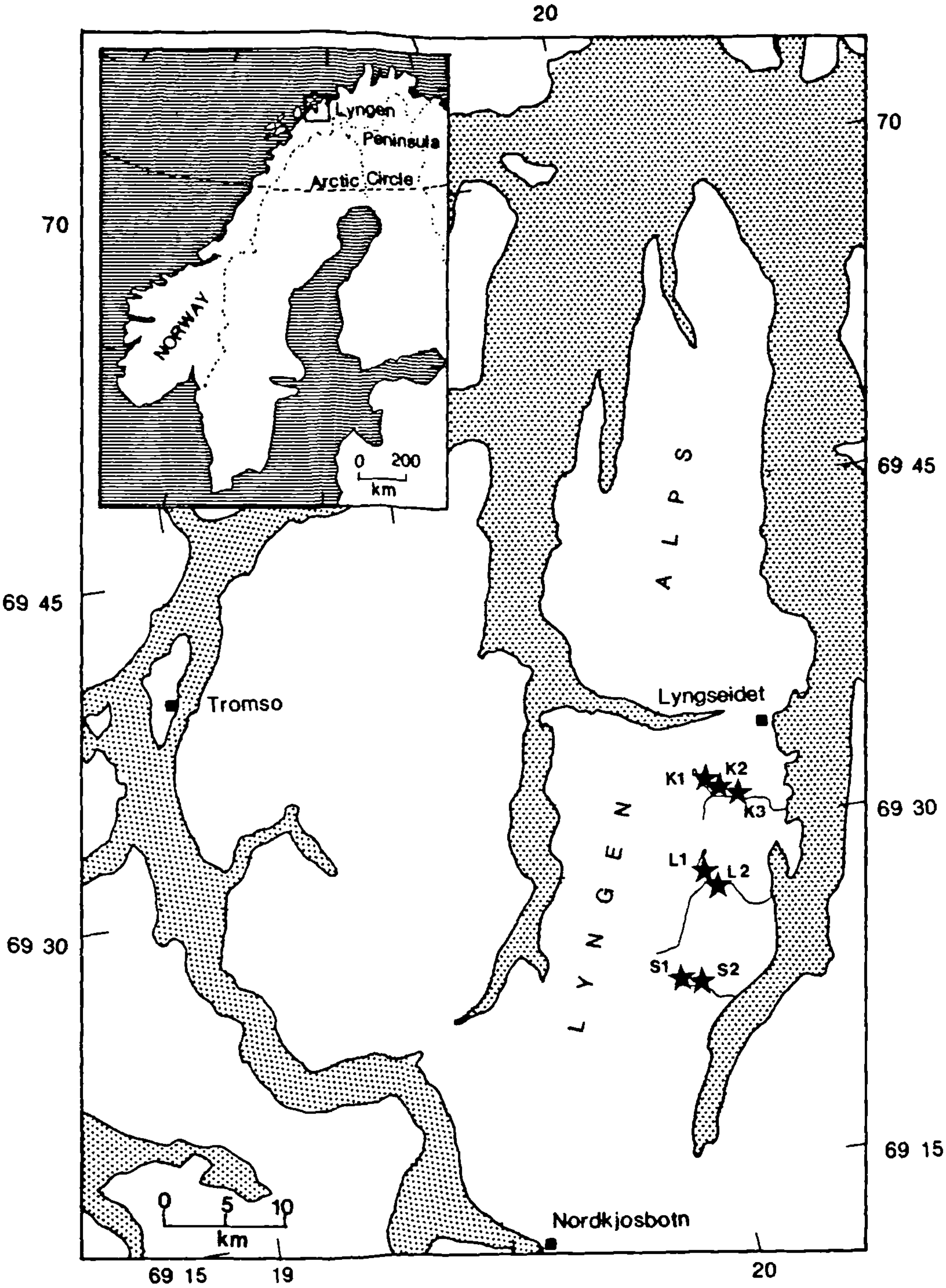


Figure 5.19 Location of the study sites in Lyngen, Northern Norway.

L: Lyngsdalen K: Kvalvikdalen

S: Steindalen

Table 5.4

The Lyngen study sites.

site	Type	Grid *	Altitude	Aspect
K1	3	DC 633147	720 m	220
K2	3	DC 638143	700 m	200
K3	1	DC 643134	460 m	100
L1	1	DC 615068	240 m	290
L2	2	GC 617062	220 m	75
S1	2	DB 587 989	420 m	270
S2	2	DB 589989	415 m	270

* Norske Hovedkarteserie 2nd series, 1:50,000 topographic maps.

site code
K = .Kvalvikdalen
L = Lyngsdalen
S = Steindalen

Landform type
1 Alluvial fan
2 Fluvially-modified debris cone
3 Debris cone

of the valleys, including the three study areas of Steindalen, Lyngsdalen and Kvalvikdalen. A total of 7 fans and cones were selected on the basis of aerial photograph analysis and were subsequently investigated in the field. Background information has been summarised in table 5.4 for each of the sites studied. All of the sites occur on metamorphic rock comprising mainly medium to fine-grained amphibolites of the Kjosen formation (Randall, 1971). The glacial record of the Lyngen peninsula is complex with many glacial limits. The outermost moraine sequences are found in the fjord valley sides and are thought to relate to advances during the Lateglacial (Andersen, 1979). Corner (1980) has tentatively suggested a Pre-boreal age for the most distant moraines found within the Lateglacial limits in the valleys adjacent to the fjords. All sites considered in this study lie outside the moraines deposited by the maximum readvance of the "Little Ice Age" c 1750 AD but within the Pre-boreal glacial limits and thus are probably older than c 9,000 years BP, a timespan similar to that for Holocene fan and cone development in the Scottish Highlands. Data collection in Norway was similar to that carried out in the Scottish Highlands but the slope survey was accomplished with an abney level and only the B axis of each stone (roughly comparable to (A+B+C)/3)) and angularity were measured. Clast form was not measured in Lyngen in view of the findings discussed above.

Generalised characteristics of the study sites are summarised in table 5.5. An assessment of similarity to the Scottish data can be made by comparing this Lyngen data set with the envelope of minimum and maximum variable values that describe the characteristics of Scottish alluvial fans, fluvially-modified debris cones, debris cones and talus cones (table 5.3). The variables analysed in this way are FGRAD, MP-ANG, SCALE, FINING and FORM.

The results of this comparative test are illustrated in table 5.6, the D symbol indicating that the Lyngen value falls outside the envelope described by the Scottish data. These deviations will be discussed first before comparing Lyngen fan and cone long profile form and down-fan fining patterns with comparable characteristics for the Scottish sites.

With the exception of K1 and S2 the sites have mean medial gradients within the range of comparable Scottish sites. At site K1 FGRAD is only 1 degree steeper than that found on the 6 Scottish debris cones. Site S2 is a steep cone formed predominantly by debris flow deposition issuing from a gully (plate 5.6). Fluvial deposits at the basal part of this site indicate that it is a composite cone (type 2). However, fluvial activity on S2 is more limited than at the neighbouring site S1, consequently FGRAD is steeper than the values for Scottish fluvially-modified debris cones but falls within the envelope for debris cones.

Table 5.5

Lyngen data

SITES	type	CLASSIFICATION CRITERIA				
		FGRAD	MP-ANG	SCALE	FINING	FORM
K1	3	26°	1.9	2	0.6	1.3
K2	3	20°	1.9	1	1.0	1.9
L1	1	6°	2.7	1	3.5	3.3
L2	1	8°	2.1	3	2.7	1.5
S1	2	17°	no data	no data	no data	3.6
S2	2	19°	no data	no data	no data	2.8
K3	2	12°	no data	no data	no data	1.4

type 1 = Alluvial fan, 2 = Fluvially-modified debris cone,
3 = Debris cone.

Table 5.6
Similarity and dissimilarity of Lyngen and Scottish fans and cones.

SITES	type	CLASSIFICATION CRITERIA FGRAD	MP-ANG	SCALE	FINING	FORM
K1	3	D	S	S	S	S
K2	3	S	S	D	S	S
L1	1	S	S	S	S	S
L2	1	S	D	S	S	S
S1	2	S	no data	no data	no data	S
S2	2	D	no data	no data	no data	S
K3	2	S	no data	no data	no data	S

S	SIMILAR	: ie data fall within the envelope described by the Scottish data for that group
D	DISSIMILAR	:ie data fall outside the envelope described by the Scottish data for that group

(The implications of the differences between the Lyngen sites and the Scottish sites are explained in the text.)

PLate 5.6 A fluvially-modified debris cone in Steindalen, Lyngen Peninsula, Northern Norway. (site S2).

Values for FORM (table 5.5) at all sites in Lyngen fall within the ranges described by the Scottish data, but it should be remembered that this was the weakest discriminator of different types of fan and cone with considerable overlap occurring in the different landform classes. The long profile form of the Lyngen sites is illustrated in figure 5.20. The two debris cones (K1 and K2) are shown at the top, the three fluvially-modified debris cones in the middle and the two alluvial fans at the bottom of the figure. All of the profiles are comparable with the Scottish sites in terms of their process group.

In general, clasts are much more angular on non-glacially derived rock debris in Lyngen than on comparable deposits found in Scotland. This is certainly the case at site L2 (table 5.5) which has significantly more angular debris than any of the Scottish alluvial fans.

Both K1 and K2 have slightly lower SCALE (table 5.5) values than the 6 debris cones studied in Scotland. On both K1 and K2 clast sizes were not especially large but total distance from apex to toe is greater than that found on some of the Scottish sites (eg GC 11 is only 76m long). Gross down cone changes in clast size suggests downslope increase in clast size site K1 (FINING = 0.6). At this site debris flow activity has been primarily one of reworking existing talus debris: the survival of generally larger clast sizes (reflecting past rockfall deposition) in the distal part of the slope is illustrated in figure 5.21.

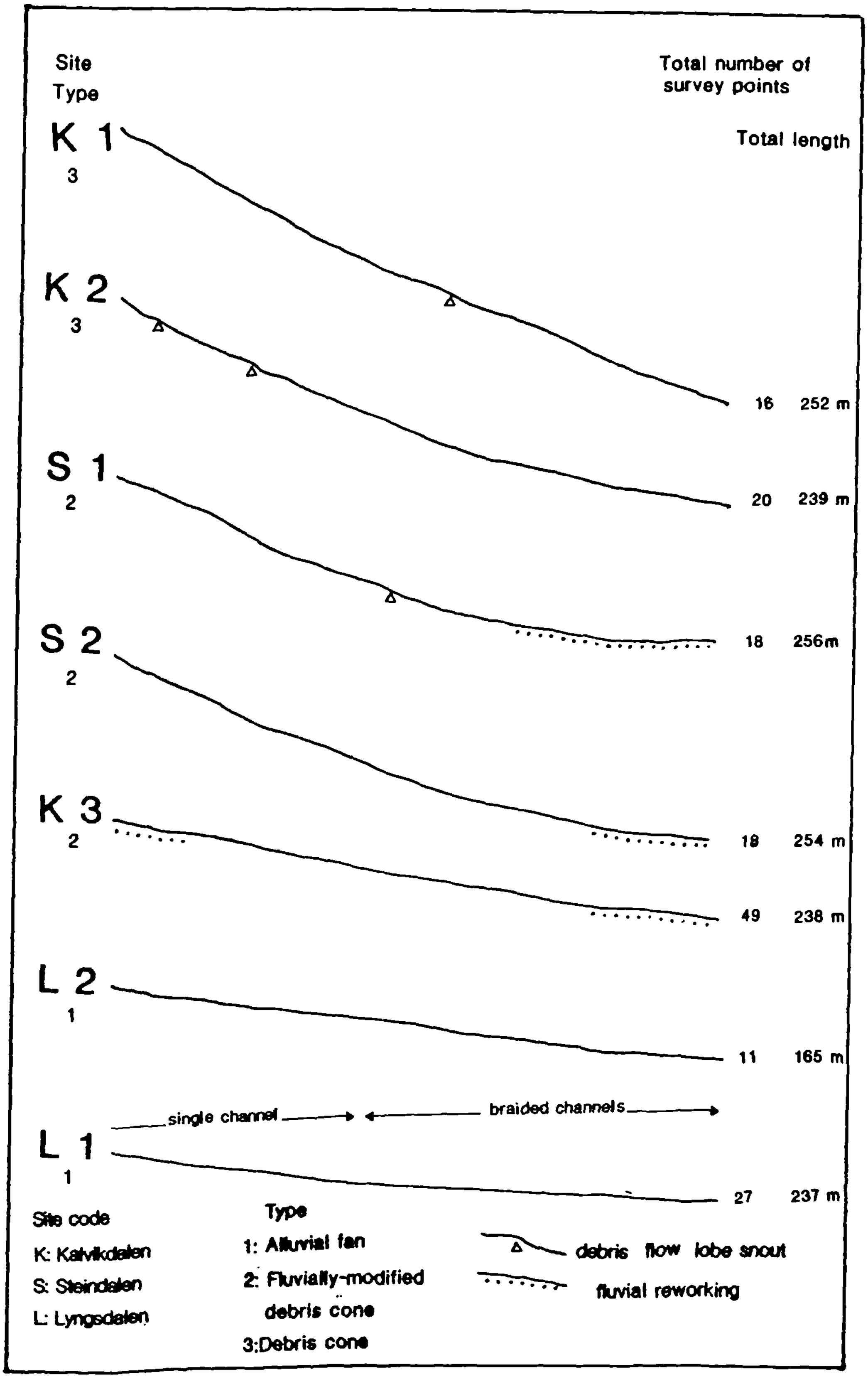


Figure 5.20 The morphological character of the long profile of alluvial fans, fluvially-modified debris cones and debris cones in Lyngen, Northern Norway.

The patterns of down-fan changes in sediment size and sorting illustrated in figure 5.21 are also similar to the Scottish findings. However, L1 shows a greater degree of down-fan fining and increased sorting of sediment than that found on any of the Scottish alluvial fans. This site is actively aggrading and is supplied with both sediment and meltwater from a glacier in its catchment. In the upper part of the fan, large boulders derived from a moraine upstream have been deposited in a chaotic pattern probably by an extreme flood event. The upper part of the fan is fed by a single large stream channel. However, this pattern is replaced downstream by lower-energy braided distributaries that cover much of the lower half of the fan. Both a marked decline in gradient and an increase in the degree of fining and sorting of sediment reflect this change in channel pattern and stream competence. Median clast size at this point on the fan is equal to the cutoff of 100mm used by Boothroyd and Nummedal (1978) to define proximal (clasts greater than 100mm) and medial (clast sizes between 100mm and 2mm) core fan facies. More pronounced down-fan fining of sediment on this Lyngen alluvial fan compared with the Scottish sites appears to be a function of active aggradation, greater probability of regular low flow discharges (at least during the runoff season), lack of vegetation cover, and a braided stream pattern over the distal active segment. Visual inspection of the site suggested that there is probably greater lateral continuity in these down-fan sedimentary patterns than on FI 5 (see

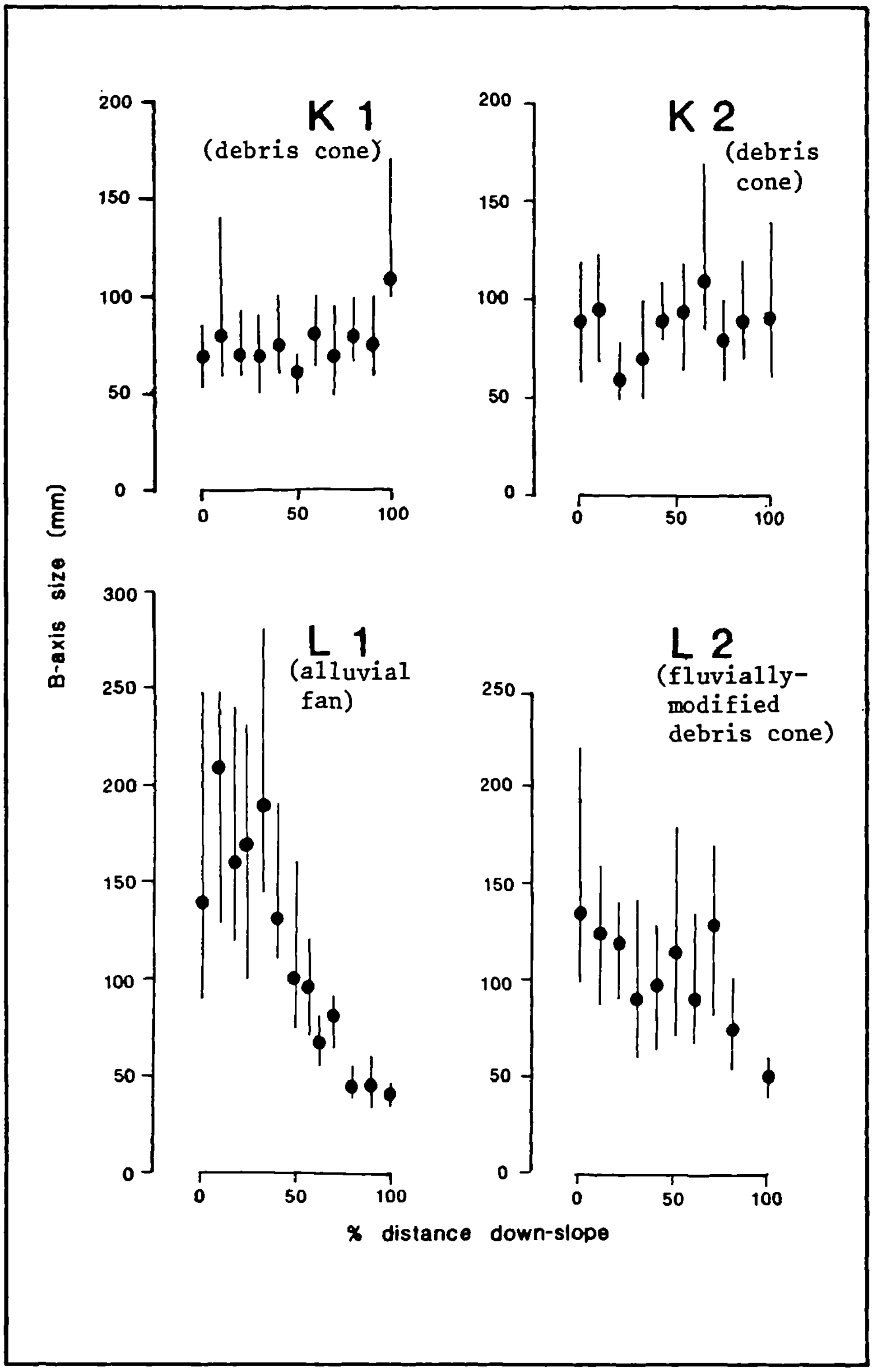


Figure 5.21 Median and interquartile range in mean clast size changes with distance downslope on four fans and cones in Lyngen, Northern Norway.

figure 5.13 above).

5.4. CONCLUSION: REASSESSMENT OF THE A PRIORI CLASSIFICATION.

Several aspects of the *a priori* model of fans and cones have been demonstrated to be correct in Scotland and Lyngen. The fundamental theme of a continuum of landforms was shown to be appropriate when considering alluvial fan, fluvially-modified debris cone and debris cone development in environments such as the Scottish Highlands and Northern Norway. However, it was not possible to examine the nature of the continuum between debris cones and talus cones because talus cones modified by debris flow were not studied. Within the continuum, fans or cones formed by the dominance of one or more processes have certain characteristics that distinguish them from each other. However, not all of the expected properties that were thought to be diagnostic of different types of fan and cone were found in any of the study areas. Such variations from the *a priori* model have arisen through a combination of factors that in general relate to the relatively short timespan of fan and cone formation compared with, for example, alluvial fan formation in semi-arid tectonically active regions. Therefore certain modifications to the model are necessary in order to characterise alluvial fans, composite cones, debris cones and talus cones found in deglaciated mountain environments. The generic properties of such fans and cones will be summarised below. It must be stressed that these findings are based upon a relatively small sample of sites from each group, so that modification of the classification of fans and cones should be employed with a degree of caution regarding the presence or absence of all of the diagnostic characteristics.

5.4.1 Summary.

Mean medial gradient.

The alluvial fans that were studied had mean gradients ranging from 2° to 10°, fluvially-modified debris cones 9° to 19°, debris cones 20° to 26°, and talus cones from 25° to 33°. Mean medial gradients therefore show a gradual steepening that reflects different process domains, ranging from fluvial, mixed fluvial and debris flow, and debris flow to rockfall.

Slope form.

The *a priori* model does not accurately describe the form of alluvial fans in relation to other features within the continuum, as these features proved not to have the expected smooth profile or high degree of concavity, especially when compared with composite cones. Similarly, some of the talus cones had more complex profiles than anticipated.

Alluvial fan long profile form in the Scottish Highlands is irregular where local incision has occurred. Fluvially-modified debris cones, that have steeper and often very irregular apex areas, have the greatest degree of slope concavity. In contrast, debris cone long profile form was found to be less concave than expected and often very irregular. Most talus cones studied had upper rectilinear slope segments, but the anticipated lower slope concavity was often absent because of basal erosion, and in one case because the cone had aggraded to the edge of a rock ledge. Talus cone long profiles were more irregular than expected, but this reflected erosion at the sites studied and may not be a characteristic of Scottish talus cones in general.

Clast shape.

Because of strong lithological controls on sediment character, aggregate clast form (C/A) was found to be an inadequate criterion for identifying differences between types of fan and cone. Nevertheless, differences in clast roundness do occur between the process groups. Alluvial fans generally have sub-angular clasts, composite cones have rather more angular clasts, debris cones have angular clasts, and talus cones have the most angular clasts. Some minor variation within these groups does occur depending on lithology with, for example, the most angular clasts being derived from fissile schists. No appreciable differences in rounding were found in a down-fan direction on Scottish Highland fans or cones.

Clast size.

Changes in clast size with distance downslope from the apex do not always reflect the predictions of the *a priori* model. The alluvial fans studied display some degree of overall down-fan fining, but the pattern is often highly irregular depending upon the position and sorting characteristics of individual sedimentary units such as bars and gravel sheets. Examination of changes in clast size-distance relationships across the surface of the active area of one alluvial fan revealed irregular patterns over the entire active fan surface, probably reflecting very rapid deposition and insufficiently competent flows to rework such sediment. The general coarseness of fan sediments (broadly equivalent to proximal core fan facies as defined by Boothroyd and Nummedal (1978)), overall short fan lengths, reworking of older and often very coarse sediments by flash floods, and lack of competent moderate to low flow conditions for sorting medium and small sized clasts has meant that the surface sedimentary characteristics of Scottish alluvial fans are more chaotic, and at the individual sedimentary unit scale more immature, than those found on actively aggrading fans such as one studied in Lyngsdalen. Thus down-fan fining patterns may be clearer at alluvial fan sites in other deglaciated mountain environments where fans are larger, have an adequate sediment supply, and experience suitable flow conditions.

The fluvially-modified debris cones studied have large and often poorly-sorted clasts in their upper areas. However, the degree of downslope fining tends to increase as a result of overbank fluvial deposition in the area nearer the toe of such composite features. In contrast, unmodified debris cones show no consistant patterns of downslope fining or coarsening. Lateral variations on one cone illustrated the influence of individual debris flow lobe snouts on down cone clast size patterns. Individual lobes may have a distinct increase in clast size toward the lobe snout. However, distal debris flow deposits may exhibit much smaller ranges in clast size, with less apparent contrast in clast size between the lobe tread and the riser.

The expected pattern of downslope increase in clast size was found on most of the talus cones, but the degree of such fall sorting was found to be influenced by lithology. Sites studied in Glen Feshie had only a small size range available as a result of a high joint frequency in their source areas compared with more massive lavas that have given a much greater clast size range on the talus cones in Glencoe. Basal erosion on some cones has also truncated expected increases in clast size downslope.

The results of this research are summarised in tables 5.7a and 5.7b, which represents an <u>a posteriori</u> model of fan and cone morphological and surface sedimentary character pertinent to the identification of such landforms in the Scottish Highlands, and possibly elsewhere in upland Britain.

TALUS CONE	Debris flow modified talus cone (no data)	DEBRIS CONE	FLUVIALLY-MODIFIED DEBRIS CONE	ALLUVIAL FAN	
ROCKFALL		DEBRIS FLOW	FLUVIAL		Dominant process
$25° - 33°$		$20° - 26°$	$9° - 19°$	$2° - 10°$	Mean gradient
Generally talus cones have an upper rectilinear slope and a concave basal fringe. However, the basal concavity may be absent on cones that have been basally eroded; such slopes may also be more irregular in form. Furthermore, talus cone slope form may also be affected by single large rockfalls and by overhanging rock walls.		Debris cones generally have irregular and almost linear long profiles. A convex upper slope element may occur as a result of either debris flow erosion or abundant viscous debris flow deposition near the apex. Lower slope concavity may be enhanced by a predominance of more fluid types of debris flow deposition.	F.M.D.C.s have marked long profile concavity. Proximal slopes may be irregular and steep, reflecting debris flow deposition. Distal slopes are generally smoother and have much lower slope angles, reflecting fluvial deposition.	Alluvial fans generally have concave longprofiles, but the slope may be irregular on fans that have been incised.	Slope form

Table 5.7a. An *a posteriori* model of fan and cone landform characteristics in the Scottish Highlands.

TALUS CONE	Debris flow modified talus cone no data	DEBRIS CONE	FLUVIALLY-MODIFIED DEBRIS CONE	ALLUVIAL FAN	
ROCKFALL	**DEBRIS FLOW**		**FLUVIAL**		Dominant process
The most angular clasts of these landforms.	Angular clasts.		Angulat to sub angular clasts.	Predominantly sub angular clasts, with some sub rounded clasts.	Average clast shape
Downslope increase in clast size is generally good. However, lithological control of the clast size range may limit the degree of "fall sorting". Basal erosion may also result in the removal of the characteristic apron of boulders at the foot of rockfall talus cones.	An overall decrease in clast size with distance downslope, but any trends may be interrupted by highly localised clast size changes associated with individual depositional units. Generally the coarsest debris is concentarated in the lobe snout and levée areas of individual debris flow deposits. Deposits that were laid down by viscous debris flow tend to be poorly sorted compared with deposits of more fluid type debris flow deposition.		An overall decrease in clast size with distance from the cone apex. Proximal deposits are generally largest and most poorly sorted. Distal deposit s may exhibit good sorting.	An overall development of down-fan fining may be masked by the character of individual depositional units, where deposition may have occurred very rapidly during flood conditions. Scottish fan sediment-distance relationships appear to correspond with Proximal Core Fan Facies (Boothroyd & Nummedal, 1978).	Clast size and distance downslope

Table 5.7b An *a posteriori* model of fan and cone landform characteristics in the Scottish Highlands

CHAPTER 6

ENVIRONMENTAL AND MORPHOMETRIC CONTROLS OF FAN AND CONE DEVELOPMENT.

6.1 INTRODUCTION

This chapter has two aims:

1. to establish where different types of fan and cone occur in the Grampian Highlands, and

2. to establish how different morphometric and environmental variables influence the distribution and nature of fan or cone development.

Prior to this study the only systematic documentation of fan and cone distribution in the Scottish Highlands took the form of references to "alluvial fans" in the Geological Survey Memoirs published during the early part of this century. Recent statements by Innes (1982, 1983a) suggested that debris cone distribution is more limited than that of hillslope debris flow activity in the Scottish Highlands. However, this view is challenged by abundant evidence for widespread debris cone as well as alluvial fan development. It is appropriate that the significance of fan and cone development in general, and processes such as debris flow activity in particular, are re-evaluated with regard to our understanding of postglacial landform development in the Scottish Highlands.

A number of factors that may influence the type of fan or cone development were summarised in section 4.5.1 of chapter 4. These factors included lithology, glacial history, aspect, altitude, precipitation, vegetation cover, relief and gully or valley configuration. Each of these will be considered, with the exception of the degree of vegetation cover, which proved to be problematic. It was intended to assess from aerial photographs whether or not debris cone development is associated with a greater extent of bare ground in the catchment than is found in the contributing areas of alluvial fans (cf Johnson, 1984; chapter 4). The percentage of vegetation cover could not, however, be measured realistically because the data base only reflects conditions during the year in which each photograph was taken. The amount of bare ground may vary considerably from one year to the next, especially in areas where moorland management requires periodic burning of heather. The final choice of variables relied on both their potential meaningfulness and also their ease of measurement, so that it was possible to document from aerial photographs the majority of fans and cones found in the Grampian Highlands transect.

The problem of evaluating the role of environmental and morphometric factors involved in fan and cone development is complex. Previous studies in North America have concentrated on bivariate morphometric relationships between fans and their contributing basins (Melton, 1965; Ryder, 1971a;

Church and Mark, 1980; Kostaschuk et al, 1986), and have attempted to interpret the results with regard to certain environmental controls such as glacial history (Ryder, 1971a). The relevance and implications of the conclusions of this previous research are reviewed below in relation to fan and cone formation in the Scottish Highlands (section 6.3.2).

Simple bivariate relationships, however, do little to explain the morphometric controls that determine the three dominant processes that give rise to different types of fans and cones, since such relationships are essentially multivariate. In this study discriminant analysis was employed in order to establish the best linear combination of several variables that define morphometric control of fan and cone processes. These results, along with the interpretation of environmental controls, allow an assessment and interpretation of the distribution and significance of fan and cone landforms. This will lead on to a more detailed discussion of the chronology and evolution of fans and cones in the next chapter.

6.2 DATA COLLECTION

The data collection was designed to provide a comprehensive list of factors that may influence the type and distribution of fan and cone development in the Grampian Highlands. The data set consists of a casewise record of information on site location, environment, and basin and fan morphometric variables. The content of the data matrix falls into two parts, namely dependent variables describing the fan morphometry and independent variables describing contributing area morphometry and environment (table 6.1). A total of 253 sites are documented in the environmental and morphometric data set, with a supplementary data set composed of environmental data adding a further 112 sites. The methodology of data collection will be discussed in relation to the total areal extent of the survey, the measurement of the different variables and sources of error during data collection.

The total extent of the survey area has been described in detail in chapter 3. Panchromatic aerial photographs provided the initial data base for the identification of different types of fan and cone, with the morphometric measurements being made on 1:25,000 topographic maps. Initially, the survey was intended to be an exhaustive documentation of all fans and cones found within the Grampian Highlands. However, this proved unfeasible not only because of the large area under consideration, but also because the original variable list was unrealistic (see above). It was therefore necessary to limit the number of fans and cones documented for each area. A minimum size for documentation was introduced, which will be discussed later in relation to errors in data collection. Similarly, very large alluvial fans found in areas of extensive low ground, such as the Spey Basin, were excluded because their

Table 6.1

Environmental and morphometric data set: list of variables.

Total number of cases : 253

1. a. INDEPENDENT VARIABLES: SITE ENVIRONMENT

ID regional site identification tag.
NGR National grid reference (8 characters)
LITH solid geology
GL relationship with Loch Lomond Readvance limits
PPT mean annual precipitation
ASP fan / cone aspect
ALT fan apex altitude

1. b. INDEPENDENT VARIABLES: CONTRIBUTING AREA MORPHOMETRY

BH maximum basin height
BL maximum basin length
BGRAD basin gradient (in degrees)
BW maximum basin width
BAREA adjusted basin area

2. DEPENDENT VARIABLES

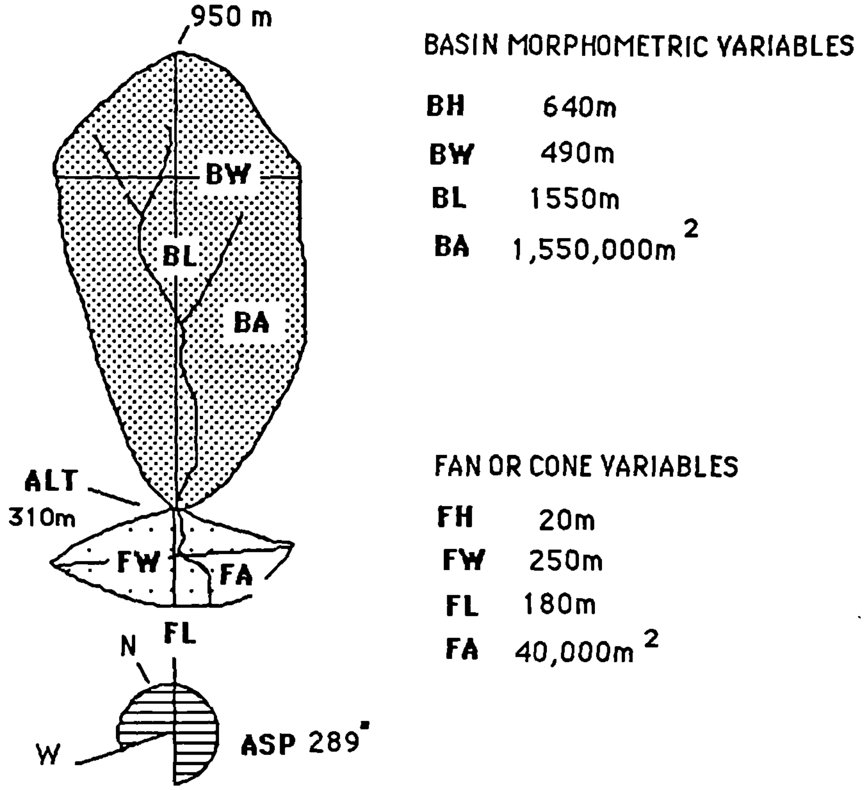
FH maximum fan / cone height
FL fan / cone length
FW maximum fan / cone width
FAREA adjusted fan / cone area
FGRAD fan / cone gradient (in degrees)
GROUP dominant process group

catchment characteristics do not necessarily reflect general patterns associated with upland fan development. For these reasons both large floodplain confluence alluvial fans and fans and cones smaller than the size threshold were excluded from the data collection.

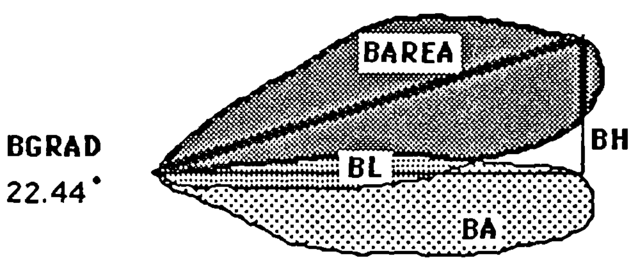
Fans and cones were identified from aerial photographs by their characteristic "fan-shaped" planform. Each site was assigned to one of three different dominant process groups identified by the occurrence of certain diagnostic attributes such as debris flow lobes and levees, and other features as discussed above in chapters 4 and 5 (table 5.1). When evidence for one process was observed over at least two thirds of the landform surface, then that site was assigned to that dominant process group, either as an alluvial fan (group 1), debris cone (group 2), or talus cone (group 3). No intermediate types were examined in this chapter, which is primarily concerned with the controls of dominant fan- or cone-forming processes. It should be stressed, therefore, that these alluvial fan, debris cone and talus cone groups identified in this survey are not exactly the same as the alluvial fans, fluvially-modified debris cones, debris cones and talus cones as described in the previous chapter.

Site location was recorded by both a regional alphanumeric code (ID) and by an eight-character National Grid Reference (NGR) that represents the location of the apex of each feature. Thus it was possible to compute maps from the combined data sets of the distribution of fans and

Figure 6.1a Measurement of fan or cone and basin variables.



6.1.b. measurement of adjusted basin area (BAREA)



cones by using the GHOST-80 graphical package (figures 6.7 to 6.9 below).

Independent environmental data include the altitude of the fan or cone apex (ALT) in metres above OD and aspect (ASP) of the medial axis of the fan away from the mountain front measured in degrees relative to grid north. The medial axis of the fan was defined by constructing a line from the apex that bisected the midpoint of the widest part of the fan (FW in figure 6.1a). Aspect (ASP) was measured in degrees in the down-fan direction of this medial line, with grid north at 0 (figure 6.1a). Maximum mean annual precipitation (PPT) in the contributing basin area was estimated from the 1:125,000 isohyte map for the standard period 1940-1971 (Meteorological Office, 1977). Binary notation was used to indicate fan or cone position relative to the Loch Lomond Readvance glacial limits (GL), with 1 = inside and 0 = outside. A twofold classification was used to describe the dominant lithological make-up of the contributing area (LITH), with any combination of two of the following: granites, lavas, mica-schists, and quartzites.

Independent morphometric data were measured within the limits of the drainage basin unit. The term basin is used here to indicate the contributing area of any type of fan or cone, regardless of whether it comprises a rockface or gully or valley. The following five morphometric variables were measured from the 1:25,000 Ordnance Survey topographic maps: BH, BL, BGRAD, BW and BAREA (table 6.1; figures 6.1a and

6.1b).

BH, or basin height is the maximum relief of the drainage basin unit, derived by subtracting the fan apex altitude at the mouth of the basin from the maximum basin altitude. Basin length (BL) is the maximum straight line distance as measured from the maps between the fan apex and the farthest point in the basin, following as closely as possible to the central drainage course. However, when "dog leg" shaped basins were encountered it was necessary to make two straight line measurements along the midpoint of the basin.

Basin gradient (BGRAD) is the measurement in degrees of the mean basin slope found by calculating the inverse tangent of BH/BL. This variable provides a measure of average basin slope that may be important in determining which process or processes are dominant in fan or cone formation (cf chapter 4). Both BGRAD and the tangent of basin slope have been used elsewhere in the literature in morphometric analyses of fan and basin relationships.

Maximum basin width (BW) was measured across the widest part of the contributing area at a right angle to BL. This rule of measurement was adopted in order to minimise operator bias. Basin width alone probably cannot be interpreted in terms of process control, but in combination with other morphometric variables BW may prove to be an important factor governing the subsequent processes of fan or cone formation. Narrow source area widths may also be fundamental controls of talus cone development where the configuration of the rockface or rock gully favours a concentration of rockfalls in one area.

Basin area (BA) was first measured in plan from the topographic maps, with boundaries defined by the watershed. Planform basin area has been widely used in the literature on fan or cone and basin morphometric relationships as an indication of the maximum potential source area of sediment and runoff (eg Melton, 1965; Ryder, 1971a; Church and Mark, 1980; Kostaschuk _et al_, 1986). However, the use of plan basin area (BA) is likely to underestimate significantly the true surface area of steeper catchments (figure 6.1b). Thus a temporary variable was created within the SPSS-X routines used in the data analysis which gave the adjusted basin area (BAREA). BAREA was calculated as:

BAREA = BA / cos BGRAD.

The effect of this simple trigonometric calculation is to tilt and stretch the plan area BA by raising it to the angle BGRAD (figure 6.1b). In the example shown in figure 6.1b BH = 640m and BL = 1,550m which gives BGRAD = 22.44, so by dividing BA (1,550,000 m^2) by the cosine of BGRAD (0.9243) we get an adjusted basin area of _c_ 1,677,000 m^2.

Five dependent morphometric variables were measured on the fan or cone, namely FH, FL, FW, FAREA and FGRAD (table 6.1, figure 6.1a). Measurements of these variables correspond to those made of comparable basin variables. FH or fan or cone height was calculated by subtracting the altitude of the fan or cone toe from ALT, the altitude of the apex. Fan or cone length (FL) was measured along the medial axis of the fan as described in the calculation of ASP. Mean fan or cone gradient (FGRAD) was derived by calculating the inverse tangent of FH/FL. Fan or cone width (FW) was measured across the widest part of the landform. Planform fan or cone area (FA) was defined from the areal extent of fan or cone deposits as seen from the aerial photographs and not as defined by contour intervals, as the latter proved insufficiently accurate. FA was adjusted to FAREA using the same method of calculation as that described for deriving BAREA (ie FAREA = FA / cos FGRAD). FAREA was then used throughout the analysis in preference to FA because it gives the most realistic indication of the area of sedimentation at a site, without at this stage involving the estimation of fan or cone volume, which is considered later in chapter 7, section 7.3.

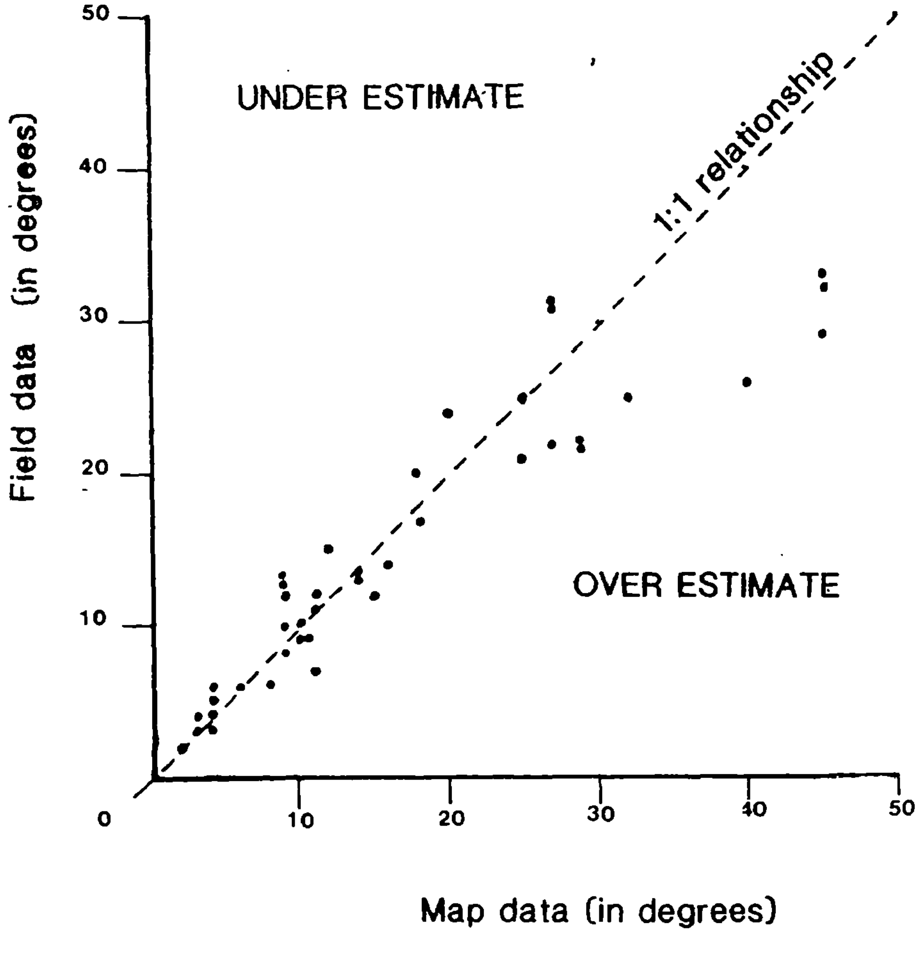
There are several sources of error inherent in using only maps and aerial photographs as the data base, as well as possible operator bias. These are outlined below.

The assignment of a site to an inappropriate process group (such as a talus cone classified as an alluvial fan) would render the information used in later analysis invalid. The degree of accuracy was partly a function of the resolution of the panchromatic aerial photographs. Because dominant process can only be assessed on the surface of the landform it is possible that at some sites other processes may have been of greater importance during aggradation history. Provided that the process indicators visible on the fan surface have been correctly identified, the inclusion of that site into the analysis on that particular process group is valid. Further comments on the appropriateness of the threefold process classification are considered in section 6.3.3.

Other sources of error are associated with the limitations of the scale of the data base, which in this instance involved the use of 1:25,000 Ordnance Survey topographic maps with contour intervals set at either 10m or 25ft (7.62m). For example, possible errors associated with using a map data base include the measurement of height, planform length and planform width, although such errors decrease proportionally with increasing size of map area.

An indication of the errors arising from map-based measurements can be gained from figure 6.2, which illustrates the difference between tacheometric ground survey of fan or cone gradients and map measurement of FGRAD at a subsample of 40 sites. A noticeable increase in

Figure 6.2 Errors associated with the measurement of mean fan or cone gradient from a 1:25,000 topographic map data base, compared to field survey of mean fan or cone gradient.



overestimation occurs as slope angles exceed 25°. The relationship illustrated in figure 6.2 indicates that there is a greater probability of overestimation of gradient on steeper slopes than on gentler gradients. The gradients of gentle and moderate fan slopes show no evidence of systematic over- or under-measurement. However, it is not possible to calibrate this error precisely for the whole data set on account of basin-to-basin variation in the position of contour lines relative to the fan or cone apex. For example, where the contour line coincides with the fan or cone apex and the toe the measurement of ALT will be more accurate than for a basin of equal size where either the apex, the toe or both lie between contour lines. This factor will in turn influence the accuracy of derived variables such as FH, FGRAD and to a much lesser extent FAREA.

Another example of potential error is the minimum measurement of plan area, which was determined by the scale of the map. Only fans and cones greater than $2500m^2$ were included in the survey, corresponding to a minimum area of $4mm^2$ on the 1:25,000 topographic map. Unfortunately, this meant that many small talus cones (particularly in the Western Grampian Highlands) had to be excluded from the data set. The implications of this bias are considered below in relation to talus cone development inside and outside the Loch Lomond Readvance glacial limits (section 6.3.1).

Plan area measurements from topographic maps were carried out with the use of a Tektronix digitiser. The effect of operator variance was assessed by repeating nine times the measurement of a 1km2 map area. All nine measurements of this areal unit were found to be correct within 1.1% of the true value.

The extent and nature of the errors associated with the compilation of the data set are considered to be acceptable for a data set derived entirely from 1:25,000 maps and aerial photographs. However, a note of caution is necessary in the interpretation of the results reported below, as small-scale landforms are under-represented and the process domains may be subject to oversimplification in terms of implied long-term development.

6.3 DATA REDUCTION, ANALYSIS AND DISCUSSION

6.3.1 Fan and cone distribution

Innes (1983a) used shaded 100km2 grid squares to illustrate the presence of hillslope debris flow deposits in the Scottish Highlands. For comparative purposes the same method of data presentation has been used in this study with figures 6.3, 6.4 and 6.6 showing the distribution pattern of alluvial fans, debris cones and talus cones respectively, along with figure 6.5 which is a revised version of Innes' (1983a) map from Ballantyne (1986c). The data base for these maps was the distribution of over 360 fans and cones (>2,500 m^2 in area), identified on aerial photographs and

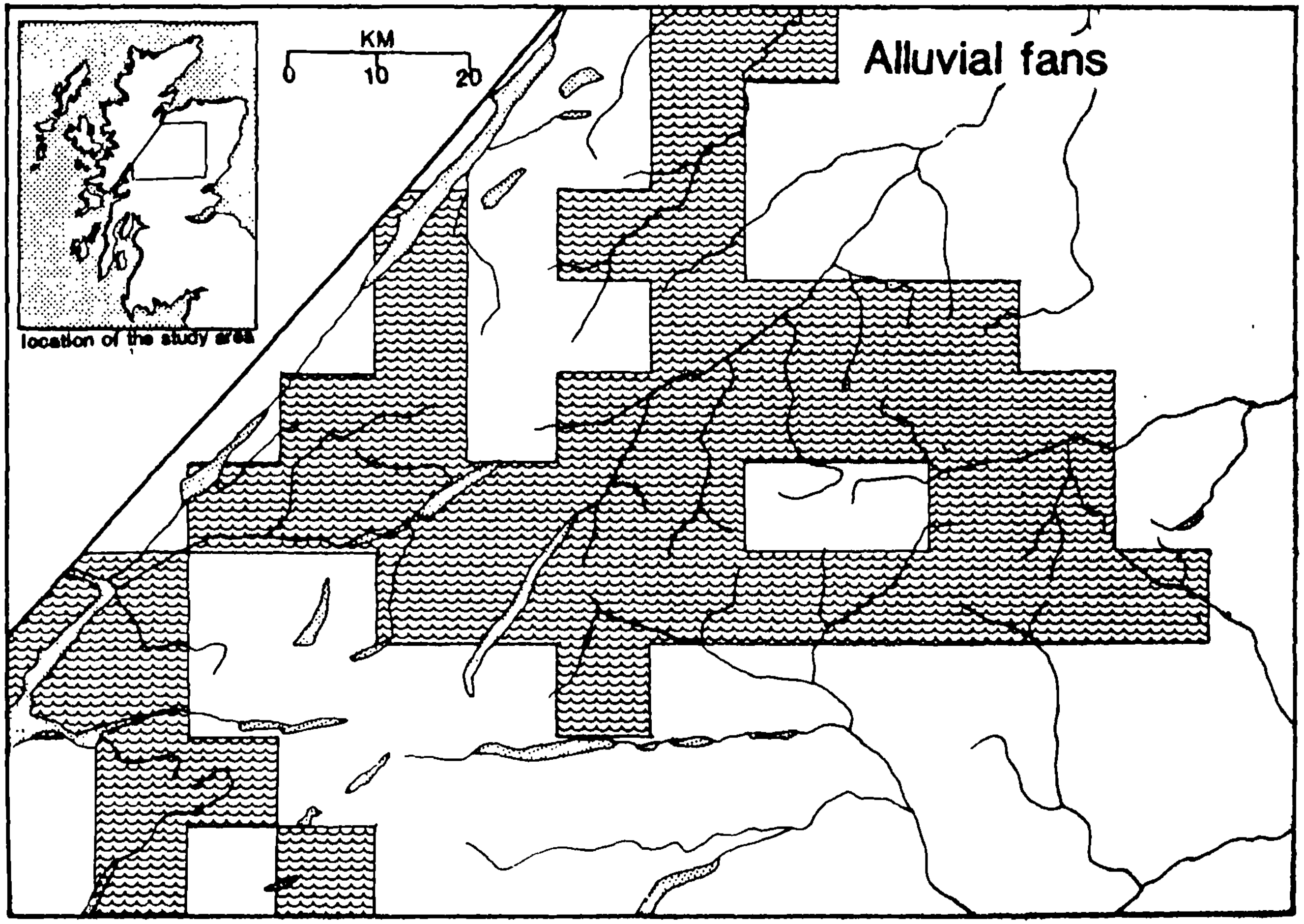


Figure 6.3 Alluvial fan distribution in the Grampian Highlands. Fan presence shown by shaded 100 km^2 grid.

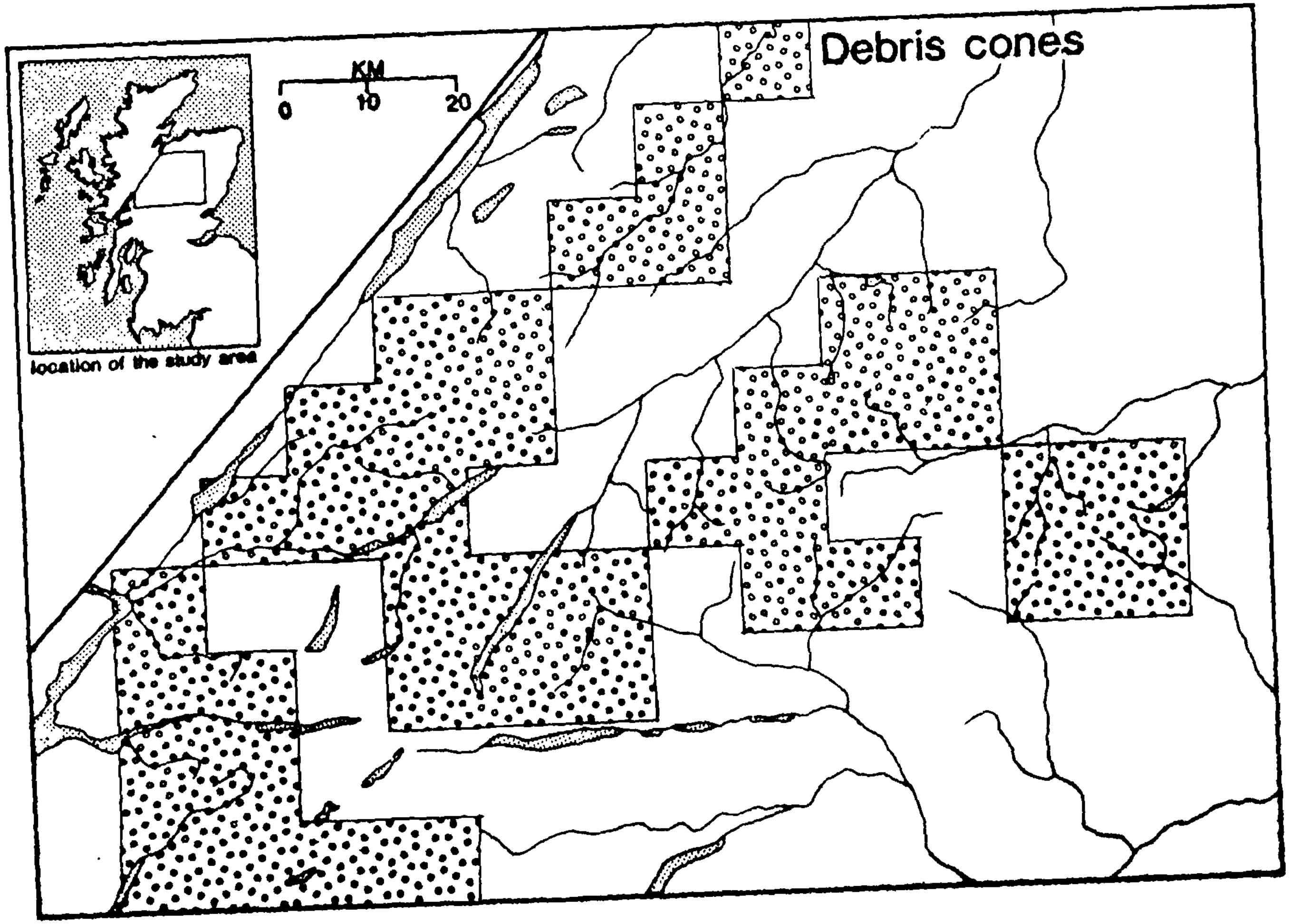


Figure 6.4 Debris cone distribution in the Grampian Highlands. Cone presence shown by shaded 100 km^2 grid.

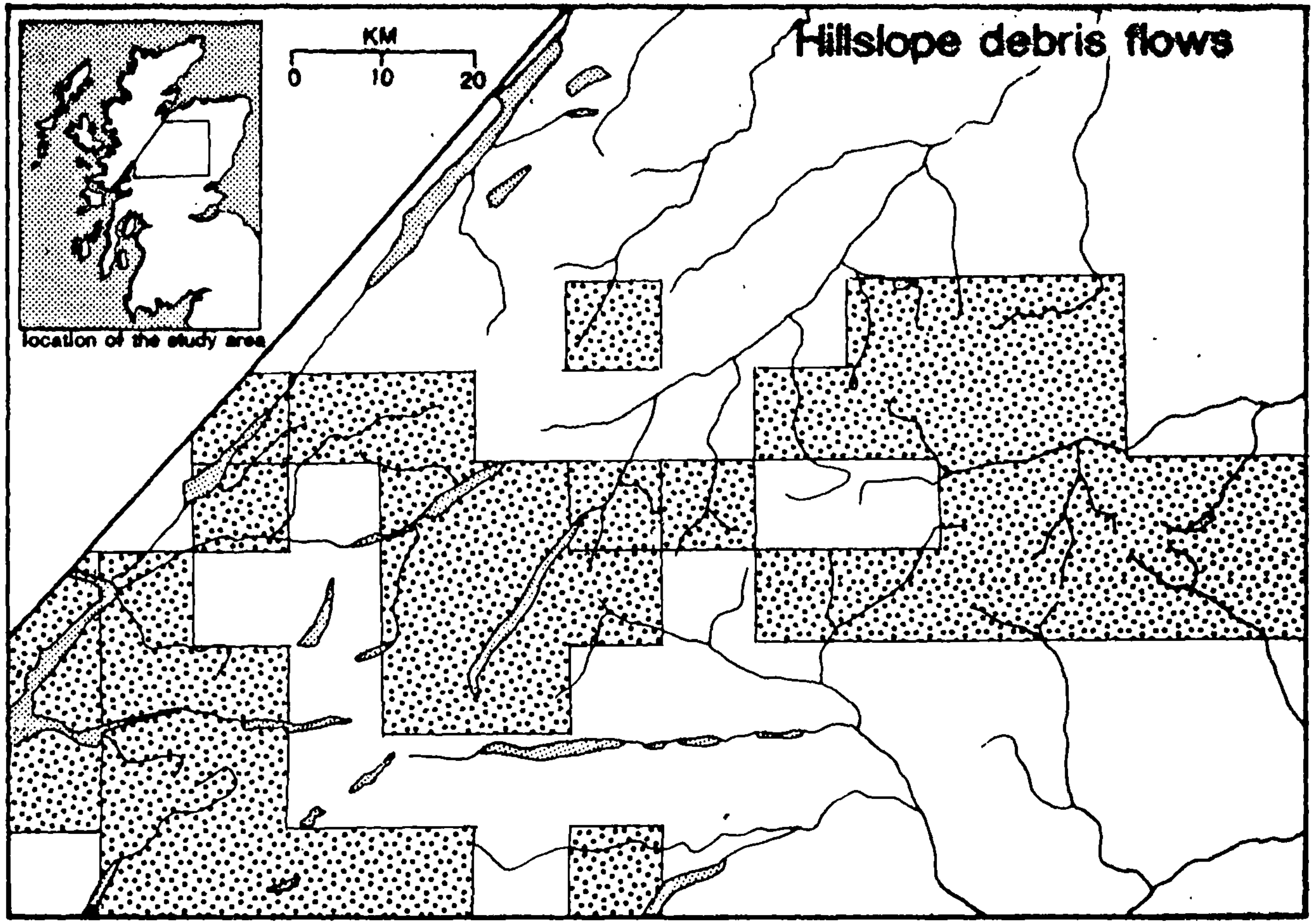


Figure 6.5 Hillslope debris flow distribution in the Grampian Highlands. Debris flow presence shown by shaded 100 km^2 grid. (source: Innes, 1983a; Ballantyne, 1986c).

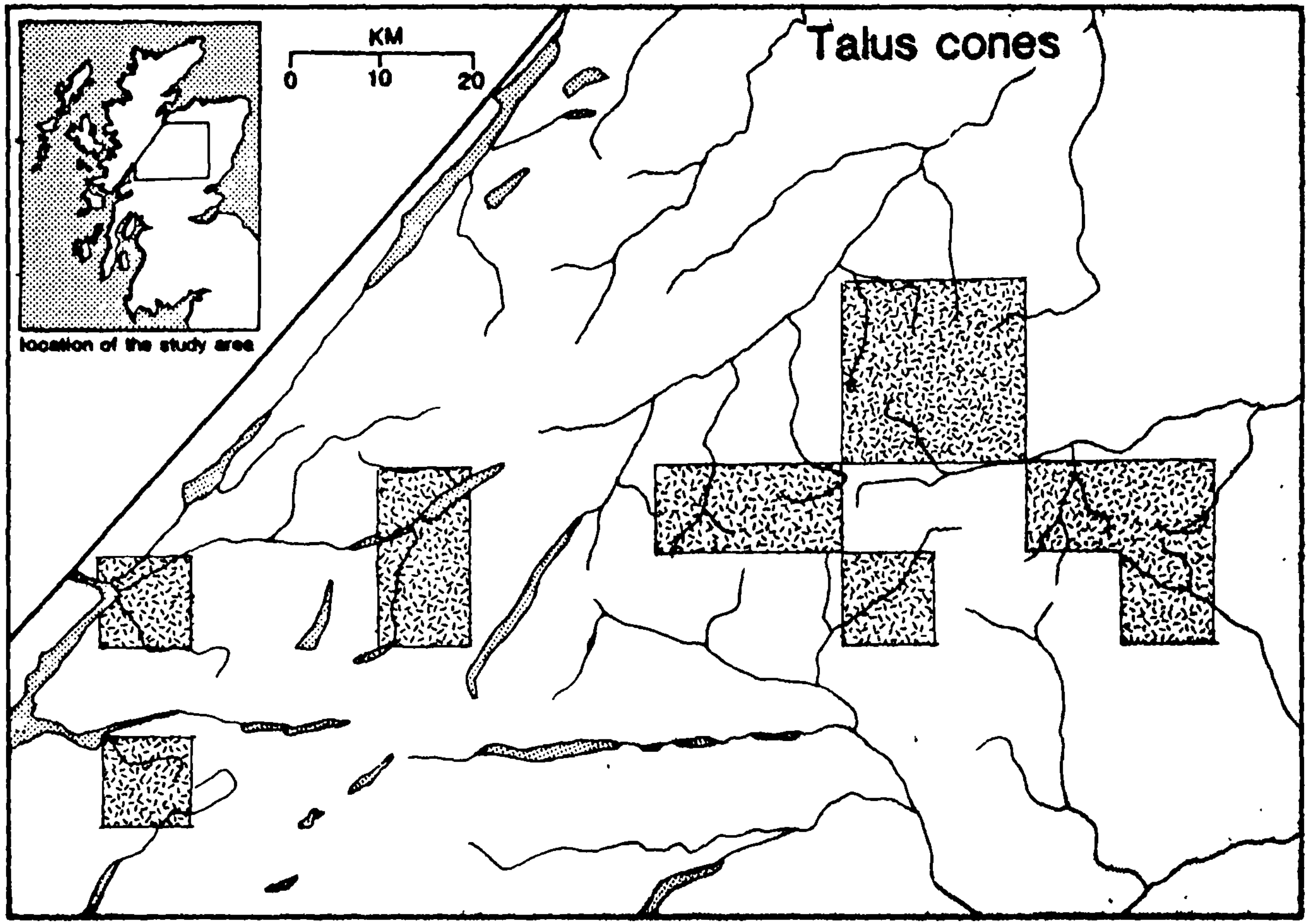


Figure 6.6 Talus cone distribution in the Grampian Highlands. Cone presence shown by shaded 100 km^2 grid.

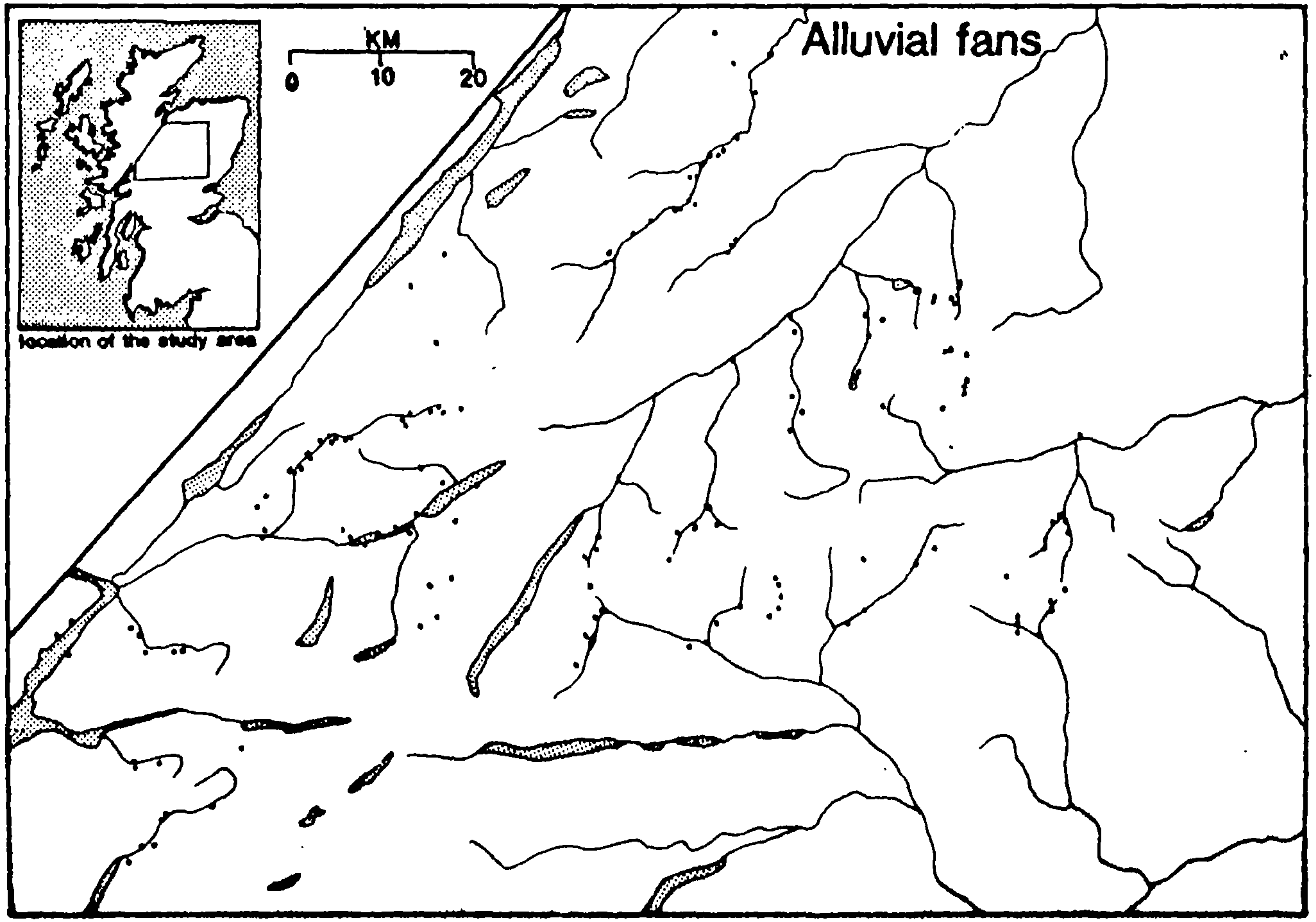


Figure 6.7 Location of the alluvial fans studied in this chapter.

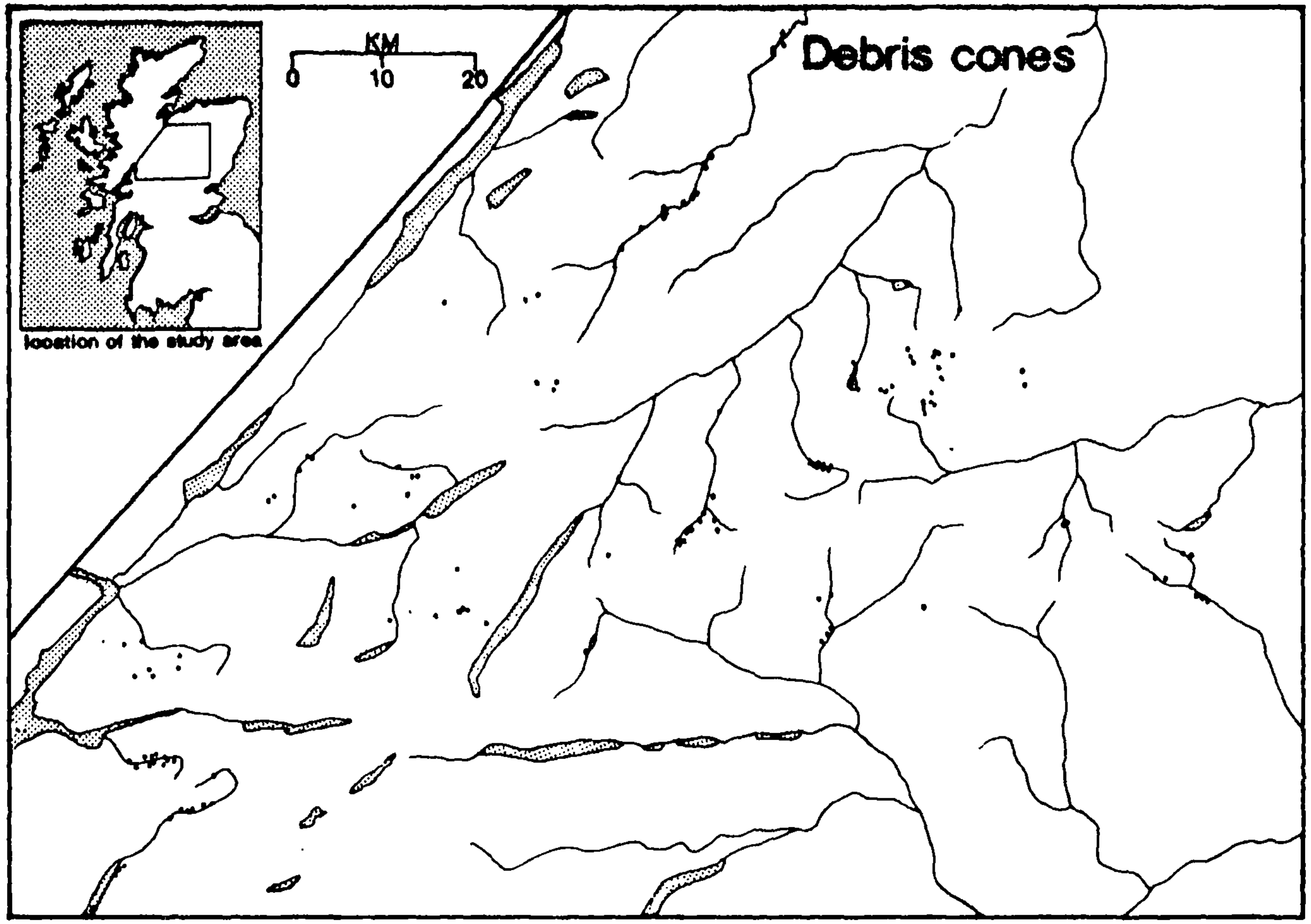


Figure 6.8 Location of the debris cones studied in this chapter.

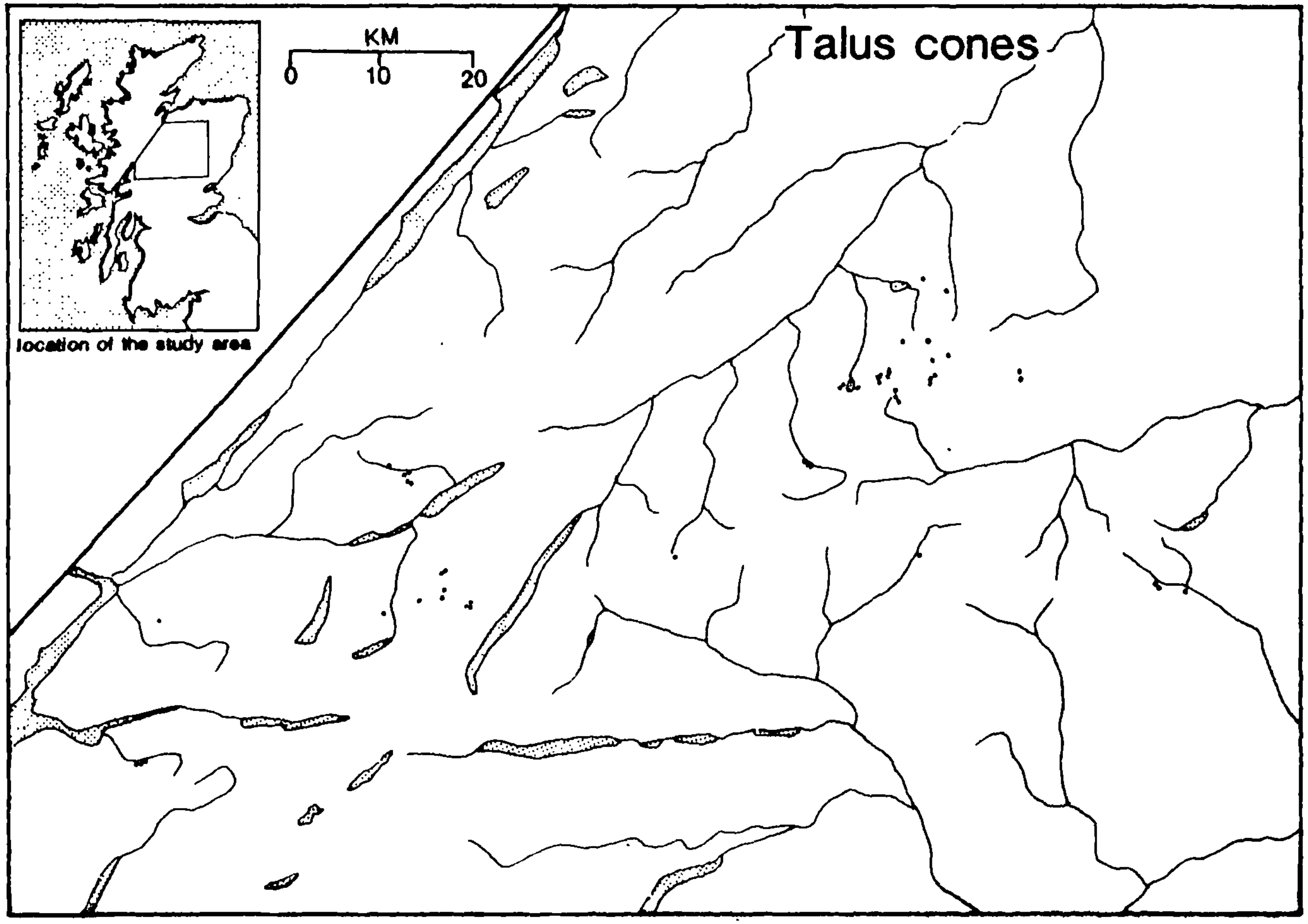


Figure 6.9 Location of the talus cones studied in this chapter.

mountain areas.

The broad distribution of fans and cones may therefore be considered in terms of position relative to the centre of mountain massifs, with talus cones well within mountainous areas, debris cones in adjacent areas, and alluvial fans farthest out in the lowest-lying areas. The hypothesis that contributing area relief is critical in determining the type of fan or cone development will be considered in greater detail along with other morphometric factors below in section 6.3.3.

A comparison of figures 6.4 and 6.5 illustrates that debris cones occur in the majority of locations where hillslope debris flows are found, as well as in a few areas where debris flow deposits have not previously been identified, such as in the Findhorn valley in the northern part of the maps. One area apparently devoid of both hillslope debris flow and debris cone deposits is that east of Ben Nevis near Loch Trieg. The topography and climate of this area are similar to neighbouring areas where debris flow activity has been common. One possible reason for the lack of debris flow deposits is that hillslope regolith in this area is limited in extent owing to glacial scouring (cf Ballantyne, 1986c). Another area where glacial scouring has also resulted in limited regolith cover is Glen Etive, but here debris cone formation and hillslope debris flow activity have been more common and are closely related to local lithological weaknesses associated with intrusions of the Etive dyke swarm (chapter 3).

Indeed, debris cone development is often associated with the occurrence of intrusive rock (chapter 3, geology of the macro-scale study area, figure 3.5), with fewer cones emanating from Dalradian or Moinian schist source areas. The weathering of granites in particular provides a sandy cohesionless regolith which, when mixed with coarser debris and water, gives a favourable medium for generating debris flows (Innes, 1983c). Lithological weakness associated with igneous intrusions, such as shattered contact rock, provide suitable conditions for gully development, as seen in Glencoe and Gen Etive.

This lithological control also extends to the distribution of talus cones, 64 of which are exclusively associated with granitic mountain massifs whilst only 15 are developed below schist outcrops and gullies. The configuration of joints in the granite provides optimal conditions for the development of steep narrow rock gullies that direct and concentrate the trajectory of rockfall debris. In contrast, alluvial fans occur on a greater variety of lithologies, including areas of predominantly metamorphic rock, for example in the Gaick Plateau area. The relationships between the dimensions of valleys or gullies and dominant fan or cone forming processes will be examined in section 6.3.3.

Extreme precipitation has been associated with debris flow initiation (Caine, 1980) and with floods reworking deposits on alluvial fans (eg Acreman, 1983; chapter 3). However, in Scotland there is insufficient evidence available to relate the effect of individual storms to the incidence of debris flow or stream erosion and consequent aggradation on fans and cones. In particular, reliable data on short-duration rainfall intensities are only rarely available. In this study mean annual precipitation values extracted from a map data base were used as an approximation of precipitation control on fan and cone aggradation, but it is stressed that the true relationship between fan or cone development and precipitation may not be revealed by this information and hence only descriptive analysis can be carried out.

There may be a weak relationship between the frequency of sites in the different groups and mean annual precipitation, such that alluvial fans are associated with slightly lower precipitation values (ranging from 1,000 to 3,200 mm / year) than debris cones (1,100 to 3,600 mm / year), whilst the majority of talus cones appear to be associated with the highest precipitation values ranging from 1,400 to 3,600 mm year. These relationships cannot, however, be directly associated with individual processes because they are the product of an altitude relationship already discussed above. Similarly, a comparison with the distribution of maximum 2 hour and maximum 24 hour rainfall (chapter 3, figure 3.3) was also inconclusive. On the basis of the data sources available it is difficult to assess what role, if any, precipitation has had on the distribution of different types of fan and cone development.

Fan and cone aspect (ASP) values have been plotted as percentage frequency of sites at 30^{o} intervals (figure 6.10). Visually there are some differences in aspect pattern between the three dominant process groups. The sample sizes of the alluvial fan and debris cone groups are similar (159 and 142 respectively), but it should be noted that the sample size of the talus cone group (64) is less than half that of either the alluvial fan or debris cone groups. Thus individual sites in the talus cone group have greater influence in terms of percentage value than sites in either the alluvial fan or debris cone groups. Therefore the interpretation of the aspect results depicted in figure 6.10 will comprise comparison of general patterns and not absolute strengths in aspect maxima and minima.

The main trend in aspect for alluvial fans is in the northwest quadrant, with secondary maxima in the southeast and southwest. The lowest representation of alluvial fan aspects is in the northeast. The general pattern of debris cone aspect is more uniform compared with that of alluvial fans. However, two apparent debris cone maxima occur in a westerly and easterly direction. The greatest visual contrast in aspect pattern can be made by comparing the talus cones with alluvial fans and debris cones. Two

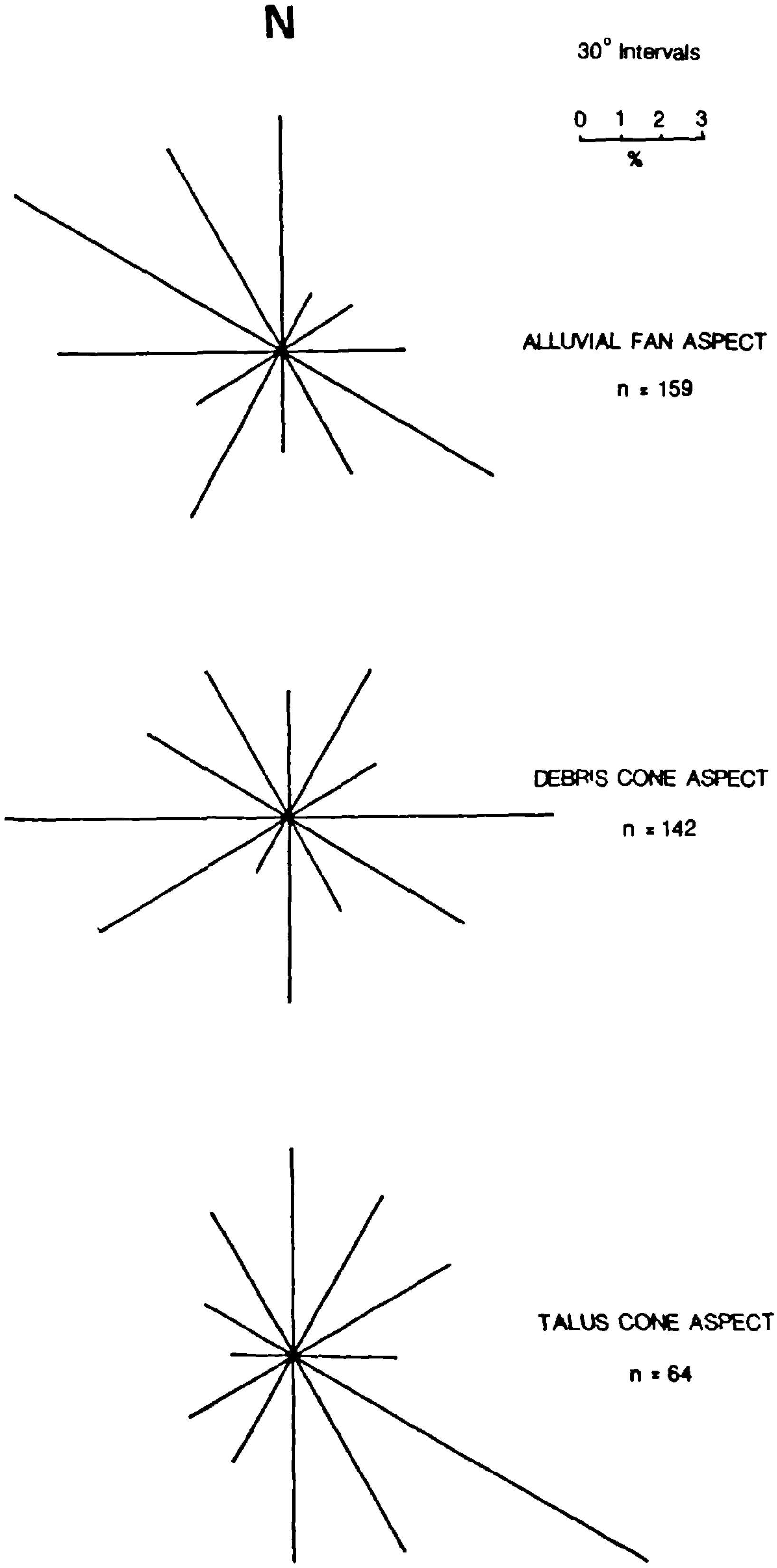


Figure 6.10 Medial fan or cone aspect.

apparent preferred trends in talus cone orientation can be identified, one in the northwest to northeast quadrant and the other in the southwest to southeast quadrant.

The general differences in aspect between the different groups of fan and cone are slight, and may not necessarily reflect direct process control. The weak trends observed for alluvial fan and debris cone aspect appear to reflect the principal trends in the direction of many rivers. For example, alluvial fans in Strathdearn generally have northwesterly or southeasterly aspects which are approximately orthogonal to the northeasterly direction of flow of the river Findhorn. Similarly, debris cones found on the flanks of many northerly-draining catchments generally have westerly and easterly trending aspects. Structural control also provides some explanation for trends in talus cone aspect. Studies in the Scottish Highlands by Sugden (1969) and Evans (1977) of mean medial corrie orientations revealed that the majority are in the northeast quadrant with some in the southeast. Many of the talus cones were identified below rockwalls in glacial corries, and as such reflect corrie orientation and not necessarily the amount of freeze-thaw activity determined by insolation.

Theoretically, fans and cones that have built up outside the Loch Lomond Readvance limits will (other things being equal) be larger than those developed at comparable sites within these glacial limits because they have had a longer time period to accumulate. It is also possible that rates of fan and/or cone accumulation were enhanced under the periglacial conditions in glacier-free areas during the Loch Lomond Stadial (chapter 4, section 4.2.1, the periglacial hypothesis). The validity of this hypothesis was assessed by using the Mann-Whitney U test on alluvial fan and debris cone FAREA values inside and outside the Loch Lomond Readvance limits. Talus cones were omitted from the analysis, as the majority of talus cones observed within these glacial limits had been excluded from the survey because their plan areas are less than the sampling size limit of 2,500 m^2. From the talus cones observed during fieldwork, however, it is suggested that in general talus cones are larger outside the glacial limits than within them, and as such they probably reflect higher rates of rockfall during the Lateglacial than during the Holocene (cf Ballantyne and Eckford, 1984; Ballantyne and Kirkbride, 1987). Further work outside the scope of the present study is necessary to establish the validity of this statement.

The results of the Man-Whitney U test indicate that alluvial fans found outside the Loch Lomond Readvance limits are significantly larger (at the 95% confidence level) than those found within the limits. No significant difference (at even the 90% confidence level) was observed in debris cone size in relation to the glacial limits. Alluvial fan size could be a product of contributing catchment area size, but no significant difference was found in contributing area size relative to the glacial limits. Therefore the periglacial hypothesis cannot be refuted as an explanation of larger alluvial fan development in areas outside the Loch Lomond Readvance limits. In contrast, debris cone size does not appear to have been influenced by position relative to the Loch Lomond Readvance glacial limits. This may suggest that a number of other factors may have been more important in determining debris cone size, for example:

1. Debris cone accumulation may have been more favoured by temperate climatic conditions than periglacial conditions;

2. The stability and supply of debris flow susceptible sediment in the source areas has had greater influence on debris cone size than the maximum potential length of time in which aggradation could have taken place.

The two case studies discussed in chapter 7 (section 7.2.1 and 7.2.2) illustrate the problems associated with using debris cone position relative to glacial limits as a method of potential age estimation.

In sum, both alluvial fans and debris cones are widespread across the Grampian Highlands, with talus cone development more restricted to the innermost parts of the mountain areas. Of the environmental controls considered above lithology and relief appear to offer the best general explanation of the distribution patterns of different types of fan and cone development, with glacial history also influencing the scale of developement of alluvial fans. The role of catchment morphology will be examined in greater detail in the following two sections.

6.3.2 Bivariate analysis of fans and cones and their contributing basin area properties.

Previous research has shown that certain statistical relationships exist between fan and basin variables. Such relationships appear to be strongest in arid and semi-arid environments subject to recent tectonic activity, and have been interpreted as indicating geomorphic equilibrium (Melton, 1965). The results reported in the literature are illustrated in table 6.2 which gives Pearson's product moment correlation coefficients for the strength of the relationship between the tangent of fan slope (FS) and Melton's (1965) index of basin ruggedness (BRUG). Basin ruggedness is calculated by dividing BH by the square root of the drainage basin area. However, bivariate morphometric analysis has revealed great local variability in the strength of such relationships in mid-latitude glaciated mountain environments. This is believed to have arisen partially because of lithological differences and also as a result of differences in glacial history; weaker relationships in particular have been interpreted as indicative of a period of paraglacial sedimentation (Ryder, 1971a). The paraglacial model of fan and cone development implies that the duration and amount of aggradation is largely dependent upon a limited supply of glacigenic sediment and is not a product of contemporaneous basin weathering. Recent research in the Canadian Rockies has

Table 6.2

Pearson's product moment correlation coefficients reported in the literature for Melton's (1965) basin ruggedness number (BRUG) and fan slope (FS).

author	region	special characteristics	n	r
Melton (1965)	Arizona	semi-arid	15	0.94
Crowley *	S. California		16	0.66
Ryder (1971a)	British Columbia			
	Similkameen		10	0.92
	Thompson		8	0.79
	Fraser West		14	0.75
	Bonaparte		10	0.66
	Fraser East	great lithological variety	13	0.5
	Kamloops	silt fans	10	0.37
Kostaschuk _et al._	British Columbia			
(1986)	Bow Valley	alluvial fans	8	0.98
	Bow valley	debris cones	12	0.79

N.B. Crowley* as referenced by Ryder (1971a)

significance level:
0.01
0.05

also shown that different fan (or cone) and basin relationships are associated with debris cone and alluvial fan formation (Kostaschuk et al, 1986). A methodology similar to that employed by Ryder (1971a) was used to test the strength of relationships between fan and basin variables in order to test the paraglacial hypothesis and to assess the effect of different types of dominant fan- or cone-forming processes on such relationships. Spearman's Rank correlation was used because the raw data are not normally distributed. Several reasons preclude precise comparison with actual results of previous research, as follows.

1. The sample sizes used in previous studies are often small. Larger sample sizes, such as those in this study, may result in weaker relationships that are still statistically significant.

2. With the notable exception of the work by Kostaschuk et al (1986) there is a lack of distinction in previous research between fans and cones formed by different depositional processes.

3. Previous research has used parametric statistical methods in bivariate analysis of fan (or cone) and basin relationships, whereas this study uses nonparametric correlation analysis. However, this is less problematic than points 1 and 2 because Spearman's Rank method is 90% as powerful as product moment correlation techniques such as Pearson's r.

Therefore only general comparison with the results of previous research (table 6.2) is possible. The morphometric variables used in the analysis include FAREA and FGRAD which were correlated with BAREA, BGRAD, BH and BW.

Spearman rank correlation was first carried out on FAREA and BAREA values in the alluvial fan and debris cone groups, subdivided in relation to the Loch Lomond Readvance limits. These results (table 6.3) demonstrate that, irrespective of dominant process, the relationship between FAREA and BAREA in the Grampian Highlands is generally poor but statistically significant in 3 out of the 4 cases, and is weaker for fans and cones inside the former glacial limits than for those outside them. The generally poor relationship between FAREA and BAREA implies that the extent of fan or cone aggradation is not closely related to the size of the contributing catchment area. This may suggest that alluvial fan and debris cone development in the Grampian Highlands has been largely paraglacial. If this is so then the weaker relationship observed within the Loch Lomond Readvance limits may indicate that such areas are less well adjusted to deglaciation than are areas which have been deglaciated since ice sheet wastage. However, regionally the relationship between FAREA and BAREA may not be so clear cut.

The transect was split into four sub-areas. The Western Grampians (W GRAMP) includes the area west of Loch Ossian and south of the Spean and Spey rivers. This area contains the most deeply dissected topography and is

Table 6.3

Spearman Rank correlation coefficients for FAREA with BAREA, for alluvial fans and debris cones situated either inside or outside of the Loch Lomond Readvance limits.

GROUP	INSIDE	n	OUTSIDE	n
1. Alluvial fans	0.16	57	0.31 *	56
2. Debris cones	0.32 *	63	0.42 *	33

* significance level of 0.01

lithologically complex, especially in areas adjacent to igneous intrusions. The Central and Eastern Grampians (C-E GRAMP) stretch eastward from Loch Ossian to Glen Clova, in the area south of the Cairngorm mountains. This area is probably the most lithologically and topographically uniform of all the areas, with extensive tracts of gentle plateau dissected by glacial troughs and underlain by Moine schists. The Cairngorm mountains area (CAIRN) is underlain by various grades of granite and also consists of rolling plateau interrupted by deep glacial troughs, and the Monadliath Mountains (MONAD) comprise the area between the Spey and the Great Glen, and are characterised by considerable lithological variety and relatively gentle topography.

Table 6.4 shows regional Spearman rank correlation coefficients for FAREA with BAREA, divided into the three different dominant process groups. Overall (region ALL) the correlation coefficient for alluvial fans is weak but statistically significant. The strength of relationship between FAREA and BAREA is greatest for alluvial fans in the Central and Eastern Grampians and Monadliath mountain areas, and weakest for the Western Grampians. A similar contrast in the strength of FAREA and BAREA relationships was noted above, in relation to alluvial fan and debris cone development inside and outside of the Loch Lomond Readvance limits. Indeed, the Western Grampians were covered by extensive areas of glacier ice during the stadial compared with more limited glacier development in the Central and

Table 6·4

Regional analysis of fan and basin relationships:

Spearman Rank correlation coefficients for FAREA with BAREA

1. GROUP 1, ALLUVIAL FANS.

REGION	N	r^s
ALL	118	0.2402 *
W GRAMP	20	0.1023
C-E GRAMP	40	0.4223 *
CAIRN	5	-----
MONAD	53	0.4442 **

2. GROUP 2, DEBRIS CONES

REGION	N	r^s
ALL	98	0.3714 **
W GRAMP	32	0.2331
C-E GRAMP	26	0.6038 **
CAIRN	10	0.5030
MONAD	30	0.2102

3. GROUP 3, TALUS CONES.

REGION	N	r^s
ALL	37	0.1846
C-E GRAMP	20	0.4708
CAIRN	13	0.0937

significance level

** 0.01   * 0.05

---- insufficient data

Eastern Grampians, and localised corrie glaciation in the southern part of the Monadliath Mountains. The correlation coefficient for FAREA with BAREA for all regions is slightly higher for debris cones when compared with alluvial fans and talus cones. However, *regional differences* do occur with the strongest coefficients for debris cones also found in Central and Eastern Grampians and Cairngorm mountains. The correlation coefficients are smallest in the Western Grampians and Monadliath mountains, indicating little relationship between debris cone FAREA and BAREA values in these areas. The weakest overall correlation coefficient for FAREA and BAREA is that found for group 3, the talus cones. Again the Central and Eastern Grampians show the strongest correlation between FAREA and BAREA.

These results illustrate how fan or cone and basin relationships can vary from one region to another. The Central and Eastern Grampians consistently have the best correlations, which may suggest that within this area fan and cone development is more a direct product of basin area weathering and erosion than found elsewhere. However, from these results alone it is not possible to assess to what extent paraglacial-type fan and cone development has occurred, although the generally weaker fan or cone and basin relationships found in the Western Grampians may point to paraglacial sedimentation. A definitive test of the problem would involve accurate dating of fan and cone deposits. Two sites have been dated by radiocarbon analysis and allow further discussion of the paraglacial hypothesis in the following chapter (sections 7.2.1 and 7.2.2).

Table 6.5 shows the Spearman rank correlation matrices for FGRAD with selected basin morphometric variables. A glance at the matrices for all groups shows that the correlated values are generally low. Only some of the relationships will be considered here.

One might expect different correlations between FGRAD and BGRAD for each of the three dominant process groups, with poor relationships between talus cone mean gradient and variable rockface or rock gully mean gradient, whereas the relationships between alluvial fans or debris cones and their basins may be more stronger. Indeed, the results of the analysis for all regions show statistically highly significant positive correlations for alluvial fan and debris cone mean gradients and their mean basin gradients, but no significant relationship for talus cone mean gradient with mean source area gradient. None of the regional correlations between talus cone FGRAD and BGRAD is statistically significant. This contrasts with some of the results for alluvial fans and debris cones. The range of correlation coefficients for FGRAD with BGRAD for alluvial fans is much smaller than for debris cones; coefficients for the latter range from a highly significant correlation of 0.8263 in the Central and Eastern Grampians to as low as 0.0092 in the Cairngorm Mountains. The results of this analysis suggest that many alluvial fan and debris cone mean

Table 6.5

Regional analysis of fan and basin relationships:
Spearman Rank correlation coefficients for FGRAD with
BH, BAREA and BW.

GROUP 1; ALLUVIAL FANS.

REGION	N	BH	BAREA	BGRAD	BW
ALL	118	-0.0557	-0.3044 **	0.5162 **	-0.3197 **
W GRAMP	20	0.1804	-0.4881	0.578 *	-0.6383 *
C-E GRAMP	40	-0.0975	-0.4396 *	0.332	-0.4908 **
CAIRN	5	- - - - -	- - - - -	- - - - -	- - - - -
MONAD	53	0.3346	-0.4611 **	0.4273	-0.1624

GROUP 2; DEBRIS CONES.

REGION	N	BH	BAREA	BGRAD	BW
ALL	98	-0.0296	-0.3336 **	0.5253 **	-0.2787
W GRAMP	32	-0.169	-0.3057	0.4814 *	-0.2486 *
C-E GRAMP	26	-0.488 *	-0.6794 **	0.8263 **	-0.7732 **
CAIRN	10	-0.1774	-0.526	0.0092	-0.2769
MONAD	30	0.2137	-0.0478	0.1579	-0.1907

GROUP 3; TALUS CONES.

REGION	N	BH	BAREA	BGRAD	BW
ALL	37	0.1852	-0.4953 **	0.3472	0.0145
W GRAMP	2	- - - - -	- - - - -	- - - - -	- - - - -
C-E GRAMP	20	0.1549	-0.5058	0.3153	-0.1765
CAIRN	13	-0.391	-0.1198	0.1858	0.2643
MONAD	2	- - - - -	- - - - -	- - - - -	- - - - -

* * 0.01 SIGNIFICANCE LEVEL

* 0.05 SIGNIFICANCE LEVEL

- - - - - INSUFFICIENT DATA

gradients are positively related to their mean basin gradients, but talus cone mean gradients are often unrelated to their source area gradients.

Correlation coefficients for other variables in table 6.5 indicate that there is some consistent pattern concerning the strongest statistically-significant relationships and individual regions within the fluvial and debris flow dominant process groups. The clearest example of this can be seen for debris cones in the Central and Eastern Grampians. In this group the weakest relationships occur in the Cairngorm Mountains. Such regional variations in the strength of fan (or cone) and basin relationships appear to imply that the influence of local environmental factors (including glacial history) is important. Thus the assessment of the influence of paraglacial sedimentation may be further complicated by area-specific factors.

The results discussed above cannot be compared directly with previous research (table 6.2), so variables FS and BRUG were created for each of the three dominant process groups, and were correlated for each region (table 6.6). These results may be compared with table 6.2, bearing in mind the problems listed above concerning the compatibility of previous studies. The strongest relationship was found for debris cones in Central and Eastern Grampians with a coefficient of 0.67, which is similar to some of the coefficients in table 6.2, for example for the Bonaparte river fans (Ryder, 1971a) and those in Southern California

Table 6.6

Regional analysis of fan and basin relationships:

Spearman Rank correlation coefficients for fan slope (FS)

with Melton's (1965) basin ruggedness number (BRUG).

REGION	GROUP 1	GROUP 2	GROUP 3
ALL	0.30 ** N = 118	0.33 ** N = 98	0.53 ** N = 37
W GRAMP	0.58 * N = 20	0.17 N = 32	----
C-E GRAMP	0.39 * N = 40	0.67 ** N = 26	0.52 * N = 20
CAIRN	----	0.43 N = 10	-0.31 N = 13
MONAD	0.28 N = 53	0.03 N = 30	----

significance levels: ** 0.001 * 0.01

(Crowley in Ryder, 1971a). However, the majority of coefficients in table 6.2 are lower than those found for fans in North America, a finding that probably reflects a greater degree in heterogeneity of the Scottish study regions. Differences do exist between the different dominant process groups, for example for the whole study area (ALL) the coefficient is lowest for alluvial fans, slightly higher for debris cones and much higher for talus cones. However, when examined in each region this trend is less clear. For example, for the Central and Eastern Grampians (where other morphometric relationships have been observed to be consistently good) it is evident that the correlation between debris cones and their source areas is stronger than for alluvial fans, which is the opposite trend to that observed by Kostaschuk et al (1986) (cf table 6.2). Ryder (1971a) also noted regional differences in the strength of fan and basin relationships and suggested that these differences were partly a product of different lithological controls as well as glacial history.

Indeed, lithology probably offers the best explanation of the regional differences observed above. For example, the strong relationships for debris cones (tables 6.4, 6.5 and 6.6) suggest that their formation in the Central and Eastern Grampians is consistently more closely associated with gully properties than elsewhere. The lithology of the Central and Eastern Grampians is less complex than other areas, with an absence of large numbers of dykes compared with, for example, the Glencoe ring fault area in the Western Grampians. Consequently, gully systems in the Central and Eastern Grampians tend to be not as deep as those following marked lithological weaknesses such as dykes. Indeed it is probable that many of the spectacular gullies in the Western Grampians survived glaciation, implying that much gully incision occurred before postglacial debris cone formation. Gully development in the Central and Eastern Grampians may also predate the Loch Lomond Readvance and even ice sheet glaciation, but because these gullies are less well developed than their western Grampian counterparts, the relationships between the dimensions of the gully systems and the cones they feed are stronger.

In sum, the main points of the Spearman rank correlation analysis are:

1. In general the strength of fan and basin relationships is weaker than that found for arid and semi-arid tectonically-active areas, or other glaciated mountain areas such as British Columbia. This may partly reflect the greater degree of study area heterogeneity in the Grampian Highlands compared with, for example Ryder's (1971a) study valleys. Furthermore, there has been a general lack of differentiation of dominant process types by previous researchers. This is liable to give higher FS/BRUG relationships, especially if both alluvial fans and debris cones are incorporated in the analysis.

2. The nature of the relationships between fan and basin variables varies with different dominant process groups. Generally the strongest morphometric relationships are between alluvial fans and debris cones and their basins.

3. Within individual process groups there is considerable regional variation in the strength of fan and basin relationships. Generally, the best relationships are found in the Central and Eastern Grampians Highlands, and the weakest in Cairngorms. This suggests that the strength of the relationships partly reflects geologic and topographic controls that vary regionally.

There are two reasons why further analysis of bivariate relationships between fans or cones and their contributing basin areas cannot usefully add to the explanation of how basin variables control fan or cone development.

1. The majority of Spearman's Rank correlation coefficients are low, implying that there is a wide scatter in the data and that line fitting methods such as regression would not provide realistic models of fan or cone and basin relationships.

2. One of the objectives of this project is to examine the continuum of fan and cone landforms. In this respect the combined roles of a number of basin properties in controlling dominant fan or cone forming processes need to be clarified.

Thus no attempt has been made to replicate the regression or functional analyses that have commonly been employed in

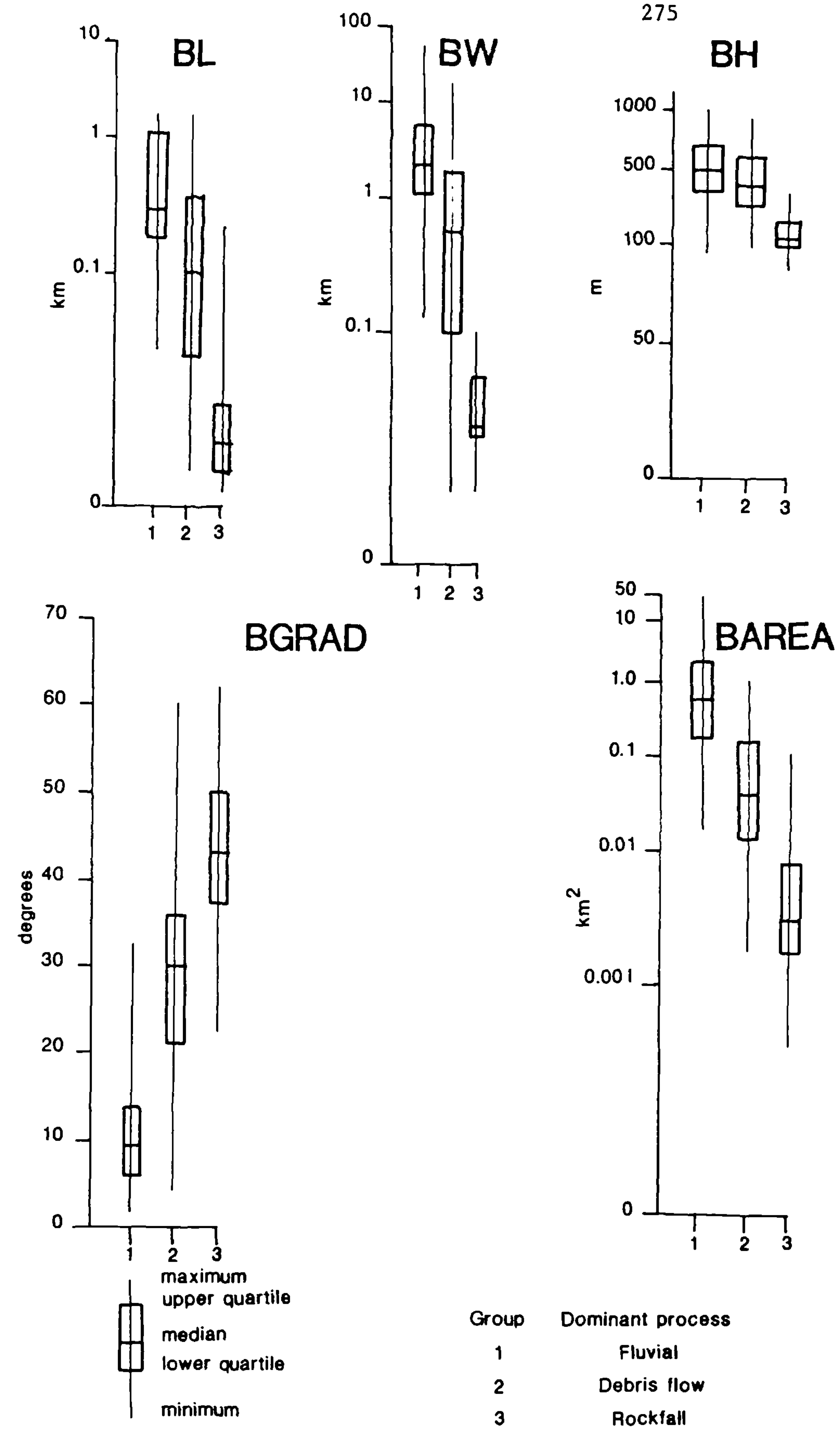


Figure 6.11 Basin morphometric characteristics.

earlier studies of fan and basin relationships (Ryder, 1971a; Church and Mark, 1980; Kostaschuk et al, 1986). Indeed, some of Ryder's scatterplots (1971a, eg figure 8a) indicate that her regression equations offer little explanation of the nature of some fan and basin relationships for sites in parts of British Columbia. Instead Kruskall-Wallis test (the nonparametric equivalent of analysis of variance) and linear discriminant analysis were used in this next section to examine how basin morphometric variables combine and result in different types of fan and cone development.

6.3.3 Discriminant analysis of basin morphometric variables.

6.3.3.1 Data analysis.

Before proceeding with linear discriminant analysis several preliminary univariate analyses were undertaken to clarify potential multivariate relationships. Group discrimination at the univariate level was visually assessed by plotting the range, median and upper and lower quartiles for 5 morphometric variables (figure 6.11) and tested statistically using the Kruskall-Wallis nonparametric analysis of variance. Nonparametric data description and analysis are used because most of the data distributions are skew.

The basin morphometric variables included in the analysis in this section are BL, BW, BH, BGRAD and BAREA. All the basin variables succeed to some extent in discriminating the three process groups (figure 6.11). Kruskall-Wallis nonparametric analysis of variance was used to test the null hypothesis that there is no significant difference in the mean ranks of a variable for each of the three process groups. The KRUSKALL-WALLIS subroutine in the SPSS-X2 procedure NPAR was used to carry out the analysis. The results are shown in table 6.7. Chi square tests carried out on the mean ranks demonstrate that all of the variables distinguish between the dominant process groups at the <0.0001 significance level. Comparison of the distribution plots (figure 6.11) and the mean rank values (table 6.7) shows that the only variable that does not distinguish between all of the groups is BH, which shows the greatest amount of overlap between groups 1 and 2. If the chi square values for each variable are ranked, some indication is obtained of the relative amount of univariate discrimination provided by each of the morphometric variables (table 6.7). These chi square values are comparable regardless of the different scales and methods of measurements because they are based on the mean rank of a variable and not on the absolute values. The rankings show that BGRAD, closely followed by BAREA, best discriminates between the three groups at the univariate level. BH is the least successful univariate discriminator. These results cannot, however, evaluate how the combined variables

Table 6.7

Univariate discrimination provided by basin morphometric variables, assessed by Kruskall-Wallis non-parametric analysis of variance.

VARIABLE NAME	MEAN RANK GROUP 1 N=118	GROUP 2 N=98	GROUP 3 N=37	chi square value	significance
BL	179.5	95.6	42.7	127.98	<0.0001
BW	177.5	99.5	38.7	124.05	<0.0001
BH	157.23	122.84	41.61	70.83	<0.0001
BGRAD	69.83	161.11	216.5	149.62	<0.0001
BAREA	180.21	96.85	32.95	141.08	<0.0001

RANKED ORDER OF MORPHOMETRIC VARIABLES BASED ON CHI SQUARE VALUE

1 BGRAD
2 BAREA
3 BL
4 BW
5 BH

discriminate between the three dominant process groups. Linear discriminant analysis provides a formal statistical framework for evaluating how successfully the combined variables discriminate between the three process groups.

Linear discriminant analysis has two main uses:

1. it is a statistical method for determining the best linear combination of variables that simultaneously discriminate different groups; and

2. it can be used to assign individual cases into different groups on the basis of a comparison of their data characteristics compared with the characteristics of known groups.

Here we are primarily concerned with interpreting the relationships between combinations of different morphometric variables that determine the three different process groups. The potential for classifying other valleys or gullies on the basis of their combined morphometric properties will also be discussed toward the end of the section.

The basic assumptions of linear discriminant analysis have been outlined in some detail by Klecka (1980). The potential violation of two of the assumptions and the appropriate solutions adopted to satisfy these will be discussed before proceeding with discriminant analysis.

One of the requirements of the general linear model is that the data are normally distributed. However, the raw data distributions of the morphometric variables do not approximate a normal distribution (table 6.8). Many of the variables have particularly high kurtosis values (K) and exhibit some degree of positive skewness (S). These distributional properties of the raw data were derived by using the SPSS-X2 procedure CONDESCRIPTIVE, which uses the moments of the data distribution to calculate skewness and kurtosis.

The departure from desired normality was assessed for each of the basin variable distributions within the process groups by comparing the skewness and kurtosis values of the data with expected normal characteristics of asymmetry (root beta 1), and peakedness (beta 2) (Griffiths, 1967). Tabulated root beta 1 and beta 2 values can be found in the Biometrica Tables (Pearson and Hartley, 1976) where values for each are given according to sample size at different percent probability levels; in this study the 5% values were used. Root beta 1 and beta 2 are also derived from moment measures, so that these values can be converted to skewness and kurtosis equivalents (table 6.9). Most of the raw data distributions were found to be both too positively skewed and too peaked in comparison with the expected normal data characteristics to be employed in linear discriminant analysis without transformations. The high kurtosis values may to some extent reflect sampling design, which excluded

Table 6.8

Skewness (S) and kurtosis (K) of basin morphometric data

VARIABLE	GROUP 1 N=118	GROUP 2 N=98	GROUP 3 N=37	
BL	4.521	3.686	3.961	S
	28.615	15.225	15.337	K
BW	2.609	2.544	3.315	S
	8.304	6.876	11.856	K
BH	1.321	0.689	0.540	S
	3.806	-0.53	-0.861	K
BGRAD	1.104	0.299	0.126	S
	0.524	0.453	-0.43	K
BAREA	3.17	2.54	3.456	S
	10.06	7.742	12.883	K

Table 6.9

Acceptable root beta 1 and beta 2 values (at the 5% level) for normally distributed data, and skewness and kurtosis equivalents.

sample size	$\sqrt{\beta_1}$	β_2 LOWER	β_2 UPPER
118	0.35	2.4	3.7
97	0.39	2.35	3.8
37	0.62	2.07	4.1

Source: Pearson and Hartley (1976)

(values correct to two descimal places)

skewness = $\dfrac{\sqrt{\beta_1}}{2}$ kurtosis = $\beta_2 - 3$

SAMPLE SIZE	SKEWNESS	KURTOSIS LOWER	KURTOSIS UPPER
118	0.18	-0.6	0.70
97	0.20	-0.65	0.77
37	0.31	-0.93	1.12

both very large and very small fans and cones and thus their associated very large and very small catchments. Data transformations were carried out to find the best approximation to a normal distribution that most closely satisfied the root beta 1 and beta 2 criteria. The results of the most appropriate transformations are summarised in table 6.10. In some instances the transformations do not quite satisfy the root beta 1 and beta 2 criteria, but in all cases skewness and kurtosis are reduced significantly from those of the untransformed data distributions. Multiple transformations, such as the log 10 of a log 10 transformed variable, were not calculated when single transformations did not adequately satisfy the normality criteria because of difficulties associated with the interpretation of such distorted data (Johnston, 1976b). Furthermore, Lachenbruch (1975) has suggested that discriminant analysis is a sufficiently robust technique to withstand slight departures from normal distributions in the data. The final list of data transformations are: log 10 transformations for BL (LBL), BW (LBW), and BAREA (LBAREA); quartic root transformation of BGRAD (XBGRAD) and cube root transformation of BH (CBH) (table 6.10).

Linear discriminant analysis also requires that no discriminating variable is a linear combination of any of the other discriminating variables. The pooled within-groups correlation matrix (table 6.11) is similar to Pearson's product moment correlation, with strong

Table 6.10

Skew (S) and Kurtosis (K) of transformed basin morphometric data

VARIABLE	GROUP 1 N=118	GROUP 2 N=98	GROUP 3 N=37	
LBL LOG 10	-0.646	0.353	1.409	S
	-0.353	-1.084	2.832	K
LBW LOG 10	0.116	-0.144	1.487	S
	-0.680	-0.985	1.352	K
CBH **(1/3)	0.009	0.182	0.131	S
	0.330	-0.906	-1.096	K
XBGRAD **(1/4)	0.198	0.853	0.314	S
	-0.612	0.798	-0.028	K
LBAREA LOG 10	0.087	-0.055	0.572	S
	-0.483	-0.957	0.500	K

relationships indicated by values approaching 1, and the direction of the relationship indicated by the position either below (negative) or above (positive) the diagonal line. Table 6.11 shows the relationship between each of the morphometric variables included in the analysis. The following variables are significantly collinear: LBW with LBAREA; LBL with LBW; and LBL with LBAREA.

In stepwise discriminant analysis the criterion used to minimise collinearity of variables included in the analysis is the tolerance test. The tolerance can be set at any level less than 1.0. For example, a tolerance of 0.25 indicates that each variable accepted into the analysis must provide at least 25% of the discrimination not explained by other variables. The choice of tolerance level was guided by plotting the number of variables retained in the analysis against .05 increases in tolerance level (figure 6.12). The five transformed morphometric variables were all included in the stepwise discriminant analysis, and all were retained with tolerance levels equal to or less than 0.30. However, when the tolerance criterion was raised to 0.35 one potential discriminating variable was excluded, and another at the 0.45 level. Three discriminating variables were retained until the tolerance level of 0.70. The tolerance level of 0.70 was used in one of the analyses reported here, which implies that the final three discriminating variables provide a unique discrimination of up to 70% not accounted for by other variables retained in the analysis.

Table 6.11

POOLED WITHIN-GROUPS CORRELATION MATRIX

	XBGRAD	LBW	LBAREA	CBH	LBL
XBGRAD				0.35050	
LBW	-0.20202		0.79003	0.31807	0.68912
LBAREA	-0.34252			0.30625	0.66622
CBH					0.41421
LBL	-0.26220				

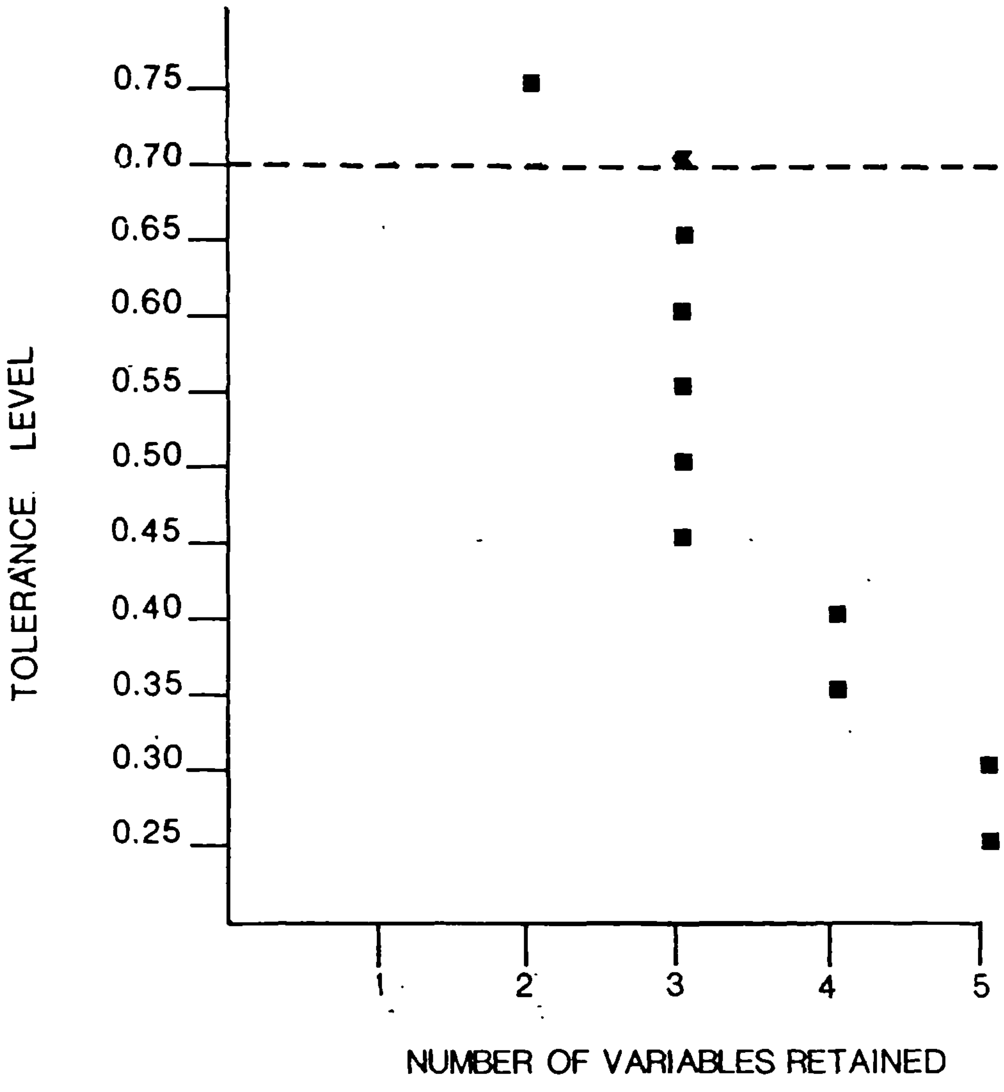
positive relationship above the diagonal line

negative relationship below the diagonal line

Figure 6.12

THE EFFECT OF CHANGING TOLERANCE LEVELS

IN DISCRIMINANT ANALYSIS



A forward stepwise procedure was used from the options available in the DISCRIMINANT procedure in SPSS-X2 to select the most useful combination of discriminating variables (Klecka, 1980). This method starts with the best univariate level discriminating variable, in this case XBGRAD, which as BGRAD had already been identified as a strong discriminator from the results of the Kruskall-Wallis nonparametric analysis of variance. The procedure then compares this variable with all of the other basin morphometric variables and selects the variable that provides the best discrimination in combination with, but not already accounted for, by the first variable XBGRAD.

The criteria which the variable has to satisfy before it can be accepted into the analysis are the partial F statistic and the tolerance test described above. The partial multivariate F statistic tests the additional discrimination introduced by a variable if it were to be entered at that step, with the largest F value indicating the most favourable variable for selection. Also available from the routine is the F-to-remove, which is also a partial multivariate F statistic that is used to assess whether a variable already included in the analysis has become redundant because variables included subsequently provide the same and additional discriminating information. However, in the analysis of this particular data set, this option did not reject any variables already included in the analysis.

The criterion for variable selection used in this analysis was Wilks's lambda, which is a measure of between-group differences as well as within-group variance provided by a variable. This statistic is calculated at each step in the analysis (Klecka, 1980). Since Wilk's lambda is an inverse statistic, variables with low Wilk's lambda values will be preferentially selected into the analysis. Ideally the best discriminating variable selected at any one step will give the greatest separation between groups as well as providing the smallest scatter within groups. The stepwise procedure continues until all the variables have been entered or until those remaining outside the analysis do not contribute significantly to the discrimination. Variables already selected in the earlier steps may be removed at later steps if another variable that is subsequently entered contributes the same and more discriminating information. Thus the stepwise procedure aims to select the optimal linear combination of discriminating variables.

The results of discriminant analysis using the 0.70 tolerance level are summarized in table 6.12. The combination of variables selected are XBGRAD, CBH and LBW, which gave a final Wilks's lambda of 0.2731, indicating good discrimination between the three groups. The canonical correlation coefficients (or total structure coefficients) give the geometric structure of the data space (table 6.12a).

Table 6.1 2

Discriminant analysis results.

0.70 tolerance level

percentage of groups correctly classified **80.56%**

A CANONICAL DISCRIMINANT FUNCTIONS

function	eigenvalue	% variance	canonical correlation
1	2.559	97.8	0.848
2	0.057	2.2	0.233

after function	Wilk's lambda	chi-square	df	significance
0	0.266	328.6	6	0.0000
1	0.946	13.8	2	0.001

B RANKED STANDARDISED CANONICAL DISCRIMINANT FUNCTION COEFFICENTS

FUNCTION 1		FUNCTION 2	
XBGRAD	0.899	CBH	0.591
CBH	-0.625	XBGRAD	0.543
LBW	-0.202	LBW	0.293

C STRUCTURE MATRIX

(pooled within-groups correlations between discriminating variables and canonical discriminant functions)

	FUNCTION 1	FUNCTION 2
XBGRAD	0.72*	0.69
LBW	-0.58*	0.37
CBH	-0.37	0.87*

N.B. * denotes which function the variable shows the greatest similarity in discriminating information.

The role taken in discriminant analysis by an individual function can be assessed and interpreted in a number of ways. The total number of functions given in discriminant analysis is equal to the total number of groups minus one. In this instance two functions are provided to describe the mathematical space in which the combinations of discriminating variables separate the individual process groups. Figure 6.13 illustrates the nature of the mathematical space with regard to the relative positions of the three process groups, with the scale expressed in standard deviation units.

The implications of these diagrams will be considered later after discussion on the role of the discriminating variables within this mathematical space. Not all of the default functions may be necessary, so one of the first tests after carrying out the stepwise discriminant procedure is to assess the validity of these results. This can be achieved by comparing the eigenvalues for the different canonical discriminant functions (table 6.12a). The eigenvalue for function one (2.559) is two orders of magnitude greater than that for function two (0.057). In absolute terms this indicates that function one accounts for 97.8% of the total discriminating power, and function two only 2.2%. Wilks lambda can also be used to evaluate the relevance of both functions. Thus before function one is derived we have a low lambda value of 0.266 which indicates that there was good separation between the three groups.

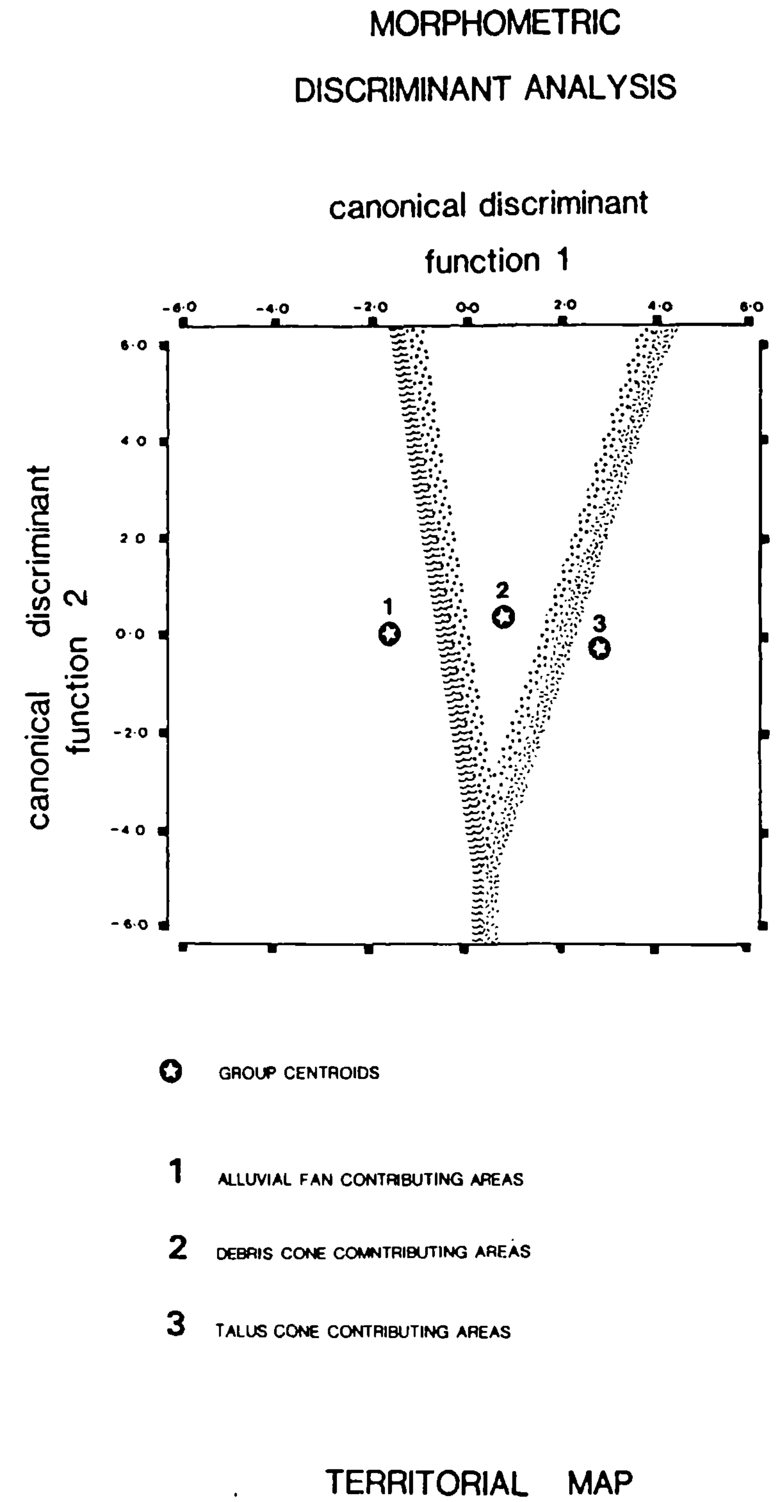
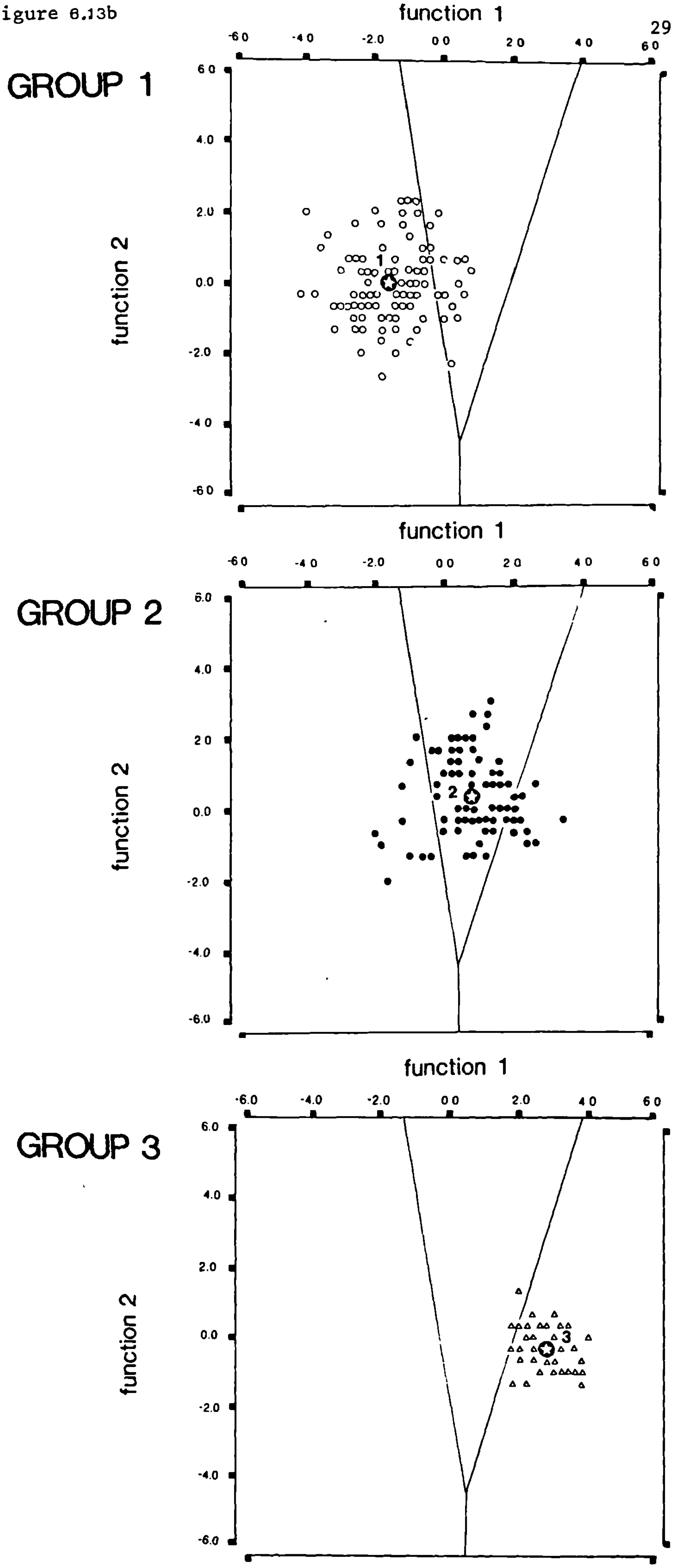


Figure 6.13a Location of the three group centroids, plotted on the territorial map.

Figure 6.13b


GROUP 1
function 1
-6.0
-4.0
-2.0
0.0
2.0
4.0
6.0
function 2
1
GROUP 2
2
GROUP 3
3

However, the Wilks's lambda value is much higher after function one (0.946), which implies that the amount of residual discrimination left to be explained is low. The significance of the lambda can be tested by converting it to a chi square value, which can be compared with significance tables. The results for before function one show that the lambda value 0.266 is very highly significant. The results for after function one are also significant, so that retention of two function in the analysis is statistically justified. The analysis of the relationships between each of the variables and the discriminant functions can assist with the interpretation of discriminant analysis and will be considered next.

In table 6.12b the ranked standardised canonical discriminant function coefficients show which variables make the greatest contribution to determining scores on each function. Thus XBGRAD makes the greatest contribution to function one, and CBH makes the greater contribution to the second function in relation to XBGRAD.

The structure matrix (table 6.12c) shows the bivariate product-moment correlation of each discriminating variable and the two functions. High correlation coefficients indicate that the variable shares similar discriminating information to that supplied by the function. The highest correlation coefficient of 0.87 indicates that the discrimination information provided by function two is very similar to that provided by CBH. Thus CBH can be used to explain, for example, the slight differences in the canonical discriminant coefficients for function two evaluated for the group centroids. However it has already been shown that function two is much weaker than function one, providing only a further 2% of the discriminating information to that supplied by function one (table 6.12a). Thus, on function two the role of CBH as a discriminator between the three different process groups is overall much less important than the discriminatory role of both XBGRAD and, to a lesser extent, LBW.

Thus it has been possible to assess the relative importance of the two discriminant functions and establish which discriminating variables can be used to interpret group separation given by the functions. The separation of the three process groups will now be considered in terms of what the discriminating variables XBGRAD, LBW and CBH imply. The three process group centroids have been plotted on the territorial map (figure 6.13). On function one, XBGRAD and LBW provide most of the discriminating information required to separate the three groups, with CBH providing much of the limited discriminating information provided by function two. A summary of the discriminating information given by the different variables explains the discriminating properties of the two-dimensional mathematical space.

1. On function one, low basin gradients and wide basin widths combine with large overall basin height values on function two to define group 1, alluvial fan catchments.

2. Basin gradient is higher, basin width narrower and basin height less for group 2, thus defining debris cone catchments.

3. The highest basin gradients, narrowest basin widths and smallest basin heights are associated with group 3, talus cone catchment characteristics.

These findings are illustrated schematically in figure 6.14.

Discussion of discriminant analysis results.

Reference to figure 6.11 gives some indication of the dimensions of these contributing area characteristics. Interquartile ranges will be considered here rather than the absolute range of values, to minimize the inclusion of possibly unrepresentative data such as over-estimated slope angle values derived from the map data base (section 6.2; also discussed below).

The strongest discriminating variable is basin gradient. The interquartile range for BGRAD gives some indication of the threshold for the three processes when operative in valleys or gullies. Group 1 interquartile values range from 6° to 14°, group 2 from 21° to 36° and group 3 from 37° to 50°.

The interquartile mean slope angles for fluvially-dominated catchments lie below the lowest value reported for landslips leading to debris flow (chapter 4). These mean slope angles are considerably higher than larger catchment mean slope angles such as those illustrated in

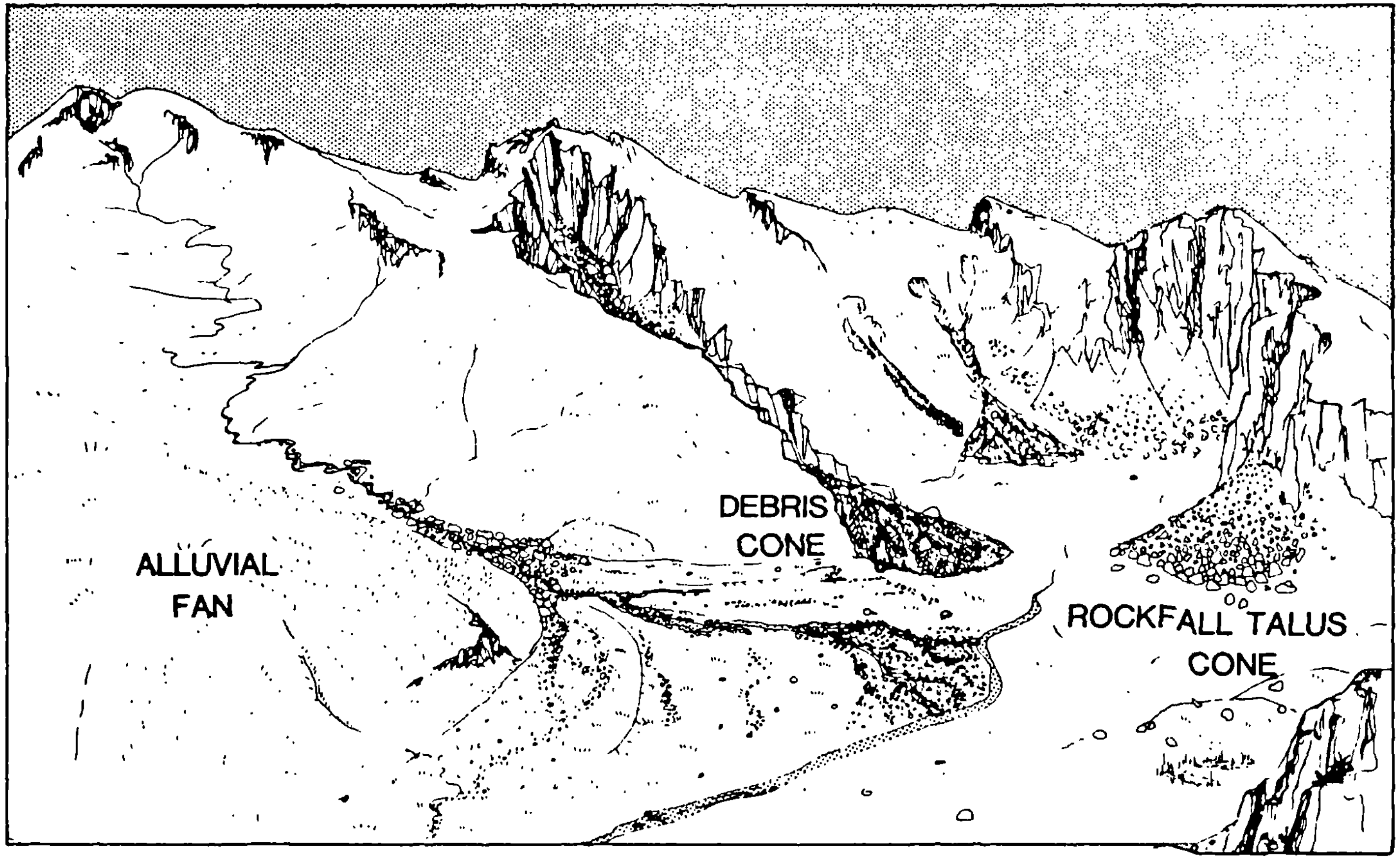


Figure 6.14 Scematic representation of the morphometric properties of alluvial fan, debris cone and rockfall talus cone catchments.

table 3.1 (ranging from 1° for Strathdearn to 5.7° in Glencoe). Relatively steep fluvially-dominated catchments are most favourable for rapid and flashy runoff, which is consistent with the characteristically weak down-fan fining evident on Scottish alluvial fans described in the previous chapter (section 5.3.2.3).

The range of mean gradients for gullies susceptible to debris flow (21° to 36°) are compatible with the range described by many authors (Williams and Guy, 1973; Owens, 1974; Brunsden, 1979). The lower quartile value for mean gradients of the Scottish debris flow susceptible gullies is, however, not as low as the minimum value of 15° reported by Innes (1983c).

The inverse tangents of thirteen fan and cone catchment relief ratios given in table 1 of Wells and Harvey (1987) may be compared with BGRAD values for alluvial fan and debris cone groups. Fans dominated by facies types S2 and S3 (linear longitudinal bar and planar stacked sheet deposits respectively) deposited during the June 1982 storm have catchment gradients ranging from 11.9° to 22.8°, type T1 (transitional or hyperconcentrated debris flow deposits) from 18.8° to 21.3°, and type D1 (narrow lobate debris flow deposits) from 25.2° to 29.2°. Debris cone BGRAD values correspond particularly well with mean slope values for dominant facies types D1 and T1. Of the basin gradients given for fans dominated by S2 and S3, only one (East Grain Gill) falls within the interquartile envelope for the alluvial fan group and the rest of the values are slightly higher, with the maximum value of 22.8° within the lower part of the interquartile range for the debris cone group (21° to 36°). However, it should be noted that the Howgill fans and cones have been classified by their recent deposits, which in terms of the degree of surface cover may not reflect dominant process as defined in section 6.2 above. For example Wells and Harvey described the old surface of the Leath Gill fan (type S2) as having relict lobate topography, which may imply debris flow activity in the past. Other dominant facies types S2 and S3 deposited during the 1982 storm partly comprise sediment eroded from old fan deposits where there is bedrock exposed in the source area (eg West Hazel Gill). This suggests that although sufficient gradient for debris flow exists in such catchments there was a lack of suitable sediment, resulting in fluvial erosion and reworking of the fan or cone deposits rather than debris flow (see also chapter 7, section 7.2.1).

The interquartile values for talus cone mean source area gradients range from 37° to 50°, the majority of which exceed 39° to 40°. However, rock faces on either side of the gully floor have considerably steeper gradients not accounted for by the mean gradient of the medial axis of the source area. Thus BGRAD may not accurately reflect the actual angle necessary for rock fall as opposed to the sliding or flow of debris from the source area. Minimal angles necessary for rockfall may be better approximated by

Statham's (1976b) estimates for rock slopes in the Cuillin Hills in Skye (50° to 70°) and in the Red Hills (around 50°).

In conjunction with mean basin gradient, basin width and basin height also define the morphometric controls of the dominant process in a source area. Maximum basin width (BW) gives an indication of the degree of confinement of the gully or valley, as well as an indirect indication of overall basin area. The narrowest gullies are found in talus cone catchments with values of around 50m. This value probably overestimates the maximum width of some of the smaller gully widths, as data were gathered from 1:25,000 topographic maps where 1mm represents 25m on the ground. However, the small range of gully widths reported for talus cones is representative of the conditions necessary for talus cone as opposed to talus sheet development. The probable lithological controls of talus cone gully formation have been discussed above (section 6.3.1), with joint spacing and other structural controls interpreted as critical for the development of narrow gullies suitable for channeling rock fall paths. In sum, it seems likely that gully width has to be restricted in order that a talus cone (rather than talus sheet) can accumulate below.

In comparison with talus cones, the maximum gully widths of catchments supplying debris cones are wider, ranging from 100m to 1,000m. Debris cone gullies are in general long and narrow, morphometric conditions that are optimal for sediment supply from the gully walls, but less likely to produce high runoff discharges (cf Wells and Harvey, 1987). Thus there is a greater probability that the sediment:water ratio will favour debris flow as opposed to water flow so long as there is sufficient sediment supplied to the gully floor (cf Statham, 1976a; Smith and Hart, 1982; Johnson, 1984; chapter 4, section 4.3.1). Certain lithological conditions favour narrow gully development (section 6.3.1 above), which is best illustrated by the selective weathering of porphyritic intrusions of the Etive dyke swarm such as Dalness Chasm (Bailey and Maufe, 1916; Bailey, 1960; chapter 7, section 7.2.1).

Fluvially-dominated catchments have the widest maximum basin widths, reflecting the larger basin areas which favour runoff rather than sediment supply to the channel, in contrast to debris flow dominated catchments. The interquartile range is quite large with measured basin width values ranging from 1,119m to 7,230m. Such basin dimensions are best developed in the comparatively gentle plateau topography of the Central and Eastern Grampian Highlands and the Monadliath Mountains.

The interquartile range for basin height reflects the local topography where the three process groups are found, and to some extent confirms the topographic findings of section 6.3.1. Thus rock gullies giving rise to talus cone formation are generally of limited height (interquartile range of 108m to 252m), reflecting corrie backwall heights and the generally small size of steep rock outcrops in the

Scottish Highlands. The interquartile range of debris cone gullies is greater (250m to 584m), because many of the gullies are developed along valley or mountain sides. The alluvial fan catchments have the largest overall interquartile range in BH values (360m to 696m), which often reflect the maximum height of mountain summits in any one catchment. Thus alluvial fans in the Cairngorm mountains are more likely to have greater BH values compared with fans developed in the neighbouring lower Gaick Plateau.

There is a certain amount of overlap for each of these discriminating variables, and this has influenced the degree of within-group homogeneity. The scatter of individual cases (figure 6.12) within the original three dominant process groups shows that both alluvial fan and debris cone catchments have less homogenous distributions than talus cone basin properties, and that some of their cases do not lie within the area defined around their process group centroid. The procedure whereby sites were classified into dominant process groups can be assessed in the light of the discriminant analysis. This test is necessary if the mathematical properties of the basin morphometric controls discussed above are to be used in future research. The results of the classification revealed that 80.56% of grouped cases were classified correctly by the discriminant analysis using the 0.70 tolerance test (table 6.12). The classification results at the group level help to explain why the discriminant analysis did not correctly classify

100% of the cases for the following reasons.

1. In group 1, 17 of the basins originally classified as alluvial catchments share similar characteristics to those that characterise debris flow dominated catchments.

2. In group 2, 12 of the contributing areas are more similar to alluvial fan catchments than they are to typical debris flow dominated catchments. Also, 18 of the contributing areas originally identified as dominated by debris flow activity share morphometric characteristics similar to those typical of rockfall-dominated catchments.

3. Two of the cases originally assigned to the rockfall group are also morphometrically similar to catchments in group 2.

In the previous chapter on fan and cone classification it was shown that both fluvial and debris flow processes can occur on one site, and there is abundant evidence for debris flow activity taking place on taluses (eg Ballantyne and Eckford, 1984). It is, therefore, not unexpected that the end members of the dominant process group contributing areas (particularly for group 2) should be morphometrically similar, especially when it is probable that more than one process could have occurred in them. No site was misclassified by more than one group distance (ie no alluvial fan basins were called talus cone contributing catchments or _vice versa_). The percentage of groups correctly classified (80.56%) is significantly higher than that which might have occurred by chance (ie 33.3% correct for each dominant process group). The proportional reduction in error statistic (tau) was used to measure the improvement made by the classification based on the discriminating variables. The tau value of 0.7098 means that the discriminant classification gave 70.98% fewer errors than would be expected by random assignment. It follows that we can accept the classification of sites on the basis of diagnositic features related to dominant process. Thus the data provide a reliable means for the statistical modelling of the linear combination of basin properties that discriminate the different process thresholds.

Within the calculated level of accuracy (80.56%) we can therefore identify the linear combination of variables that define the morphometric character of contributing areas where fluvial, debris flow or rockfall processes dominate (table 6.13b). Fisher's classification function coefficients may be used to classify other basins on the basis of these combined catchment properties. Further research is necessary to test the generality of this model in compatible environments, however the comparison with the Howgill catchments in terms of the most significant variable (BGRAD) suggests that the model can be applied to other areas of upland Britain. Improvements to the model would involve the inclusion of a more sensitive measure of basin gradient that could account for within-basin relief, particularly with regard to defining slope angle controls of rockfall and debris flow initiation in confined gullies.

table 6.13

Discriminant analysis classification results.

A. . A comparison of actual and predicted group membership.

ACTUAL GROUP	PREDICTED GROUP MEMBERSHIP			
	n	GROUP 1	GROUP 2	GROUP 3
GROUP 1	118	101 85.6 %	17 14.4 %	0 0.0 %
GROUP 2	97	12 12.4 %	67 69.1 %	18 18.6%
GROUP 3	37	0 0.0 %	2 5.4%	35 94.6%

PERCENT OF GROUPED CASES CORRECTLY CLASSIFIED : 80.56 %

B. Classification function coefficients.

(Fisher's linear discriminant functions).

	GROUP 1	GROUP 2	GROUP 3
XBGRAD	25.7918	34.19589	39.6441
LBW	10.29932	9.732831	8.767022
CBH	1.475669	0.4890407	-0.8599131
(CONSTANT)	-47.75732	-55.35407	-57.58958

6.4 CONCLUSION

The research reported in this chapter had two main aims:

1. to establish where different types of fan and cone occur in the Scottish Highlands, and

2. to establish how different morphometric and environmental variables influence the distribution and nature of fan and cone development.

Alluvial fans, debris cones, and to a lesser extent talus cones, are widespread throughout the Grampian Highlands. The distribution patterns of these landforms indicate that there is some relationship between proximity to the central mountain area and dominant type of fan or cone development. This implies that the morphometric and environmental characteristics of certain parts of the "mountain area" may be critical in controlling the dominant type of process, and hence the resulting fan or cone type.

A number of environmental factors were considered individually that might influence the distribution pattern of different types of fan and cone landforms, namely; precipitation, lithology, aspect and position relative to the Loch Lomond Readvance glacial limits. Of these only two (lithology and glacial history) are believed to have significantly influenced the nature of fan and cone development.

The results of analysing the relationship between fan and cone size and the Loch Lomond Readvance glacier limits revealed that, in general, larger alluvial fans have developed outside the limits, implying that conditions for alluvial fan developement may have been especially favourable during the Lateglacial, during part of which periglacial conditions prevailed. In contrast, no significant difference was found between the sizes of debris cones inside the Loch Lomond Readvance limits compared with the sizes of such cones outside these limits.

The effect of former glaciation is also important when interpreting the strength of relationships between fans and cones and their contributing catchment area characteristics. The correlation between alluvial fan adjusted area and basin adjusted area overall gave a very weak coefficient of 0.24 (significant at the 0.05 level), whilst the coefficient for debris cones was marginally stronger 0.37 (significant at the 0.01 level; table 6.4). When, however, the same relationships are examined in relation to sites inside or outside the Loch Lomond Readvance limits we find that the correlation coefficients are weaker within the limits than outside them (table 6.5). These results may suggest that fan and cone development has been to some extent paraglacial (sensu Ryder 1971a), and that readjustment to non-glacial conditions is slightly less well advanced within the Loch Lomond Readvance limits than outside them.

Regional environmental and topographic characteristics also determine the strength of fan and basin relationships. Generally the strongest fan and basin relationships were found for the Central and Eastern Grampian Highlands, which are characterised by dissected plateau topography and moderately uniform lithologies. In contrast, the weakest fan and basin relationships were found in the Western Grampian Highlands and in the Cairngorm Mountains. Both areas have mixed grades of igneous bedrock, which in the Western Grampians have been selectively weathered. Therefore the relationship between fan or cone and its contributing area may show considerable local variation, a phenomenon also noted by Ryder (1971a).

The results of the discriminant analysis suggested that catchment morphometry controls the probability of occurrence of each type of dominant process. The thresholds can be defined by the linear combination of three variables: mean basin gradient, maximum basin width and basin height. Values for these three variables correspond well with the findings of comparable previous research. The generality of the model developed here needs to be tested in comparable environments, and a suggested improvement (the inclusion of a measure of within-basin relief) may make it possible to define more precisely the thresholds between each of the process groups.

CHAPTER 7

CHRONOLOGY AND EVOLUTION.

7.1 INTRODUCTION

The continuum of fans and cones comprises some of the most widespread postglacial landforms found on valley floors in upland Britain, yet remarkably little is known about the chronology or evolution of these features. In this chapter attention will be focussed on the nature and rate of development of landforms of one part of this continuum (debris cones and fluvially-modified debris cones) during a maximum timespan of c 13,000 years since ice sheet deglaciation.

The morphological properties of many debris cones in the Grampian Highlands imply that there has been a marked change in dominant process during cone evolution. This suggests the possibility of changes in the background environmental controls of fan and cone development. However, the problems of interpreting the morphological development of these forms may be illustrated by the following examples. Two neighbouring cones in upper Glen Feshie (figure 7.1) show differing degrees of fluvial reworking of the original debris cones. The smaller cone has a very small surficial "alluvial fan" component built out near the cone toe. In contrast, the morphological properties of cone GF 12 (plate 7.1) imply several stages of evolution. The original debris cone grades into the highest

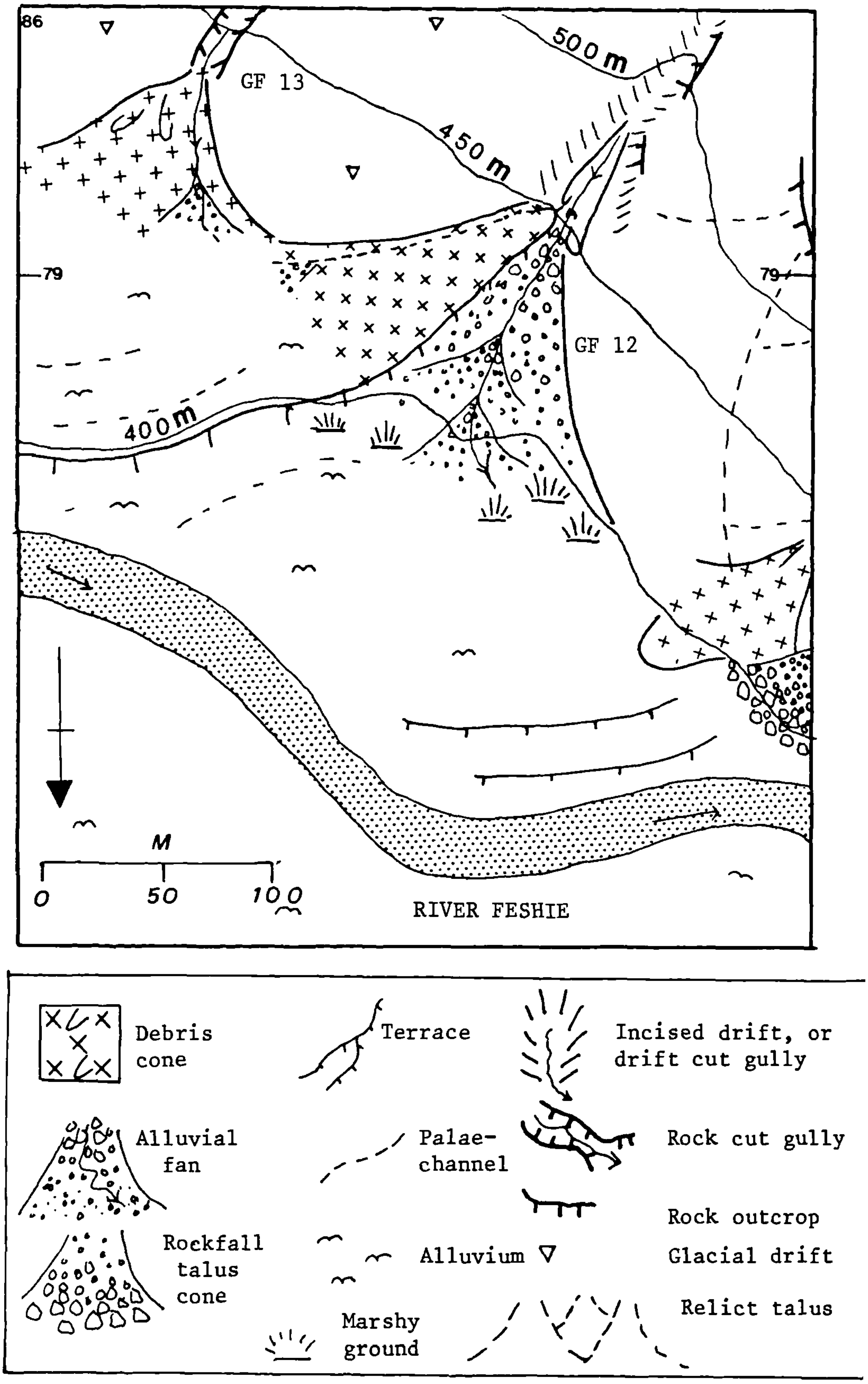


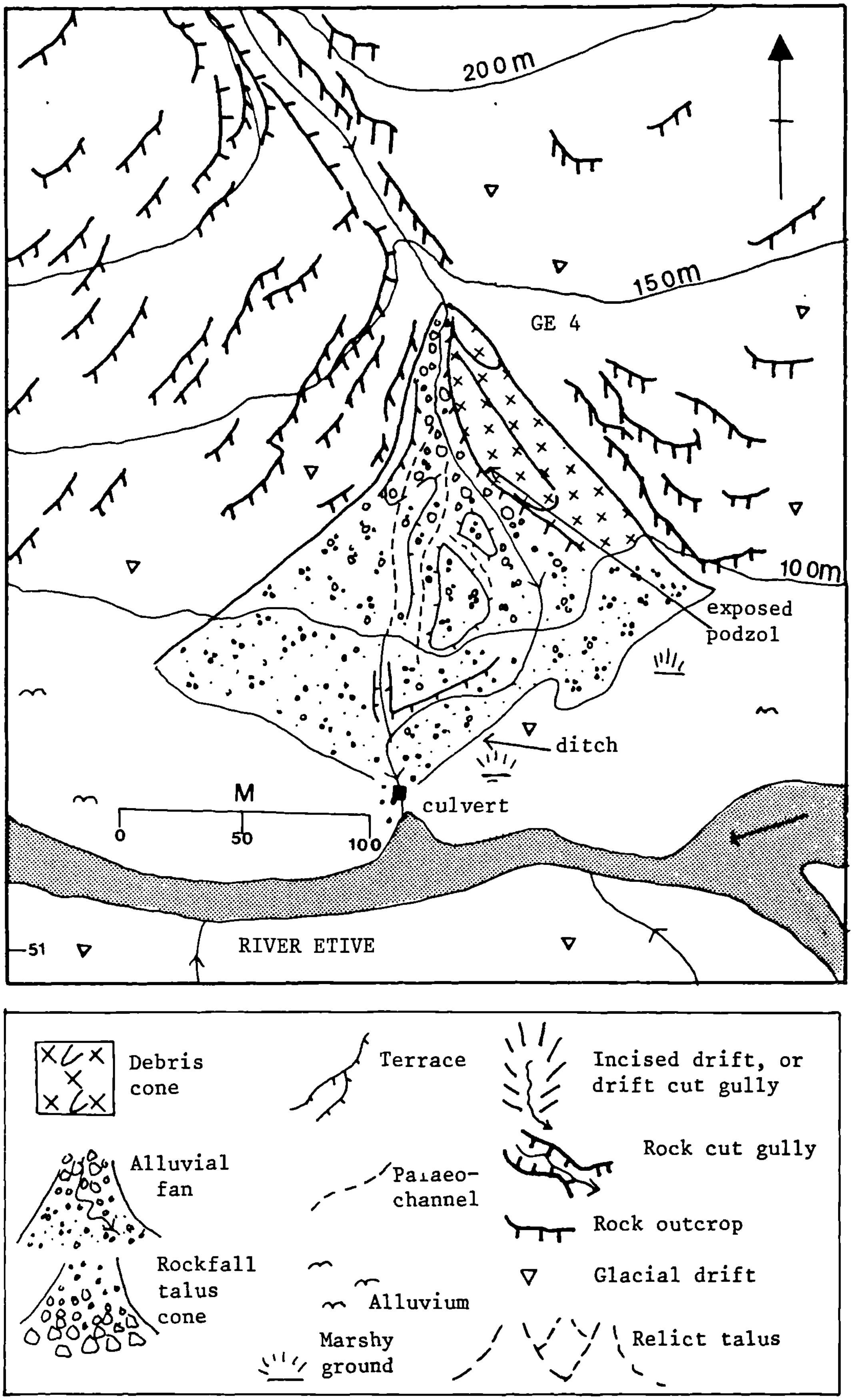
Figure 7.1 Geomorphological map of GF 12, a fluvially-modified debris cone in upper Glen Feshie.

Plate 7.1 A fluvially-modified debris cone in upper Glen Feshie.
(GF 12)

terrace in this part of upper Glen Feshie and is thought to have formed at the same time as the terrace. The terrace has not been dated, but because it lies outside the Loch Lomond Readvance glacial limits it has a maximum age of c 13,000 BP. Therefore, sometime after c 13,000 BP the terrace was formed by incision by the River Feshie and the debris cone was dissected by its stream. The surface of the dissected part of the debris cone shows that fluvial modification has been effective over the entire surface of the northern segment. Relatively small-scale stream incision down the centre of this fluvially-reworked segment has given rise to two small "telescoping" alluvial fans that have prograded on to poorly-drained ground on a lower terrace.

Perhaps the most striking morphological example of the effectiveness of fluvial modification is that of cone GE 4 (figure 7.2; plate 5.1), in Dalness, upper Glen Etive. This site has already been described in relation to its long profile form (chapter 5, section 5.3.2.1.2). Only a relatively small fragment of the original debris cone can be identified on the surface. Debris flow accumulation at this site is interpreted as having ceased probably during the Mid Flandrian, on the basis of the similarity in the degree of podzolisation between the sediments exposed along the incised fragment edge and dated soil development at the nearby Dalness Chasm cone (section 7.2.1 plate 7.3, figure 7.5 below). Many of the boulders on the fluvially-modified segment of the cone

Figure 7.2 Geomorphological map of GE 4, a fluvially-modified debris cone in Glen Etive.



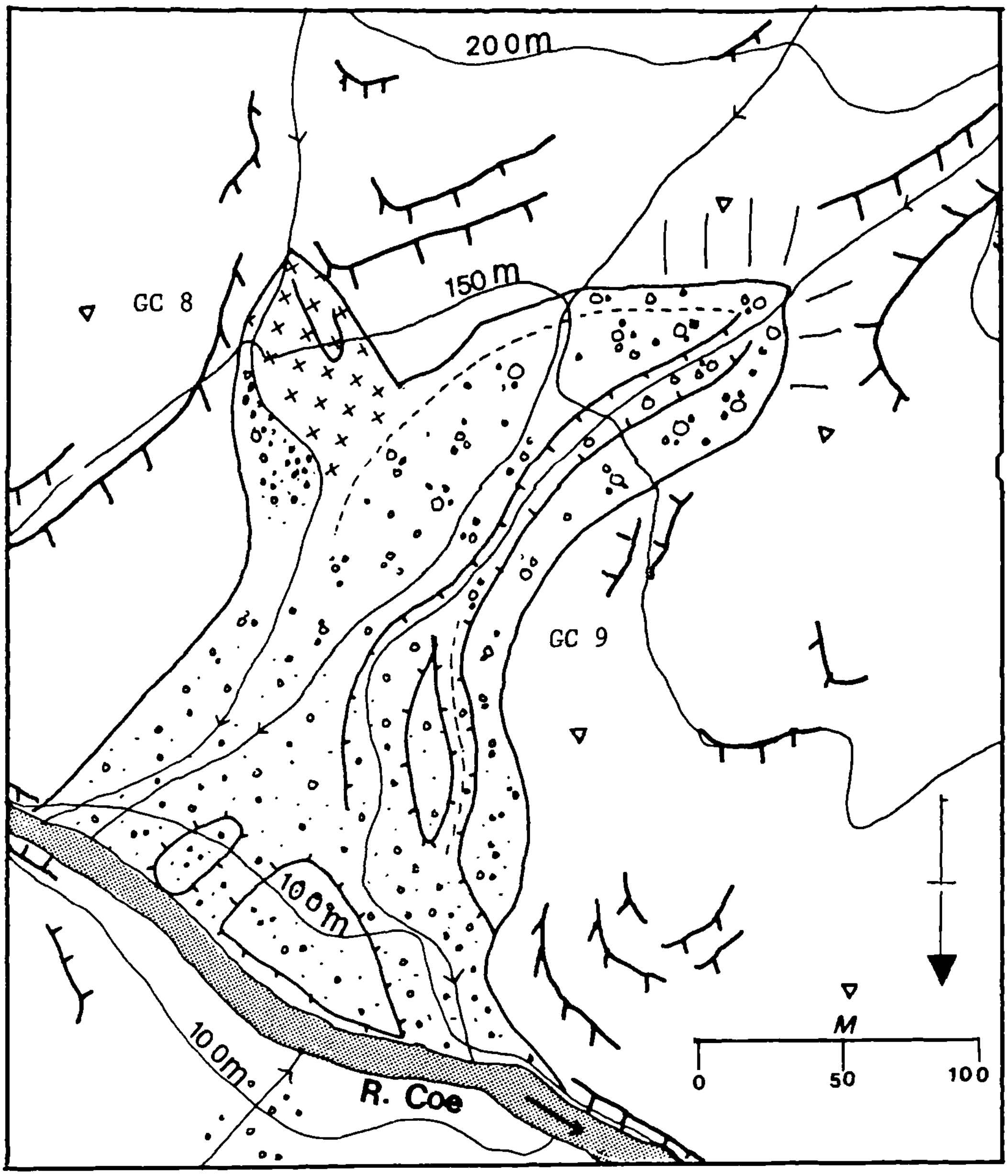
support lichens, and these have been used to date recent extensive fluvial activity (section 7.4 below). The reason for the change in dominant process type from debris flow accumulation to fluvial activity appears to reflect a change in the nature of the sediment available in the source area of the cone. Debris flow activity is dependent upon a number of factors, including the availability of fines to provide a suitable matrix. At present the rock gully floor supplying GE 4 is packed with boulders, but finer debris is largely absent, so that debris flow activity is unlikely to occur despite the favourable topographic configuration of the gully. Indeed, the steep configuration of the gully catchment favours flashy runoff that has mobilised some of the coarse sediment in the gully as well as leading to the reworking of the relict debris cone. Recent floods have deposited small clasts on marshy ground to the right of the cone. In a 0.05 m deep section exposed in a ditch cut through peaty material at the foot of the cone it was noted that only a single sand lens 1mm thick is interbedded in the peat. This suggests that the cone has only recently prograded on to the poorly-drained valley floor. Thus fluvial reworking of the debris cone has resulted in a recent extension of the toe of the cone, thereby reducing its overall gradient.

Not all relict debris cones have been so dramatically reworked by fluvial incision and redeposition of debris downstream. For example, only a small area adjacent to a small stream has been reworked on cone GC 8 (figure 7.3). Overbank deposition of flood sediments at this site has only thinly masked the underlying debris cone deposits, so that the cone has retained much of its original morphological character.

Reworking of cone sediments has not been restricted to fluvially-modified debris cones. Figure 7.3 also illustrates some of the general morphological characteristics of GC 9 (plate 7.2), a steep alluvial fan in upper Glencoe. This site exhibits very complex local topographic changes resulting from incision over much of its surface. Unlike cone GF 12, however, such incision cannot be put into a broad long term chronological framework because individual flash floods have been observed to lead to ephemeral "terracing" which is destroyed during later floods (cf Werritty and Ferguson, 1980). The recent chronology of some of the surface fragments of fan GC 9 are investigated in section 7.4.

The purpose of this chapter is threefold. First, in an attempt to elucidate the timing, nature and rate of postglacial fan and cone evolution, two study sites are examined in detail. These sites yield much more detailed information concerning debris cone development in the Highlands than can be gained from the morphological analysis above. Second, the magnitude of debris cone aggradation and associated gully denudation are assessed for a number of sites in the Grampian Highlands. Third, the significance of

Figure 7.3 Geomorphological map of GC 8, a small fluvially-modified debris cone (left) and GC 9, an alluvial fan (right).



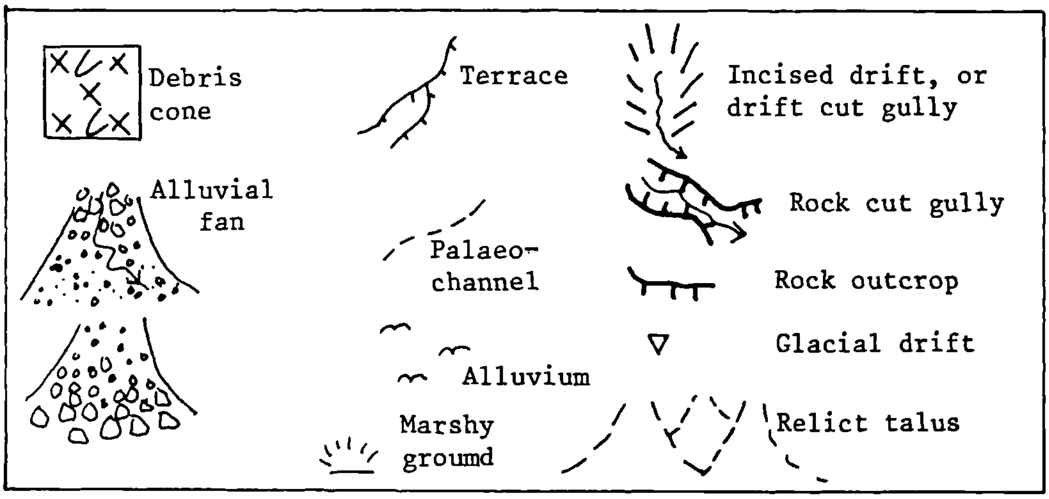


Plate 7.2 Corrie nan Lochan alluvial fan, GC 9.

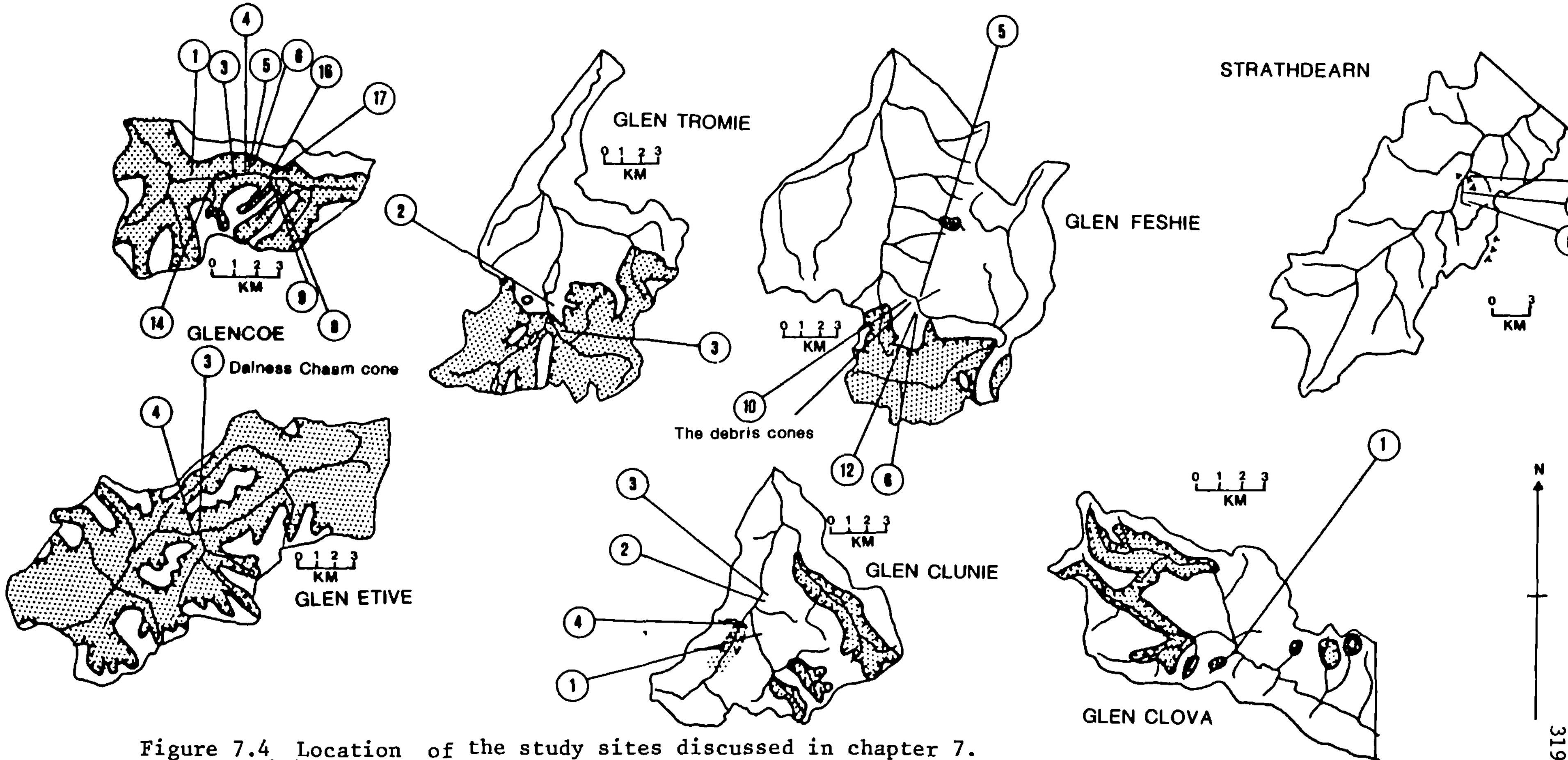


Figure 7.4 Location of the study sites discussed in chapter 7.
Stippled areas represents Loch Lomond Readvance glacial limits based on maps presented in chapter 3.

recent fluvial and debris flow activity on fans and cones in Glencoe is investigated. The location of all sites to be discussed in this chapter is illustrated in figure 7.4, which is based on maps presented in chapter 3.

During the discussions that follow, the chronology and evolution of fan and cone landforms will be considered in relation to a number of hypotheses that have been suggested in previous chapters. These hypotheses are briefly summarised below.

1. The paraglacial hypothesis (chapter 4). This states that fan and cone development is rapid during the period immediately following deglaciation, when there is little or no vegetation cover and when there is an abundant supply of potentially unstable sediment. Once this sediment supply has been significantly depleted and the source area has stabilized, then the nature and rate of fan or cone sedimentation is likely to change dramatically, with many features becoming relict or subject to reworking.

2. The periglacial hypothesis (chapter 4). This suggests that the most significant period of fan or cone aggradation occurs under periglacial conditions, or as a result of past periglacial weathering in the source area. Thus this explanation may be appropriate for fan and cone development in areas that remained outside the glacial limits during the Loch Lomond Stadial, as well as for features formed from debris that had been weathered under periglacial conditions.

3. Climatic fluctuations. A number of possible effects of climatic fluctuations on the nature and rate of fan and cone development were considered at the end of chapters 2 and 3. In essence it was suggested that fan and cone development may have been controlled by comparatively minor climatic fluctuations, including periods of increased storminess, throughout the Lateglacial and Flandrian. The random occurrence of such extreme events may considerably complicate environmental interpretation of landform development.

4. Anthropogenic interference. The evidence for human interference leading to accelerated rates of geomorphic activity on slopes and valley floors in upland environments was introduced in chapter 2. This hypothesis suggests that human activity, whether direct (eg forest clearance) or indirect (eg grazing livestock) has disrupted the vegetation cover, with the resulting accelerated slope erosion contributing to the evolution of the valley floor landforms.

7.2 TWO CASE STUDIES OF FLANDRIAN CONE EVOLUTION: DALNESS CHASM CONE AND THE FESHIE DEBRIS CONES

7.2.1 Dalness Chasm cone

7.2.1.1 Site characteristics

The first study cone (figure 7.5; plate 7.3) is situated at the foot of Dalness Chasm at 160m OD in upper Glen Etive (NN 192 514). The glacial origin of Glen Etive has been described in detail by Bailey and Maufe (1916).

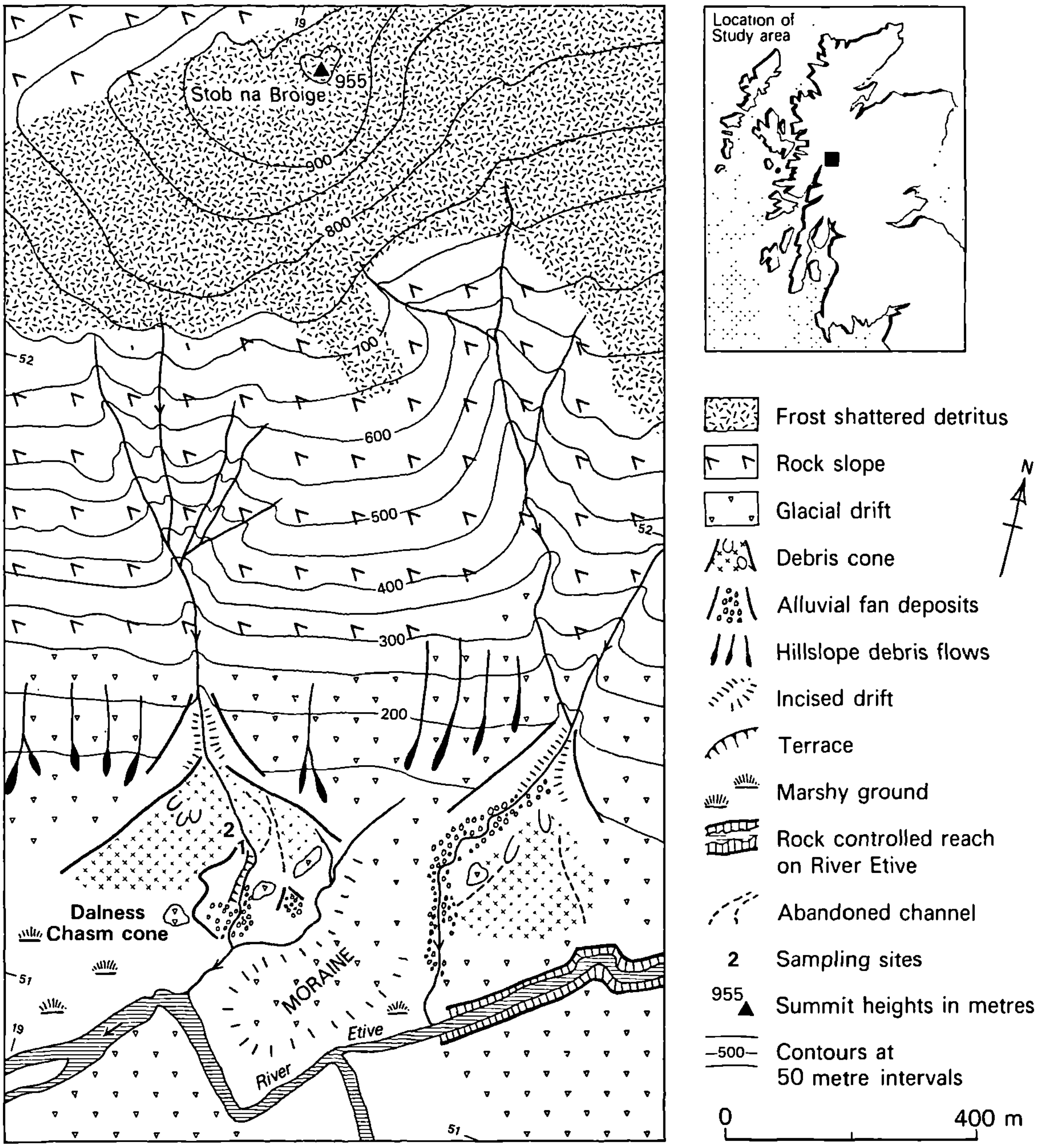


Figure 7.5 Geomporphological map of the Dalness Chasm cone and the surrounding area.

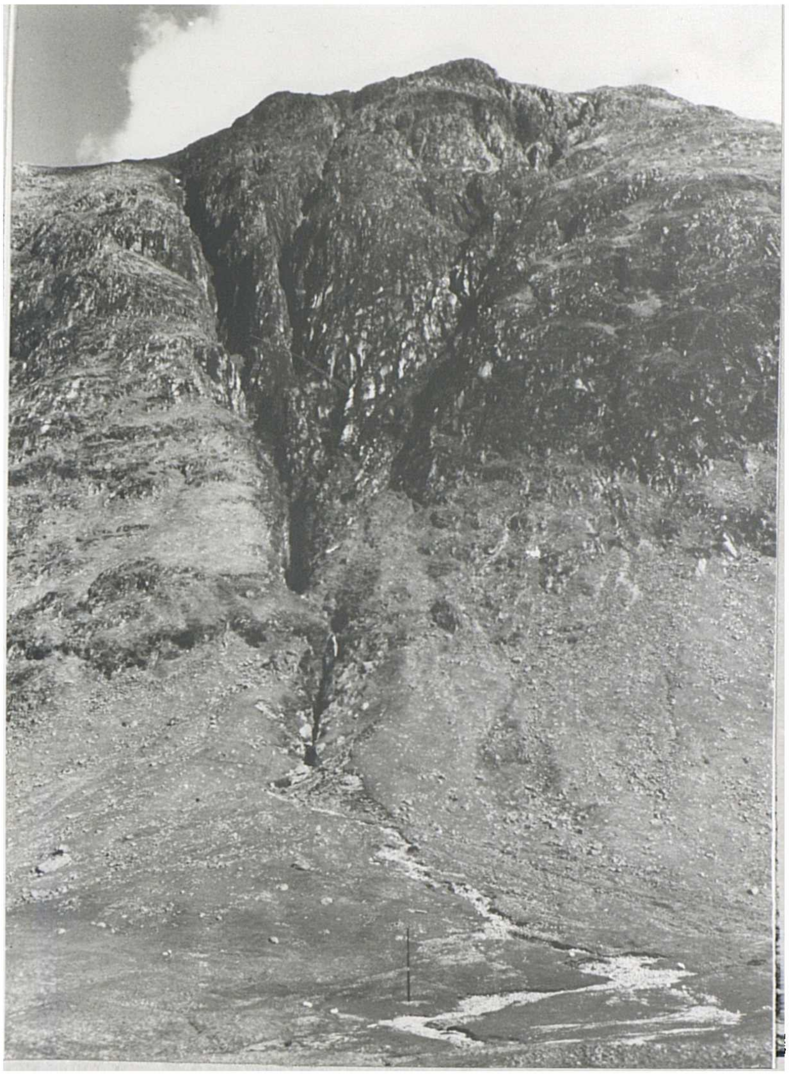


Plate 7.3 Dalness Chasm cone; a fluvially-modified debris cone in upper Glen Etive.

They noted several distinctive morainic mounds adjacent to Dalness Chasm cone (figure 7.5), and suggested that these are end moraines. The significance of these moraines, however, has not received any detailed attention since Bailey and Maufe mapped the area. It is suggested here that these morainic mounds are associated with a distinct drift limit that descends from Fionn Ghleann, the tributary valley that joins Glen Etive opposite the study cone. This evidence appears to imply deposition by a former glacier that issued from that glen. The moraines do not mark the maximum extent of glacier ice in Glen Etive during the Loch Lomond Readvance, however, as this limit has been established much farther down-valley at the mouth of Loch Etive (McCann, 1966; Gray, 1972). It is possible, however, that the Dalness moraines mark a minor readvance or stillstand during ice wastage. In this part of the glen the ice thickness during the Loch Lomond Readvance maximum is thought to have reached an altitude of 650 m OD (Thorp, 1981). Thus Dalness Chasm cone, and others in Glen Etive, must have formed since ice wastage c 10,000 BP.

Dalness Chasm cone comprises two distinct units: a proximal debris cone and a distal alluvial fan produced by fluvial erosion of the debris cone and redeposition of the sediment downstream, processes that are currently active. The composite cone has a mean medial gradient of 11.8° and is predominantly concave down-slope. The mean gradient of the upper third of this long profile (13.7°) is distinctly steeper and topographically more irregular, reflecting debris flow deposition, in comparison with that of the lower third of the profile (6.2^{o}) where fluvial modification of the cone becomes increasingly important (chapter 5).

7.2.1.2 Stratigraphy

Fluvial incision of Dalness Chasm cone has exposed the stratigraphy of this site along most of the present stream course. Two sampling sites were chosen for investigation of the stratigraphy of the deposits (figure 7.5): sampling site 1 is located immediately downstream of the apex of the alluvial fan, and site 2 is c 20m upstream of the fan apex on the debris cone itself.

The lowermost stratigraphic unit visible at site 1 (figure 7.6; plate 7.4) comprises a typical coarse debris flow deposit, with poorly-sorted clasts embedded in a predominantly silty matrix. The overlying sediments consist of poorly-sorted alluvial gravels with an abundant coarse sandy infill; farther downslope the same unit exhibits both increased sorting and pronounced stratification. The granulometry of the debris flow matrix compared with the alluvial infill illustrates the contrast in character of these two stratigraphic units.

Two bulk samples, one from each unit, were removed from the section face and dried at 105^{o}C for 24 hours. The samples were then sieved through a 2mm sieve. Granulometric analysis was carried out on the fraction of sediment less

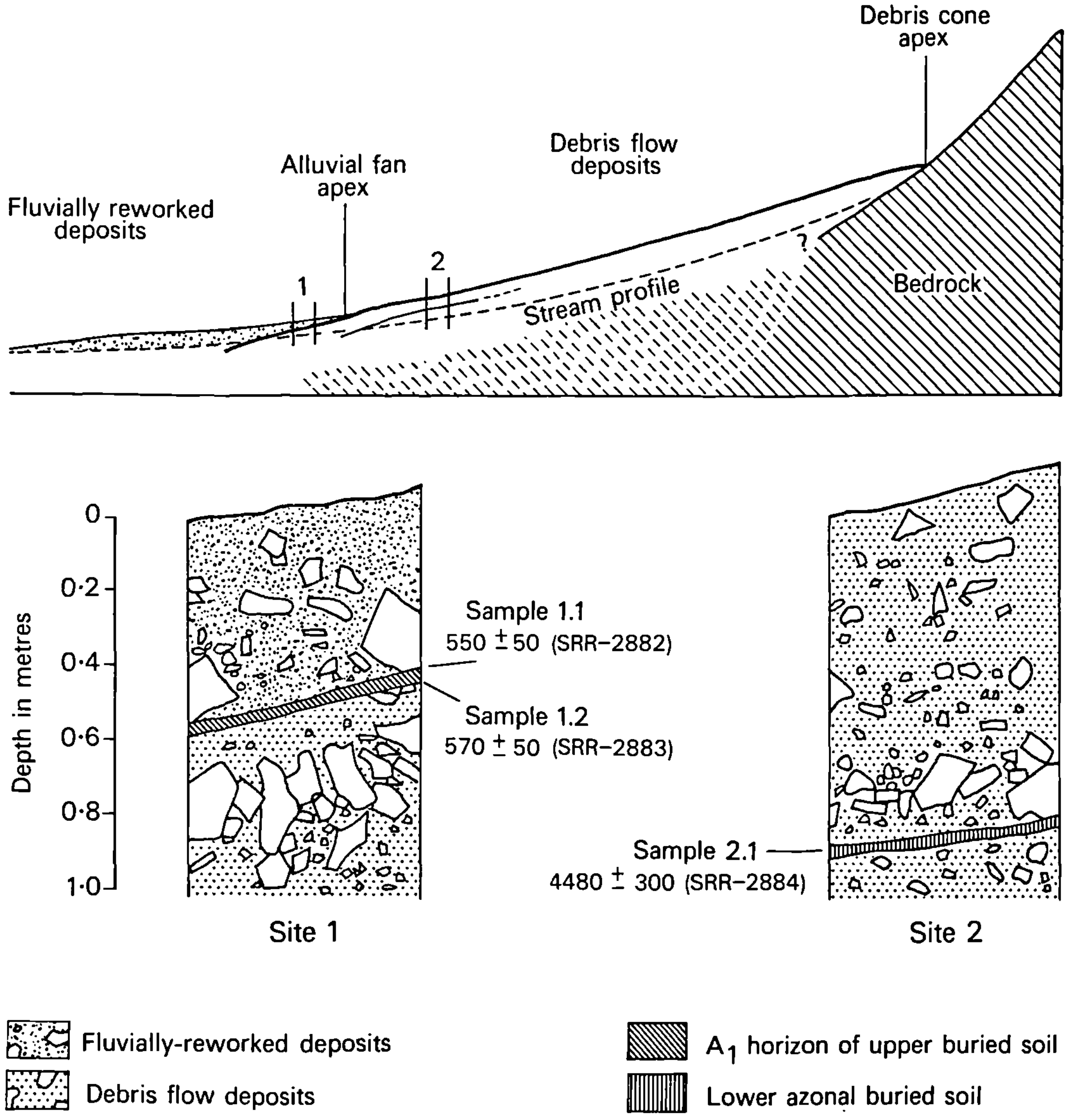


Figure 7.6 Near-surface stratigraphy of the Dalness Chasm cone. The upper diagram is schematic and not drawn to scale.

Plate 7.4 Debris flow deposits overlain by alluvial deposits, which form an alluvial fan on the lower part of Dalness Chasm cone, upper Glen Etive. The surface of the buried debris cone is marked by a podsol. Organic samples were withdrawn from the top and bottom of the A_1 horizon of the soil, for radiocarbon analysis (samples 1.1 and 1.2).

than 2mm. The samples were subdivided by using a sample divider and weighed. One subsample was wet-sieved through a nest of one phi interval metal sieves for 20 minutes, and the sediment trapped on each sieve was then dried and weighed. The wet-sieving results give the size distribution of the sediment between 2mm and 63 microns. The second subsample was then dry sieved and the fine fraction of less than 63 microns was weighed and retained for Coulter Counter analysis. A small subsample of these fines was prepared in a drop of phosphate-free detergent (to prevent the flocculation of clays) which was then added to 200 ml of electrolite solution and dispersed in an ultrasonic bath for 20 seconds. Analysis of the size distribution was then carried out on a 15% concentration of weight for volume of fines using a Coulter Counter.

The granulometric characteristics of the debris flow matrix are illustrated in figure 7.7. The clay fraction of the matrix is very low (less than 0.01%) and is within the range of values given by Innes (1983c) for sandy-matrix hillslope debris flows, but the total silt content was high (85 %). In contrast, the fluvial infill is much coarser, with much less silt than in the debris flow matrix (figure 7.7). The generally coarse, poorly-sorted character of the fluvial deposits at the alluvial fan apex implies rapid overbank deposition during flash floods, conditions that would have favoured flushing out of fine sediments.

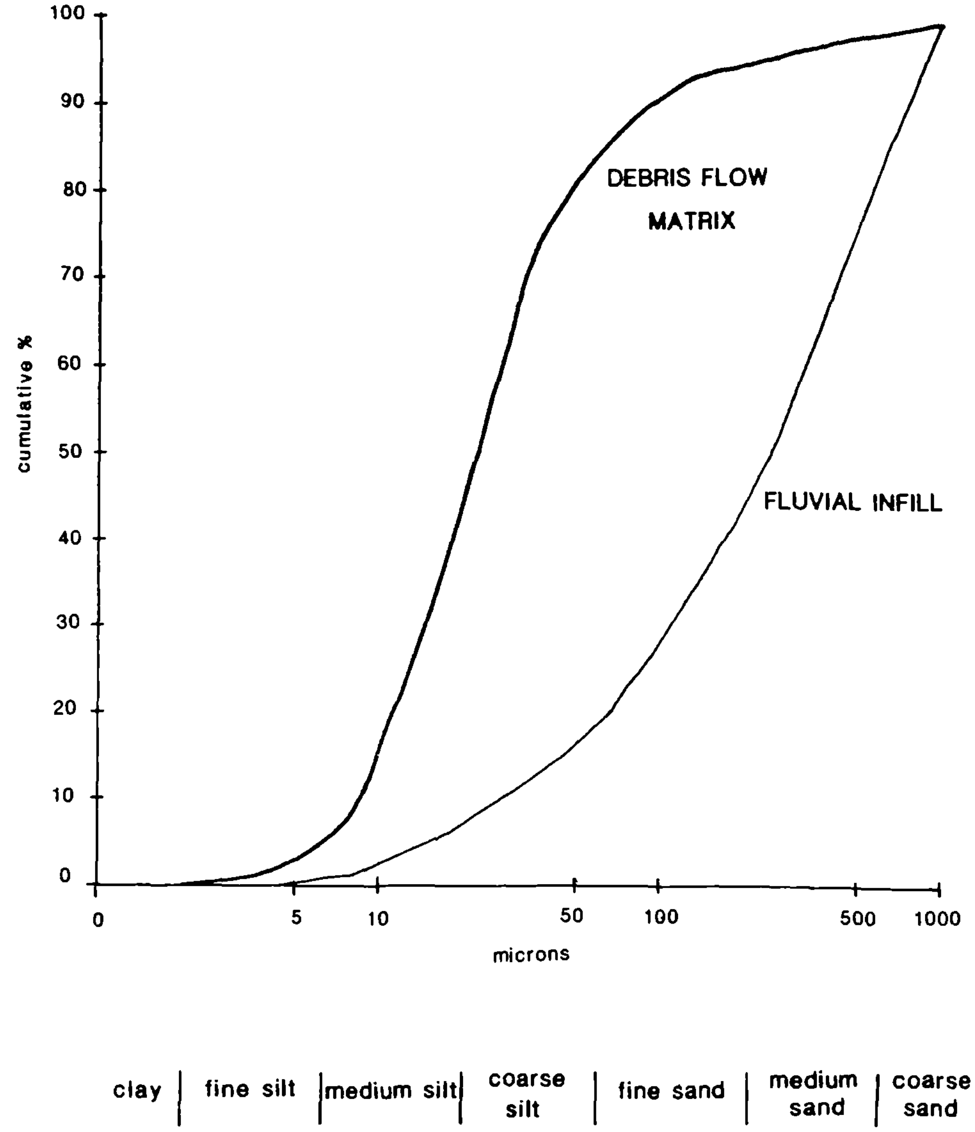


Figure 7.7 Granulometric character of the debris flow matrix compared to the fluvial infill, from samples removed from the section face at site 1, Dalness Chasm cone.

The lower unit at site 1 (debris flow deposits) has been strongly podzolised and retains an organic A1 horizon of variable thickness of 20 to 50mm, a well-developed bleached A2 horizon and an iron-rich B horizon. This soil clearly represents the former surface of the debris cone prior to burial, as the soil rises toward the present debris cone surface at the alluvial fan apex and is stratigraphically continuous with the present-day soil upslope of the fan apex. In contrast to the podzolised debris flow unit at site 1, the overlying fluvial deposits show only immature soil development at several levels. When compared with the length of time implied by the development of the podzol in the buried debris flow deposits, these soils appear to reflect episodic fluvial deposition over a relatively short time period.

At sampling site 2 an immature buried soil up to 100mm thick separates two debris flow units. The upper one is the continuation of the lower unit at site 1, and is interpreted as representing the final debris flow event to affect this part of the cone. Moreover, the similarity in the degree of podzol development here and in an exposure near the debris cone apex suggests that this unit may well represent the final debris flow event anywhere on the cone (M.S.E. Robertson-Rintoul, pers. comm.).

Three phases of development may be inferred from the above evidence:

1. an initial phase of episodic debris cone aggradation that ended with the deposition of the upper unit at site 2 (lower unit at site 1);

2. a period of prolonged stability during which a mature podzol developed on the cone surface; and

3. a period of stream incision into the upper part of the cone with the deposition of fluvially-reworked sediments on the lower part of the cone (upper unit at site 1).

7.2.1.3 Radiocarbon dating.

Three samples were obtained for radiocarbon dating from the buried soils at sites 1 and 2 (figure 7.6). The stratigraphically uppermost sample (1.1) was taken from the top 5mm of the organic A1 horizon of the buried soil at site 1, and the second sample (1.2) was taken from the lowermost 5mm of the same organic horizon. The third sample (2.1) was taken from the uppermost 5mm of the buried soil at site 2. The radiocarbon analyses were carried out at the Scottish Universities Research and Reactor Centre under the direction of Dr. D.D. Harkness. The soil samples were digested in 2M HCl ($80^{\circ}C$ for 24 hours), followed by washing to neutral pH.

The results of the radiocarbon analysis are given in table 7.1 (Brazier _et al_, in press). Although all of the age determinations are stratigraphically consistent, the

Table 7.1

Dalness Chasm Cone: Radiocarbon Dates Associated with Buried Soils

Sample No.	Sample Location	Laboratory Code	Radiocarbon age (years BP)
1.1	Top 5mm of buried organic horizon at 0.60m depth, sampling site 1	SRR-2882	550 + 50 $\delta^{13}C=-28.9‰$
1.2	Bottom 5mm of buried organic horizon at 0.65m depth, sampling site 1	SRR-2883	570 + 50 $\delta^{13}C=-28.5‰$
2.1	Top 5mm of immature azonal aoil at 0.9m depth, sampling site 2	SRR-2884	4480 + 300 $\delta^{13}C=-27.6‰$

radiocarbon date of 570 +/- 50 BP given for sample 1.2 is thought to be unrealistic, particularly as it is statistically indistinguishable from that of 550 +/- 50 BP obtained from the top of the same organic-rich horizon. This could have arisen partly as a result of translocation of younger organic material through the profile, so that the organic material at the base of the A1 horizon of the podzol has no bearing on the age of the deposition of the debris flow unit below. Furthermore, the degree of pedogenesis and the characteristic decline in pollen concentration through the debris flow unit at site 1 (figure 7.8) indicate a much older age for the debris flow unit than the minimal age of 570 +/- 50 BP implies. It is thus inferred that the age of 4480 +/- 300 BP for sample 2.1 more closely approximates the age of the final debris flow event on Dalness Chasm cone. Allowance may have to be made for apparent mean residence time effects, although these have been minimised by sampling the very top of the soil (cf Matthews and Dresser, 1983; Ellis and Matthews, 1984). The date of 550 +/- 50 BP is accepted as a maximum age recording the initiation of fluvial reworking at site 1.

7.2.1.4 Pollen analysis.

Fifteen pollen samples were withdrawn at regular intervals vertical from the section face at site 1, in order to investigate vegetation changes that might have been associated with the initiation of fluvial reworking after *c* 550 BP (figure 7.8). Preparation of the pollen samples was

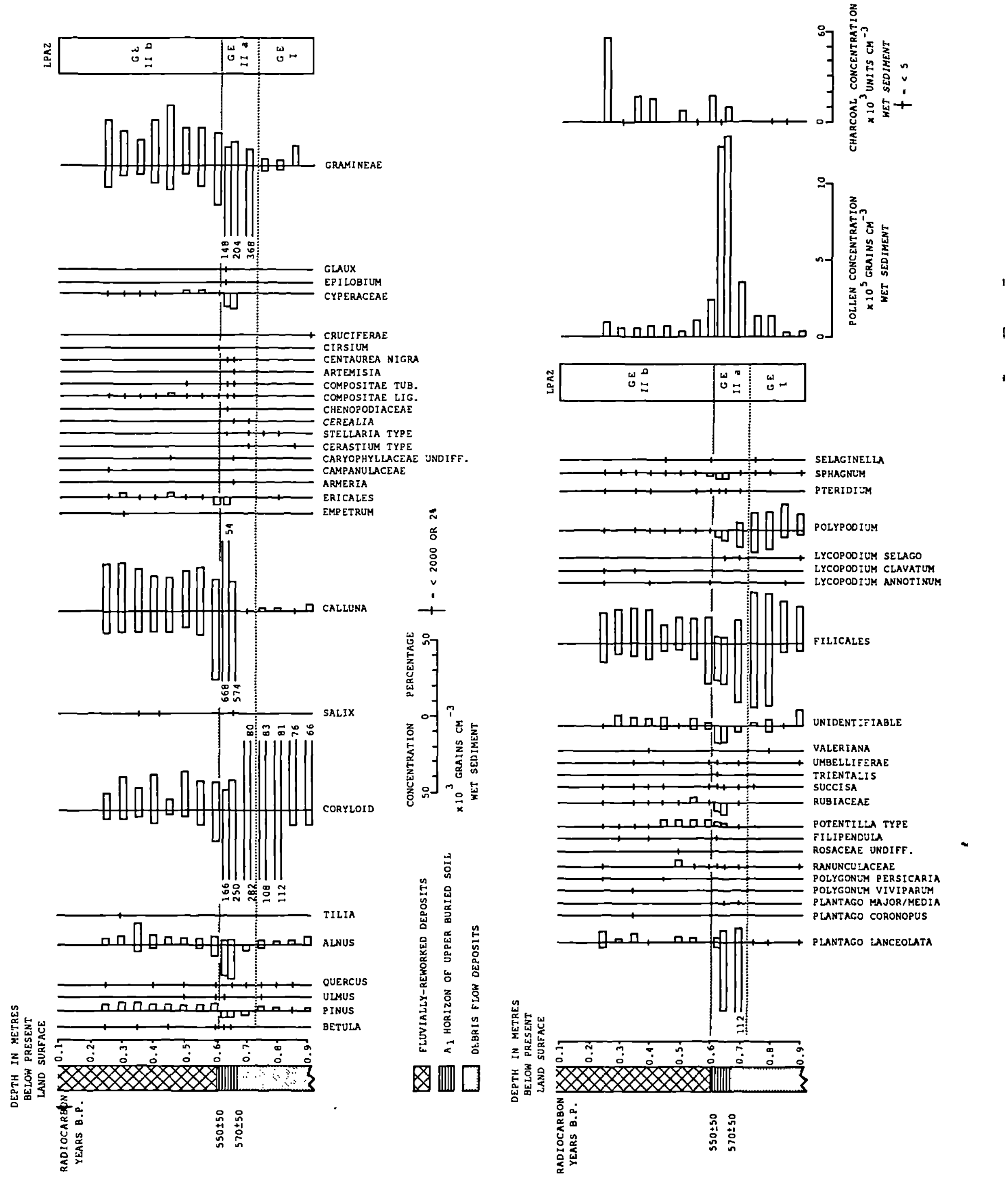


Figure 7.8 Stratigraphy, pollen concentrations, relative pollen sums, charcoal concentrations and radiocarbon dates for samples taken from a vertical column at sampling site 1.
One charcoal unit is a charcoal fargment of dimensions 20 × 20μm

undertaken by Mrs. L. Wood and the interpretation of the pollen diagram has been provided by Dr. G. Whittington. It is acknowledged that soil pollen analysis may be more problematic than palynological investigations in waterlogged sites because of differential preservation of pollen and spores, as well as the difficulty in establishing contemporaneity of pollen grain deposition owing to translocation during pedogenesis (cf Dimbleby 1957, 1961; Havinga 1964, 1984). However, the latter is less important in this particular study because attention was focused on gross changes in the type and concentration of pollen assemblages below, through, and above the dated discontinuity that marks the former surface of the debris cone at sampling site 1.

Two local pollen assemblage zones (GE I and GE II) were identified, the latter being split into two sub-zones (GE IIa and GE IIb). Zone GE I corresponds broadly with the debris flow deposits below the dated organic layer, GE IIa incorporates the organic layer and the underlying 50 mm of soil, and zone GE IIb corresponds exactly with the overlying fluvially-reworked deposits (figure 7.6). Zone GE I is dominated by *Corylus* / *Myrica* pollen and the associated taxa indicate that the pollen represented here is that of *Corylus avellana*. Fern (*Polypodium* and Filicales) spores are also present, together with some pine and alder pollen. Zone GE IIa is characterised by high concentrations of Coryloid pollen, *Calluna vulgaris*, and *Plantago lanceolata*. A similar assemblage occurs in zone GE IIb, with decreased concentrations of Gramineae and Filicales.

This evidence suggests that prior to burial the debris cone surface at site 1 supported an extensive cover of *Corylus avellana*, which presumably shaded out herbaceous species. The *Alnus* present is likely to be representative of stands along stream courses, whereas the *Pinus* pollen grains probably reflect wind transport from farther afield. The transition between GE I and GE IIa is marked not only by changes in pollen taxa, but also by a presence of abundant charcoal fragments. *Corylus* is progressively replaced by Gramineae, *Plantago*, and *Calluna*. The high concentrations of charcoal indicate the use of fire in shrub clearance, and the appearance of *Cerealia* (cereal) pollen and that of several agricultural weeds (eg *Polygonum persicaria, Polygonum viviparum, Artemisia* and *Plantago* spp.) implies the introduction of both arable and pastoral farming. Indeed, the presence of lazy beds on the lower cone surface to the east of sampling site 2 confirms that the cone has been used for arable farming sometime in the past. In sub-zone GE IIb, through the overlying fluvial deposits, variable pollen concentrations suggest several phases of alluviation, an interpretation supported by the occurrence of buried immature azonal soils within the fluvially-reworked deposits farther down-fan. Agricultural activity, suggested by the persistence of the pollen of agricultural weeds, may have contributed to continued instability at this site.

7.2.1.5 Discussion.

The stratigraphic evidence described earlier revealed three phases in the evolution of Dalness Chasm cone:

1. debris cone accumulation;
2. prolonged stability of the surface of the relict debris cone and associated soil development; and
3. stream incision of the debris cone and redeposition of eroded sediment downstream forming a small alluvial fan.

The radiocarbon and pollen analyses provide evidence concerning the timing and causes of these changes.

Deglaciation of Glen Etive c 10,000 BP provides a maximal age for debris cone development, and the date of 4,480 +/- 300 BP (sample 2.1 at site 2) is maximal for the cessation of accumulation and the beginning of the period of stability. Provided that apparent mean residence time effects are not large, this implies that the bulk of cone sedimentation (c 170,000 m^3 ; see section 7.4 for explanation of the method of measurement) occurred during the first c 6,000 years of the Flandrian. This evidence conflicts with Innes' (1983c) views regarding the recent nature of most debris flow activity in the Scottish Highlands. A marked increase in hillslope debris flow activity during historical time cannot be denied, yet in the context of Flandrian slope activity as a whole the significance of recent debris flow activity may not be as great as advocated by Innes. Indeed, the evidence from Dalness Chasm cone suggests that at this site at least a far greater magnitude of debris flow activity was operative during the early Flandrian following deglaciation.

The cessation of debris flow deposition, the long period of stability, and the subsequent incision and fluvial reworking of the cone imply changes in the supply of sediment from the source area. The original sediment source was probably glacial and rockfall debris in Dalness Chasm. This steep rock gully has developed as a result of preferential erosion of a porphyritic dyke, part of the Etive dyke swarm (Bailey and Maufe, 1916; Bailey, 1960). Indeed, Thorp (1981) has suggested that the abundant shatter planes in the porphyrite have made them more susceptible to frost weathering in comparison with the other rock types found in the Etive area (cf chapter 3). Frost shattering may have occurred during the Loch Lomond Stadial in the upper parts of the gully, in the area above the ice marked by the lower limit of frost-weathered debris on Stob na Broige (figure 7.5). Frequent rock release in the gully may also have continued for a short time following deglaciation. Present-day rates of rockfall, however, appear negligible. There is little evidence of fresh scars on many of the rock faces in the gully, most of which support lichens and mosses and some small birch trees. A very small rock failure occurred from a face on the opposite side of the valley during the winter of 1985/1986, illustrating the insignificance of this process in Glen Etive today. The other source of sediment in the rock gully was probably glacigenic in origin, as evidenced by the survival of fragments of a thick drift cone flanking the rock gully mouth (figure 7.5). Therefore both of the original sources of sediment were non-renewable and probably dated from end of the Lateglacial and the early Flandrian. It is suggested that the debris cone ceased to aggrade in response to the depletion of this sediment source prior to c 4,000 BP, and that thereafter the cone remained stable until c 550 BP.

The maximal age of fluvial reworking of the site, c 550 BP, was obtained from the top of the buried soil at site 1. The pollen evidence indicates that the onset of alluvial deposition and the marked changes in the vegetation cover initiated by the burning of shrub cover were contemporaneous. Subsequent fluvial incision and reworking of sediment have resulted in the formation of the alluvial fan that partially buries the foot of the original debris cone. The evidence of fresh incision and deposition of gravel spreads farther downstream indicates that this process is still active today. The estimated volume of fluvially-reworked debris is of the order of 100 m3, which is proportional to the amount of incision of the main channel.

The wider implications of this site are as follows: First, the initial aggradation of the debris cone involved the reworking of an abundant sediment source by debris flows following deglaciation. In this respect the debris cone is essentially a paraglacial feature (sensu Ryder, 1971a, 1971b). By implication, therefore, many other essentially relict fans and cones in the Scottish Highlands may also be paraglacial, if it can be demonstrated that their formation has been similarly dependent upon a limited supply of sediment following deglaciation.

Second, many debris cones in the Scottish Highlands and elsewhere in upland Britain exhibit fluvial incision and deposition of reworked sediment (cf chapter 5). It seems possible, therefore, that relatively recent human disruption of a stable vegetation cover may be of widespread importance in initiating such fluvial reworking. However, further studies at similar sites will be necessary before this assertion is confirmed. Nevertheless, the evidence presented for the late Flandrian evolution of Dalness Chasm cone does contribute to a growing awareness of the impact that human activity has had on both the nature and rate of recent geomorphic processes in upland Britain. Indeed it has been claimed that vegetation changes induced by either clearance or the grazing of animals has not only affected the processes operating on valley floors and lower valley side slopes (eg Harvey et al, 1981, 1984; Innes, 1983a; Robertson-Rintoul, 1986) but has also been partly responsible for recent accelerated wind erosion and possibly mass-movement on some Scottish Highland mountains (Ballantyne, 1986a, 1987; Ballantyne and Whittington, 1987).

7.2.2 The Glen Feshie debris cones.

7.2.2.1 Data collection and results.

Three coalescing debris cones have built out from the steep gullied walls of the glacial trough in upper Glen Feshie (NN 854 903) at a mean altitude of 390 m OD (plate 7.5). Basal erosion of these cones by the River Feshie has resulted in the exposure of an extensive section over 60 m long and in places up to 10 m high (plate 7.6). The exposure cut by the River Feshie consists almost entirely of coarse debris flow deposits, with poorly sorted and dominantly angular clasts embedded in a coarse sandy matrix. These deposits extend down to the level of the river with the exception of part of the northernmost cone (cone 1), which has buried a low river terrace. Stratification is largely absent, although when the section was freshly exposed in 1984, linear discontinuities marked boundaries between individual debris flow units (figure 7.9, upper diagram). At this time three types of discontinuity could be identified, as follows.

1. Step-like discontinuities (plate 7.7) that mark the boundaries between individual debris flows which may have been deposited within a very short time period or even during the same event. There is no evidence of soil

Plate 7.5 The Feshie debris cones and associated source areas.

Plate 7.6 The section eroded by the River Feshie. NB the level of one of the buried soils.(arrow).

Plate 7.7 The ranging rod marks the base of sampling site 1, of the Feshie debris cones. Behind the ranging rod are two distinct debris flow units separated by bench-like dicontinuity (ie with no intervening organic material). In the foreground (lower left) is an organic soil.

development between debris flow units marked by such steps.

2. Buried immature soils also mark the boundary between individual debris flow units. These soils are organic-mineral A horizons and may be identified by their finer texture, increased organic content and colour variation in comparison to the underlying and overlying debris flow deposits. This fine material is interpreted as having been washed out of adjacent recently-deposited debris flows nearby and subsequently stabilised at the cone surface, allowing limited soil formation before being buried by later debris flows.

3. Discontinuities were also marked by the development of buried immature soils containing abundant woody plant remains, mostly in the form of roots.

The aim of investigations at this site was to establish the timing of debris cone initiation and to evaluate the significance of the periodicity of debris flow activity. Four sampling sites were chosen for the extraction of organic material for radiocarbon dating (figure 7.9, lower diagram).

All the soil and wood samples were collected and placed in clean polythene bags, and stored in a freezer, prior to submission for radiocarbon analysis at the Scottish Universities Research and Reactor Centre at East Kilbride. Where abundant woody roots were present (type 3 discontinuity, above) these were collected for radiocarbon analysis in preference to organic soils. Where woody roots

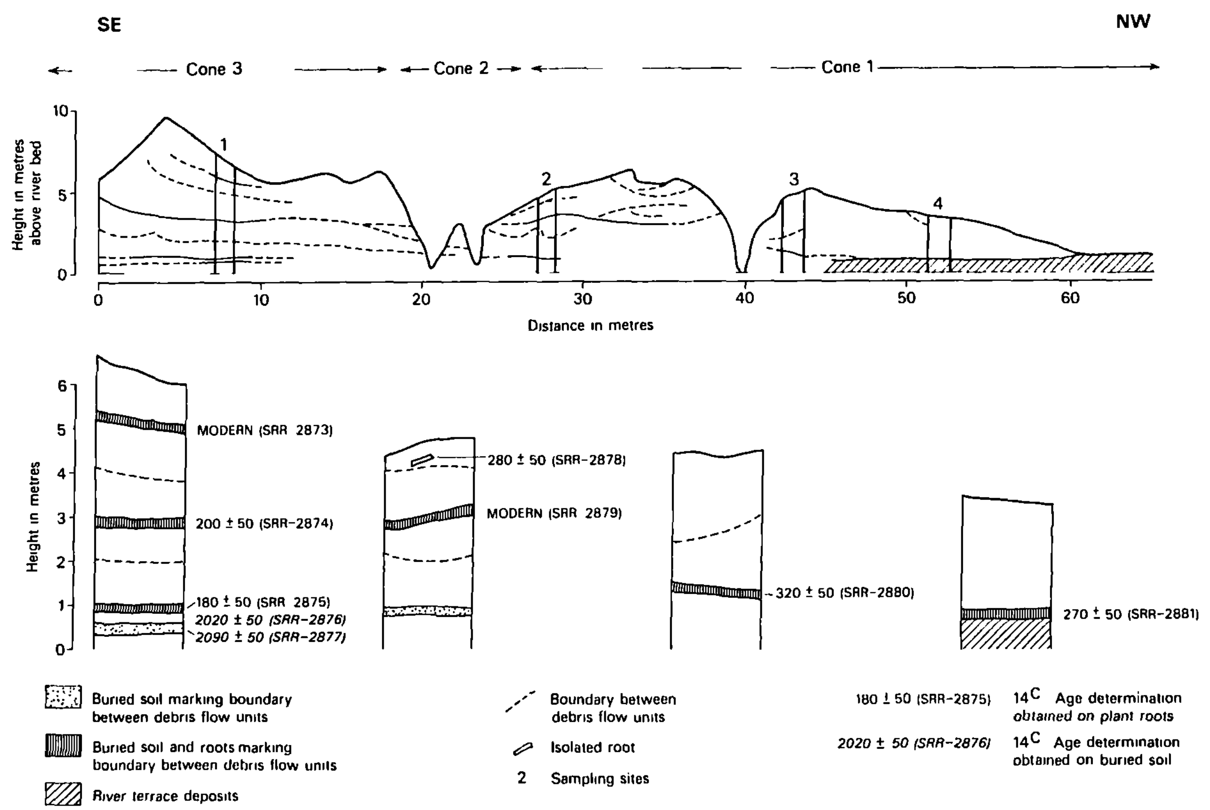


Figure 7.9 Stratigraphy of the Feshie debris cones.

were absent, 10 mm thick samples of organic soil (type 2 discontinuity, above) were collected from the top and base of the organic soil horizon. The soil samples were pretreated by digestion in 2M HCL (80^{o} C for 24 hours), followed by washing to a neutral pH. The root samples were subjected to successive digestion in hot KOH (2M) solution until free from alkali-soluble humic material (Dr. D.D. Harkness, pers. comm.). These were then acidified and washed until neutral. Samples of the wood fragments were sent to Jodrell Laboratory, Kew Gardens, London, for identification. Table 7.2 gives a breakdown of the characteristics of each sample. Only one sample (2.1), that of a large pine root, was probably not _in situ_ and was also not embedded in an organic soil, although it was located near the boundary of two debris flow units.

The results of the radiocarbon analyses are illustrated along the sides of the appropriate stratigraphic columns in figure 7.9, and also in table 7.2a. The oldest radiocarbon ages are from the base of site 1, near the centre and therefore the oldest part of cone three. Because the soil is immature, with no visual evidence of distinct soil horizon development, the closeness of dates 2020 +/- 50 BP and 2090 +/- 50 BP (samples 1.4.and 1.5) is not unexpected. No evaluation can be made concerning the length of time this soil took to develop because the standard deviations for the radiocarbon dates overlap (table 7.2b).

Table 7·2

The Feshie Debris Cones: Radiocarbon Dates Associated with Buried Roots and Soils

A.

Sample No.	Depth (m)	Character	Laboratory Code		Radiocarbon Age (years BP)
1.1	1.1	*in situ* roots (species undetermined)	SRR-2873	>MODERN	$\delta^{13}C=245.3 \pm 21.9‰$ $\delta C=-25.1‰$
1.2	3.3	*in situ* roots *Juniperus* sp.	SRR-2874	MODERN	(200 ± 50) $\delta^{13}C=-24.3‰$
1.3	5.2	*in situ* roots *Juniperus* sp.	SRR-2875	MODERN	(180 ± 50) $\delta^{13}C=-23.8‰$
1.4	5.6	top 10mm of organic soil	SRR-2876		2020 ± 50 $\delta^{13}C=-28.2‰$
1.5	5.8	basal 10mm of organic soil	SRR-2877		2090 ± 50 $\delta^{13}C=-27.5‰$
2.1	0.4	large root *Pinus* sp.	SRR-2878		280 ± 50 $\delta^{13}C=-27.7‰$
2.2	1.7	*in situ* roots *Calluna* sp.	SRR-2879	MODERN	(0 ± 80) $\delta^{13}C=-29.3‰$
3.1	3.1	*in situ* roots *Calluna* sp.	SRR-2880		320 ± 50 $\delta^{13}C=-27.8‰$
4.1	2.4	*in situ* roots *Calluna* sp.	SRR-2881		270 ± 50 $\delta^{13}C=-27.5‰$

B

Sample No.	Radiocarbon Age (years BP)	95% Confidence (years BP)
1.2	200 ± 50	102 to 298
1.3	180 ± 50	82 to 278
2.1	280 ± 50	182 to 378
3.1	320 ± 50	222 to 418
4.1	270 ± 50	172 to 368
1.4	2020 ± 50	1922 to 2118
1.5	2090 ± 50	1992 to 2188

All of the other radiocarbon dates are too similar (table 7.2b) to permit any meaningful analysis of the periodicity of debris flow activity on the cones. Moreover, some of the dates are stratigraphically reversed. What is especially striking is that these dates are all very recent, ranging from 320 +/-50 BP (3.1) to "modern". The term "modern" is standard notation for all samples that record a ^{14}C depletion of less than 3% relative to the AD 1950 standard activity. The term also reflects the dating uncertainty that arises from the progressive dilution of atmospheric ^{14}C concentration by fossil fuel emissions (D.D. Harkness pers. comm.). Thus the dates given in table 7.2 for samples 1.1, 1.2 1.3 and 2.2 are all "modern". The numerical age values given for samples 1.2, 1.3 and 2.2 represent the conventional age calculation, ignoring possible fossil CO_2 dilution these samples. Furthermore, in one instance (sample 1.1) a positive ^{14}C enrichment was identified and this has been interpreted as representing "post-bomb" growth, the addition of ^{14}C from nuclear fall-out (Jenkinson and Rayner, 1977; Goh et al, 1977; Ballantyne, 1986a; D.D. Harkness pers. comm.). Sample 1.1 was extracted from the section face at a depth of 1.1m. The debris flow deposits at this level appear to be recent, and have probably been deposited after ^{14}C enrichment. A minimum age for the river terrace buried by cone 1 (figure 7.9; plate 7.8) is provided by sample 4.1, which gave a radiocarbon age of 270 +/- 50 BP. The youthfulness of this terrace fragment is also supported by the immature surface

Plate 7.8 Debris flow deposits of cone 1 overlying a low alluvial terrace . Sample 4.1 (Calluna sp roots) was collected from the soil developed on the terrace surface, at the position of the trowel (lower left). Roots can be seen protruding from the top of the buried alluvial deposits.

soil profile present at this site. Soil stratigraphic evidence suggests a date of no older than about 500 BP (M. S. E. Robertson-Rintoul, pers. comm.).

In sum, two groups of radiocarbon ages were revealed at the Feshie debris cones site and these imply at least three phases in the evolution of the cones. It is suggested that the earliest period of geomorphic activity preserved at this site was the burial of the immature soil at sampling site 1.4, either by shallow fluid debris flow deposits or by sediment transported in suspension out from the front of a nearby debris flow, around 2,000 BP. The site then remained stable for about 1,700 years. In contrast to the history of debris cone aggradation at the Glen Etive site, the main period of debris cone accumulation recorded at this Glen Feshie site appears to have occurred within the last c 300 years. Indeed, one debris flow event on the surface of cone 1 (figure 7.9) occurred very recently. This is attested by live pine branches in the lobe deposits seen in July 1984, and also by the lack of evidence for post-depositional modification of the deposits. More generally, during cone development, debris flow activity has been episodic, with some periods of quiescence which allowed vegetation colonisation and immature soil development. The significance of the chronology of debris cones development as recorded at this site is discussed below.

7.2.2.2 Discussion.

The evidence presented above indicates that the aggradation of the debris cones in upper Glen Feshie was initiated by c 2,000 BP. The site may then have remained stable for c 1,700 years until rapid and episodic debris flow aggradation formed, within approximately the last 300 years, the bulk of the deposits visible in the stream-cut exposure. Prior to discussing the implications of the radiocarbon dates, it is necessary to consider the general setting of the debris cones.

These cones have built out from the steep walls of the glacial breach in upper Glen Feshie. Their distal deposits have been truncated and removed by the lateral migration of the river. The abundance of palaeochannels and the well-defined terraces preserved on the valley floor opposite the cones indicates that the formerly braided River Feshie has repeatedly migrated across the valley floor episodically reworking this reach of the valley fill. It is therefore possible that prior to c 2,000 BP the river may have eroded earlier slope deposits in the site currently occupied by the debris cones; the stratigraphy of the present cones only provides evidence for debris flow activity at this site during a maximum timespan of c 2,000 years. Moreover, the history of fluvial erosion undercutting the base of this valley side has probably enhanced the susceptibility of the slope to instability and erosion and the rapid formation of features such as the Feshie debris cones.

The nature of the source areas supplying the debris cones is illustrated in plates 7.9 and 7.10. The slope has been severely gullied, but fragments of relict talus or debris slopes can be identified. For example, very angular frost-shattered rock debris with abundant fine infill forms a talus-like slope fragment to the north of the lower part of the main gully above cone 1 (plate 7.5 above). Plate 7.9 shows the gully wall cut into this drift cover, and illustrates the abundance of fine debris, which appears to increase in quantity with depth. Similar assemblages of slope deposits have been identified elsewhere in the glen and are best illustrated by a recently-gullied part of the valley wall on the eastern side (plate 7.10). In the light of these observations it is suggested that the slope deposits are composite in origin, with glacigenic debris rich in fines near the rock-drift interface, overlain by rockfall debris. Indeed, the eastern side of the valley supports extensive talus slopes that have not been subject to basal erosion because they are protected by the high terraces described above. The occurrence of talus-like slope fragments implies that the western valley side once supported more extensive slope deposits than it does at present. These slope deposits cover impermeable and often easily-erodible fissile schist on steep slopes, and thus provide conditions favourable for debris flow activity. If the debris slope deposits are Lateglacial in age, this implies that debris flow activity could have occurred at any time during the Flandrian. However, at the debris cone site

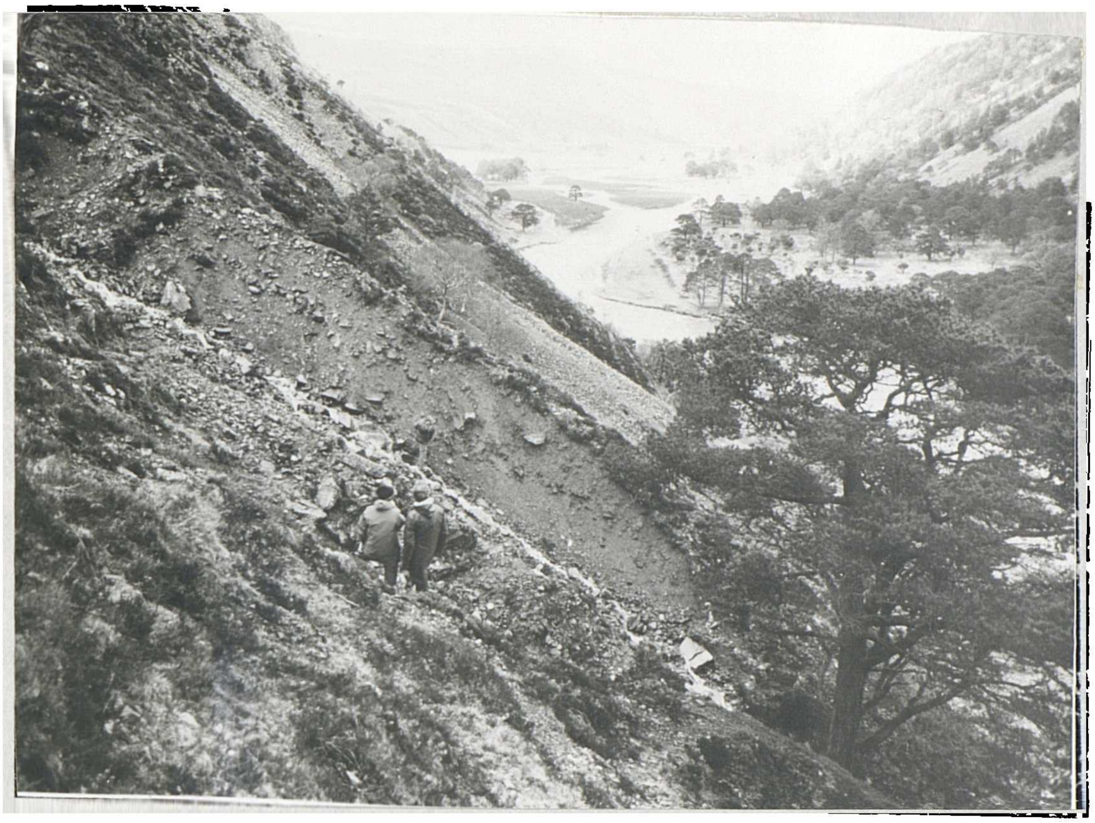


Plate 7.9 Slope deposits exposed in the gully walls above cone 1, of the Feshie debris cones.
These deposits are thought to be fragments of once extensive talus slopes overlying glacigenic debris, possibly of Lateglacial age.

Plate 7.10 Gullied relict talus overlying much finer glacigenic deposits. These sediments provide a suitable medium for debris flow, when combined with sufficient slope and high pore water pressures.

the radiocarbon date evidence indicates that there was a long period of quiescence between two periods of activity during the late Flandrian. This raises the question of what might have triggered renewed debris flow activity at this site.

Two of the hypotheses discussed at the start of this chapter may offer an explanation for the chronology proposed for these Feshie debris cones, namely anthropogenic interference and climatic fluctuations. The likelihood of each will be considered in turn.

Initially it might be thought that the evidence for a dramatic increase in debris flow activity at this site during the last 300 years supports Innes' (1983a; 1983b; 1983c; 1983d; chapter 2) suggestion that the majority of hillslope debris flows occurred within that timespan in response to changes in landuse practices. However, a number of problems arise with the proposition that human activity, such as forest clearance or overgrazing, may have triggered renewed debris flow activity at this site. First, no charcoal fragments indicative of vegetation burning were identified during microscope analysis of 15 samples extracted at close vertical intervals from the basal soil at sampling site 2. Second, the catchment area above the cones is steep, and in places rocky. It is highly unlikely that such an environment would be chosen for forest clearance and grazing of animals when other parts of Glen Feshie have extensive and well-drained flat terraces. Indeed some of the native Scots pine trees in this part of the glen are 200 years old (D. Gowans, pers. comm.). If forest clearance had been widespread since 300 BP then there would be few remaining trees of such great age. Furthermore, the areas most favourable for present-day forest rejuvenation are the steep slopes of the glacial breach because few deer graze on such steep slopes (D. Gowans, pers. comm.). Therefore it is unlikely that grazing animals have been the critical factor affecting slope stability in the cone catchments.

The second proposition is that slope stability may have affected by secular climatic change or extreme events. Two periods of debris flow activity were identified at this site. The earlier period of activity was probably triggered by an intense rainstorm, and may have been exacerbated by basal undercutting of the slope when the river was migrating across the valley floor. This may have occurred during progressive climatic deterioration in the late Flandrian. Indeed, an increased incidence of soil erosion and mass movement activity at other sites in upland Britain may have been associated with this climatic deterioration (Edwards and Rowntree, 1980; Tallis and Johnson, 1980; Innes, 1983d). However, Innes (1983d) remained cautious about associating the incidence of episodic "alluvial talus" activity on Skye (dated to c 2,000 BP) with climatic change because of the moderating maritime influences in Western Scotland.

The second period of debris flow activity recorded at the Feshie debris cones has occurred within the last 300 years. Climatic deterioration associated with the so-called "Little Ice Age" has been well documented (cf chapter 2). However, the most important aspect of the associated climatic deterioration that would have affected the occurrence of debris flows is the incidence of storm events, rather than temperature decline (Lamb, 1977). Thus a greater frequency of intense rainstorms increases the probability of debris flows occurring in susceptible catchments such as the gullies above the Feshie debris cones. However, not all storms would have resulted in debris flow activity. The degree of soil development and vegetation colonisation evident between some debris flow units in the section face (figure 7.9) implies that there were significant, if brief, periods of stability within the main period of debris cone aggradation. The occurrence of small landslips (plate 7.11) and the rate at which debris accumulates on gully floors controls the incidence of debris flow events on the cones. Susceptibility to slope failure may be enhanced by uprooting of pine trees during storms, which exposes substantial areas of bare ground.

In sum, the incidence of periods of debris flow activity at this site appears more likely to be related to natural triggers and not primarily a response to anthropogenic interference. The relationship between river undercutting and the source area slope has probably been

Plate 7. 11 Two nested landslide scars that have supplied debris to the gully above cone 1 of the Feshie debris cones.

fundamental in governing long-term slope stability at this site. It is suggested that climatic factors, such as storm events, were probably responsible for upsetting the delicate balance between stability and instability in the source area. Thus a combination of a single storm event, or a series of such storms, and river undercutting may have triggered localised debris flow activity c 2,000 BP at cone 1. There then followed a prolonged period of stability that was dramatically ended c 300 BP. It is suggested that at this time an increase in the frequency of intense rain storms, such as the 1829 storm (cf chapter 3), occurred, with the result that conditions within the source area crossed an erosional threshold and subsequently failed to restabilise, probably because the vegetation cover had insufficient time in which to recolonise and stabilise eroded areas between storm events. The episodic pattern of subsequent debris flows reflects the availability of sediment in the source area as well as the frequency of debris flow-triggering storm events. Five individual debris flow units with two intervening root-bearing buried soils are visible in the section face at sampling site 1 (cone 3; figure 7.9). This implies that between 3 and 5 independent depositional events occurred, and that these collectively formed the bulk of this cone during a short timespan. The significance of such rapid aggradation is considered below in section 7.3.

7.2.3 Wider implications for debris cone chronology and evolution in the Scottish Highlands.

There are differences in the nature and timing of cone evolution as revealed by the study of Dalness Chasm cone and the Feshie debris cones. Dalness Chasm cone is a relict paraglacial debris cone that has undergone fluvial modification within historical times, apparently as a direct result of forest clearance by man. In contrast, the bulk of the Feshie debris cones accumulated within the last c 300 years, apparently in response to both the long-term history of river erosion of the debris slope on the west side of the Feshie breach, and also to an increase in storm-induced debris flow activity.

These two case histories may be reconciled by examining the broad pattern of debris cone development rather than the absolute timing. The development of the alluvial fan at Dalness Chasm cone involved the reworking of a relict, paraglacial cone. It can similarly be argued that the Feshie debris cones represent the reworking of relict talus or debris slope deposits, and Lateglacial glacigenic debris, that may be regarded as a combination of periglacial and paraglacial sediments. The susceptibility of such deposits to reworking is dependent upon some external factor triggering slope instability, probably through removal of the protective vegetation cover and exposure of the underlying sediments. The morphological similarity of many relict debris cones to Dalness Chasm cone in particular may suggest that many debris cones in the Scottish Highlands could also be paraglacial in origin, and that subsequent reworking may be initiated by external factors such as storm damage and landuse practices.

7.3 FAN AND CONE ACCUMULATION, AND CONTRIBUTING AREA DENUDATION.

This section examines the impact of fan and cone development on the evolution of the postglacial landscape in terms of the overall quantity of debris removed from the source areas and stored in fans or cones.

7.3.1 Data collection.

Twenty-three fans and cones within the seven study areas described in chapter 3 were selected for volumetric survey. Sites with bedrock exposed near the apex and, where possible, the toe were selected. The majority of the selected fans and cones are located well away from the major river on the valley floor and show no sign of fluvial truncation. There are six exceptions to this rule, five of which are from upper Glen Feshie and comprise the three debris cones described in the previous section, a neighbouring talus cone (GF 10) built out on to the same low terrace, and a fluvially-modified debris cone illustrated in figure 7.1 and described in the introduction to this chapter. The sixth case is a relict alluvial fan (Clunie 4) in lower Glen Baddoch that shows evidence of past basal trimming (section 7.3.3).

A series of 3 to 5 radial long profiles were surveyed at each site, together with 3 or 4 cross profiles (figure 7.10). A Wild T2 theodolite and Beatle EDM were used for the profile surveys, with height readings correct to the nearest centimetre. A higher degree of survey precision was not adopted because the vertical distance was affected by the positioning of the prism staff either on top of or adjacent to individual clasts. From this ground-based survey two estimates of fan or cone volume were calculated.

Minimum volume (MINVOL) was determined by drawing a straight line between the altitude of individual cross profiles at either side of the cone (figure 7.10). It was assumed that the depth of sediments gradually increased down-slope from the apex toward the centre of the cone, and then declined gradually towards the toe. The estimated depth of sedimentation was checked by comparison with the altitude of bedrock outcrops at the apex or near the toe. The volume of each segment between intersecting survey lines was calculated by multiplying the plan area by the mean depth of sediment, the latter having been determined by dividing the vertical area of each segment face by its horizontal length. The volumes of the segments were then summed to give the minimum volume of the fan or cone. This method of volume estimation is similar to that used by Innes (1982) in calculating volumes of individual debris flow lobes, although it should be noted that Innes calculated plan area by multiplying lobe width by length, which may

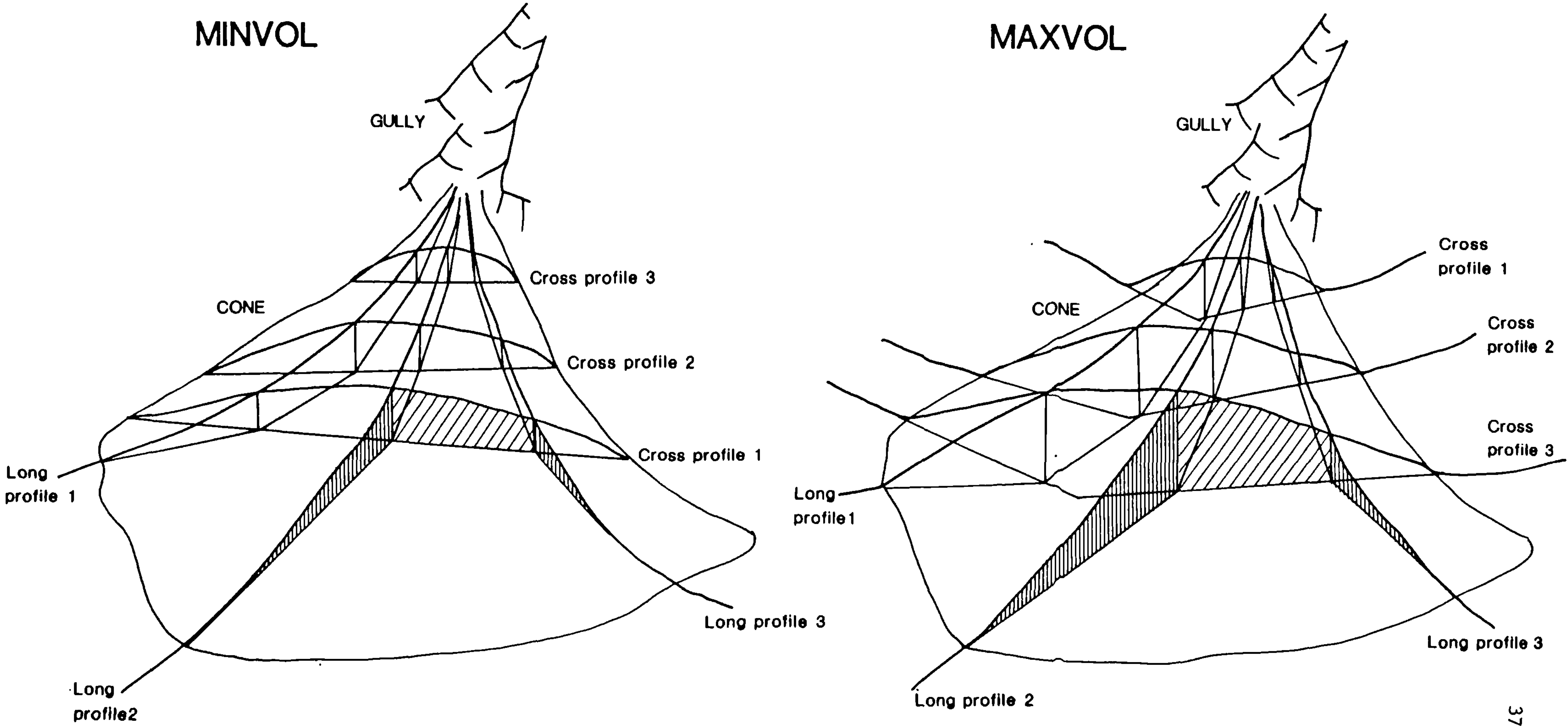


Figure 7.10 Survey method used to calculate minimum and maximum fan and cone volume.

have led to overestimation of plan area.

The calculation of minimum volume does not take into account the topography of the underlying bedrock, which may permit much greater depths of sediment than that expressed by the surface amplitude of the fan or cone. For example, the steep-sided rock cleft of the Clachaig gully (part of the Glencoe ring fault) almost certainly continues under the valley-floor sediments to the opposite side of the glen where the fault is visible as a gully near Achnambiethach farm. It was thus considered necessary to calculate a maximum volume to provide an 'envelope' of possible volumes. The assessment of maximum fan or cone volume (MAXVOL) was carried out in order to account for such greater depths of sedimentation (figure 7.10). The survey lines were extended beyond the limits of the fan or cone, in order that the general topography of the adjacent slopes could be extrapolated beneath the feature. An additional method was employed to account for the valley side slope buried by the fan or cone. The mean gradient of the lower third of the contributing gully or valley floor was measured from the topographic maps, and was extrapolated beneath the fan or cone. The slope of this line was compared with the altitude of available bedrock outcrops at the apex or near the toe of the cone. The volumes of individual segments were then calculated in the same manner as that described above, and summed to give the maximum fan or cone volume. An approximation of the gross sediment yield from each of the contributing areas was estimated by dividing the fan or cone volume by valley or gully area. Two measures of contributing area were calculated, namely adjusted maximum and minimum "basin" areas (MAXBAREA2 and MINBAREA2). All data were derived from 1:10,000 topographic maps, and 1:25,000 aerial photographs. The term "basin" is used here to indicate the contributing area upslope of a fan or cone, regardless of whether it is a valley, gully or rockface.

The plan areal extent of the first of the basin area measurements, MAXBAREA2, was defined in terms of the watershed of the catchment supplying the fan or cone. Therefore, in the case of narrow gullies, any adjacent slopes that could supply runoff to the gully system were included. The plan area of the basin (BA) was adjusted using the method for deriving BRAEA described in section 6.2 above. One of the deficiencies of the model of morphometric control on dominant process was the lack of any measure of within-basin relief. A second adjustment of basin area for within-basin relief was developed to give a better approximation of the "true" surface area of the contributing basin. This was accomplished by taking the mean of ten randomly-placed measurements of gradient within the basin. Randomness was achieved by taking a tracing of the basin area and marking ten points on the paper without looking. Each point marked the midpoint of a 10mm long line that was constructed orthogonal to the trend of the contour lines. The gradient of each of these lines was then calculated and averaged to give a mean measure of within-basin gradients (WBGRAD). The mean angle was then used to calculate maximum adjusted basin area (MAXBAREA2):

MAXBAREA2 = maximum BAREA / cos WBGRAD

Not all of the catchment area may supply sediment to the fan or cone. Therefore, in order to assess the yield from the part of the basin that effectively contributes sediment a second measure of area (MINBAREA2) was calculated, using the same method as that described for MAXBAREA2, except that the initial definition of the contributing area was determined by the area of incised basin sides (ie the area within a gully and not the whole basin as defined by the watershed).

Two measures of denudation were calculated; mean surface lowering and sediment yield. Four estimates of mean surface lowering (in metres) were derived by dividing fan or cone MINVOL and MAXVOL by MINBAREA2 and MAXBAREA2. The gross sediment yield of the source area is also the product of fan or cone volume divided by the adjusted basin area, except that the volumes were adjusted for void ratio (assumed to be 30%) and converted into tonnes by multiplying by 2.65 (the specific gravity of quartzo-feldspathic rock). A void ratio of 30% has been used by other researchers working on coarse sediments such as bedload in rivers (Richards and McCaig, 1985) and protalus rampart debris (Ballantyne and Kirkbride, 1987). It is thus thought to be appropriate for alluvial fans and talus cones. However, it is probable that the percentage of voids is rather less than 30% in debris flow deposits when clasts are supported by a silty matrix, which implies that the results obtained for cones composed of such deposits may be slight underestimates. The results of the volumetric survey and their implications in terms of fan and cone development will be considered below.

7.3.2 Data analysis and discussion.

7.3.2.1 Fan and cone accumulation.

Minimum and maximum fan and cone volumes are illustrated in figure 7.11. The largest volume values range from 402,700m^3 (MINVOL) to 836,700m^3 (MAXVOL) for a large debris cone in Glencoe (GC 15). The main road has been cut through this cone, providing evidence of a considerable depth of sediment (in excess of 5m) in the upper half of the cone. The smallest volumes were calculated for a small talus cone (GF 10) that has built out on to the same low terrace fragment as the Feshie debris cones (section 7.2.2) implying accumulation of between 900m^3 (MINVOL) and 1,200m^3 (MAXVOL) of rock debris subsequent to terrace formation during the late Flandrian. No systematic difference between alluvial fan, fluvially-modified debris cone, debris cone and talus cone volumes can be made, because the samples for each group are generally small.

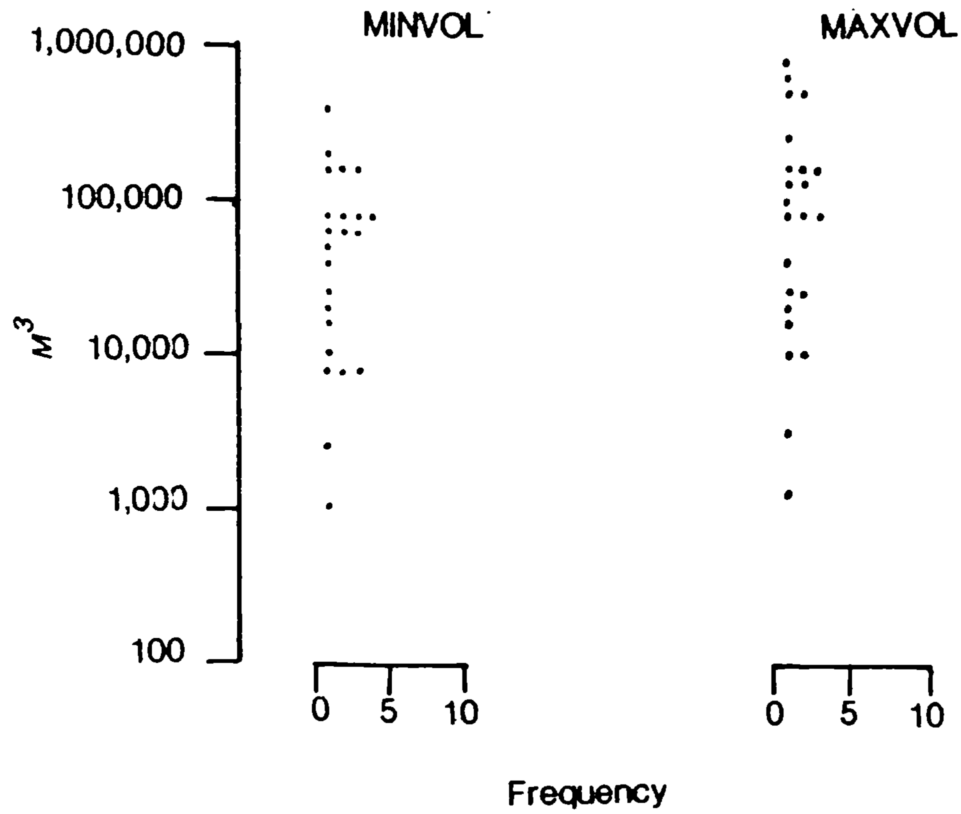


Figure 7.11 Minimum and maximum fan and cone volumes.

Minimum and maximum average depth of sediment accumulation are plotted in figure 7.12. The highest value for average minimum accumulation (8 m) is associated with the large debris cone GC 15, which has built out below a underlying rock gully in upper Glencoe. When the estimated volume for this site is adjusted for burial of the steep rock hollow the average maximum accumulation depth reaches 16m. This latter figure, however, does not take into account the possibility that buried glacigenic debris partly infills the hollow under the cone sediments. Another site that has a considerable average maximum depth of sediment is Dalness Chasm cone, with a value of 13m. Both these sites have good control provided by rock outcrops at the apex and near the toe in the estimates of MAXVOL. These results are therefore accepted as representative of the average maximum depth of sediment. All sites record an average minimum of over 1m depth of sedimentation. The values of average accumulation are, however, several orders of magnitude smaller than those reported for fans and cones in other environments, especially alluvial fans developed in tectonically-active regions where great depths can be achieved (Nilson and Moore, 1984). This further illustrates the fact that the fans and cones found in the Grampian Highlands may be only distantly related to fans and cones in non-glaciated mountain environments.

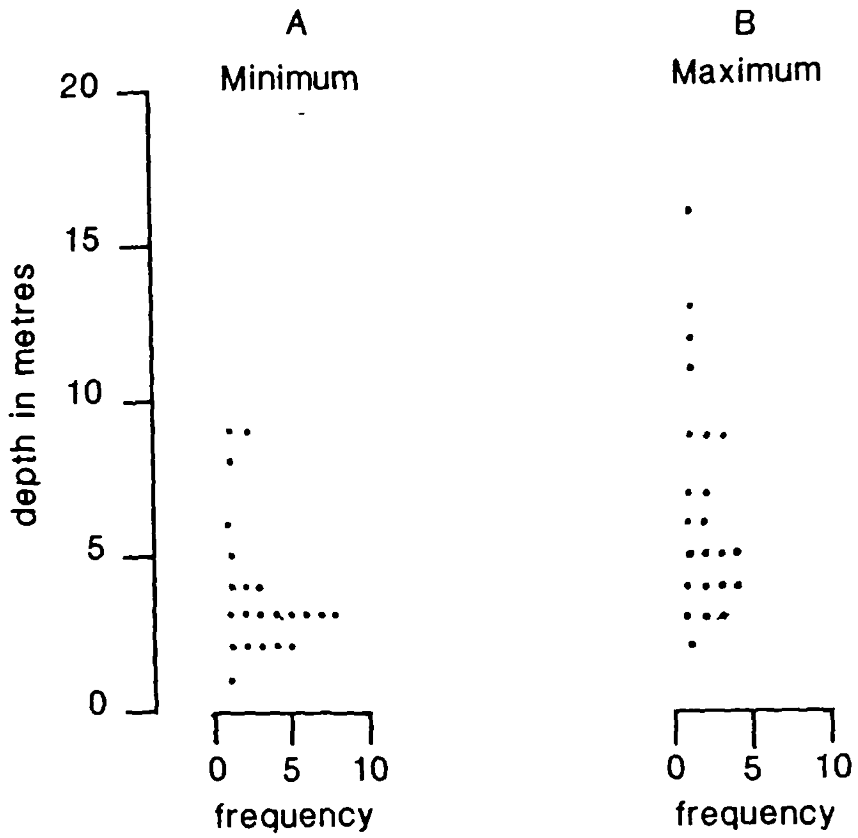


Figure 7.12 Average fan and cone accumulation depth.

The data for 15 debris flow dominated cones were plotted on double logarithmic scales in order to linearise the relationship between fan or cone area (FA) and either MINVOL or MAXVOL (figures 7.13 and 7.14). The plot of debris flow volume against deposit surface area derived by Innes (1982) illustrates that, in terms of total volume, debris flow dominated cones are several orders of magnitude larger than hillslope debris flows (figure 7.15; Innes, 1982, figure 5.51, p. 376). One hundred and fourteen individual debris flow lobes surveyed by Innes on the surface of the Chancellor debris cone (GC 7) ranged in volume from $4m^3$ to $180m^3$ (Innes, 1982, p609 Appendix 5; NB debris flow lobe volumes were derived from the plan area of the lobe). However, these deposits may not be representative of the magnitude of debris flows that formed the bulk of the Chancellor cone. Indeed, Innes's (1982) lichenometric data suggest that the whole surface of the Chancellor cone has been affected by debris flow activity within the last 250 years. Evidence of much greater volumes of debris flow deposition during debris cone formation can be seen in specific sections such as those at the Feshie debris cones and at Dalness Chasm cone (figures 7.6 and 7.9, above). The volumetric estimate for Dalness Chasm cone indicates that between $170,000m^3$ (MINVOL) and $566,000m^3$ (MAXVOL) was deposited during a maximum time period of c 6,000 years, giving a range in average accumulation rates of between $28m^3$ / year and $94m^3$ / year. However, as debris flow activity is episodic, the actual rate of accumulation

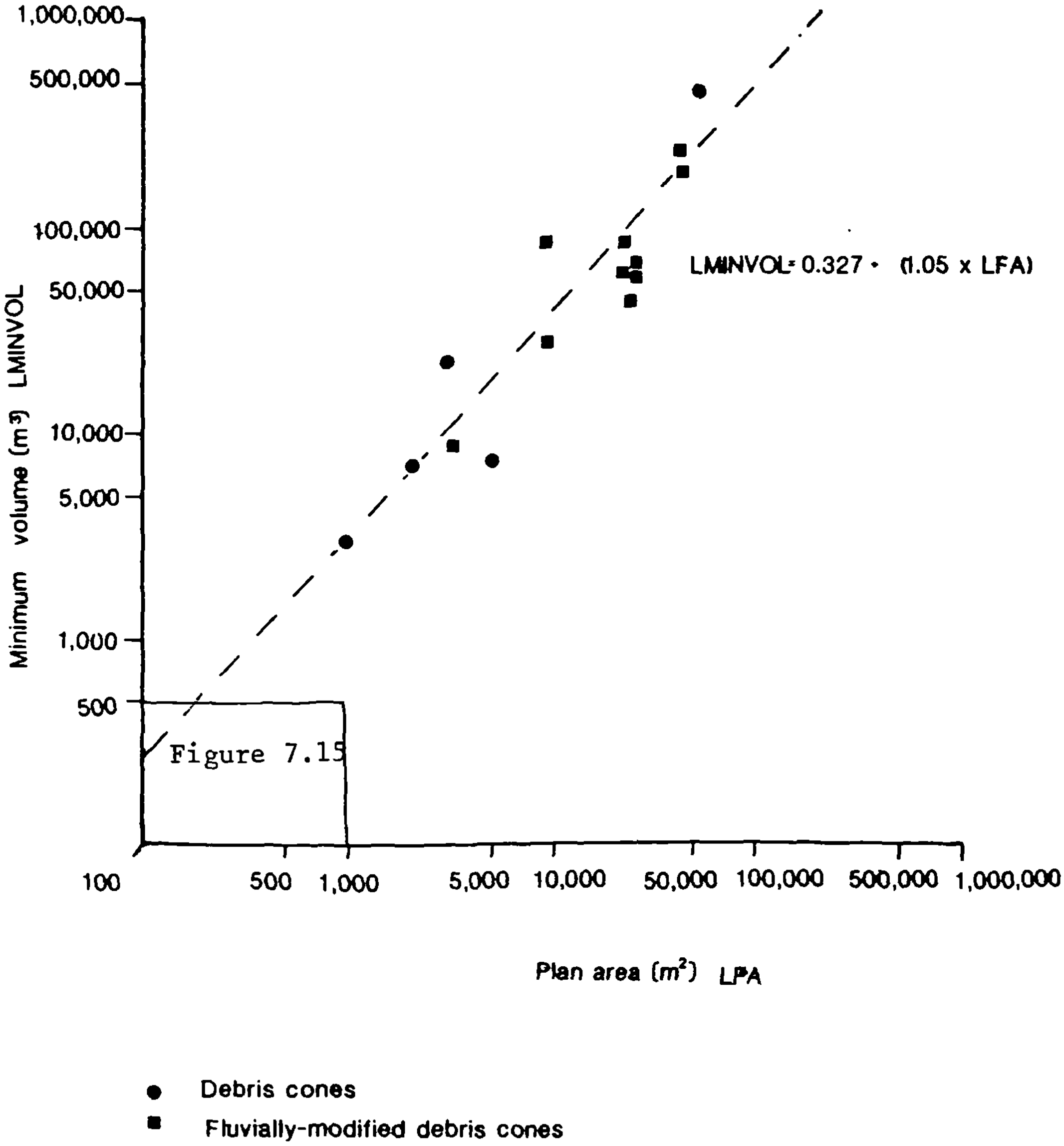


Figure 7.13 Regression line describing the relationship between debris cone plan area and volume, for 15 cones in the Grampian Highlands.

Note that the scale of figure 7.15 (above) is smaller than either that of figure 7.13, or figure 7.14.

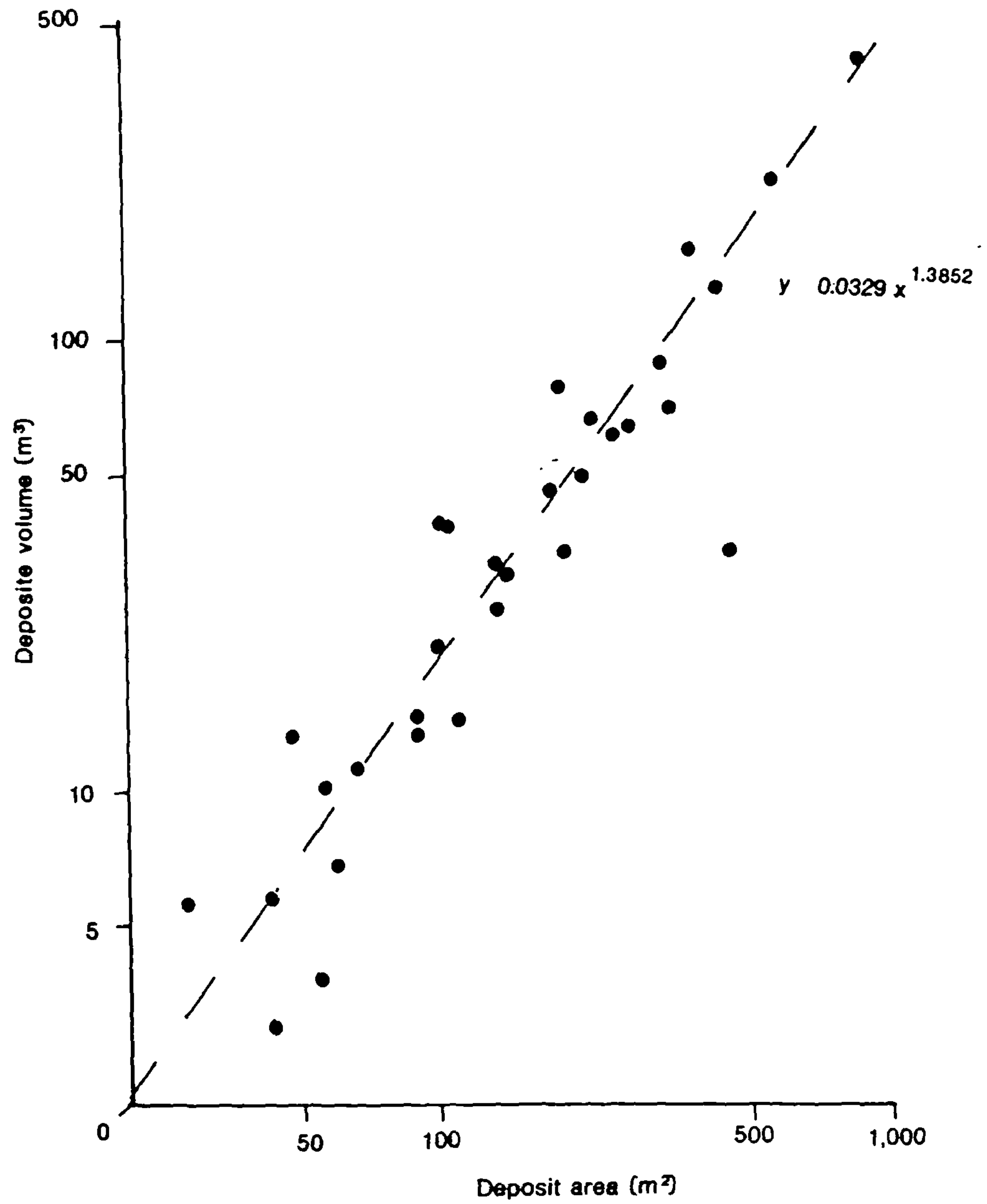


Figure 7.15 The relationship between plan area and volume of individual debris flow lobes. (Source: Innes, 1982, 1983a).

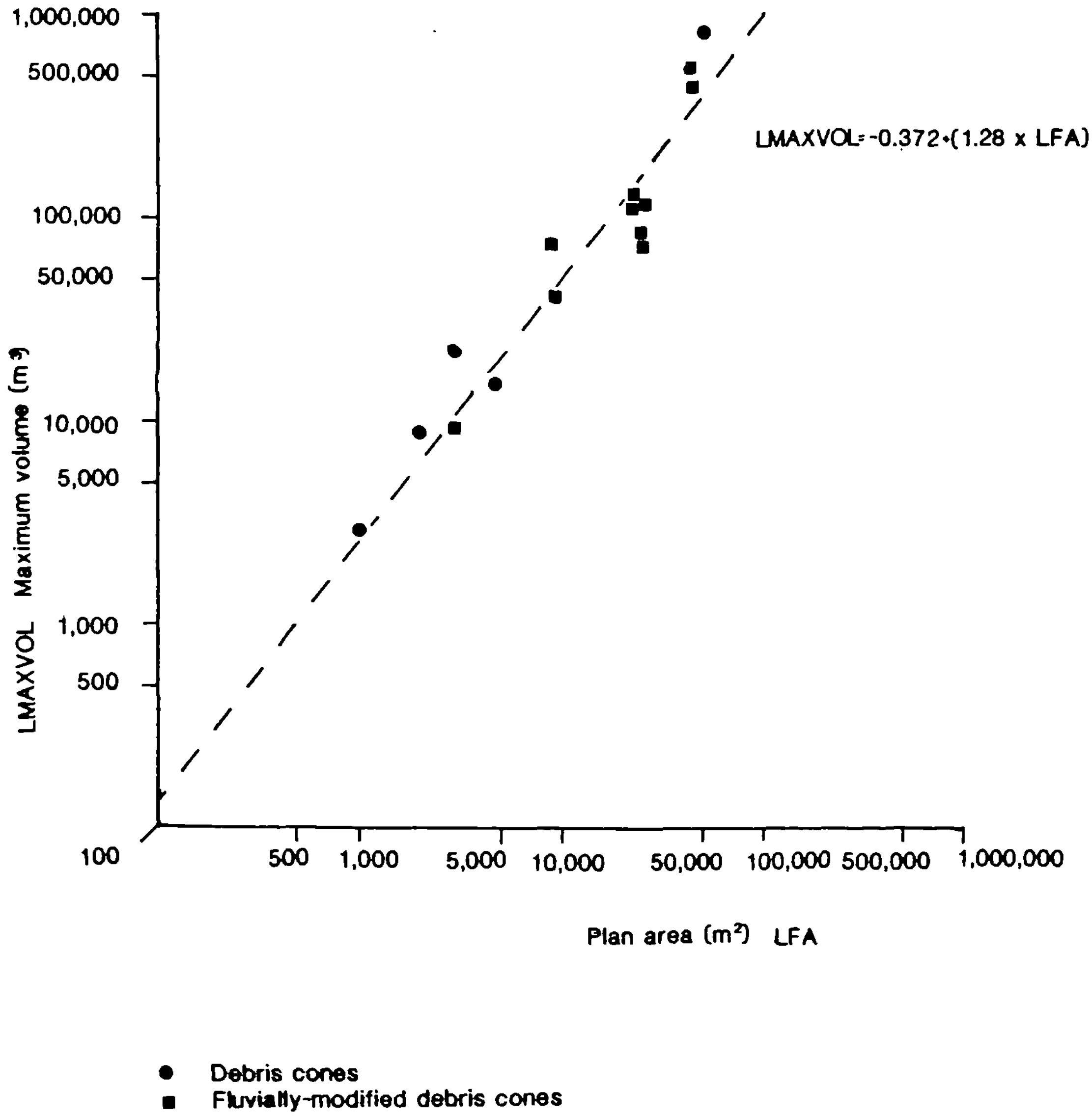


Figure 7.14 Regression line describing the relationship between debris cone plan area and maximum volume, for 15 cones in the Grampian Highlands.

must have varied considerably during debris cone formation, with individual debris flows several orders of magnitude larger than the Late Flandrian Scottish hillslope flows described by Innes (1982, 1983a; figure 7.15).

The minimum and maximum volume estimates for the three Feshie debris cones range from 7,100m^3 to 8,900m^3 for cone 1, from 2,400m^3 to 3,400m for cone 2, and from 22,300m^3 to 23,300m^3 for cone 3. The bulk of these debris cones is believed to have accumulated in approximately the last 300 years, which implies a gross accumulation rate of between as much as 64m^3 / year (MINVOL, cone 3) to 66m^3 / year (MAXVOL, cone 3). The actual rate of sedimentation would have been much higher for any year in which debris flows occurred, with only 5 discrete debris flow units visible at cone 3 dating since *c* 300 BP (figure 7.9). At this site debris flow units are striking, similar in both their depth and considerable lateral extent. For example, the fourth debris flow unit down from the surface at sampling site 1 on cone 3 can be traced both along the section face (as illustrated), and in the walls of a gully up the central axis of cone 3 to the apex. The uniformity and extent of this deposit suggests that debris flow deposition was more sheet-like than lobate in form, depositing 1,600m^3 of sediment down one side of cone 3 during a single event.

The importance of debris flow activity in the evolution of the Scottish Highland postglacial landscape has probably been of rather greater significance than is implied by Innes (1983a). In order to estimate the gross magnitude of the contribution made by debris flow deposition on debris cones in the Grampian Highlands, the observed relationship between FA and both MINVOL and MAXVOL (figures 7.13 and 7.14) was used to determine volumes for sites where only plan area had been recorded (chapter 6, section 6.2; appendix 2). Regression of Log_{10} MINVOL (LMINVOL) and Log_{10} MAXVOL (LMAXVOL) against Log_{10} FA (LFA) yielded the following two equations:

LMINVOL=0.327 + (1.05 * LFA) n=15 r^2 adj=0.861 p=<0.001 (7.1)

LMAXVOL=-0.372 + (1.28 * LFA) n=15 r^2 adj=0.921 p=<0.001 (7.2)

The adjusted coefficient of determination is 0.861 for equation 7.1, and 0.921 for equation 7.2. The adjusted coefficient of determination is corrected for degrees of freedom, giving an approximately unbiased estimate of the population r squared which is not dependant on the sample size. Therefore, equation 7.1 is 86.1% effective in predicting LMINVOL from LFA, and equation 7.2 is 92.1% effective when predicting LMAXVOL from LFA regardless of sample size. The 15 sites used to derive the regression relationships are equivalent to GROUP 2 debris flow dominated cones as defined in chapter 6. Therefore it is possible to use the above equations to derive values for

MINVOL and MAXVOL from FA for the full sample of 97 debris flow dominated cones.

The dispersion diagrams in figure 7.16 illustrate the range in volumes estimated for 97 debris flow dominated cones in the Grampian Highlands. The total volume of debris flow deposits in these cones ranges from MINVOL of 10,426,750 m^3 to MAXVOL of 27,285,900m^3. These figures imply that the average sediment accumulation associated with debris cone development in the Grampian Highlands is of the order of 0.2 to 0.5 Mt.

7.3.3 Denudation in the contributing area catchments.

Effective analysis of total sediment loss from the contributing basin requires that the fans and cones have formed over similar timescales. Assumptions regarding the maximum potential time taken for fan or cone development have been made (ie time since deglaciation), but it is stressed that in the light of the radiocarbon dates from Dalness Chasm cone and the Feshie debris cones that fan and cone development could, in some cases at least, have been relatively short-lived. It is therefore quite possible that fans or cones within one area may have developed over different timescales not identified by using their maximum potential age. For example, all fans and cones in Glen Etive must have formed since deglaciation towards the end of the Loch Lomond Stadial. The Etive fans and cones have, therefore, a maximum potential age of about 10,000 years,

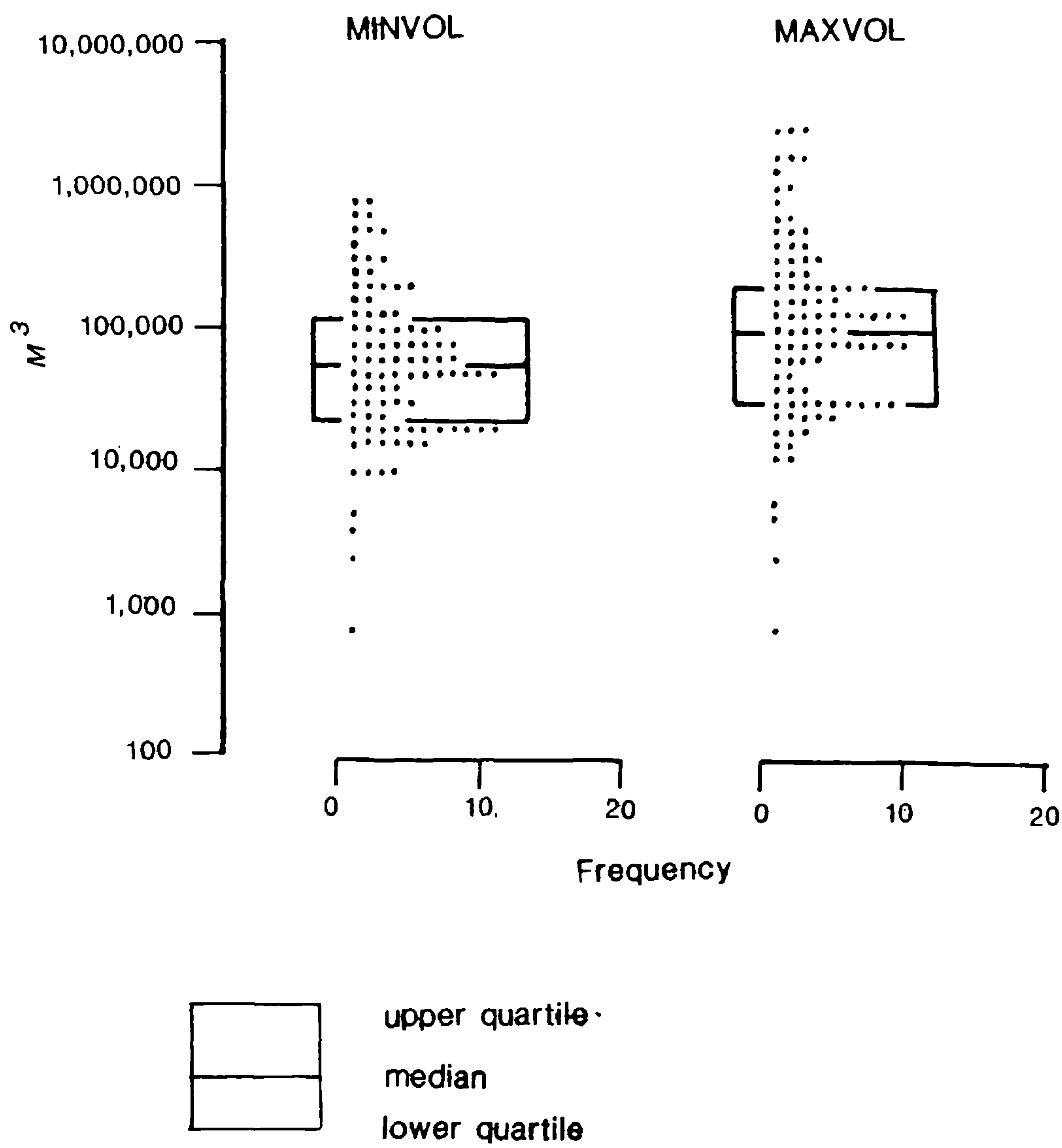


Figure 7.16 Estimated minimum and maximum volumes of 97 debris flow dominated cones in the Grampian Highlands.

but radiocarbon evidence from Dalness Chasm cone implies that debris cone sedimentation only lasted a maximum of about 6,000 years. Thus it is only possible realistically to assess the rate of erosion in the source areas for Dalness Chasm cone and the Feshie debris cones, given the absence of absolute dating of the length of time it has taken for other fans and cones to aggrade. However, the gross values derived for the other sites may provide a broad comparison, and may be employed to assess the average rate of source area erosion by fluvial, debris flow or rockfall processes since deglaciation.

For example, the maximum potential ages of cones GF 10, GC 3, GC 6 and GT 3 are questionable for various reasons. The talus cone GF 10 has a maximum potential age of c 13,000 years because it has developed outside the Loch Lomond Readvance limits. However, the site is located on a low river terrace fragment that is much younger in age, probably about 500 BP (M.S.E. Robertson-Rintoul, pers. comm.). Similarly, the debris flow dominated cones GC 3 and GC 6 may be considerably younger than their implied maximum potential ages of c 10,000 years. Innes (1982) reports evidence that "landslides" buried lazy beds adjacent to the present apex of GC 3 in approximately 1823 AD, implying that the bulk of this cone was formed in recent historical times. However, lichenometric evidence reported below (section 7.4) implies that a substantial part of the cone is much older (figure 7.18c). In contrast to this site lichenometric evidence presented in figure 7.19a for GC 6 suggests that the whole surface of the feature has been recently active. Indeed, the cone itself is small, being formed of a few large debris flows, which implies that the lichenometric evidence for this site gives a better approximation of the cones age than that of 10,000 years, bearing in mind the problems associated with the technique (chapter 2).

In upper Glen Tromie the location of GT 3 is just inside the Loch Lomond Readvance glacial limit (figure 7.4) as mapped by Sissons (1974). However, the geomorphological evidence for the terminal location of the glacier is questionable, as the "moraine" mapped by Sissons appears to be a relict avalanche boulder tongue. Moreover, the supposed drift limit he mapped along the sides of Amhachn Gharbh Ghaig corresponds with a marked outcrop of Quartz-porphyry. Farther upstream a clearer drift limit descends steeply to the valley floor, and delimits the extent of fluvially-dissected hummocky moraines. This is interpreted as marking the true terminal position of a small lobe of glacier ice that descended into the upper reaches of Amhachn Gharbh Ghaig from the Gaick Plateau during the Loch Lomond Readvance. Further research by M.S.E. Robertson-Rintoul is currently being undertaken in order to clarify the chronology of this valley floor since deglaciation. Preliminary findings based on soil-chronostratigraphic evidence have suggested that the outwash terrace fragment mapped by Sissons (1974), adjacent to GT 3 and within his postulated limits. actually predates the Loch Lomond Readvance (M.S.E. Robertson-Rintoul pers. comm.). Therefore it is probable that the fluvially-modified debris cone GT 3 may have an older maximum potential age of c 13,000 years. From the morphological evidence at this site three stages of development were identified: an initial steep drift/debris cone masking the mouth of the gully, a large debris cone inset within this fragment, and recent headward erosion and fluvial modification of part of the toe section.

In the light of the above findings it is only realistic to report the overall loss of sediment from the contributing areas. and then to discuss speculatively the reasons for apparent differences in denudation values. bearing in mind the potential problems inherent in comparing sites of different ages which may have developed over very different timescales.

Four measures of surface lowering (tables 7.4a and 7.4b) in the basins were derived by dividing MINVOL and MAXVOL by MAXBAREA2 and MINBAREA2 (table 7.3). The following discussion will centre on surface lowering calculated by dividing minimum fan or cone volume (MINVOL; table 7.4a) by either maximum basin area or minimum basin area, though it should be noted that many of the values derived from using MAXVOL (table 7.4b) are similar in magnitude to those calculated using MINVOL. With three notable exceptions (Clunie 3. GC 15 and GF 12) the values

Table 7·3

Maximum and Minimum adjusted basin areas (m^2)

Type	Site	MAXBAREA2	MINBAREA2
TC	GF 10	14,563	2,973
TC	CLOVA 1	131,054	20,970
TC	CLUNIE 3	5,005	5,005
TC	CLUNIE 2	29,751	16,695
DC	GC 15	307,000	191,100
DC	GC 6	151,620	25,100
DC	FESHIE CONE 3	63,982	8,345
DC	FESHIE CONE 2	33,238	3,922
DC	FESIIE CONE 1	81,667	3,155
DC	GF 6	26,363	3,750
FMDC	GF 12	19,803	7,600
FMDC	GF 5	519,370	52,601
FMDC	GC 1	453,446	95,184
FMDC	GC 3	196,074	158,025
FMDC	DALNESS CHASM CONE	337,394	75,109
FMDC	GE 4	66,434	52,430
FMDC	GT 2	519,240	37,196
FMDC	GT 3	677,290	38,940
FMDC	FI 10	435,422	15,121
FMDC	CLUNIE 1	172,160	26,921
AF	FI 8	1,015,957	33,186
AF	FI 7	745,382	61,644
AF	CLUNIE 4	1,313,000	1,023,000

Type code

TC	Talus Cone	FMDC	Fluvially-modified debris cone
DC	Debris Cone	AF	Alluvial Fan

Table 7.4a

Total Surface Lowering (m)

MINVOL

Type	Site	Surface Lowering Over MAXBAREA2	Surface Lowering Over MINBAREA2
TC	GF 10	0.06	0.31
TC	CLOVA 1	0.61	3.81
TC	CLUNIE 3	1.66	1.66
TC	CLUNIE 2	0.54	0.96
DC	GC 15	1.31	2.11
DC	GC 6	0.11	0.29
DC	FESHIE CONE 3	0.35	2.67
DC	FESHIE CONE 2	0.07	0.62
DC	FESIIE CONE 1	0.09	2.26
DC	GF 6	0.33	2.38
FMDC	GF 12	3.94	10.26
FMDC	GF 5	0.40	3.93
FMDC	GC 1	0.35	1.66
FMDC	GC 3	0.29	0.36
FMDC	DALNESS CHASM CONE	0.50	2.23
FMDC	GE 4	0.88	1.12
FMDC	GT 2	0.11	1.51
FMDC	GT 3	0.11	1.99
FMDC	FI 10	0.09	2.61
FMDC	CLUNIE 1	0.16	1.01
AF	FI 8	0.07	2.19
AF	FI 7	0.21	2.53
AF	CLUNIE 4	0.05	0.07

Type code

TC Talus Cone
DC Debris Cone
FMDC Fluvially-modified debris cone
AF Alluvial Fan

Table 7.4b

Total Surface Lowering (m)

MAXVOL

Type	Site	Surface Lowering Over MAXBAREA2	Surface Lowering Over MINBAREA2
TC	GF 10	0.08	0.40
TC	CLOVA 1	2.01	12.56
TC	CLUNIE 3	5.33	5.33
TC	CLUNIE 2	0.66	1.18
DC	GC 15	2.73	4.38
DC	GC 6	0.11	0.65
DC	FESHIE CONE 3	0.36	2.79
DC	FESHIE CONE 2	0.10	0.87
DC	FESIIE CONE 1	0.11	2.83
DC	GF 6	0.33	2.38
FMDC	GF 12	3.94	10.26
FMDC	GF 5	0.93	9.15
FMDC	GC 1	1.06	5.07
FMDC	GC 3	0.68	0.87
FMDC	DALNESS CHASM CONE	1.68	7.53
FMDC	GE 4	1.14	1.44
FMDC	GT 2	0.24	3.40
FMDC	GT 3	0.22	3.74
FMDC	FI 10	0.20	5.77
FMDC	CLUNIE 1	0.25	1.58
AF	FI 8	0.10	2.91
AF	FI 7	0.21	2.53
AF	CLUNIE 4	0.11	0.14

Type code

TC Talus Cone
DC Debris Cone
FMDC Fluvially-modified debris cone
AF Alluvial Fan

for MINVOL divided by MAXBAREA2 are remarkably similar to MAXVOL values divided by MAXBAREA2.

Considering total surface lowering from MAXBAREA2 (table 7.4a), the range for rockwall and rock gully retreat for 3 of the 4 talus cones surveyed ranges from 0.54m to 1.66m. Values for GF 10 are much lower, presumably because this site is relatively young (see above). The other three sites are located outside the Loch Lomond Readvance limits, and have an implied maximum age of c 13,000 years. The value of 1.66m estimated at Clunie 3 is similar to the average amount of rockwall retreat calculated on the basis of the volumes of eight Loch Lomond Stadial age protalus ramparts (assuming void space of 30%) which range from 1.14m to 1.61m (Ballantyne and Kirkbride, 1987). This similarity in rockwall retreat may imply that Clova 1, Clunie 2 and Clunie 3 formed largely under severe periglacial conditions before the end of the Loch Lomond Stadial (cf Ballantyne and Eckford, 1984). Indeed, the talus cones studied are essentially relict (except GF 10), with one site showing considerable surface modification resulting from debris flow activity (Clova 1).

Total surface lowering values in table 7.4a for basins supplying sediment to debris cones and fluvially-modified debris cones range from 0.07m to 3.94m when calculated using MAXBAREA2, and from 0.29m to 10.26m when calculated using MINBAREA2. The average amount of surface lowering calculated for 97 basins below which debris cones have developed (with maximum BAREA not adjusted for within basin relief) is c 0.7m when calculated from MINVOL and c 1.8m when calculated using MAXVOL. The majority of values for surface lowering in the MAXBAREA of debris cones and fluvially-modified debris cones (table 7.4a and 7.4b) are of similar magnitude. Within the sample of 15 debris cones and fluvially-modified debris cones, values for surface lowering over MAXBAREA2 are slightly lower in Glen Tromie, Strathdearn (Findhorn) and Glen Clunie when compared with those for cones in Glen Etive, Glencoe and Glen Feshie. This may reflect the slightly larger extent and lower gradients of the maximum contributing areas in the former three areas compared with those in the latter three. When surface lowering is calculated over the area of the contributing gullies excluding adjacent slopes (MINBAREA2) the values are more uniform, with no apparent regional variations.

Erosion of drift in the gully supplying cone 1 of the Feshie debris cones illustrates the amount of incision that can occur over a few tens or hundreds of years. Minimum cone volume divided by minimum basin area (table 7.4a) implies 2.26m of surface lowering in this gully, which is comparable to the depth of incision recorded in plate 7.9 above. The majority of other MINBAREA2 surface lowering values in table 7.4a also lie within the range 1m to 3m. One notable exception is the amount of denudation estimated for the gully system above GF 12, for which calculated denudation exceeds 10m.

Surface lowering associated with the development of two alluvial fans (FI 7 and FI 8) is similar to that calculated for debris cone and fluvially-modified debris cone catchments (table 7.4a). However, site Clunie 4 has significantly lower values, especially when denudation is calculated over the minimum contributing area (0.07m). Clunie 4 comprises a large relict alluvial fan that has developed just within the terminal moraine deposited by the Loch Lomond Readvance glacier that occupied Glen Baddoch. The distal part of the fan forms a steep bluff over 3m high that grades into outwash terrace fragments downstream of the moraine. This evidence implies that both the fan and outwash terraces have been trimmed during the Flandrian, so that the volume measured at this site underestimates the quantity of debris removed from the catchment.

Tables 7.5a and 7.5b give the specific sediment yield of debris from the fan and cone catchments in tonnes per square kilometre, as calculated on the basis of MINVOL and MAXVOL respectively. These values have been used to derive average "annual" sediment yields from the catchments (tables 7.6a and 7.6b). Stratigraphic evidence from sections, such as those illustrated for Dalness Chasm cone and the Feshie debris cones, demonstrates that deposition on the cones is not constant but is episodic and is punctuated by prolonged periods of quiescence and stability. Therefore the sediment yields given in tables 7.5a, 7.5b, 7.6a and 7.6b should only

Table 7.5a

Specific Sediment Yield Tonnes/km^2

Derived from MINVOL

Type	Site	Sediment Yield Over MAXBAREA2	Sediment Yield Over MINBAREA2
TC	GF 10	116,400	570,100
TC	CLOVA 1	1,129,700	1,129,700
TC	CLUNIE 3	3,079,100	3,079,100
TC	CLUNIE 2	1,000,000	1,782,000
DC	GC 15	2,433,300	3,909,000
DC	GC 6	90,000	543,600
DC	FESHIE CONE 3	646,900	4,960,000
DC	FESHIE CONE 2	134,900	1,143,500
DC	FESIIE CONE 1	162,300	4,201,600
DC	GF 6	628,200	4,416,000
FMDC	GF 12	7,300,900	19,023,600
FMDC	GF 5	738,300	7,289,400
FMDC	GC 1	646,700	3,081,000
FMDC	GC 3	536,700	665,900
FMDC	DALNESS CHASM CONE	922,600	4,144,300
FMDC	GE 4	1,636,600	2,073,800
FMDC	GT 2	200,800	2,803,700
FMDC	GT 3	212,100	3,689,900
FMDC	FI 10	168,300	4,846,100
FMDC	CLUNIE 1	292,600	1,871,100
AF	FI 8	132,500	4,054,900
AF	FI 7	387,900	4,688,800
AF	CLUNIE 4	98,000	125,800

Type code

TC Talus Cone
DC Debris Cone
FMDC Fluvially-modified debris cone
AF Alluvial Fan

Table 7.5b

Specific Sediment Yield Tonnes/km^2

Derived from MAXVOL

Type	Site	Sediment Yield Over MAXBAREA2	Sediment Yield Over MINBAREA2
TC	GF 10	152,700	747,600
TC	CLOVA 1	3,727,700	23,296,900
TC	CLUNIE 3	9,889,900	9,890,000
TC	CLUNIE 2	1,228,000	2,188,300
DC	GC 15	5,055,800	8,122,200
DC	GC 6	200,900	1,213,500
DC	FESHIE CONE 3	674,400	762,700
DC	FESHIE CONE 2	191,500	1,622,900
DC	FESIIE CONE 1	202,800	5,249,800
DC	GF 6	628,200	4,416,000
FMDC	GF 12	7,300,900	19,023,600
FMDC	GF 5	1,754,300	17,321,600
FMDC	GC 1	1,972,900	9,398,600
FMDC	GC 3	1,258,500	1,561,500
FMDC	DALNESS CHASM CONE	3,109,300	13,967,200
FMDC	GE 4	2,108,000	2,671,000
FMDC	GT 2	452,100	6,311,200
FMDC	GT 3	399,100	6,941,300
FMDC	FI 10	371,800	10,707,200
FMDC	CLUNIE 1	458,800	2,934,000
AF	FI 8	716,300	5,396,300
AF	FI 7	387,900	4,688,800
AF	CLUNIE 4	205,100	263,200

Type code

TC	Talus Cone	FMDC	Fluvially-modified debris cone
DC	Debris Cone	AF	Alluvial Fan

Table 7.6a

Annual Sediment Yield Tonnes/km^2/year

Derived from MINVOL

Type	Site	Maximum Age	Rate Over MAXBAREA2	Rate Over MINBAREA2
TC	GF 10	13,000	9	44
TC	CLOVA 1	13,000	87	87
TC	CLUNIE 3	13,000	237	237
TC	CLUNIE 2	13,000	77	137
DC	GC 15	10,000	243	391
DC	GC 6	10,000	9	54
DC	FESHIE CONE 3	300	2,156	16,533
DC	FESHIE CONE 2	300	450	3,812
DC	FESHIE CONE 1	300	541	14,005
DC	GF 6	13,000	48	340
FMDC	GF 12	13,000	562	1,463
FMDC	GF 5	13,000	57	561
FMDC	GC 1	10,000	65	308
FMDC	GC 3	10,000	54	67
FMDC	DALNESS CHASM CONE	6,000	154	691
FMDC	GE 4	10,000	164	207
FMDC	GT 2	13,000	15	216
FMDC	GT 3	10,000	21	369
FMDC	FI 10	13,000	13	373
FMDC	CLUNIE 1	13,000	23	144
AF	FI 8	13,000	10	312
AF	FI 7	13,000	30	361
AF	CLUNIE 4	10,000	10	13

Type code

TC Talus Cone
DC Debris Cone
FMDC Fluvially-modified debris cone
AF Alluvial Fan

Table 7.6b

Annual Sediment Yield Tonnes/km^2/year

Derived from MAXVOL

Type	Site	Maximum Age	Rate Over MAXBAREA2	Rate Over MINBAREA2
TC	GF 10	13,000	12	58
TC	CLOVA 1	13,000	287	1,792
TC	CLUNIE 3	13,000	761	761
TC	CLUNIE 2	13,000	94	168
DC	GC 15	10,000	506	812
DC	GC 6	10,000	20	121
DC	FESHIE CONE 3	300	2,248	17,236
DC	FESHIE CONE 2	300	638	5,410
DC	FESHIE CONE 1	300	676	17,499
DC	GF 6	13,000	48	340
FMDC	GF 12	13,000	562	1,463
FMDC	GF 5	13,000	135	1,332
FMDC	GC 1	10,000	197	940
FMDC	GC 3	10,000	126	156
FMDC	DALNESS CHASM CONE	6,000	518	2,328
FMDC	GE 4	10,000	211	267
FMDC	GT 2	13,000	350	485
FMDC	GT 3	10,000	40	694
FMDC	FI 10	13,000	29	824
FMDC	CLUNIE 1	13,000	35	226
AF	FI 8	13,000	14	415
AF	FI 7	13,000	29	361
AF	CLUNIE 4	10,000	21	26

Type code

TC Talus Cone
DC Debris Cone
FMDC Fluvially-modified debris cone
AF Alluvial Fan

be used with caution. The magnitude of the sediment yields based on the minimum areas of the Feshie debris cone gullies are several orders of magnitude greater than those calculated for other fan or cone sites. The sediment yields for a single year when debris flow activity occurred would probably be at least two orders of magnitude greater again.

Table 7.7 shows sediment yields reported in the literature for catchments in upland Britain and lowland Scotland. It should be noted that plan basin area has been used to calculate these values. The magnitude of the sediment yields from the fan and cone catchments in table 7.6a for MAXBAREA2 may be compared with the values in table 7.7. With the exception of the Grains Gill gully value, debris cone and talus cone MAXBAREA2 sediment yields range from similar to much higher than those in table 7.7, though sediment yield values derived from alluvial fan volumes are similar to the bedload values calculated by Richards and McCaig (1985; tables 7.6a and 7.6b). However, many of the lower values of sediment yield reported in the literature relate to lowland fluvial basins. These sediment yield values may underestimate sediment delivery in such catchments when debris becomes stored within the system in features such as terraces. The actual annual sediment yields, when gully erosion is active, may approximate to the value of 40,000 t/km^2/year reported for the Grains Gill gullies (Harvey, 1974), but no comparable data are available for gullies in Scotland.

Table 7.7

Sediment Yield Reported for Scotland and Upland Britain

Author	Site		Sediment Yield tonnes/km^2/yr
Richards and McCraig 1985	Ben Nevis, Scotland Allt a Mhuillin $6.19km^2$	Bedload	25.7
	Allt Daim	Bedload	18
Harvey 1974	Howgill Fells, New England Grains Gill gulleys $0.003km^2$	Gully erosion	40,000
Duck and McManus (in press)	Reservoir catchments in lowland Scotland		
Table 3	Lambieletham		2.1
	Herperleas		13.8
	Drumain		3.9
	Cullaloe		30.8
	Glenfarg		52.0
	Glenquey		15.1
	Kelley		41.0
	North Esk		26.0
	Hopes		25.0
Newson 1981 Table 3.1	Small upland catchments in mid water un-disturbed grassland		
	Cyff		2.5
	Cownwy		2.5
	Pen y Banc		9.9
	Maesnant		1.1
	Iago		1.2

7.3.4 Conclusion.

Considerable volumes of sediment are stored in fans and cones in the Grampian Highlands with, for example, as much as 19.3Mt to 50.6Mt of debris flow and fluvially-reworked debris flow deposits stored in the 97 debris cones recorded in the macroscale study area. The total volume of debris flow material in cone development has therefore been considerable, with evidence that only a small number of individual debris flow events may be necessary to form substantial cones; for example cone 3 of the Feshie debris cones largely developed during as little as c 300 years from as few as 5 debris flows. The magnitude of such debris cone forming events is much greater than that for individual hillslope debris flows (compare figures 7.13. 7.14 and 7.15). It is suggested, therefore, that although hillslope debris flows may be more numerous, their overall significance in terms of the evolution of the postglacial landscape has (at least in some parts of the Grampians) been less important than the formation of debris cones.

Values for total surface lowering in the source areas are fairly uniform, with some notable exceptions. In general more than one metre of post-glacial surface lowering has occurred in the gullies supplying debris cones and fluvially-modified cones. The associated rate of denudation may have been very high if other fans and cones formed over similar time periods to that of the Feshie debris cones. If this is the case, then debris flow activity leading to cone formation has been locally and briefly far more effective in eroding and transporting debris from the contributing areas than fluvial processes in other upland catchments in Britain.

7.4 RECENT FAN AND CONE ACTIVITY IN GLENCOE.

The impact of recent debris flow and fluvial activity on cones and fans in the Glencoe area is visually striking. In particular, the density of debris cones is probably one of the highest in the Scottish Highlands and some of these cones are also among the largest, such as the Chancellor cone (chapter 5) and cone GC 15 (section 7.3 and below). Innes' (1982) lichen data for debris flows on the Chancellor cone imply that debris flows have been deposited over the entire surface during the last 250 years. The generality of this finding for both fans and cones in Glencoe will be explored below. As far as has been possible the methodology developed by Innes (1982, 1983a, 1983e, 1983f. 1985a. 1985b) for the dating of debris flows has been employed in this study so that the results can be compared. Similar lichenometric studies have also been successfully undertaken on fluvial deposits elsewhere (Harvey et al, 1984; Macklin. 1986).

A total of nine alluvial fans, fluvially-modified debris cones and debris cones were investigated in Glencoe, together with one fluvially-modified debris cone in neighbouring Glen Etive. The principal geomorphological units of each site, including debris flow lobes and alluvial fan terraces, were mapped in the field on to enlargements of 1:10,000 O.S. topographic maps. The relative ages of each of these geomorphological units was assessed by measuring the largest lichens that they support. Sampling was systematic with lichen measurements being made along closely-spaced parallel transects across the deposits. Only Rhizocarpon section Rhizocarpon lichens (also known as the Geographicum group) were sampled, owing to the potential inaccuracy of using aggregate lichen species that have distinct growth rate patterns (cf Innes 1983f). Lichens were not discriminated against on the basis of shape unless their growth had been enclosed by agglomeration with neighbouring lichens. A metal metric ruler was used to measure the largest diameter of each thallus, including the area of black prothallus. Readings were made to the nearest millimetre on at least 20 of the largest lichens on each depositional unit.

The mean of the five largest lichens measured was then determined for each geomorphological unit. This mean value was preferred over the size of the single largest lichen because it reduces the potential for error arising from, for example, anomalously large lichens (eg lichens that have survived transportation) on a substrate. The mean largest lichen sizes were then grouped at 25mm intervals into 7 lichen age zones (figure 7.17). These zones were then represented on each of the site maps (figures 7.18 and

7.19). The corresponding ages for each of the lichen zones (figure 7.17) were derived from Innes' lichen growth curve for Glencoe (Innes, 1983e, figure 3).

Figure 7.18 depicts the areal extent of the different lichen age zones found on two alluvial fans (GC 14 and GC 9), and three fluvially-modified debris cones (GC 8, GC 3 and GE 4). Stream incision on GC 14 (figure 7.18a; plate 7.12) has been restricted to the western segment of the alluvial fan. Most recent activity (zone 1) has been confined to a narrow area along the course of the main stream. Zone 2 deposits are found overlying a low terrace. Older overbank deposits are found on higher terrace levels, and these have been flushed part-way down palaeochannels. It has been noted in chapter 5 (section 5.3.2.3) that the average clast sizes of these deposits show apparent down-fan increase, reflecting the competance of individual depositional events.

In contrast to GC 14 (plate 7.12), the second alluvial fan (GC 9, plate 7.2 below) investigated has had a larger part of its surface reworked during the last c 140 years (figure 7.18b). Most recently-reworked deposits lie adjacent to the Corrie nan Lochan burn, which rises in a steep narrow valley. In contrast, the second stream supplying the fan from near the apex has not markedly altered the surface character of the alluvial fan during the recent past. This burn may not generate such high stream power because it has a comparatively small catchment area

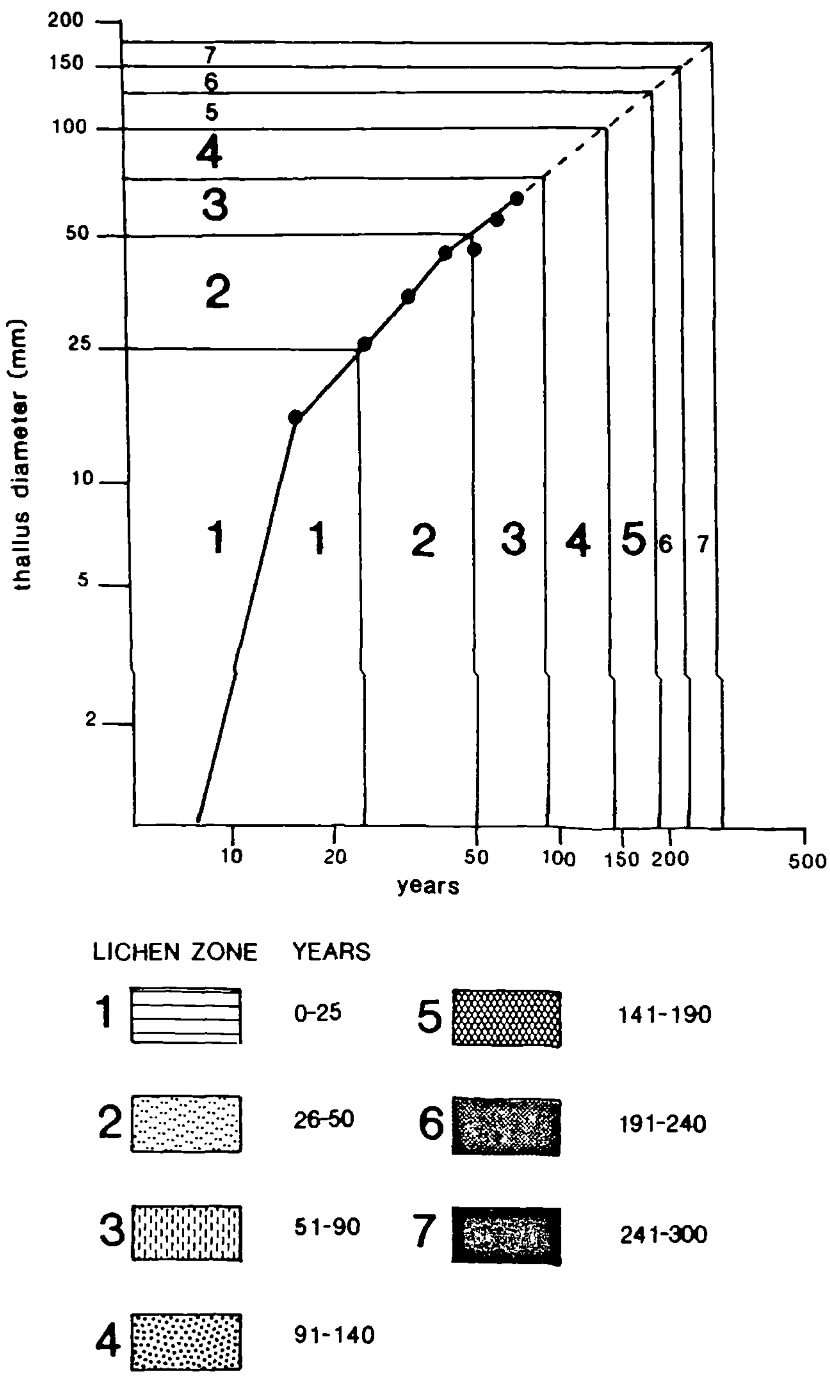
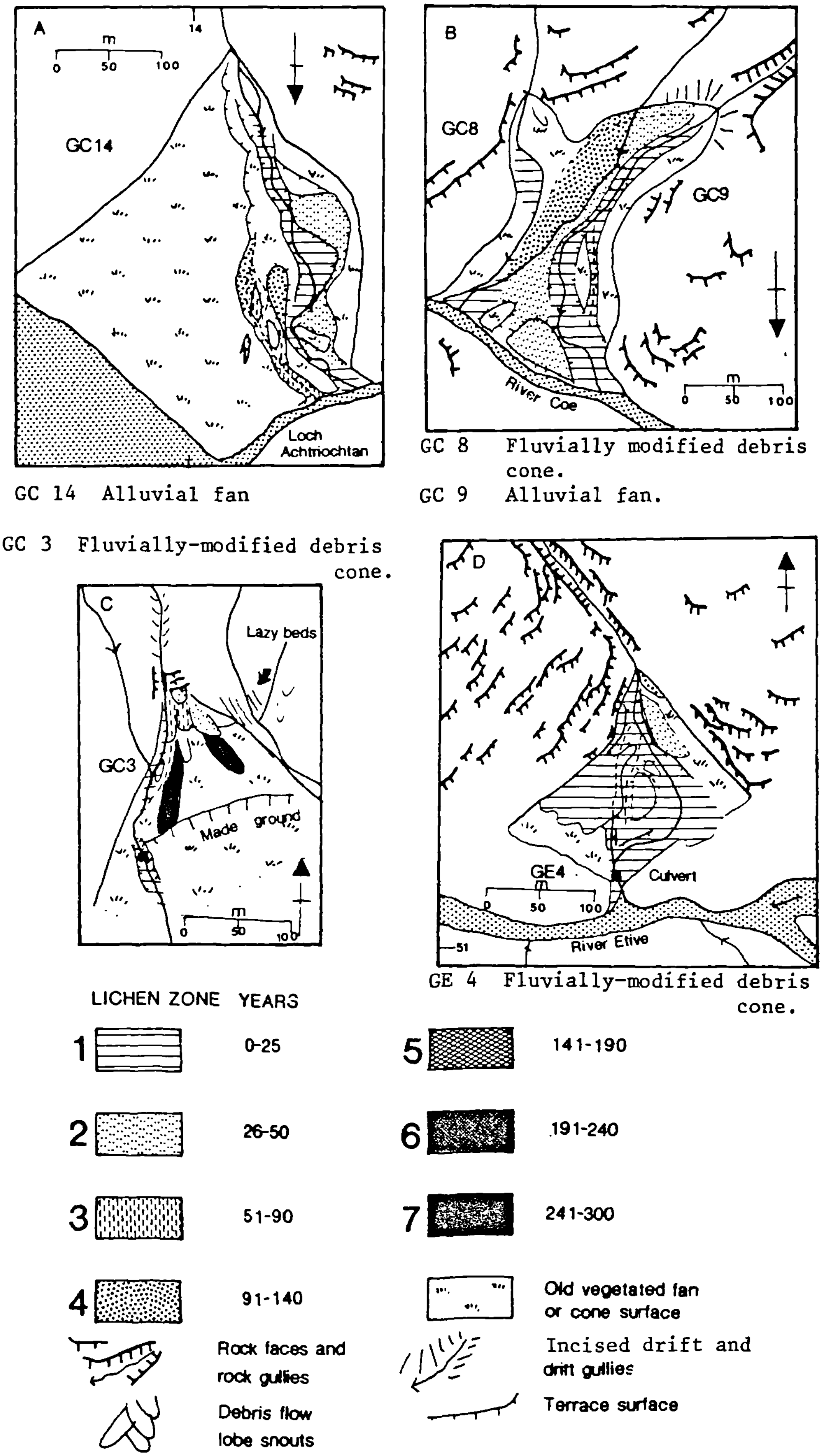


Figure 7.17 Lichen growth curve for Glencoe (Innes, 1983e, figure 3).
(& Lichen zone key)

Figure 7.18 Lichen ages of surface deposits on alluvial fans and fluvially modified debris cones in Glen Etive and Glencoe



GC 14 Alluvial fan

GC 8 Fluvially modified debris cone.

GC 9 Alluvial fan.

GC 3 Fluvially-modified debris cone.

GE 4 Fluvially-modified debris cone.

Plate 7.12 The western segment of Achnambeithach alluvial fan, which shows evidence for fluvial incision and reworking of fan sediments during the recent past (see figure 7.18a).

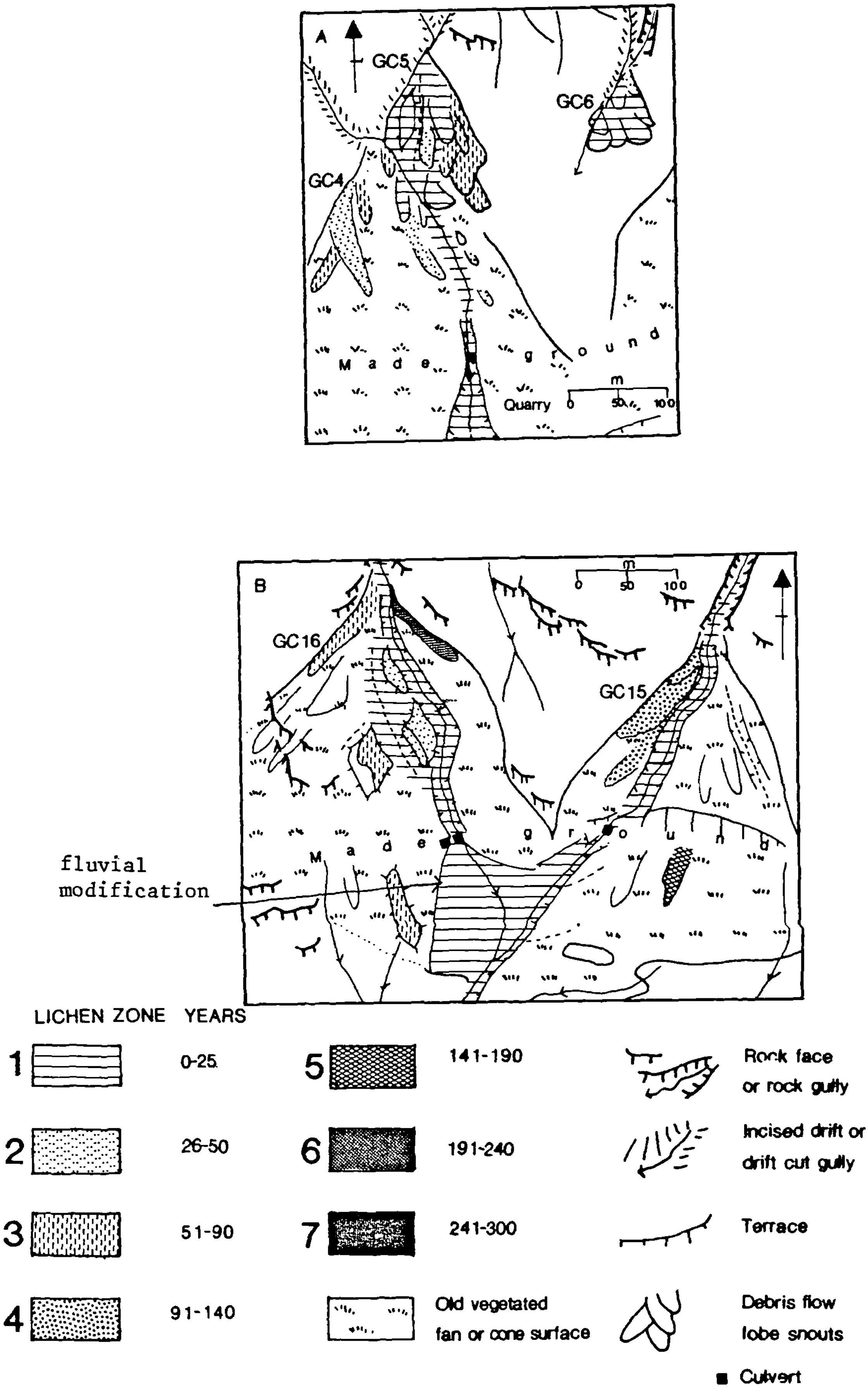
compared with that for the Corrie nan Lochan burn. Only minor incision has occurred on the adjacent fluvially-modified debris cone GC 8, which is also supplied by a small burn. The partially-vegetated debris flow deposits investigated at this site have numerous amalgamated lichens, so that it was not possible to measure realistically lichen sizes over the entire cone surface. However, the deposits are clearly considerably older than the surface deposits of neighbouring GC 9.

The fluvially-modified debris cone GC 3 partially buries lazy beds to the east of its apex (figure 7.18c); according to Innes (1982) burial may have occurred around AD 1823. Lichens measured on debris flow lobes near the apex range in size from zone 2 to zone 7, with a maximum age range of 241 to 300 years (zone 7). Deposition over a substantial area of the lower part of the cone must predate these zone 7 debris flow lobes.

The fourth map on figure 7.18 illustrates the remarkable extent of recent fluvial modification of GE 4 (see section 7.1 above; plate 5.1). Fragments of the surviving debris cone segment suggest that the last debris flow event preserved at the site occurred between 91 and 140 years ago (zone 4). The reliability of this estimate is called into question because the lichen-bearing stones were small and partly buried by vegetation. It is therefore possible that the deposits have been re-exhumed by overgrazing (A. Dugmore pers. com.) or that optimal lichen size has been limited by clast size (Innes, pers. comm.). A stream-cut exposure (figure 7.2 above) in GE 4 has revealed that the debris flow unit supporting the zone 2 lichen-bearing clasts is strongly podzolised, with a degree of iron staining in the B horizon similar to that seen in the Mid Flandrian age debris flow unit at site 1 on the neighbouring Dalness Chasm cone. This suggests that the main period of debris flow activity at this site ceased well before lichen zone 4. The unusual extent of fluvial modification at this site is thought to reflect the steep rocky configuration of the source area, which evidently has a very flashy response during storms, as witnessed during a storm in September 1985.

Two patterns of recent debris flow activity may be identified in figure 7.19. First, two of the debris cones (GC 5 and GC 6) are striking in that their entire surface deposits are colonised by lichens no older than zone 3, implying extensive debris flow deposition over the last c 90 years. Second, only limited parts of GC 4, GC 16 and GC 15 have been active within the last c 240 years. Areas of fluvial reworking have occurred on three of the cones and these are associated with channel routeing through road culverts. Sediment is usually deposited on the upslope side of the culvert by debris flows, which sometimes cause blockage of the culvert (eg western culvert, GC 16). Sediment-free streams passing through such culverts are capable of causing considerable amounts of erosion

Figure 7.19 Lichen ages of surface deposits on fluvially-modified debris cones and debris cones in Glencoe.



downstream, even to the extent of damaging culvert foundations (eg at GC 4; road maintenance staff, Highland Regional Council, pers. comm.). The culverts were first installed during road construction in 1930, so that associated erosion and reworking has presumably occurred since then. Indeed, the second culvert in GC 16 appears to have been responsible for the formation of an alluvial fan inset into the distal part of the debris cone. These sites illustrate that modern anthropogenic interference has locally had a significant impact on cone evolution in parts of Glencoe.

In sum, the lichenometric evidence presented for nine sites in Glencoe and one in Glen Etive demonstrates that significant areas of fan and cone surfaces have been affected by debris flow deposition and fluvial erosion and reworking during the last c 300 years. The entire surface areas of two debris cones have been affected by debris flow deposition during the recent past, confirming in general terms Innes' (1983a) findings for the Chancellor debris cone. The Chancellor cone has built out from a fault-line gully system and this has influenced cone development by providing large quantities of weathered rock debris. Similarly, the two very recently active debris cones, which have built out from slopes adjacent to the Chancellor cone, also reflect localised lithological control. For example, the pattern of debris flow activity in the Lairig Eilde also appears to be related to the location of dyke intrusions.

The density of debris flow activity appears to decline rapidly with distance from the Glencoe ring fault and associated deeply-gullied dyke swarm areas, with far fewer debris flows observed in, for example, the Glen Ogle and Loch Tay areas. However, evidence for other larger types of landslide are common in both of these areas away from the ring fault (Ballantyne, 1986c), and may have obscured earlier debris flows. Therefore, although there appears to be a close relationship between the incidence of dykes and debris flows in the Glencoe area, the absence of debris flows in other areas may not be simply a product of less complex bedrock control.

Recent fluvial activity on alluvial fans and fluvially-modified debris cones in Glencoe and Glen Etive is thought to reflect flashy runoff from steep rocky catchments. Culvert construction has directly influenced the evolution of areas of fluvial modification on debris cones crossed by the road in upper Glencoe.

The evidence described above suggests that in many respects the deep gullies and the flashy character of runoff in many steep rocky source areas in the Glencoe area have been especially favourable for recent debris flow and fluvial activity. Similarly, in upper Glen Feshie both the history and pattern of fluvial reworking of the valley floor and lithological weaknesses associated with fissile schist outcrops in the glacial breach have probably influenced the degree of recent slope instability. In these respects these two glens and Glen Etive contrast with the rest of the study areas, where the incidence of recent debris flow activity is generally lower. However, the extent of recent fluvial activity on alluvial fans and fluvially-modified debris cones in all of the study areas appears to be closely related to the flashy nature of runoff from the source area and is therefore primarily controlled by the topography of the basin and the incidence, intensity and duration of suitable storm events. This is well illustrated by differences in the areal extent of reworking that occurred during the 1981 storm (chapter 3) on similar-sized alluvial fans found along the eastern side of Strathdearn. A second important influence on fluvial activity, particularly reworking of relict deposits, is direct anthropogenic interference such as construction of road culverts or destruction of the vegetation cover. Evidence presented by Macklin (1986) for the Nent valley (Cumbria) also demonstrates how human activity (in this case mining ore) has had a long-term influence on channel and floodplain metamorphosis.

7.5 CONCLUSION.

The chronology and evolution of two sites was considered in detail at the start of this chapter. The main conclusions regarding the history of development of Dalness Chasm cone suggested that debris cone aggradation was largely paraglacial, occuring in the first half of the Flandrian. There then followed a long period of stability once the original sediment source was depleted. Stability was disrupted by fluvial erosion and reworking of the relict cone, apparently in response to burning and clearance of the natural shrub vegetation cover. Subsequent fluvial reworking may also have been influenced by human activity. The morphological similarity of Dalness Chasm cone to many other fluvially-modified debris cones in the Grampian Highlands may imply that the pattern, but not necessarily the causes or timing, of such development has been widespread. It is suggested that the model of debris cone evolution offered by Dalness Chasm cone can be applied elsewhere in the Grampian Highlands.

However, it must be noted that the impact of climatic fluctuations during the Flandrian may have been equally important in initiating reworking at other sites. Indeed, climatic fluctuations are interpreted as triggering the main period of instability in the contributing catchments that led to the formation of much of the three debris cones in upper Glen Feshie in as little as 300 years. Whilst it is recognised that the Feshie debris cones are in some senses unusual in that their formation is probably partly a product of the long-term pattern of river erosion in the glacial breach, it is suggested that they illustrate a rapidity of recent debris cone formation that had not previously been envisaged for sites in the Scottish Highlands.

The impact of fan and cone development on the evolution of the postglacial landscape has also been considerable. Not only are alluvial fans and debris flow-dominated cones widespread throughout the Grampian Highlands, but their impact also in terms of debris removed from the source areas has been substantial. Indeed, it is argued that locally the volume of debris flow sediment transport associated with debris cone formation is several orders of magnitude larger than the volumes of sediment transported by much smaller (if more widespread and numerous) hillslope debris flows. If debris cone accumulation in the Grampian Highlands has been largely paraglacial, then the greatest period of debris flow activity in volumetric terms may have been (in some areas at least) during the early and not the late Flandrian. This conclusion does not necessarily invalidate the findings of Innes (1983a) but attempts to put them into the broader context of debris flow activity throughout the entire Flandrian. The impact of man in accelerating hillslope debris flow activity during historical times is not disputed, but the effect of lithological control in Glencoe in particular is thought to have been of some considerable importance in influencing susceptibility to recent debris flow activity.

The evidence of the Feshie debris cones demonstrates very rapid rates of denudation within their contributing catchment areas. Furthermore, the episodic nature of debris flow activity implies that the denudational impact of debris flow events can be highly variable, with intermittent high loss of sediment from the source areas when flows occur.

It has been difficult to distinguish whether alluvial fan formation has been more greatly affected by periglacial or by paraglacial modes of development. In chapter 6 it was suggested that alluvial fans that have built up outside the Loch Lomond Readvance limits are generally larger than those found within these limits, and it was suggested that this may partly reflect fan aggradation under the periglacial conditions of the Loch Lomond Stadial. In contrast, alluvial fans developed within the glacial limits cannot have been affected directly by periglacial processes, though it is possible that debris weathered by periglacial processes has been supplied to some alluvial fans. For example, a substantial part of the catchment area of fan GE 1 in upper Glen Etive (see also chapter 5) lies above the periglacial trimline mapped by Thorp (1981, 1986). The direct contribution of periglacial sediments to such alluvial fans is likely to be less important in large catchments where sediment is stored "en route" and fails to reach the fan. As with the proposed model of debris cone evolution it is suggested that both human activity and the impact of climatic fluctuations may have influenced the pattern and timing of reworking on largely relict alluvial fans, invariably affecting only a restricted area of the fan adjacent to the main axis of the stream. The areal extent of reworking may be influenced by the incidence of flashy runoff (eg on alluvial fan GC 9 and fluvially-modified debris cone GE 4) which is partly a function of the steepness and size of the source area. Thus there may be regional differences in the degree of reworking on alluvial fans, with the most extensive reworked segments identified on fans in Glencoe, Glen Etive and Strathdearn. The last-mentioned area is well known for storm-induced flooding (chapter 3).

Some of the talus cones studied during the course of this research (see also chapter 5) occur along the lower valley sides of the glacial breach in Glen Feshie, near the Feshie debris cones. Their generally small size reflects the relatively short time they have had to accumulate on low river terraces of Late Flandrian age. The implied rates of rockfall calculated for these talus cones are high, reflecting the easily-erodible nature of the fissile schist outcrops found in the glacial breach. In contrast, talus cones studied in Glen Clova and Glen Clunie are relict. The similarity of the overall rockwall retreat at these sites and values calculated from the volume of Lateglacial protalus ramparts (Ballantyne and Kirkbride, 1987) suggests that these cones, like the ramparts, were formed under periglacial conditions before the end of the Loch Lomond Stadial (cf Ballantyne and Eckford, 1984).

The hypotheses introduced at the start of this chapter have been examined in relation to fan and cone development in the seven study areas in the Grampian Highlands. In general, it has been suggested that debris cone development may have been largely paraglacial, with many cones being effectively stable for long time periods. Subsequent instability and reworking of relict debris cone deposits may have been triggered by human activity, as at the Dalness Chasm site, but could equally be triggered by exceptional rainstorms. Local site factors, such as lithological control of gully development or basal undercutting of a slope by river impingement, may have enhanced susceptibility of some areas to recent debris flow activity, consequently masking the generality of the paraglacial model to debris cone evolution across the Grampians. Thus no one hypothesis may adequately account for the development of cones in upland Scotland. Furthermore, temporal variations in environmental conditions are likely to be combined with spatial variations in lithological controls, thus complicating interpretation of the valley side and valley floor landform assemblages.

CHAPTER 8

CONCLUSIONS

The main objective of this project was to determine the nature and significance of fan and cone landform development in the Grampian Highlands of Scotland. The three component parts of this objective identified in chapter 1 comprised:

1. establishment of the morphological and surface sedimentary characteristics of alluvial fans, debris cones and talus cones;

2. identification of the factors controlling the formation and distribution of fan and cone landforms; and

3. determination of the timing, nature and rate of fan- and cone-forming processes.

The principal findings of the research will be reviewed briefly below in relation to each of these three aims, and the potential for further research will be assessed.

8.1 PRINCIPAL FINDINGS.

8.1.1 The morphological and surface sedimentary characteristics of alluvial fans, debris cones and rockfall talus cones.

Although some workers have suggested the possibility of a continuum of landforms from alluvial fans through to talus cones, detailed analysis has tended to focus attention on the individual landform types. There has been little attempt to examine systematically the concept of a continuum or to assess critically the criteria on which different members of this continuum may be distinguished. An *a priori* model of a continuum of fan and cone morphological and sedimentary properties was established from the literature. Field examination of sites in the Grampian Highlands and in Lyngen, Northern Norway, enabled the generality of the model to be tested, and on the basis of the results the model was subsequently modified. Six properties of fans and cones were assessed, namely long profile gradient, slope form, downslope changes in clast size, roundness and form, and the ratio of the largest clast to total fan or cone length. Cluster analysis of these variables indicated that, of the features formed by a single type of depositional process, debris cones are more similar to alluvial fans than they are to rockfall talus cones.

Field research demonstrated that a characteristic range of mean gradients is associated with each of the three dominant depositional process types. Talus cone mean gradients range from 25°-33°, and just overlap the range of 20°-26° for debris flow dominated cones. Fluvially-modified debris cones are characterised by lower mean gradients (9°-19°) but are in turn generally steeper than alluvial fans, which have mean gradients of 2°-10°.

The dominant depositional process also influences the character of the long profile form. Steep, almost rectilinear slopes characterise rockfall talus cones, irregular slopes are typical of most debris cones, markedly concave slopes are associated with fluvially-modified debris cones, and low angled, gently concave slopes are typical of alluvial fans.

In contrast to the predictions of the _a priori_ model, Scottish alluvial fan profiles display considerable surface irregularity, which is commonly associated with incision and reworking. This aspect of Scottish fans is in contrast to the fans studied in Lyngen, Northern Norway, where, for example, at least one fan is actively aggrading. It should be noted, however, that the extent of recent activity on Scottish alluvial fans tends to be restricted to a narrow reworked segment.

The surface sedimentary properties of Scottish alluvial fans are, in general, less clear than was expected from the *a priori* model. Typically, Scottish alluvial fan sediments appear poorly sorted on any part of the active segment, and overall the pattern of down-fan fining varies considerably depending on the position of individual sedimentary units, such as bars, that relate to flood events of differing magnitudes. Such surface sedimentary properties are in marked contrast to those of the actively-aggrading alluvial fan in Lyngen. Comparison of this site with the Scottish fans suggests that recent deposition on the surfaces of the latter has been influenced by more flashy stream-flow regimes and high magnitude runoff events. Episodic reworking on Scottish fans has resulted in deposition of a complex assemblage of sediments under flood conditions, and such flood deposits have tended to mask any simple down-fan fining patterns. The coarseness and poor sorting of the surface sediments of Scottish alluvial fans corresponds well to the proximal core fan facies model described by Boothroyd and Nummedal (1978); the other facies described by these authors appear to be absent or only poorly developed, a feature that probably reflects the limited sizes of the fans studied in the Grampian Highlands.

In comparison to alluvial fans and debris cones, rockfall talus cones exhibit the most consistent relationships between clast size and distance downslope. It is notable, however, that the degree of such "fall sorting" is controlled by the lithology of the source area. For example, talus cones formed predominantly of lavas in Glencoe show very clear downslope increases in clast size whilst talus cones composed of fissile schist fragments in Glen Feshie do not exhibit the same downslope trend.

As might be expected, lithology also affects the degree of rounding of clasts on fans and cones. However, this influence does not obscure the tendency for talus cones to have the most angular clasts and for alluvial fans to have the most rounded clasts. No pattern of downslope change in the degree of rounding was evident on any of the fans or cones studied. In the case of the alluvial fans this is thought to reflect the generally short travel distances over which rounding could take place, and also the flashy streamflow regime on most Scottish alluvial fans.

The results of the analyses in chapter 5 suggest that may be possible to characterise different types of fan and cone landforms on the basis of their morphological and surface sedimentary properties. With the exception of the degree of down-fan fining, the generality of the findings of the Scottish research are supported by the evidence from Lyngen. However, it is stressed that future use of a genetic classification of fans and cones, such as that presented in the _a posteriori_ model, should be flexible and allow for variations in regime as well the type of dominant depositional process operative on a fan or cone.

8.1.2 Factors controlling the formation and distribution of fan and cone landforms.

The research has shown that alluvial fans and debris cones are widespread throughout the Grampian Highlands, but that talus cones are largely restricted to the innermost mountain areas. Several possible factors that might have influenced the distribution of these landforms and nature of their development were identified in chapter 4, and were examined in chapter 6 in relation to fans and cones in the Grampian Highlands. Three factors appear to have significantly influenced the distribution and nature of fan or cone development. These are glacial history, lithology and the morphometry of the contributing area.

In general, the morphometric relationships between fans or cones and their source areas are often weak. The relationship between alluvial fan size and source area size proved considerably weaker for sites within the Loch Lomond Readvance glacial limits than for those outside them. Alluvial fans outside these limits were found to be significantly larger than those inside, which seems to imply enhanced fan accummulation during the Lateglacial period (c 13,000 to 10,000 BP). However, no such pattern of development was found for debris cones, which suggests that debris cones have formed in response to rather different controls.

Regional patterns in the strength of morphometric relationships between fans and cones and their contributing basins were interpreted as reflecting differences in both relief and lithology. Weaker relationships were found for the generally steeper slopes of the Western Grampians and the Cairngorms, both of which are underlain by igneous lithologies. In contrast, stronger positive relationships were found to be associated with the gentler relief of the Central and Eastern Grampians, which are largely underlain by schistose rock.

Discriminant analysis of five basin morphometric properties identified a combination of three variables that best define dominant process control. These variables are basin gradient, basin width and basin height. Alluvial fans are associated with the gentlest basin gradients and have tended to form at the mouths of large, wide catchments. In such catchments sediment may not be delivered directly from weathering and erosion of the valley sides to the fan, but may be stored in valley-side or valley-floor deposits. The breadth of fluvially-dominated catchments favours runoff rather than sediment delivery to the fan apex. In contrast, debris flow dominated catchments are characteristically steeper and narrower than alluvial fan basins. The shape of debris flow dominated gullies is optimum for sediment delivery, with little overall distance between the gully walls and the gully floor, and steep gully floors favouring run-out of debris flows. The contributing areas above talus cones are generally the steepest and narrowest, reflecting conditions necessary for restricting rockfall delivery to cone apices.

8.1.3 The timing, nature and rate of fan- and cone-forming processes.

Detailed stratigraphic investigations and radiocarbon analyses were carried out at two sites in an attempt to establish their chronology of evolution. These sites are particularly interesting as they suggest contrasts in the history of debris cone development. Dalness Chasm cone, in Glen Etive, consists of a relict debris cone with a volume of *c* 170,000 m3. This probably accumulated during the early Flandrian from *c* 10,000 BP to *c* 4,000 BP. Aggradation apparently ceased when the sediment supply in the gully upslope was depleted. The cone surface remained stable until *c* 550 BP, when fluvial incision and reworking resulted in the formation of an alluvial fan that has buried the distal part of the debris cone. At a section near the apex of this fan, a marked change in the pollen stratigraphy and abundant charcoal fragments at the level of the former debris cone surface indicate that incision and subsequent alluvial fan formation were probably triggered by shrub clearance.

The morphological similarity of many fluvially-modified debris cones in the Scottish Highlands, suggests that the pattern, if not the timing and causes, of paraglacial debris cone evolution exhibited at Dalness Chasm cone may have been widespread.

Examples of recent fluvial modification of debris cones were also studied in Glencoe. Some of the large debris cones have substantial areas of recent fluvial modification that are probably associated with road culverts constructed in the 1930s. However, because lithologies such as the Glencoe ring fault dykes, are erosion susceptible, considerable volumes of very recent debris flow deposition have occurred on some of the debris cones in the area. It is probable that the influence of lithological weaknesses in such areas may have masked a general pattern of paraglacial-type debris cone evolution across the Grampian Highlands.

In contrast to the model of debris cone evolution suggested by the Dalness Chasm cone, radiocarbon-dated buried roots and soils sampled from within three coalescing debris cones in upper Glen Feshie indicate two phases of debris cone aggradation. The earlier phase of activity ended _c_ 2,000 BP. This was followed by a long period of stability that ended _c_ 300 BP, after which considerable aggradation of the present three cones occurred. No conclusive evidence was found in support of an anthropogenic trigger for debris flow initiation at the Feshie debris cone site, and it is suggested that instability and reworking of Lateglacial slope deposits upslope was triggered and maintained by repeated storm damage after _c_ 300 BP. The site is unusual, however, in that slope instability may have been exacerbated by lateral undercutting by the River Feshie, which flows along the foot of the cones.

The impact of fan and cone development on the evolution of the postglacial landscape in the Grampian Highlands has been considerable. Volumetric data from a number of cones revealed average surface lowering in their source areas of one to three metres since deglaciation. The aggradation of much of the Feshie debris cones since c 300 BP, may imply rates of gully erosion of the order of 14,000 t to 17,000 t / km^2 / year. Rates calculated over the entire period of time since deglaciation indicate that denudation by debris flow and rock fall has locally been more effective than the denudation by fluvial erosion that is implied by the volumes of alluvial fan deposits.

Changes in the source area environment can alter fundamentally the nature of landform evolution. The long-term character of the gully system may be influenced by both lithology and glacial history, but it is also clear that high-magnitude low-frequency events may also bring about significant changes to fan or cone evolution. Therefore, although a process continuum of landforms exist with gradations from fluid flow to dry material transfer, changes in the time dimension of the continuum are also significant. The available evidence seems to suggest that the long-term effect of cone reworking is to change the landform from one dominant process type to a neighbouring type in the continuum.

8.2 FUTURE PROSPECTS.

In this thesis three principal areas of research have been undertaken. These were an examination of the properties of the fan or cone surface, investigation of the characteristics of the contributing gully or valley environment that have determined the potential for particular types of dominant process, and assessment of the nature and rate of changes in fan or cone evolution over time. Findings from these integrated aspects of fan and cone landform systems have demonstrated a number of important controls on the development of fans and cones in Highland Scotland. The conceptual framework provided by the results may be usefully employed in future work on fan and cone landform development in Scotland, and possibly in the study of fans and cones in other tectonically-stable glaciated mountain environments.

A number of possible avenues for further research exist, including refinements to the analysis of morphometric controls of process. Not only may the model described in chapter 6 be modified, but also the method could be profitably employed in isolating the critical environmental constraints on transitional types of debris flow and water flow. Indeed, further research into the nature and significance of debris flow types, such as hyperconcentrated flow, would make possible a fuller evaluation of the significance of debris flow activity in general, and in particular the role of such transitional processes in the evolution of landform continua.

One of the most important aspects of fan and cone development that has been revealed by this research has centred on a chronological approach to changes in the nature and rate of fan- and cone-forming processes. At present detailed information exists for only two contrasting sites, and further research is necessary to establish the generality of these findings. The potential for soil chronosequence analysis of Flandrian landforms in the Grampians is, in particular, promising. Much more detailed research is needed before the significance of Flandrian slope and valley floor process activity can be assessed within the context of Late Quaternary landscape evolution in upland Britain.

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APPENDIX 1.

CHAPTER 5 DATA

NUMBER	TYPE	SITE CODE	N.G.R.	MEAN GRADIENT (degrees)	FORM	FINING	MP-ANG	C/A	TOTAL LENGTH m	MAX. CLAST SIZE (mm)	SCALE
37	1	fi02	27788240	3	1.33	1.44	2.8	53	286	810	3
38	1	fi03	27738238	4	1.67	1.69	2.4	53	450	514	1
27	2	fi04	27538224	13	1.67	1.32	2.2	42	170	560	3
33	1	fi05	27478214	6	1.40	1.74	2.8	66	293	760	3
15	3	fi06	27448194	13	1.36	1.19	2.3	58	170	450	3
34	1	fi07	27938256	7	2.50	1.32	3.0	62	195	473	2
36	1	fi08	27498183	8	1.80	1.91	2.3	40	170	263	2
35	1	fi09	27248177	2	3.00	1.94	3.1	64	570	590	1
20	2	gc01	21287569	15	1.89	1.41	2.3	50	320	807	3
18	2	gc02	21377569	13	1.60	1.08	2.2	46	214	390	2
19	2	gc03	21467573	12	2.50	4.19	2.2	44	185	637	3
16	2	gc04	21527574	11	6.67	1.77	2.1	47	397	440	1
11	3	gc05	21547575	24	0.96	1.72	2.0	43	134	670	5
12	3	gc06	21527576	25	1.58	0.79	1.7	46	245	415	2
10	3	gc07	21557575	20	1.86	6.67	2.1	39	520	1600	3
17	2	gc08	21657564	17	2.67	1.29	2.1	44	116	220	2
29	1	gc09	21637564	9	2.17	1.13	2.5	31	300	527	2
01	4	gc10	21487565	29	1.30	0.20	1.5	37	42	623	15
09	3	gc11	21477565	22	2.33	1.36	1.4	39	76	683	9
02	4	gc12	21477565	31	1.10	0.23	1.6	44	45	933	21
03	4	gc13	21447562	25	0.84	0.14	1.3	52	61	1390	23
28	1	gc14	21397563	6	2.67	0.89	2.7	47	314	620	2

30	1	ge01	22247522	6	1.00	1.23	2.5	38	229	593	3
23	2	ge02	21967515	09	2.80	1.21	2.8	41	350	637	2
22	2	ge03	21927514	12	2.33	0.75	2.0	31	203	537	3
21	2	ge04	21847512	14	2.38	1.30	2.5	40	180	625	4
32	1	ge05	21717514	3	1.33	3.54	2.8	37	482	897	2
31	1	ge06	21677505	10	1.20	1.12	2.8	35	295	613	2
25	2	gf02	28587905	10	2.00	2.02	2.2	50	130	410	3
26	2	gf03	28587904	13	2.71	5.77	2.5	49	190	637	3
13	3	gf04	28617903	22	1.20	1.67	1.9	65	125	490	14
24	2	gf05	28647899	12	2.80	2.88	2.5	50	310	847	3
14	3	gf06	28597899	21	1.23	1.90	2.2	51	65	337	5
04	4	gf07	28567902	27	1.94	1.00	1.2	53	16	350	22
06	4	gf08	28527904	31	2.32	0.57	1.1	68	10	218	22
05	4	gf09	28527904	26	1.27	0.32	1.7	52	31	387	13
08	4	gf10	28517904	32	1.85	0.44	1.1	68	20	177	9
07	4	gf11	28517905	33	1.00	0.52	1.3	52	23	282	12

FAN OR CONE TYPE:
1 ALLUVIAL FAN
2 FLUVIALLY-MODIFIED DEBRIS CONE
3 DEBRIS CONE
4 ROCKFALL TALUS CONE

Eplanation of the derivation of the variables is give on pages 144 to 152 of chapter5.

APPENDIX 2

MORPHOMETRIC AND ENVIRONMENTAL DATA SET FOR CHAPTER 6

	SITE	NGR	LITH	GEN	GROUP	GL	PPT	ASP	ALT	BH	BL	BGRAD	BW	BA	RECORD 1
	FH	FL	FW		FA		FGRAD								RECORD 2
RECORD 1	LI01	20717725	33	1	1	1	2000	210	16	754	5250	8	2750	12187	
RECORD 2	16	600	750		01938		2								
	LI02	20657691	31	1	1	1	2000	5	115	984	8500	7	7140	1625	
	15	500	575		02031		2								
	LI03	20577708	33	1	1	1	2000	200	20	538	2000	5	1250	43562	
	20	200	175		00344		6								
	TR01	22537584	54	1	1	1	2800	122	366	533	2900	10	1250	2625	
	8	550	500		01563		1								
	OS01	24197702	55	1	1	1	2000	15	405	709	6750	6	3500	22187	
	24	550	600		01025		2								
	OS02	24107722	55	3	1	1	2000	150	431	257	350	36	50	018	
	42	175	100		00100		13								
	OS03	24077727	55	5	1	1	2000	95	457	200	250	39	50	007	
	40	100	100		00100		21								
	FI01	27478214	14	1	2	2	1400	58	360	378	3500	6	1500	3746	
	15	240	290		0470		6								
	FI02	27418189	11	1	1	2	1400	50	396	342	1500	13	1250	787	
	30	160	180		0220		11								
	FI03	27248177	14	1	1	2	1600	120	389	401	5250	4	1750	8157	
	16	620	710		3800		3								
	FI04	27538224	14	2	1	2	1600	355	380	268	750	20	875	493	
	30	120	150		1100		15								
	FI05	27498183	11	1	1	2	1600	33	396	239	1000	13	875	573	

30 200 170 0240 9

FI06 27448194 14 3 1 2 1600 3 419 277 6250 24 3500 1004
53 220 160 0231 15

FI07 27938256 11 1 2 2 1200 79 330 247 41250 3 25000 56206
15 300 355 4300 5

FI08 27788240 11 1 2 2 1200 52 350 356 42500 5 16250 97316
30 400 620 1430 4

FI09 27738238 11 1 2 2 1200 72 360 346 38750 5 15000 42234
35 470 620 1550 5

FI10 26558116 14 3 2 1600 10 557 116 3750 17 750 686
30 150 0193 11

FI11 26518121 14 1 2 1600 180 525 200 32500 4 13500 30314
30 250 200 0259 7

FI12 26548131 14 1 2 1600 170 496 285 51500 3 28500 82760
15 250 250 0309 3

FI13 26638134 11 1 1 2 1600 75 518 153 2000 4 5000 8750
23 175 75 0112 7

FI14 26808154 14 1 1 2 1600 180 450 357 4875 4 23750 257300
23 175 200 0410 7

FI15 26858157 14 3 1 2 1600 230 442 138 525 14 1750 0970
15 75 75 0047 11

FI16 27008167 14 1 1 2 1600 200 411 396 6500 3 37500 167600
15 400 325 0417 2

FI17 27088169 14 3 1 2 1600 50 449 161 250 33 500 0104
53 125 75 0033 7

FI18 27088172 14 3 1 2 1600 45 426 206 550 21 1500 0730
30 125 100 0065 13

FI19 27088180 14 2 1 2 1600 220 434 211 1625 7 4500 4920
46 250 450 0630 10

FI20 27308178 14 1 2 2 1600 50 396 394 4750 5 37500 157062
30 625 700 2683 3

FI21 27298186 44 3 1 2 1600 210 387 222 525 23 1250 000722
23 50 75 0017 25

FI22 27378191 44 3 1 2 1400 225 369 315 2000 9 9000 9344
23 75 125 0048 10

FI23 27468209 44 1 2 1400 35 400 216 1000 12 1250 1533
15 150 200 0209 6

```
FI24 27418214044 1   2 1400 240  380  150     625  13    1000     1777
  10  175  250    0303  3

FI25 27468225 44 1 1 2 1200 165  352  392   75000  3    3125    272328
  10  500  500    1396  1

FI26 27638238 44 1 1 2 1200  25  360  158   37500  2    2375     11572
  10  250  375    0586  2

FI27 27588235 44 1 1 2 1200  85  360  158   12500  7     750      5163
  10  150  225    0325  4

FI29 27888335 44 1 1 2 1100 310  280  271   21250  7    2000     21730
  10  375  500    0919  2

FI30 27688369 44 1 1 2 1100   4  295  319   57500  3    3000    154980
  20 1300 1000   11310  1

FI31 28298343 14 1 1 2 1100   0  365  180   15000  7     775      8010
  15  100  100    0063  9

FI32 28268351 41 3 1 2 1100 195  270  160    2750 30     100      0140
  10   75   75    0032  8

FI33 28278353 41 3 1 2 1100 200  270  165    3000 29      75     01861
  15   75   75    0056 11

FI34 28378355 41 3 1 2 1100  35  270  190    3000 32      50      0180
  25  100  100    0156 14

FI35 28388356 41 3 1 2 1100  50  265  185    3000 32     100      0366
  25  125  150    0179 11

FI36 28378368 44 3 1 2 1100 215  310  220    5750 21     250      0894
  40  375  325    0871  6

FI37 28148305 44 1 1 2 1100 300  330  329   63750  3     450    294256
  10  375  375    1114  2

GR01 22777817 15 8 1 1R1600 305  101 1029  200000  3    1000   168713
  23 1150 2000    9126  1

GR02 22807827 16 7 1 1R1800 218  175  510    4250  7    4250    15940
  53  450  500    2243  7

GR03 22737850 16 7 1 1R1800 195  266  388    2600  8    1875     3414
  15   75  150    0171 11

GR04 22827863 16 7 1 1R1800 258  305  380    2625  3    1375     2500
  23  400  625    1249  3

GR05 22867861 11 3 1 1R1800  35  305  263     625 23      50      054
  23  125  175    0195 10
```

GR06 22797854 11 3 1 1R1800 20 259 229 625 20 125 051
23 150 150 0142 9

GR07 23087892 11 7 3 1R1800 200 259 533 1350 22 900 756
61 175 350 0605 19

GR08 23117889 11 1 1 1R1800 85 213 427 850 27 950 432
15 175 200 0330 5

GR09 23137889 11 3 1 1R1800 20 244 274 550 26 50 34
38 125 100 0072 17

GR10 23137892 11 1 1 1R1800 90 207 433 800 28 175 153
15 175 200 0186 5

GR11 23217895 11 7 3 1R1800 28 259 575 1750 18 3000 33648
68 350 575 1088 11

GR13 23217902 11 3 1 1R1800 225 243 273 1250 21 50 101
53 225 200 0288 13

GR14 23227903 11 3 1 1R1800 220 236 465 1200 21 50 050
38 200 150 0190 11

GR15 23267902 11 3 1 1R1800 30 221 419 1000 23 75 125
38 100 50 0044 21

GR16 23277903 11 3 1 1R1800 25 221 435 1000 24 100 108
38 175 75 0104 12

GR17 23307905 11 7 3 1R1800 30 266 568 2050 15 2000 2132
61 525 700 194 7

GR18 23337914 11 7 3 1R1800 220 274 496 2750 10 450 1124
53 400 525 1218 8

GR19 23407925 11 7 3 1R1800 220 274 518 4325 7 4625 15660
30 800 1250 4014 2

GR20 23507929 11 7 2 1R1800 295 305 463 2125 12 1750 2000
53 350 425 1288 9

GR21 23537921 11 7 3 1R1800 94 290 544 2925 11 1500 2834
38 700 750 3356 3

GR22 23577926 11 1 1 1R1800 310 274 351 1200 16 450 300
38 200 325 0660 11

GR23 23667918 11 1 1 1R1800 90 305 244 1000 14 150 109
15 125 125 0131 7

GR24 23697919 11 7 2 1R1800 50 290 1840 6250 8 4250 17311
15 300 400 0841 3

mm01 24768130 11 9 1 2 1400 60 244 506 7750 4 4000 22483

30 1000 1125 5776 2

MM02 24398095 11 1 1 2 1600 90 300 440 2875 9 3000 6227
8 250 375 0757 2

MM03 24708075 11 3 1 2 1600 200 450 256 3750 4 625 1321
53 175 125 0252 17

MM04 24688032 11 1 1 2 1600 70 632 264 4250 4 1875 5151
15 375 500 1448 2

MM05 24307946 15 1 1 2 1800 205 366 518 4000 7 2750 6435
15 525 775 2319 2

MM06 24337939 15 1 1 2 1800 60 360 691 4625 8 2125 7766
8 150 225 0300 3

MM07 24397953 15 1 1 2 1800 240 351 508 3000 10 1250 2929
8 300 325 0587 6

MM08 24597958 15 1 1 2 1800 230 343 553 5025 6 4250 8531
8 325 300 0572 1

MM09 24697960 15 1 1 2 1800 265 350 520 4750 6 3500 8531
15 450 450 1756 2

MM10 24747954 15 1 1 2 1800 160 335 671 5250 7 2500 9225
8 375 325 0801 1

MM11 24927959 11 1 1 2 1800 315 335 429 1700 14 1375 1199
15 175 200 0244 5

MM12 24197890 11 3 1 2 2200 29 739 328 1125 16 500 346
84 200 150 0203 23

mm13 24147895 11 5 1 2 2200 150 739 149 375 22 50 018
76 200 150 00251 21

MM14 24137896 11 5 1 2 2200 140 762 126 250 27 50 009
122 300 175 0161 22

MM15 24297861 11 3 1 2 2000 330 754 274 1800 9 375 531
68 375 100 0063 10

MM16 24217827 11 6 1 2 1600 225 261 869 5500 9 2500 8875
7 200 550 0159 2

MM17 23717848 11 3 1 2 1600 345 480 572 1525 21 625 641
38 1150 175 0141 14

MM18 23897809 11 8 1 211600 88 259 555 4875 6 2375 6628
15 450 1000 3413 2

MM19 23637825 11 1 1 2 1600 295 327 725 4700 9 3000 8999
15 300 500 0687 3

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MM20 23737814 11 8 1 211600 210 275 777 5625 8 5000 14873
 15 575 575 1851 1

MM21 24007818 11 6 1 2 1600 270 275 822 5125 9 2400 9262
 15 275 825 1547 3

MM22 25588078 11 3 1 2 1600 275 518 271 1575 10 325 372
 30 150 225 0289 11

MM23 25708083 11 3 1 2 1600 45 549 279 1125 14 1125 529
 30 150 175 0132 11

MM24 25917985 11 3 1 2 1600 345 487 245 800 17 50 103
 23 75 50 0052 17

MM25 25897979 11 3 2 2 1800 340 442 259 875 16 375 401
 30 375 450 0653 5

MM26 25707985 11 3 1 2 1800 125 732 128 200 33 50 86
 61 100 75 0064 31

DR01 26387801 11 1 1 2 1600 40 464 472 3000 9 1300 3194
 53 950 1375 6279 3

RR02 26397814 11 1 1 2 1600 35 427 448 2375 11 875 1288
 31 550 400 1415 3

GA01 27247805 41 3 1 1 1400 180 518 297 425 35 050 029
 38 100 75 0066 21

GA02 27237809 41 3 1 1 1400 185 532 245 425 30 125 051
 46 150 125 0203 17

GA03 27287808 11 3 1 1 1400 5 539 292 575 27 125 057
 68 175 200 0299 21

GA04 27247818 11 1 1 1 1400 215 488 365 3625 6 1750 3920
 23 500 600 1733 3

GA05 27327818 11 3 1 1 1400 45 518 275 550 28 200 069
 53 175 175 0239 17

GA06 27367820 11 3 1 1 1400 78 496 297 525 29 125 056
 46 150 150 0101 17

GA07 27447825 14 1 1 1 1400 75 464 412 2125 11 1450 2361
 23 350 450 0823 4

GA08 27457831 14 3 1 1 1400 210 472 312 650 26 200 081
 38 125 200 0183 17

GA09 27497839 14 3 1 1 1400 233 465 432 4000 6 4250 7634
 23 525 625 1948 2
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GA10 27657820 14 3 1 11600 115 518 328 1875 1000 1451
30 250 150 0236 7

GA11 27687827 14 1 1 1 1600 340 518 363 3875 5 1800 5209
23 300 650 1103 4

GA12 27627833 14 3 1 1 1600 300 518 248 1500 9 650 544
46 175 175 0237 15

GA13 27607847 41 1 1 1 1400 1 457 411 2250 10 1000 1525
30 300 575 1034 6

GA14 27607859 14 3 1 1 1400 12 457 368 900 22 575 310
30 150 175 0205 11

gt09 27227788 11 5 1 1 1400 10 500 150 100 56 50 004
70 100 50 0051 34

gt12 27237789 11 5 1 1 1400 15 510 140 75 62 50 002
70 100 75 0036 34

GG13 26467733 11 1 1 1 1400 295 440 496 5000 6 2875 6945
20 450 825 2942 3

GG14 27937738 11 1 1 1 1400 235 440 394 2125 11 1575 5131
10 200 275 0357 3

GG15 28247729 1 2 0 245 410 135 3125 2 1250 2750
20 200 250 0427 6

GG16 28347737 1 2 0 335 460 403 3500 7 875 2608
50 575 450 1711 5

GG17 28377749 1 2 0 10 490 441 2500 10 800 1660
50 275 250 0869 10

GG18 28347762 1 2 0 350 500 431 2250 11 625 910
50 375 450 0779 6

GG19 28317770 1 2 0 315 510 498 3000 9 1100 3037
40 375 375 1164 6

GG10 26257793 11 1 1 1 1600 175 440 430 2500 10 1500 6847
10 350 575 1115 2

GG11 26327763 11 1 1 1 1600 340 480 436 2000 12 750 1102
20 150 75 8773 8

GG12 26477793 11 3 1 1 1600 320 650 170 275 32 50 011
70 125 75 0085 29

GT01 28877714 11 3 2 2 1400 243 280 621 8500 14 3625 2850
70 475 650 1834 8

GT02 28847708 11 3 1 2 1400 200 250 250 550 24 50 39

```
  40  100  125     0075 22

GT03 28777699 11  3 1 2 1400 193  390  509   4750  6   1750    7009
  80  450  500     1254 10

GT04 28867750 11  3 1 2 1400 200  500  400    575 35     50     034
  50  150   75     0137 18

GT05 28757745 11  3 1 2 1400 355  600  250    375 34     75     026
  90  200  100     0194 24

GT06 29087720 11  1 1 2 1400 250  280  672   4075  9   1575    4836
  20  100  150     0157 11

GT07 29277734 11  1 1 2 1400  40  300  760   1800 23   1025     965
  10  150  400     0393  4

GT08 27167790 11  1 2 1 1400 225  500  436   5750  4   3250     616
  20  450  575     0509  3

NM01 27838130 55  1 1 2 1000 140  442  431  10000  2   5375   32167
  15  475  550     1288  2

NM02 27878138 55  1 1 2 1000 185  434  270   2675  6   3000    4924
  23  525  775     1598  3

NM03 27908143 55  1 1 2 1000 215  427  266   2700  6    450     776
  15  200  225     0299  4

GG01 26127676 11  1 2 1 1200 185  450  541   7000  4   6375   31321
  30 1100  950     6587  2

GG04 27557698 11  1 2 2 1000 250  263  571  10750  3   9250   60080
  20  350  500     1334  3

GG05 27347694 11  1 2 2 1000 120  300  219   3125  4   4750    9172
  30  550  550     1707  3

GG06 27697720 11  1 1 1 1600 295  430  370   2625  8   1125    2526
  30  150  200     0309 11

GG07 26397725 11  1 1 1 1600 175  430  561   4000  8   2300    6039
  10  425  425     0117  1

GG08 26267704 11  6 1 1 1600 195  440  340    900 21    200     297
  10  150  450     0212  4

GG09 26227687 11  3 1 1 1600 210  450  429   3250  6    750    1155
  30  150  200     0268 11

LL01 24387818 11  8 2 211600  97  274  826  21000  2  13500  103792
  15 1800 2300    17268  1

LL02 24897832 11  1 1 2 1600  46  396  653   2800 13   2575    5590
  38  525  700     1656  4
```

LL03 24457841 11 6 1 2 1600 240 264 806 3300 14 1125 2245
15 300 425 0756 3

LL04 24757876 11 8 2 211600 210 297 773 5000 9 2100 8759
30 1500 950 7528 1

LL05 24497890 11 1 1 1 2200 220 579 457 950 26 800 523
38 175 250 0197 12

LL06 24407881 11 3 1 1 2200 65 662 313 875 20 275 178
46 175 125 1784 15

LL07 24387876 11 5 1 1 2200 80 822 217 375 30 50 013
152 350 75 0233 23

LL08 24377875 11 5 1 1 2200 64 822 241 375 33 50 006
167 200 100 0143 40

LL09 24357877 11 5 1 1 2200 130 732 304 275 49 50 038
152 250 150 0279 31

LL10 24347881 11 3 1 1 2200 145 701 359 250 55 75 031
122 200 275 0371 31

LL11 24327884 11 5 1 1 2200 140 808 259 150 60 50 004
76 150 100 0105 27

LL12 24317884 11 5 1 1 2200 120 851 224 125 61 50 004
129 200 100 0039 33

LL13 24307885 11 5 1 1 2200 125 910 165 150 48 50 010
91 125 75 0084 36

LL14 24297884 11 5 1 1 2200 128 971 104 150 35 50 010
122 200 75 0105 31

LL15 24347887 11 5 1 1 2200 265 792 244 400 31 150 558
76 150 100 0475 27

LL16 24367888 11 5 1 1 2200 245 823 221 275 39 50 011
129 175 100 0159 36

LL17 25097873 11 6 1 2 1600 85 259 92 625 8 625 279
15 400 525 1229 2

er01 24457741 15 5 1 2 2200 120 838 168 200 40 50 013
61 125 75 0099 26

ER02 24477716 15 1 1 1 2200 250 556 544 2000 15 1250 1709
15 200 150 0202 4

ER03 24607725 15 3 1 1 2200 212 602 434 1000 23 325 242
23 75 50 0034 17

ER04	24667727	15	1	1	1	2200	240	587	545	1925	16	2050	1642
	15	320	100	0203	3								
ER05	24697746	15	5	1	2	2200	25	1030	102	75	54	50	025
	106	250	125	0026	23								
ER06	24727755	11	5	1	2	2200	135	942	94	125	37	50	019
	53	250	75	0206	12								
ER07	24857732	11	3	1	1	2200	68	655	351	350	45	50	019
	23	75	75	0050	17								
ER08	24877733	11	3	1	1	2200	65	640	396	450	41	50	019
	30	75	75	0062	22								
ER09	24907734	11	3	1	1	2200	85	640	366	625	30	50	053
	38	100	100	0123	21								
ER10	24957733	11	3	1	1	2200	80	671	477	1500	18	800	887
	91	375	125	0406	3								
ER11	24967734	11	5	1	1	2200	50	730	276	225	51	50	014
	106	125	125	0120	40								
eR12	24987734	11	5	1	1	2200	40	690	316	175	61	50	008
	150	250	125	0284	31								
er13	25007736	11	5	1	1	2200	75	792	115	150	37	25	010
	127	250	125	0227	27								
ER14	25147719	11	3	1	2	2200	10	785	234	325	36	25	201
	61	125	75	0172	26								
ER15	25507720	11	6	1	2	1600	30	366	489	2725	10	3000	7183
	8	150	300	0470	3								
ER16	25527722	11	6	1	2	1600	52	374	418	1050	22	325	247
	15	500	500	1150	2								
ER17	25597739	11	6	1	2	1600	45	396	610	2300	15	1700	1457
	23	150	175	0312	9								
ER18	24597762	11	1	1	1	2200	100	549	583	1950	17	1025	1284
	15	175	75	0137	5								
er19	24707773	11	5	1	1	2200	245	677	329	350	43	75	0022
	114	200	125	0153	30								
er20	24727774	11	5	1	1	2200	250	671	343	400	41	75	024
	99	175	150	0200	29								
ER21	24747775	11	5	1	1	2200	250	699	337	425	38	150	050
	122	250	125	0179	26								
ER22	24827769	11	1	1	1	2200	280	579	427	2000	12	1250	1654

```
38  425  375    0717  5

ER23 24837777 11 3 1 1 2200 260 635 0475   450  47   1000   2940
76  175  125   0160 23

CN71 30067991 55 3   1 2000 236  980  120   175  34   125   0140
60  200  100   0130 17

CN72 29127998 55 3   1 1800 180  570  440   550  39   125   0485
80  100  100   0380 37

CN73 29148002 55 3   1 1800 180  570  520   600  41   300   0810
80  275  225   0530 16

CN74 29128008 55 3   1 1800 176  600  430   500  41   450   0886
100  325  250   0485 17

CN75 29227999 55 1   1 1800 360  550  685   1775  21   750   16207
50  325  325   0453  9

CN76 30048004 55 3   1 2000 190  980  137   125  48   75   0070
40   75   75   0062 28

CN79 29738017 55 3   2 2000 355  860  240   325  36   0500   0200
60  150  100   0120 22

CN80 29708023 55 3   2 2000 320  840  160   275  30   0500   0105
70  150  100   014  25

CN81 29688030 55 5   2 2000 340  850  150   200  37   1000   0116
140  275  100   0290 27

CN82 29918099 55 5   2 2000 105 1000  111   175  32   0500   0070
80  225   75   0169 20

CN55 29038979 55 5   2 1800 192  830  170   150  49   050   0070
60  150   75   0060 22

CN56 29048980 55 5   2 2000 212  830  170   175  44   025   0034
50  200   75   0073 14

cn57 29048981 55 5   2 2000 240  830  170   250  34   025   0058
70  200   75   0075 19

CN58 29108983 55 3   2 2000 180  540  460   600  37   100   0025
40  100   75   0066 22

CN63 29167978 55 3   1 1800 360  600  380   425  42   200   0840
100  275  150   0062 20

CN64 29227979 55 5   1 1800  90  930   70   075  43   25   0557
60  200  100   0248 17

Cn65 29197993 55 1   1 2000  40  540  687   1725  22   1625   0230
40  225  225   0011 10
```

cn66 29477992 55 5 2 2000 270 1100 100 125 39 0025 0030
120 200 100 167 31

CN67 30017988 55 5 2 2000 205 1100 70 75 43 75 0026
150 300 75 0240 27

cn68 30027989 55 5 2 2000 208 1050 90 75 50 100 0031
150 300 75 0154 27

CN69 30037989 55 5 2 2000 220 1000 80 75 47 050 0413
120 200 75 0118 31

CN70 30057991 55 5 2 2000 232 980 90 100 42 050 0031
90 225 125 0056 22

CN83 29978032 55 5 1 2000 35 900 276 250 48 050 0080
60 200 100 0155 17

CN84 29338039 55 1 1 1600 31 500 282 2075 8 875 8150
60 550 650 0716 6

CN84 29688029 55 5 2 2000 337 850 150 125 50 05C 0065
120 200 100 018 31

CN85 29768010 55 3 2 2000 350 900 225 800 16 125 1050
80 225 125 0139 20

CN86 29308062 55 1 2 1800 78 360 936 11075 5 5800 13670
50 1750 1525 2411 2

CN87 29498056 55 1 201600 120 460 268 1950 9 1050 16014
40 150 125 0260 15

GC01 21527574 14 3 1 1 2800 265 160 780 105C 36 150 2188
63 330 300 560 11

GC02 21397563 41 1 1 1 2800 102 120 1021 205C 26 1175 18125
35 350 380 656 5

GC03 21657564 44 3 1 1 2800 90 160 490 725 34 100 250
30 90 110 0003 18

GC04 21377569 45 1 1 1 2800 275 125 842 1000 33 250 469
30 180 60 98 9

GC05 21637564 44 1 1 1 2800 140 175 940 2325 22 800 14063
61 330 155 230 15

GC07 21467573 44 3 1 1 2800 258 170 720 1050 34 175 0179
75 290 180 0036 15

GC08 21557575 44 3 1 1 2800 290 274 679 875 38 650. 4063
175 545 465 1400 18

GC09 21287569 44 3 1 1 2800 276 140 760 10750 35 750 0813
70 320 340 0497 12

GC17 21777566 44 3 1 1 2800 310 250 640 11000 30 1000 1300
70 300 75 144 13

GC18 21697570 44 3 1 1 2800 300 210 700 8000 41 4000 1300
80 300 150 263 15

GC19 21657572 44 3 1 1 2800 240 250 693 8000 52 23000 1200
100 375 225 425 15

GC20 21557566 44 3 1 1 2800 90 150 690 7000 45 2000 875
70 150 200 188 25

GC21 21517564 44 3 1 1 2800 70 180 700 5000 54 3000 125
100 250 300 575 21

GC22 21367562 44 2 1 1 2800 50 180 660 10500 32 1000 481
110 375 300 781 16

GC23 21357561 44 2 1 1 2800 60 180 660 8000 40 1000 500
80 300 125 344 15

GC24 22197552 44 3 1 1 2800 95 396 507 11000 25 5750 5000
107 575 500 11

ge01 21847512 54 2 1 1 3200 264 152 804 10500 37 3000 4813
52 178 144 270 16

ge02 21927514 54 2 3 1 3200 247 160 796 10000 39 2500 2938
46 300 300 54 9

ge03 21967515 54 2 3 1 3200 278 183 723 13000 29 4500 4219
62 355 344 51 10

ge04 22247522 54 1 1 1 3200 10 206 862 16250 28 15500 31250
30 225 300 20 8

ge05 21257452 55 3 1 1 3000 72 40 810 15000 28 6000 6560
35 180 120 108 11

ge06 21677505 51 1 2 1 3000 65 122 761 20000 21 11000 15660
61 360 510 88 10

ge07 21717514 44 1 2 1 3000 293 89 869 20000 23 17500 30940
22 470 300 102 3

ge08 22197522 54 3 1 1 3200 270 213 690 20000 19 8750 12820
38 225 75 125 10

ge09 22097520 54 3 1 1 3200 250 305 706 13000 28 6250 3750
150 625 300 875 14

ge10 21747506 24 3 1 1 3200 60 200 640 10500 32 3000 3063

110 300 375 1375 20

ge11 21597475 55 1 1 1 3000 280 110 735 1500 26 5000 5313
25 150 200 219 9

ge12 21487477 55 1 1 1 3000 30 40 1024 4625 12 31250 92500
20 200 250 313 6

ge13 21377458 55 1 1 1 3000 45 40 1038 3500 17 37500 87500
25 375 375 088 4

ge14 21197449 55 3 1 1 3000 50 50 700 875 39 4000 0094
45 200 75 009 13

ge15 21157442 55 3 1 1 3000 35 120 958 1700 29 9500 1000
120 500 575 156 13

os01 24187701 55 1 1 1 1800 12 369 779 6750 7 30000 240625
23 450 575 0819 3

gn01 21427684 12 1 1 1 3200 105 70 869 2950 16 20000 33125
30 200 250 35 9

gn02 21237696 12 3 1 1 2400 80 230 236 950 14 3500 2181
30 100 100 0094 9

gn03 21347661 12 3 1 1 3200 70 490 427 725 30 2000 656
30 75 100 63 22

gn04 21497668 12 3 1 1 3200 135 350 400 550 36 750 500
50 150 125 138 18

gn05 21497666 12 3 1 1 3200 140 400 400 500 39 1250 519
70 175 100 150 22

gn06 21557660 12 3 1 1 3200 20 520 481 850 30 3750 1813
50 100 75 75 27

gn07 21427699 52 3 1 1 3600 340 120 880 1100 67 2750 1500
70 300 100 313 23

gn08 21437698 52 3 1 1 3600 320 100 920 1250 63 1000 1156
60 300 150 313 20

gn09 21817668 22 3 1 1 2800 2 550 432 550 38 3750 2031
50 200 200 375 14

gn10 21807683 22 1 1 1 2800 90 250 751 3250 13 20000 47500
20 125 200 169 9

gn11 21837683 51 3 1 1 2800 80 270 630 950 34 5000 1875
50 200 300 250 14

gn12 21887689 51 1 1 1 2800 270 240 994 3250 17 17500 64375
20 250 250 313 5

GN14	21387706	55	1	1	1	2800	330	150	1050	18500	30	5000	5469
120	650	400	01481	10									
GN15	21337715	55	1	1	1	2800	330	50	1100	23000	25	8060	11875
30	300	175	00375	6									
bn01	21637722	55	5	1	1	3600	170	850	364	3000	51	1500	0906
60	150	100	00175	22									

(DOMINANT PROCESS)
GROUP : 1,6,7,8 & 9:ALLUVIAL 2 & 3:DEBRIS FLOW 5:ROCKFALL

Derivation of variables is described in section 6.2, chapter 6.

RECORD 1
- SITE : an arbitary reference number
- NGR : National Grid Reference
- GEN : number of major morphological phases visible on the fan or cone surface (not analysed in the thesis).
- GROUP: dominant process (see above)
- GL : relation to the Loch Lomond Stadial glacial limits. 1: inside, 2: outside. (NB these values are not the same as in the suplimentary data set, appendix 3.
- PPT : mean annual precipitation, mm.
- ASP : medial fan or cone aspect, measured in degrees from west (0), in a clockwise direction.
- ALT : altitude of the fan or cone apex, m O.D.
- BH : basin height, m.
- BL : basin length, m.
- BGRAD: basin gradient, in degrees.
- BW : basin width, m.
- BA : basin area, m^2

RECORD 2
- FH : fan height, m.
- FL : fan length, m.
- FW : fan width, m.
- FA : fan area, m^2.
- FGRAD: fan gradient, in degrees.

APPENDIX 3

SUPPL~~I~~EMENTARY DATA SET:

CHAPTER 6

site	NGR	LITH	GROUP	gl	ppt	asp	alt
GS01	31137704	11	1	0	1400	270	350
GS02	30907707	11	1	0	1600	150	400
GS03	30917718	11	1	0	1600	340	400
GS04	30917725	11	1	0	1600	330	400
GS05	31287734	11	1	1	1600	350	400
GS06	31277739	11	1	1	1600	230	400
GS07	31407755	11	1	1	1600	50	480
GS08	31437819	11	1	0	1600	330	500
GS09	31407825	11	2	0	1600	340	500
GS10	31437829	11	2	0	1600	330	450
GS11	31427832	11	1	1	1600	40	440
GS12	31207801	11	1	1	1600	40	500
GS13	31217811	11	1	1	1600	200	500
GS14	31297829	11	1	1	1600	200	450
GS15	31357837	11	1	0	1400	180	420
GS21	29817782	11	1	0	1400	50	380
GS22	29847790	11	3	0	1400	330	500
GS23	30027801	11	1	1	1600	250	550
GS24	29257790	11	1	0	1600	200	560
GS25	29867736	11	2	1	1400	180	500
GS26	30797769	11	1	1	1600	300	500

GS31	32387770	14	2	1	1600	130	650
GS32	32397769	14	2	1	1600	135	650
GS33	32507769	14	2	1	1600	340	500
GS34	32457751	14	3	1	1600	200	550
GS35	32447755	14	3	1	1600	270	550
GS36	32857750	44	2	0	1400	130	300
GS37	32897748	44	2	0	1400	130	300
GS38	32937744	44	2	0	1400	120	270
GS39	32947744	44	2	0	1400	120	310
GS40	32957742	44	2	0	1400	130	290
GS41	32967741	44	2	0	1400	120	300
GS42	32847779	44	1	1	1400	310	310
GS46	32687794	44	2	1	1400	260	390
GS47	32697795	44	2	1	1400	270	390
GS48	32777794	44	2	1	1400	283	390
FB01	28528043	11	1	0	900	80	251
FB02	28627954	14	1	0	1400	20	450
FB03	28507934	14	1	0	1400	10	400
FB04	28507970	14	1	0	1400	360	360
CN01	30977983	55	2	0	1400	360	950
CN02	30967989	55	3	0	1400	295	1000
CN03	30017989	55	3	0	1800	290	****
CN04	30007989	55	3	0	1800	290	****
CN06	30367987	55	1	0	1600	140	330
CN07	30347973	55	1	0	1600	15	180
CN09	29537982	55	2	0	2000	270	900
CN10	29647977	55	3	0	2000	225	1000

CN11	29637976	55	3	0	2000	220	1000
CN12	29617974	55	3	0	2000	255	1050
CN13	29427978	55	2	0	2000	100	1000
CN14	29457977	55	3	0	2000	90	1050
CN15	29457985	55	3	0	2000	140	1000
CN16	29447988	55	3	0	2000	210	1000
CN17	29447989	55	3	0	2000	180	1050
CN18	29457989	55	3	0	2000	270	1050
CN19	29557992	55	3	0	2000	140	1050
CN20	29567994	55	3	0	2000	140	1050
CN21	29577998	55	3	0	2000	210	1150
CN24	29467959	55	1	0	1800	35	900
CN25	29637967	55	3	0	2000	200	1000
CN26	29657964	55	3	0	2000	125	1000
CN27	29957965	55	2	0	2000	155	690
CN28	29977962	55	2	0	2000	145	670
CN29	29997961	55	2	0	2000	150	670
CN30	30117958	55	1	0	2000	290	570
CN31	30347981	55	1	0	1600	30	550
CN32	30357982	55	1	0	1600	30	550
CN05	30007980	55	3	0	1800	300	1000
CN31	29857979	55	2	0	2000	300	700
CN32	29797980	55	2	0	2000	330	650
CN33	29767975	55	2	0	2000	165	610
CN34	29777974	55	2	0	2000	170	610
CN35	29867965	55	2	0	2000	340	550
CN36	29867961	55	2	0	2000	340	550
CN37	29877959	55	2	0	2000	360	530

CN38	29877958	55	2	0	2000	360	530
CN39	29877957	55	2	0	2000	360	530
CN40	29877955	55	2	0	2000	360	530
CN41	29877953	55	2	0	2000	170	600
CN42	29887952	55	2	0	2000	360	560
CN43	29957975	55	2	0	2000	330	650
CN44	30028019	55	2	1	2000	270	800
CN45	30008020	55	2	1	2000	260	850
CN46	30008015	55	2	1	2000	120	850
CN94	30288081	55	1	0	1600	40	540
CN95	30158088	55	3	0	1600	270	700
CN96	30168088	55	3	0	1600	270	700
CN97	30178088	55	3	0	1600	275	700
CN98	30188087	55	3	0	1600	300	680
CN99	30318092	55	1	0	1400	15	520
CG01	30318096	55	1	0	1400	360	510
CN71	30067991	55	2	1	2000	236	980
CN72	29127998	55	2	1	1800	180	570
CN73	29148002	55	2	1	1800	180	570
CN74	29128008	55	2	1	1800	176	600
CN75	29227999	55	1	1	1800	360	550
CN76	30048004	55	2	1	2000	190	980
CN77	30957999	55	2	0	1600	150	950
CN78	30967997	55	3	0	1600	160	950
CN79	29738017	55	2	0	2000	355	860
CN80	29708023	55	2	0	2000	320	840
CN81	29688030	55	3	0	2000	340	850

CN82	29918099	55	3	0	2000	105	1000
CN47	30018012	55	3	1	2000	100	870
CN48	30208016	55	3	1	2000	70	850
CN49	30198017	55	3	1	2000	65	850
CN50	30188018	55	3	1	2000	55	850
CN51	30208023	55	1	1	2000	225	750
CN52	30158021	55	1	1	2000	70	750
CN53	30378018	55	1	1	2000	25	710
CN54	30378017	55	1	1	2000	55	710
CN55	29038979	55	3	0	1800	192	830
CN56	29048980	55	3	0	2000	212	830
CN57	29048981	55	3	0	2000	240	830
CN58	29108983	55	2	0	2000	180	540
CN59	29107985	55	2	1	1800	200	540
CN60	29117987	55	2	1	1800	180	540
CN61	29117988	55	2	1	1800	200	540
CN62	29137996	55	2	1	1800	190	550
CN63	29167978	55	2	1	1800	360	600
CN64	29227979	55	3	1	1800	90	930
CN65	29197993	55	1	1	2000	40	540
CN66	29477992	55	3	0	2000	270	1100
CN67	30017988	55	3	0	2000	205	1100
CN68	30027989	55	3	0	2000	208	1050
CN69	30037989	55	3	0	2000	220	1000
CN70	30057991	55	3	0	2000	232	980
CN83	29978032	55	3	1	2000	35	900
CN84	29338039	55	1	1	1600	31	500
CN84	29688029	55	3	0	2000	337	850

CN85	29768010	55	2	0	2000	350	900
CN86	29308062	55	1	0	1800	78	360
CN87	29498056	55	1	0	1600	120	460
CN88	29838087	55	1	0	2000	100	350
CN89	30038077	55	1	0	1800	35	540
CN90	30048080	55	1	0	1800	360	550
CN91	30278068	55	2	0	1800	360	600
CN93	30228080	55	1	0	1600	220	520

(DOMINANT PROCESS)

GROUP 1:ALLUVIAL 2:DEBRIS FLOW 3:ROCKFALL

Derivation of variables is discussed in section 6.2, chapter 6.

SITE : an arbitary reference number.
NGR : National Grid Refrernce.
GROUP : dominant process group, (see above).
GL : relation to the Loch Lomond Stadial glacial limits, 1: inside, 2: outside.
PPT : mean annual precipitation, mm.
ASP : medial fan or cone aspect, measured in degrees from west (0), in a clockwise direction.
ALT : altitude of the fan or cone apex, m.