THE LAST GLACIERS IN WESTERN PERTHSHIRE.

Kenneth S. R. Thompson.

Thesis submitted to the University of Edinburgh
for the degree of Doctor of Philosophy.
1972.

It is declared that this thesis is solely the work of the undersigned.

Kenneth S.R. Thompson. May, 1972.

SUMMARY.

The principal aim of the work described in this thesis was to discover the extent of the last stage of glaciation in the western part of Highland Perthshire.

After preparatory stereoscopic study of aerial photographs, an area of 450 sq. km in Glen Lyon and southern Rannoch Moor was mapped at the 1:10,560 scale and subsequently another 2250 sq. km were mapped at the 1:63,360 scale. Features of special interest, such as outwash terraces and the lake terraces or 'Parallel Roads' of Loch Tulla, were mapped in greater detail and instrumentally levelled.

Particular attention was paid to the character and extent of fresh hummocky drift, described by earlier workers as 'hummocky moraine' and thought to belong to a distinct period of glaciation. From examination of the pattern of this hummocky drift and of the constituent sediments it was concluded that the features are basically kames that are often thickly covered with ablation moraine.

Eight major valley systems were studied. They include Glen Garry - Glen Errochty, the Loch Rannoch - Loch Tummel valley, Glen Lyon, the Loch Tay valley, Glen Almond, Glen Artney, Loch Voil - Loch Earn and the Trossachs - Teith valleys, in addition to part of Rannoch Moor. The evidence of fresh glacial deposits in these valleys indicates that a system of glaciers existed in the area during the last stage of glaciation.

By discussing the valley systems in turn and regarding each as a case that can be justified independently of the others, it is concluded for three reasons that the last

glaciers in each area existed during the same lateglacial period. Firstly, there is one clear down-valley limit to the fresh hummocky drift in each valley system. Secondly, with the exception of the isolated Glen Almond area, the spread of moundy drift continues from one valley system to the next via interconnecting valleys. Thirdly, the pattern of glaciers inferred from the evidence appears to be inherently probable.

There are five principal reasons for concluding that these glaciers existed during pollen Zone III. Sediments from present or former lakes just outside the limit of the last Glen Almond glacier and just outside the terminal moraine of the last Teith glacier contain pollen from much of the Lateglacial, including the interstadial preceding Zone III, but the earliest deposits found immediately inside the Teith moraine belong to the Postglacial. Secondly, the Teith terminal moraine occupies a position at the mouth of a Highland valley analogous to those of the neighbouring Menteith and Loch Lomond terminal moraines that were dated by pollen and radiocarbon analyses as having been formed in Zone III. Thirdly, a suite of outwash terraces formed beyond the Teith moraine passes into a buried fan that was largely deposited during a period of low sea-level when the adjacent Menteith moraine was being formed, that is in Zone III. Fourthly, whereas the largest glaciers in the thesis area advanced eastwards from the west Highland watershed area, other major glaciers flowed westwards from this watershed to the western coast. It is generally considered on morphological evidence that the glaciers that terminated at Benderloch, Loch Leven, Loch

Linnhe, Loch Shiel and Loch Morar represented the Loch Lomond Readvance in Zone III, whilst radiocarbon dating of organic material proves that the Benderloch glaciers existed during Zone III. Fifthly, it seems entirely logical to expect that the limits in the Highland part of western Perthshire that do not happen to have been independently dated by pollen studies should have been formed in the same period as those that have been dated.

It is concluded that the last valley glaciers in western Perthshire were part of the Loch Lomond Readvance that is correctly correlated with pollen Zone III.

PREFACE.

The author wishes to record his sincere gratitude to Dr. J.B. Sissons, whose enthusiasm and guidance have been invaluable at every stage in the preparation of this thesis. He also wishes to thank Dr. J.A.T. Young and Dr. R.P. Kirby whose advice was of great service in the solution of a range of problems. Mr J.J. Lowe has devoted his energies to the investigation of late - and postglacial deposits relevant to this thesis and has generously made his results available. Samples of these deposits were collected in the field with the assistance of Dr. W.W. Newey, Dr. J.B. Sissons, Mr G.M. Gow, Mr J.M. Gray and Mr J.J. Lowe. The author's wife and Miss M. Jackes were indispensable levelling assistants.

Several institutions have permitted the author access to unpublished documents. The Institute of Geological Sciences, the Macaulay Institute for soil research and the Meteorological Office made available numerous maps. The North of Scotland Hydro-Electric Board, Sir M. MacDonald & Partners, Messrs. Babtie, Shaw & Morton, Messrs. James Williamson & Partners, and Mr Robert H. Cuthbertson allowed the author to study civil engineering drawings. The Ordnance Survey gave permission for 1:10,560 maps to be photographically reproduced at a reduced scale.

Dr. M.R.W. Johnson and Dr. K.R. Gill of Edinburgh University Department of Geology kindly identified samples of Rannoch Moor granite. Mr R. Carson Clark and Mr R. Harris gave their advice on cartographic matters, and Mr. R. Gillanders and Mr. I. Mackay undertook the considerable amount of cartographic reproduction involved in this thesis. The author is indebted to all of the above for their assistance, as well as to the following for the provision of photographs: the Ordnance Survey, the Institute of Geological Sciences, Dr. J.K.S. St. Joseph, the North of Scotland Hydro-Electric Board, Planair, and the Ministry of Defence (Air Force Department). Officials of the Scottish Development Department courteously tolerated the author's protracted study of aerial photographs. Lastly, it is acknowledged that the very generous provision of a research studentship by the Natural Environment Research Council was paramount in permitting the author to undertake this study.

Contents.

Illustrations.

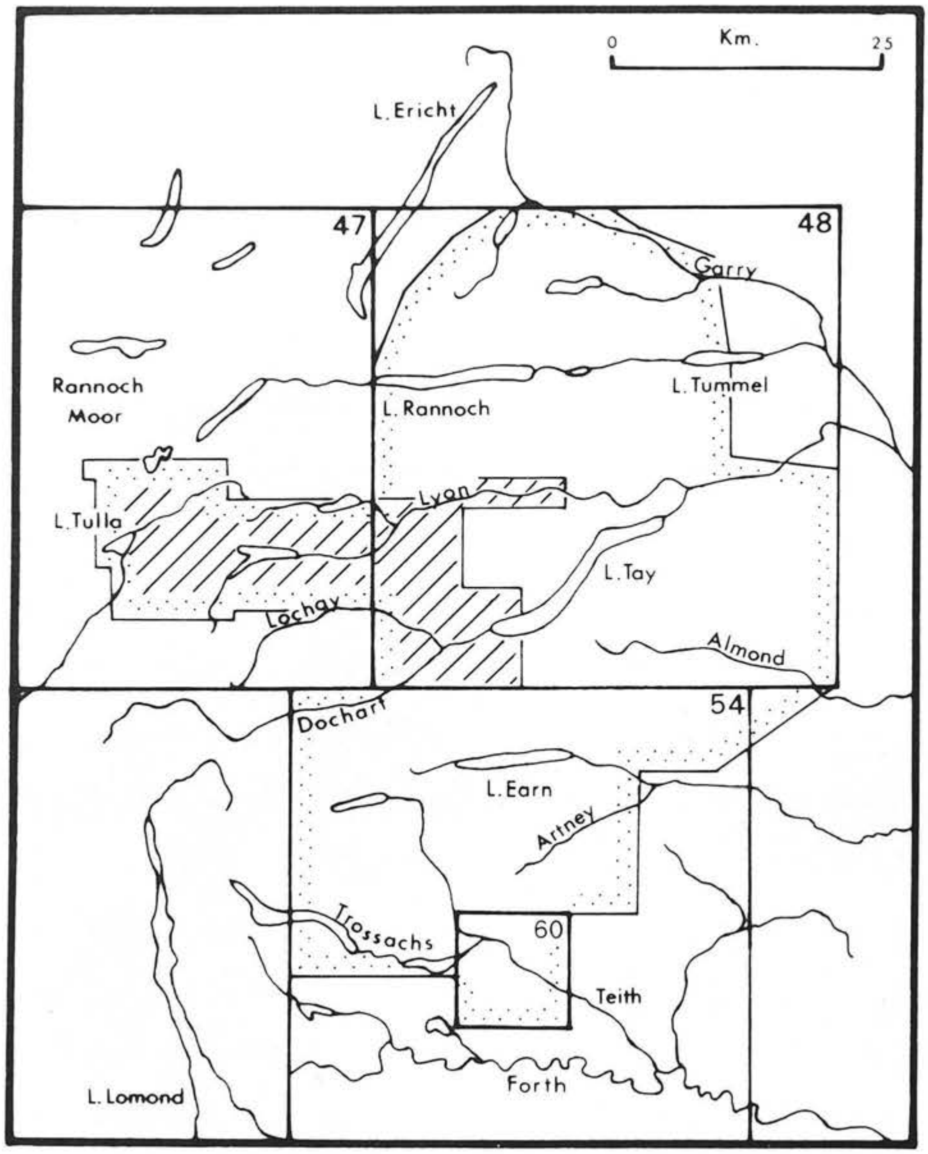


Fig. 1.1 EXTENT OF THE THESIS AREA

O.S. 1:25,000 and 1:63,360 MAP SHEETS.

Margin of the thesis area.

Area mapped at the scale of 1:10,560.

Chapter 1. INTRODUCTION.

At its inception it was decided that the principal aim of the work described in this thesis should be to attempt to discover the extent of the last stage of glaciation in the western part of Perthshire. Much of the area had already been mapped by officers of the Geological Survey when much less was known about glaciers and glacial landforms than is now the case. However, the existence of interesting features in the area was apparent from the Survey memoirs. More recent sample studies by J.B. Sissons (1967a) confirmed that evidence of the former existence of valley glaciers during lateglacial time could be found in western Perthshire.

It has long been believed that the principal centre of ice accumulation within the western Highlands was located in the Rannoch Moor district (B.N. Peach and J. Horne, 1910) (fig.1.1). Furthermore, the evidence of glacial erratics in this district (E.B. Bailey et al., 1916; L.W. Hinxman et al., 1923) was believed to indicate that the last stage of glaciation in this area involved valley glaciers that had their sources in the hills surrounding Rannoch Moor. Accordingly, the first area selected by the author for study was Glen Lyon (fig.1.1). The head of Glen Lyon is ringed by high hills, some of which border the south-eastern part of Rannoch Moor. As the present precipitation on these hills exceeds 100 inches (2500 mm), it was expected that lateglacial precipitation would have been more than adequate for glacial formation during this last stage when the main concentration of glaciers is thought to have been in the western Highlands (Sissons, 1967a, fig.59).

With these guidelines in mind, the stereoscopic examination of aerial photographs was undertaken, commencing with the head of Glen Lyon, where glaciers might be expected to have had their sources, and proceeding eastwards along the valley system. The purpose was to identify the areas occupied by a given type of landform and to label the area according to a morphological classification specially developed during the study. This classification relies largely on visual images and it assumes that landforms of a particular type tend to have a very similar appearance that contrasts with the appearances of landforms of different types. For example, an area of bedrock knobs partially covered with an irregular mantle of drift normally appears on aerial photographs to have a rough, less regular 'texture' than an area of fresh moundy drift. The classification also assumes that landforms of different types tend to occur in different sorts of localities. For example, because drift is unable to rest on slopes steeper than the angle of rest for the drift, hummocky drift is found only on the gentler slopes. Particular attention was paid to identification of glacial deposits. (The landform classification is discussed at the end of this chapter.)

The information gained from the photographs (at a scale of c.1:10,000) was transferred to 1:10,560 maps, each of which was thoroughly checked in the field. Approximately 450 sq.km, including southern Rannoch Moor, Glen Lyon, lower Glen Lochay, lower Glen Dochart and neighbouring parts of the Loch Tay valley were covered (fig.1.1). This work revealed that there is a distinct down-valley limit to the fresh hummocky drift in each valley system, beyond which such drift is absent. The evidence appeared to be the result of one particular stage of glaciation that could be expected also to have occurred in neighbouring valley systems. Accordingly the thesis area was extended northwards, eastwards, southwards and, to a small extent, westwards in order to gain a much wider knowledge of the extent of the fresh hummocky drift. Approximately 2850 sq.km were studied on aerial photographs and the information transferred to 1:63,360 map sheets according to a revised landform classification. (fig.1.6 shows the symbols used on 1:63,360 sheets 47, 48 and 54). This concentrates on hummocky drift, whose extent is shown as accurately as possible, while the areas occupied by most other types of landform are not precisely delimited. It is this system that is used in most of the maps now presented. For convenience, the area originally studied by means of 1:10,560 scale maps is also shown in this thesis at the 1:63,360 scale. However, specimens of the large-scale mapping have been included (at a reduced scale of 1:25,000 which is more easily handled) in order to illustrate the more elaborate landform classification (figs.1.2,1.3; fig.1.5 lists the symbols used).

80% of the 2850 sq.km are regarded as lying within the thesis area. The remaining 20% (c.600 sq.km), including upper Glen Lochay and Glen Orchy (sheet 47), upper Glen Dochart and Strath Fillan (sheets 47, 48 and 54), and parts of the south-eastern border of the Highlands (mainly to the east of Callander, sheet 54), have been excluded. The latter area was found to lie too far outside the limits of the last stage of glaciation in this part of Scotland and the others, though well within the limits of this stage, could not be studied in the time available and would probably not have added much to the value of the thesis.

During the aerial photograph interpretation it became apparent that the characteristically fresh hummocky topography, already known from fieldwork in the area, is quite widespread and has a clear down-valley limit in several valley systems. Almost as large an area was examined outside these limits as inside them in order to be quite certain of the true extent of these hummocks. Field checking concentrated on the limits of hummocky drift, on particular features of interest (such as the Loch Rannoch lateral moraines), on features whose nature was not quite clear on aerial photographs, and on sizeable drift exposures. More detailed mapping and instrumental levelling of landforms associated with two former glacier limits (at Callander and at Kinloch Rannoch) and of the Parallel Roads of Loch Tulla were also carried out.

The description and interpretation of the landforms are presented in twelve chapters, nine of which are concerned with the major valley systems and three of which are thematic studies of the area as a whole. As each valley system is dealt with separately, there is a degree of repetition in reviewing the literature on each. The conclusions about the lateglacial sequence in a given valley system are based largely on the evidence in the particular valleys. However, when reference is made to the conclusions reached in each of the other valley systems, it will become apparent that there is a coherent pattern of limits throughout the thesis area. This pattern is discussed in the last chapter where the principal propositions of the thesis are set out.

A number of principles are followed in the interpretation of the evidence. Geomorphological phenomena in general and in the thesis area appear to form logical coherent patterns in consequence of the factors that govern their formation. Accordingly a given type of evidence is interpreted throughout the area in a consistent manner. For example, the down-valley termination of fresh, abundant hummocky drift is held to correspond more or less with the down-valley limit of the last glacier to occupy that valley. The explanation proferred for the evidence in a locality is in general the simplest one that appears to accord with the evidence. Several explanations may come to mind in a given instance but usually only the one that explains the greatest amount of evidence most satisfactorily is presented. Unless alternative explanations are equally reasonable, they are for the most part avoided because detailed discussion of them might unnecessarily confuse the reader. It seemed preferable to try to give a clear account of the glacier sequence in each valley system and to combine all such accounts within a coherent pattern for the whole thesis area.

There are various minor limitations inherent in the maps presented in this thesis that should be borne in mind, quite apart from the fallibility of the author. The landforms were first identified on aerial photographs whose scale is approximately 1:10,000. This scale varies according to the height above the ground at which the photographs were taken, and to the degrees of tip and tilt of the aircraft in which the survey camera was mounted. Scale also varies with the distance of a given point from the centre of the photograph and with the range of ground relief represented on the photograph. During the earlier part of the study, information was transferred by visual estimation to 1:10,560 maps. Where these are Regular Edition contoured maps (upper Glen Lyon and southern Rannoch Moor) this was accurate. However, the bulk of the 450 sq.km investigated at this scale is shown on first or second edition maps where only field boundaries and a proportion of streams could serve as a guide to locating morphological information. Every effort was made to maintain accuracy here. When information was transferred to 1:63,360 maps the accuracy here and in the field was necessarily reduced. Nevertheless the errors discovered during field checking seemed to result from faulty interpretation rather than from errors of scaling-down in transfer.

The contoured Ordnance Survey base maps are of course generally reliable. Only a few errors were discovered in them. For example, in square 3836 (sheet 47) a relatively gently sloping area is shown 300 feet (90m) higher on the 1:63,360 sheet than on the corresponding and more recent 1:10,560 sheet. Again, the spot heights on summits in this area differ on the two maps. Such errors cannot normally be identified owing to the absence of highly accurate 1:10,560 maps for most of the area, and so the 1:63,360 maps have to be assumed correct. The striations marked on the maps in the thesis are mostly, though not wholly, derived from Geological Survey maps. Some were first edition 1:10,560 maps, on which positioning of features in the field could not always be done accurately by the Survey officers. Other striations were taken from old 1:63,360 maps, whose map projection differs from the Transverse Mercator of the modern maps in this thesis. Every effort was made to minimise the errors of location and map projection.

Throughout the discussion of the valley systems attention is focussed on a reconstruction of the presumed pattern of glaciers. This approach provides for more rigorous thinking and helps to identify the probable sources, upper surfaces and termini of the glaciers. In a number of cases where the evidence could be regarded as ambiguous, it is of assistance in determining whether certain deposits were formed by valley glaciers of limited extent or by much more extensive ice probably of ice sheet dimensions.

A number of assumptions have been made in order to assess the ice surface levels. Firstly, and most importantly, the highest mounds along a short section of a valley side are held to represent the minimum level of the glacier at the locality at some stage of its existence.

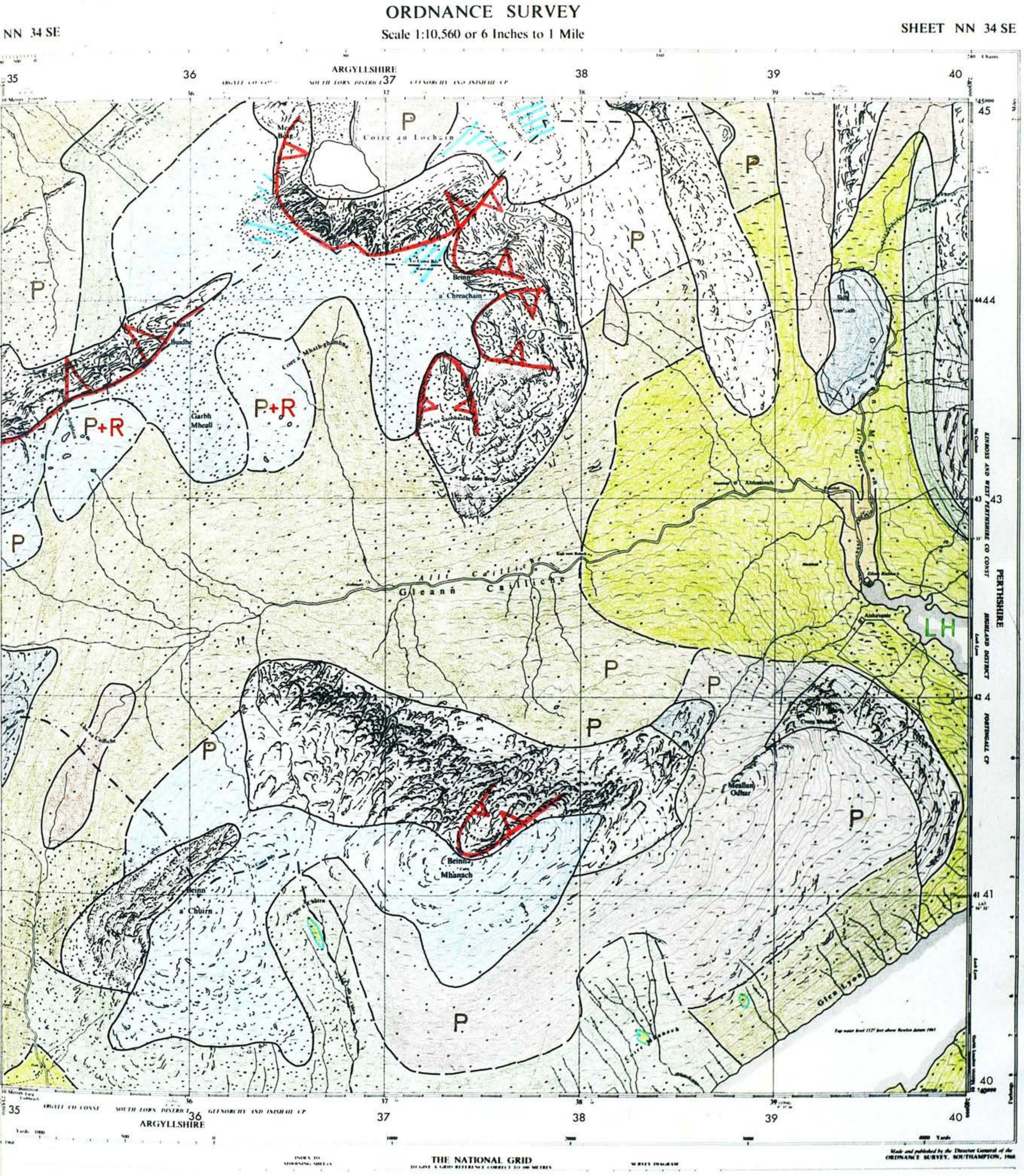
This is not to say that the ice surface could not at some time have been much higher. Nor does it imply that such minimum levels were everywhere synchronous. The upper limit of mounds along a valley side is greatly influenced by the angle of the slope, often rising and falling with the main concave break of slope along the valley side. However, in general the upper limit tends to decline down-valley. The second assumption is that minimum ice surface levels can be projected upwards up-valley. For example, where hummocky drift is well developed in the lower parts of a valley but absent from the higher, unless there is evidence to the contrary it is presumed from the calculated minimum ice surface down-valley that ice was present farther up-valley. This assumption depends on the existence of a probable ice source somewhere up-valley, usually at the valley head.

Thirdly, for simplicity the surface level of the ice is considered to be the same on each side of the glacier. Fourthly, it is presumed that the addition of tributary glaciers to or outflow of diffluent glaciers from a trunk glacier would affect the surface level of the trunk glacier, other things being equal. Addition of tributary ice would, by increasing the volume of ice, tend to maintain the surface level of the trunk glacier and so to minimise the rate of decline of the surface.

Reduction of the trunk glacier volume by diffluent outflow would tend to cause the surface level to drop more rapidly, that is to steepen the surface gradient.

An implication of this fourth assumption is that, away from sources and termini, the trunk glacier in a valley

Fig.1.2



ORDNANCE SURVEY
Scale 1:10,560 or 6 Inches to 1 Mile
NN 34 SE
SHEET NN 34 SE
ARGYLLSHIRE
PERTHSHIRE
Coire an Lochain
Beinn a' Chreachain
Garbh Mheall
Gleann Cailliche
Allt Cailliche
Beinn a' Chuirn
Beinn Mhanach
Meall an Odhar
Glen Lyon
P
P+R
LH
THE NATIONAL GRID

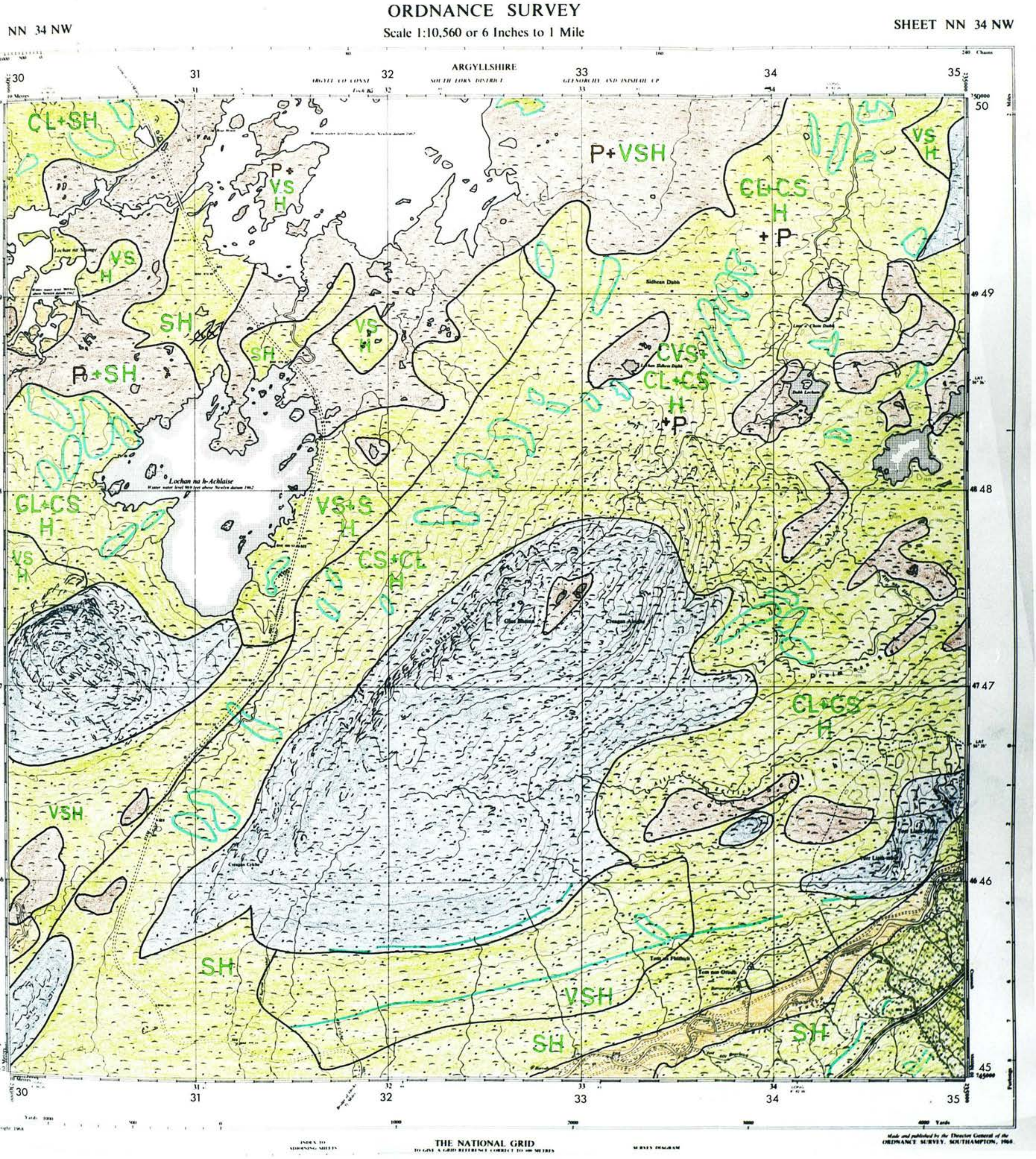
glacier system tends to have a gentler surface gradient than small isolated valley glaciers, other factors such as valley floor gradient being equal (chapter 13).

The fifth assumption is that, at the limits of their advance, the surface ice gradients tend to steepen in the terminal zone, as would be expected of an advancing glacier. The fourth and fifth assumptions about the surface gradients will be seen to be fully justified by the depositional evidence. The sixth is that the surface level of ice in the source area is usually assumed to have lain near, for example, the top of a corrie backwall. The steepness of the higher slopes in source areas does of course preclude the preservation of depositional evidence from which deductions could be made.

Lastly, in cases where there is poor evidence of ice in one valley but good evidence in its neighbour, it is assumed that glacier activity in each was similar, except at the margins of the area occupied by glaciers during the last stage of glaciation in western Perthshire. All these points are relevant to the interpretation of the three principal maps in this thesis, sheets 47, 48 and 54, and of the ice flow maps (figs. 13.1, 13.2) which are based upon them.

During the preparation of this thesis the gradual change from imperial to metric values was occurring. However, it was not found possible to dispense with the older system, simply because most of the discussion in the thesis concerns Ordnance Survey maps whose contours are numbered in feet. Accordingly the altitudes are given in feet with

Fig. 1.3



NN 34 NW
ORDNANCE SURVEY
Scale 1:10,560 or 6 Inches to 1 Mile
SHEET NN 34 NW
ARGYLLSHIRE
CL+SH
P+VSH
P+
VS
H
VS
H
CL+CS
H
+P
SH
SH
VS
H
P+SH
CVS+
CL+CS
H
+P
Lochan na h-Achlaise
GL+CS
H
VS+S
H
VS
H
CS+CL
H
CL+CS
H
VSH
SH
VSH
SH
SH
THE NATIONAL GRID

metric equivalents appended. All other measurements are metric, including metres and kilometres for distance, metres for thickness of deposits and degrees centigrade for temperature. Height values in feet derived from 1:63,360 maps are approximated to the nearest 50 feet and their metric equivalents to the nearest 5 metres. Many references to locations are given as four-figure grid references, none of which is duplicated anywhere in the thesis area.

A. Landform classification.

This subject was introduced at the beginning of this chapter where it was related to the range of fieldwork techniques employed. However, as this classification is entirely empirical and since the method of small-scale (1:63,360) mapping derives from it, a full explanation is needed. The system was used on first or second edition 1:10,560 sheets and on photographically-reduced Regular Edition 1:10,560 sheets. Two samples of the latter, at a scale of approximately 1:25,000 (fig.1.2, upper Glen Lyon; fig.1.3, south-western Rannoch Moor) are included. The system of symbols is shown on fig.1.5. None of the older 1:10,560 map sheets has been included because, owing to the absence of contours, the information on them had to be transferred to 1:63,360 sheets to facilitate interpretation (the key to the relevant symbols is fig.1.6).

The classifying of features depends on their appearance and, as far as possible, on their origin. For example, mounds of drift are grouped together, whatever their origin, but are distinguished from hummocks thought to consist principally of bedrock. The appearances of the two types may be similar but their natures are different (fig.1.4). The system of colours, greens for glacial deposits, greys for rock, blue for periglacial forms, and browns for peat and alluvium, is combined with letters or words that identify variations within these classes. The area covered by each class of feature was identified as precisely as possible, though complex boundaries too small to be drawn at the 1:25,000 scale were generalised. The aim was to bring out the principal element of the morphology. For exmaple, a slope might owe its configuration to bedrock influence but have a peat covering (fig.1.2, 3740-3941); here the rock is the main feature. On the other hand the morphology of a drift area may be completely obscured by peat, as in squares 3541 and 3944, so that peat is the dominant item. The use of qualifying terms helps to clarify intermediate cases. For example, in square 3844 peat patches obscure the bedrock, and in square 3544 peat veneers the smoothly sloping corrie floor; around point 3942 thin drift and peat patches occur; and in square 3643 there are peat patches between rock knobs that are masked with periglacial deposits.

The characteristics and significance of glacial and periglacial deposits are discussed in chapter 3.

B. Hummocky drift.

Mounds of drift are classified according to size, sharpness and sometimes by frequency. Normally most of the mounds in a given area are of similar size or range of sizes, or are mostly subdued or mostly fresh in appearance. Thus they are grouped as large, small, very small and occasionally

Fig. 1.4 Ben More and Loch Dochart.

Mounds of drift (h) just above the railway in the lower left corner of the photograph appear similar to the drift-plastered rock knobs higher up (r) that diversify the northern spur of Ben More. In the background to the right are the hills of the Loch Lomond district.

Photograph by Planair.

Fig. 1.4

very large hummocks. Particularly steep-sided mounds are described as 'clear'. Linear or unusually prominent mounds are outlined individually (the northern part of fig.1.3 contains many examples).

It should be noted that the size of mound refers to the amount of drift above the surrounding hollows and not to the total drift thickness which frequently cannot be assessed from photographs or in the field. The north-western part of fig.1.3 exemplifies this, for the very small size of many mounds (though not of all) is in part due to the thickness of peat partly burying them. On occasions mounds may be scattered across a gently undulating drift surface where the latter seems the dominant landform, as in square 3046 of fig.1.3. Squares 3145-3345 (fig.1.3) illustrate a difficult problem for here there is a transition between true moundy drift and rock knobs thinly covered with debris. Unlike the area of square 3348 there are no rock outcrops to clarify the issue. During the preparatory study of aerial photographs identification of rock-cored mounds is helped by rock drawings on the Regular Edition maps, though final identification is made by field examination.

C. Drift-covered slopes.

Hillslopes too steep to support moundy drift are often smoothly covered with drift. Provided that the bedrock is well concealed or crops out only occasionally, such slopes are classified according to the frequency of stream gullies. Gullied drift slopes, as in squares 3540-3840 (fig.1.2), contain numerous gullies, most of which operate only during heavy rainstorms. Descending from the crest of a slope it

Fig. 1.5 Symbols on figs. 1.2 and 1.3

- H — Hummocky drift
- Gullied drift
- Smooth drift
- Drift-plastered rock
- R — Bedrock at or near the surface
- Periglacial features
- Alluvium
- P — Peat
- Corrie
- Striation
- Roche moutonnée
- VS — very small
- S — small
- L — large
- C — clear

(VS, S, L, C: sizes of mounds)

- Periglacial terraces
- Parallel Roads of Loch Tulla

is apparent that gullies begin either where the drift mantle starts, or where coarse periglacial debris give way to finer materials that have moved or been carried downslope, or at a distance down from the watershed where there is a concentration of water sufficient to form a stream. Slopes of relatively smooth drift may be as steep as gullied drift slopes but lack gullies (e.g. square 3940, fig.1.2), or may be much gentler, as in squares 3542-3742.

As the drift thins, so the influence of bedrock becomes more evident. Thus the drift slope categories grade into bedrock-dominated types of slope. For example, on fig.1.4 (Ben More and Loch Dochart, sheet 54) the mounds of drift just above the railway on the left side of the photograph appear similar to the drift-plastered rock knobs higher up above the wood.

D. Rock-dominated slopes.

Fig.1.2 shows the range of rock-dominated slopes. In squares 3740-3941 the drift-mantle dies away upslope until bedrock lies at or near the surface, with only occasional patches of peat or drift. Where there are numerous rock outcrops (3146-3347, fig.1.3) or a few substantial outcrops, with intervening pockets or a veneer of drift, the feature is described as drift-plastered rock (fig.1.4). This grades into crags or cliffs of rock, which are shown by rock drawing on fig.1.2. Corrie walls are marked diagramatically because their precise form is already brought out by rock drawing.

Fig.1.6 Symbols on 1:63,360 sheets 47, 48 and 54.

	Large area } of hummocks } Hummocky drift of the last glacial stage
H	Very small area } of hummocks } Hummocky drift of the last glacial stage
	'Controlled' hummocks } Hummocky drift of the last glacial stage
GH	Gullied hummocks } Hummocky drift of the last glacial stage
LM	Lateral moraine } Hummocky drift of the last glacial stage
	Esker } Hummocky drift of the last glacial stage
	Linear mound
RCH	Rock-cored hummocks
H	Hummocky drift of the last ice sheet
D	Drift sheet
D	Upper limit of exposed drift
R	Rock at or near the surface
LS	Landslide
P	Periglacial features
P	Peat
~	Alluvium and outwash
∴∵	Prominent boulders
	Meltwater channel
	Incised stream
G G	Stream engorged in bedrock
→	Striation
	Roche moutonnée
?	Feature of uncertain origin
———	clear } boundaries
— — —	probable } boundaries
....	possible } boundaries
★	Site of stratigraphic investigation
) (	Cols around Loch Tulla
	Inferred ice margin

E. Periglacial landforms.

Normally the c.1:10,000 scale of the available aerial photographs is too small for other than major periglacial landforms to be identified. These are blockfields and solifluction sheets. No attempt was made to identify smaller forms, such as lobes, terraces and stone streams, for the aim of the research was investigation of glacial features. Solifluction terraces are represented only where obvious on photographs (3644-3744, fig.1.2).

F. Alluvium.

Flood plain and terrace deposits are grouped as alluvium except on the separate maps of the Loch Rannoch and Teith glacier outwash spreads (chapters 5 and 12).

G. Peat.

Surface peat coverings are common on drift, rock or periglacial features. However, the landform is described as peat only when other forms are obscured or peat hag is so eroded that, on aerial photographs, it resembles moundy drift (e.g. square 3944, fig.1.2).

H. Other features.

Landslides, groups of prominent boulders, including boulder trains and blockfields, meltwater channels, rock bars, roches moutonnées and striations (observed in the field) are marked individually. (Not all of these occur in the areas shown on figs.1.2 and 1.3).

Chapter 2. Previous Literature.

The purpose of this chapter is to outline the nature of the published literature that deals with the thesis area in whole or in part. Only the contributions that discuss the glacial sequence within this area will be considered in detail. The remaining items will be treated more fully in the chapters to which they particularly relate. The topics covered by the various papers include (A) the lateglacial sequence, (B) the positions of neighbouring lateglacial ice limits, (C) the dating of known limits, (D) the Geological Survey memoirs, and (E) other glacial landforms. Each of these topics will be discussed separately. Lateglacial climate will be reviewed in chapter 13.

A. The Lateglacial sequence.

In 1840 Louis Agassiz published the first paper that recognised that glaciers had once existed in Scotland. As in Switzerland he found striations, polished rock, erratics and moraines which he believed must have been produced in the same way in both countries by valley glaciers and ice sheets. Other investigators, notably W. Buckland (1840, 1842) and J.D. Forbes (1845) followed Agassiz. Buckland described moraines and abraded rock in many parts of western Perthshire. Forbes studied the Cuillins of Skye and, like Buckland, was able to demonstrate the directions of motion of former valley glaciers. C. Maclaren (1849), by concentrating on striations and roches moutonnées in the Southern Highlands, was able to show that there had been a radial movement of glaciers outwards from the present West Highland watershed. However he felt unable to believe that the striations on the

Pentland Hills near Edinburgh could have been produced by an ice sheet such as Agassiz had envisaged. Instead he relied on the more traditional theory of a great flood that had submerged even the hills, carried drift and boulders, and scraped the ground with these.

Not until 1853 did R. Chambers disprove the notion of the great flood when he presented much more evidence from many parts of Scotland. He noted the parallelism of crag-and-tail and ice-moulded rock in the Lothians, the consistent west-east alignment of these and striations in the Forth Valley, the evidence for severe glacial erosion in the North-West Highlands, and the criss-crossing or contrary directions of striations in this area. He argued that the similarity of these forms in Highland and Lowland Scotland, their frequent disregard of the alignment or presence of valleys, and the sheer force required tocreate them proved that glacier ice had been responsible throughout. In Assynt the striations on the ridges showed that ice had submerged them and moved obliquely across them, whereas the striations in the valleys showed that presumably later ice had moved along the valleys. Furthermore he often found that there could not have been any local ice accumulation centres that fitted with the pattern of striations. Consequently he proposed that there had been in Assynt a "general glaciation" of ice sheet proportions which had been succeeded by a more restricted valley glaciation.

Thereafter the work of A.C. Ramsay (1862), T.F. Jamieson (1862) and A. Geikie (1863) began a series of papers that reinforced the theory of glaciation in Scotland. James Geikie (1894), Sir Archibald Geikie (1901), Peter Macnair (1908) and W.B. Wright (1914) amongst others described numerous varieties and examples of glacial landforms, many of which lie within the thesis area. In particular they noted the existence of a distinctive type of glacial deposit within the

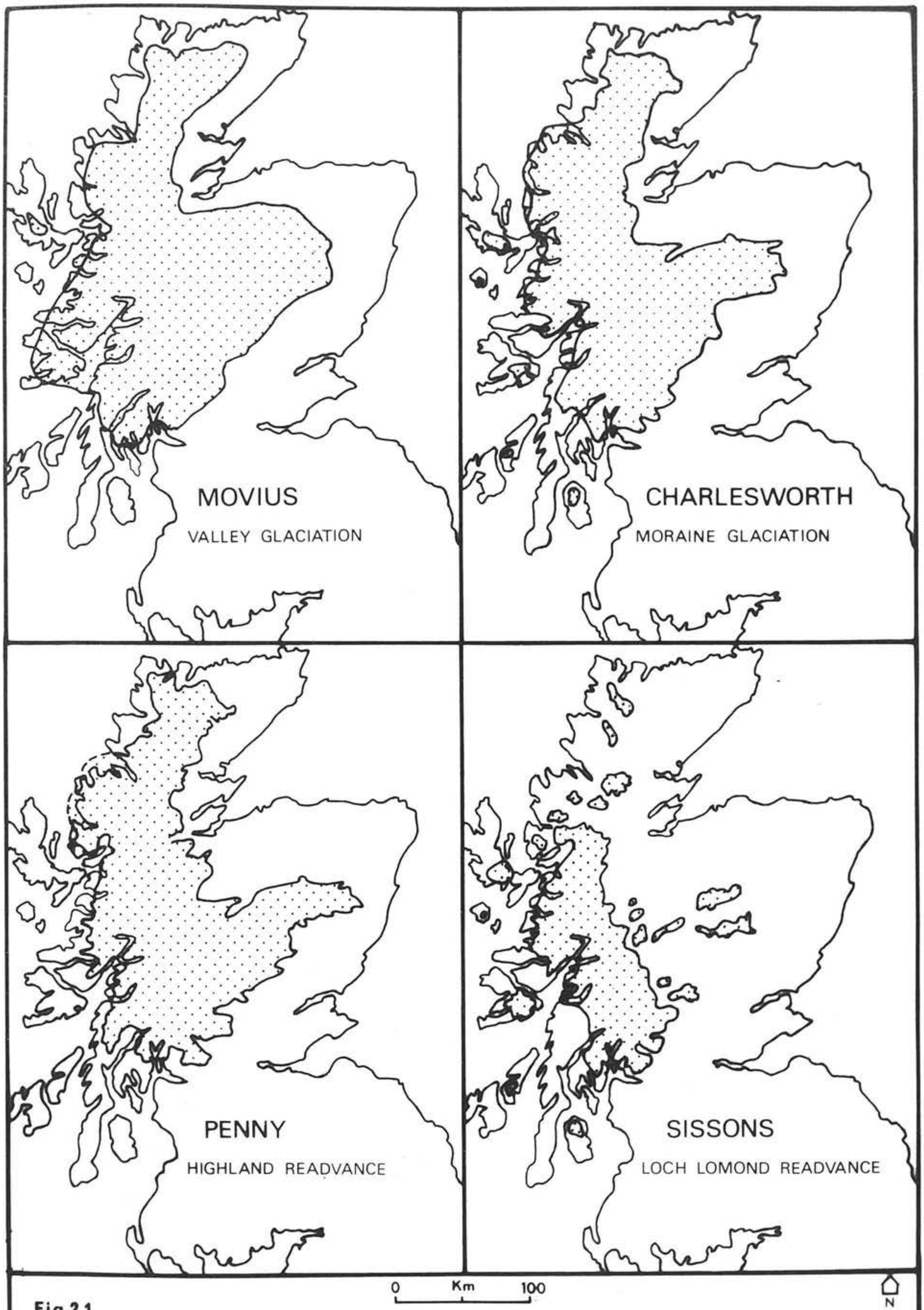


Fig. 2.1

THE LAST STAGE OF GLACIATION according to Movius (1942), Charlesworth (1955), Penny (1964), Sissons (1964).

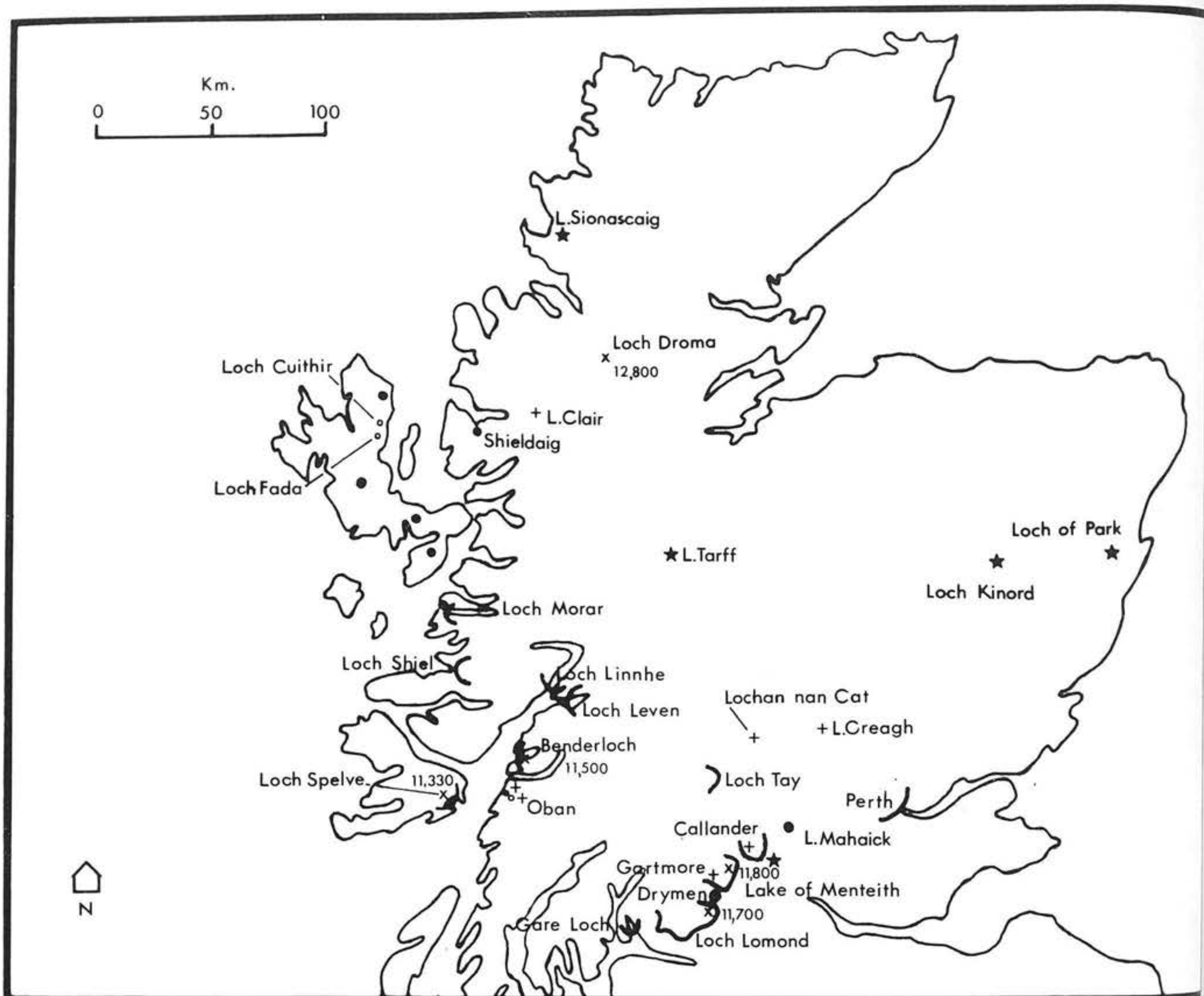
Highlands which each considered marked a more recent phase of glaciation than the deposits in the Lowlands of Scotland. These Highland deposits were by general consent termed 'moraines'. Wright stated that they were so different from other known landforms in Scotland that they appeared to be "the record of a distinct phase of the glaciation accompanied by some peculiar conditions previously non-existent". He noted that, where these moraines occur in coastal valleys in the Highlands, the '100 foot raised beach' is often found immediately outside the morainic limit but never inside it. However, apart from a few examples on the west coast, Wright did not attempt to define the extent of the Highland moraines more precisely. In the 1937 revision of his book, he did not present any more evidence about the extent of the moraines.

J.B. Simpson (1933) was the first to present detailed evidence about the extent of glaciers at the end of the Pleistocene in the Southern Highlands (fig.2.2). He showed that, after an ice sheet had extended to the vicinity of Perth, there was an interstadial period during which the ice sheet disappeared from the Lowlands. Subsequently there was a return to glacial conditions in which valley glaciers advanced down Loch Lomond and down the upper Forth valley, depositing terminal moraines at the southern end of Loch Lomond and at the Lake of Menteith. He called this stage the 'Loch Lomond Readvance'. The moraine at Loch Lomond had previously been mapped by R.L. Jack (1876).

The map of the last stage of glaciation drawn by H.L. Movius (1942) is based entirely on bibliographical study of the work of Wright, Simpson, A. Bremner, and the memoirs of the Geological Survey. The evidence presented by the

Geological Survey had already been summarised by Wright (1914) when he described a "distinct phase of glaciation" that had been confined within the Highlands. Consequently Movius' map of the last stage of glaciation approximately delimits the extent of the Highlands (fig.2.1).

J.K. Charlesworth (1955) investigated the whole of the Highlands, including the area described by Simpson (fig.2.1). "From the abounding moraines, drainage features and other marginal indications" (p.769) he recognised two stages of glaciation, of which the second or 'Moraine Glaciation' was confined within the Highlands. He divided his description of the retreat from this limit into "arbitrarily selected" substages. Because "drainage" and "lateral" features are largely absent from western Perthshire, he relied on the extent of the "100-foot raised beach" to indicate the extent of the "Moraine Glaciation" (p.905). Since no part of western Perthshire other than the Menteith area was directly affected by changing sea-levels, and since Charlesworth did not discover "well-defined terminal" moraines elsewhere in western Perthshire, it would be difficult to justify the boundary that he ascribed to the "Moraine Glaciation" in the area. On page 904 Charlesworth stated that "positive demonstration cannot be claimed for many of the correlations ..... which are no more than rough approximations". Furthermore his use of the extent of the "100-foot raised beach" to define the extent of the "Moraine Glaciation" is invalid because shoreline features at about that height were not everywhere formed at the same time (Sissons, 1967a). It is therefore considered that Charlesworth's interpretation of the lateglacial history of this area is unacceptable.



Ice limit × 11,500 Radiocarbon date

+ Location of sites studied with Post-glacial deposits only.

∘ Sites studied with Zone III deposits.

● Allerød deposits. ★ Zone I deposits.

Fig. 2.2

LATEGLACIAL ICE LIMITS AND SITES WITH ORGANIC REMAINS.

After Simpson (1933), Anderson (1949), Donner (1957, 1962), Kirk & Godwin (1963), McCann (1966), Sissons (1967 b), Vasari & Vasari (1968), Peacock (1971), Pennington & Lishman (1971), Birks (1972), Gray & Brooks (1972), Petrie (unpubl.), Lowe (unpubl.), the author.

J.J. Donner (1957), in an important paper that established the date of the Loch Lomond Readvance, discussed the lateglacial sequence throughout Scotland. Donner's map of this relied on Simpson's identification of the Readvance and on Charlesworth's extension of Simpson's work into other parts of southern Perthshire. Therefore Donner's discussion of the extent of successive ice limits within the area covered by this thesis did not differ from those mentioned above.

L.F. Penny (1964) in discussing the lateglacial sequence, did not differ from Simpson (1933) in his interpretation of features along the southern border of the Highlands, and like Simpson did not present any evidence about the extent of the last glaciation elsewhere in western Perthshire (fig.2.1).

Most recently J.B. Sissons (1967a) set out numerous examples of the deposits and limits of glaciers presumed to be contemporaneous with the Loch Lomond Readvance. Sissons identified only one possible limit within the area of this thesis, at the western end of Loch Tay (p.141). The other localities that he described lie outside the thesis area but do represent an advance in the knowledge of the lateglacial sequence in the Highlands, for many of his interpretations are based on much more detailed and accurate mapping than was undertaken by Charlesworth (fig.2.1). However, in order to delimit successive lateglacial limits on a map of Scotland, he also had to rely on less detailed accounts produced, for example, by the Geological Survey in the early years of the twentieth century. These, together with necessary interpolations where information is totally absent, cause his map of the successive ice limits to be "very generalised" (p.137), and subject to revision as more accurate information becomes available (fig.2.1).

B. Neighbouring Lateglacial ice limits.

Knowledge of particular ice limits in adjacent parts of the Highlands is relevant to this study because to a degree they show the extent of the last glacial stage of the Highlands (fig.2.2). (Fig.2.2 shows some lateglacial ice limits and sites with organic remains that are discussed in the text. The map is not intended to show all such limits and sites in Scotland. On this figure the ice limit at Callander was first mapped by the author. It is inserted to place two sites of pollen analysis in context (one inside and one outside the ice limit). These sites were identified by the writer and subsequently selected for pollen analysis by J.J. Lowe. Thus they are not to be found in literature published prior to this thesis.)

Adjacent to Lake of Menteith and Loch Lomond lies the Gare Loch, described most fully by J.G.C. Anderson (1949). Near the southern end of the Gare Loch he found glacier terminal deposits which lie on marine deposits, both of which are also covered by later marine deposits. The lateral moraines along the Gare Loch show that a glacier had moved southwards to a limit there, and the distribution of shorelines shows that this had occurred after a period of high sea-level (the '100-foot raised beach') and during one of low sea-level. Sea-level subsequently rose to approximately 35 feet O.D. (10.7m). This sequence of events accords approximately with that described for the Loch Lomond area by J. Rose (unpublished) and for Lake of Menteith by Sissons (1966). At Lake of Menteith, after a period of falling sea-level, a glacier readvance created a terminal moraine, beyond which outwash was deposited in a sea whose level did not exceed 33-38 feet O.D. (10.1-11.6m). While ice stood at the moraine the sea-level rose to 39-40 feet O.D. (11.9-12.2m) and then fell below 35 feet (10.7m).

Therefore, as far as is known, the relationship of the glacier readvance in each of these three valleys, upper Forth, Loch Lomond and Gare Loch, to the sequence of lateglacial sea-levels is approximately the same. The close proximity of these valleys to each other supports the hypothesis that the terminal moraine in the Gare Loch was formed during the Loch Lomond Readvance.

The relationship of glacier terminal outwash fans to sea-level along the west coast of the Highlands has been studied by S.B. McCann (1966). At Ballachulish on Loch Leven, at Corran on Loch Linnhe, in Benderloch, and at the western ends of Lochs Shiel and Morar, there are large outwash fans deposited when the sea-level was below about 40 feet O.D. (12.2m). Both McCann and Sissons (1967a) have suggested that the fans were formed during the Loch Lomond Readvance. Independent dating of shells underlying a fan at Benderloch supports their hypothesis (J.D. Peacock, 1971). (This will be considered in the next section of this chapter).

The evidence discussed above is relevant to this thesis because these localities are closely related geographically to the thesis area. Lake of Menteith, Loch Lomond and Gare Loch lie just to the south-west of the thesis area and are each connected by low-level breached watersheds to the Strath Fillan - Glen Dochart valley, which runs through the centre of the thesis area. This valley is similarly connected to Rannoch Moor. Beyond the western side of Rannoch Moor lies the main West Highland watershed which today receives the highest rainfall in Britain, and which is thought to have been a major source of glacier ice in the Pleistocene. At the last stage of glaciation erratics were carried eastwards from this watershed area into Rannoch Moor (Hinxman et al., 1923). These erratics are part of a continuous series of deposits that extends throughout a large part of the thesis area, and probably as far as Gare Loch, Loch Lomond and Lake of Menteith. The Benderloch, Loch Leven and Loch Linnhe outwash fans lie immediately to the west of the watershed and may have been formed by glaciers moving westwards at about the same time as others were moving eaatwards into Rannoch Moor.

C. The dating of the Loch Lomond Readvance.

This was first done by J.J. Donner in 1957-1958. Donner carried out detailed analyses of the stratigraphy and organic remains at three sites in the upper Forth valley and Loch Lomond area, and at four near Oban. These were chosen so as to be immediately inside and immediately outside the Loch Lomond Readvance moraines mapped by Simpson (1933) and the 'Moraine Glaciation' limit at Oban mapped by Charlesworth (1955). Donner accepted Charlesworth's hypothesis that both the Oban and Loch Lomond end-moraines were formed during the last stage of glaciation of the Southern Highlands. The three sites in the upper Forth - Loch Lomond area are the more relevant and so will be discussed here. The first, near Drymen (4992, sheet 54) lies on moorland above and between the Loch Lomond and Menteith moraines. The second is a small rock basin lake at Gartmore (5097, sheet 54) within the Menteith terminal moraine. The third, Loch Mahaick (7007, sheet 54), lies on the moorland above and east of the Teith valley, outside the presumed limit of the last glacier to occupy the Teith valley (Simpson, 1933, Charlesworth, 1955).

The method employed by Donner relies on the identification of the successive distinct changes in vegetation that are set out as a scheme of three lateglacial and five postglacial zones. This relative chronology has been substantiated in Britain by radiocarbon dating (Godwin, 1961). Donner's hypothesis was that sites covered by lateglacial ice should contain only part of the sequence, and sites outside the ice limit earlier parts not found inside the limit. The sequence is recorded by pollen grains preserved in limnic peat and lake sediments, and by the variations in the sediments themselves. The samples were obtained by boring into the deepest accessible part of small lakes that are partly infilled and overgrown. The main disadvantages of using this approach are that the investigator cannot be sure of finding the deepest deposits, and cannot be sure that the absence of particular deposits implies that the site was not available for deposition at the time.

Like Mitchell (1952) Donner found that the poverty of pollen from Zones I and III and predominance of herbaceous pollen in Zone II were intimately linked with a distinctive stratigraphic sequence. In this the Zone II organic layer is sandwiched between silty clays of Zones I and III. These clays are partly or predominantly pink. Pink clay has not been found in Scotland other than as a lateglacial deposit of Zone I or Zone III age. At Drymen Donner found "the threefold stratigraphical succession typical for the lateglacial" at the bottom of the lake. This consisted of a pink silty clay, covered by an organic-rich clay mud, and this covered in turn by more pink silty clay. At Loch Mahaick the sequence was the same. At both sites a continuous succession of postglacial organic deposits was found lying on top of the upper pink silty clay. However at Gartmore, within the Menteith moraine, Donner found only one layer of pink silty clay, covered by postglacial organic deposits. At all three sites glacial gravels or till lay under the lowest pink silty clay.

Summing up these results, Donner stated (p.250) that, "taking into account the pollen composition, showing an open vegetation (in Zone II), and considering what is previously known about the Lateglacial, it can be concluded that these minerogenic layers (of pink silty clay) were formed by solifluxion" during Zone I and Zone III respectively. This suggestion was supported by Godwin (1961).

The threefold succession occurs at Drymen and Loch Mahaick, above the Loch Lomond and Menteith moraines. But only a single much thinner pink silty clay layer lying on gravel was found at Gartmore, inside the Menteith moraine (fig.2.2). Because Zone III was the last period of prolonged cold that has been demonstrated in Britain, Donner concluded that the Loch Lomond and Menteith moraines were created during Zone III. This hypothesis agrees with conclusions reached elsewhere in Europe (quoted in Donner, 1957) and has subsequently been supported in various parts of Britain (Manley 1959; Godwin 1961; Donner 1962; Sissons 1967a, 1967b; the Vasaris 1968).

In 1962 Donner reported further investigations of the type described above. Apart from reviewing his study of Loch

Mahaick (1957, 1958), he included two further sites. In Loch Creagh, a small rock basin lake in a breached watershed above and south of the Tay valley (9044, sheet 48), he found organic and mineral deposits dating back to Zone IV. In the Lochan nan Cat, which occupies a large corrie on the eastern side of Ben Lawers overlooking Loch Tay (6442), he found organic and mineral deposits also dating back to Zone IV. He concluded that the evidence supported his contention that the last stage of glaciation took place during Zone III.

Both these sites lie within the limit of Charlesworth's 'Moraine Glaciation', which Donner had supposed was equivalent to Simpson's Loch Lomond Readvance (Donner, 1957, 1958). However, Donner noted that radiocarbon assay of organic remains in outwash laid down by a glacier of the 'Moraine Glaciation' stage at Loch Droma in the North-west Highlands gave the date 12,814 ± 155 B.P.(Godwin and Willis, 1961; also Kirk and Godwin, 1963). This date belongs in Zone I and, if accepted, implies that the site was not occupied by glacier ice after this date. Therefore the features in the North-west Highlands, correlated with the 'Moraine Glaciation'by Charlesworth, cannot be correlated with the later glacier limits in the Southern Highlands at Loch Lomond and Menteith. Furthermore, Donner states that "it is then obvious that the area covered by ice during the Zone III period was more restricted in Scotland than previously assumed" (p.26).

Charlesworth's correlations in the Southern Highlands may also therefore be regarded as suspect, particularly in view of the lack of clear ice limits to support his interpretations. Consequently, without further evidence regarding the extent of the last glaciers in western

Perthshire, Donner's conclusions that glacier ice did not occupy either Loch Creagh or Lochan nan Cat during or after Zone IV cannot be taken further. It is hoped to provide in this thesis a more accurate geomorphological framework within which to view Donner's work near Loch Tay and Menteith.

Absolute dates that confirm Donner's relative dating of the Loch Lomond and Menteith moraines have subsequently been obtained by Sissons (1967b). He obtained radiocarbon dates on marine shells that were picked up by the Loch Lomond and Menteith glaciers and deposited in their terminal moraine complexes. The Loch Lomond shells were dated as 11,700 $\pm$ 170 B.P., and the Menteith ones as 11,800 $\pm$ 170 B.P. These show that the sea had invaded both localities in Zone II, after the melting of the preceding ice sheet, and that the Loch Lomond and Menteith glaciers advanced, picked up and redeposited the shells during Zone III. This confirms Donner's estimate in these two localities.

J.D. Peacock (1971) has obtained radiocarbon dates from marine shells in Benderloch (fig.2.2). These were found at the western end of Loch Creran in a raised beach partly buried under the terminal outwash of a later glacier. The dates from the inner parts of the three shell samples were 11,430 $\pm$ 220 B.P., 11,530 $\pm$ 210 B.P., and 11,805 $\pm$ 180 B.P. They suggest that the sea shells of Zone II age were picked up by a glacier of the Loch Lomond Readvance in Zone III and redeposited in its outwash. McCann (1966) and Sissons (1967a), from morphological and sea-level relationships, had already concluded that the glacier belonged to the Loch Lomond Readvance. J.M. Gray has also found shells of Zone II age that were picked up and redeposited by a Zone III glacier, in this case on the east coast of Mull at

Kinlochspelve . The radiocarbon date from the marine shells was 11,330 ± 170 B.P. (J.M. Gray and C.L. Brooks, 1972).

Y. and A. Vasari (1968) followed Donner's methods in an investigation of the pollen and macrophytic plant remains in five lake sites, two in the Dee valley, two in Skye, and the site at Drymen previously studied by Donner (fig.2.2). They obtained similar but more detailed results, agreeing with Donner that Zone III was a period of renewed glacial cold climate and that the threefold mineral - organic - mineral sequence in the lakes corresponds to the Zones I-II-III pollen sequence. Vasaris' results are strengthened by the study of vegetation known to have grown at each site (from macrophytic remains), in addition to the regional pollen rain, and by the analyses of pollen in the Zone I and Zone III sediments. Donner had failed to find enough pollen for reliable analysis in sediments of these ages. The Vasaris also differ from Donner in defining a lateglacial - postglacial transition zone (Zone III - IV). The equivalent of this zone was contained in Donner's Zone IV.

At the time of writing, several analyses of lateglacial vegetation became available. Mr J.J. Lowe undertook the pollen analysis of sites inside and outside the ice limits mapped by the author. Lowe's provisional results were kindly made available and they confirm the inferences made earlier from the work of Donner and the Vasaris (chapters 5, 12, 13, 14; appendix 1). W. Pennington and J.P. Lishman (1971) analysed the carbon and iodine contents of three Highland lochs, Loch Clair, Loch Tarff and Loch Sionascaig, and the pollen in the latter. By comparison with sites in the English Lake District, particularly with Blelham Bog which is dated by ten radiocarbon analyses, they were able to show that Lochs Tarff and Sionascaig were vacated by glacier ice at about the same period as was Loch Droma, prior to 13,000 B.P. From the apparent absence of lateglacial deposits they inferred that Loch Clair may have been occupied by glacier ice during Zone III. Loch Clair is thought by Sissons to have been covered by ice at this time (1967a, p.132). H.J.B. Birks kindly made available to J.B. Sissons a summary of results to be published in 1972. Birks found organic material dating back to Zone II at four sites (and a possible fifth) outside the limits of the last glaciers in Skye and at one site outside the limit of the last glacier to flow down Loch Morar. (McCann had earlier suggested that this glacier belonged to Zone III). A.R. Gunson communicated to J.B. Sissons that J.J.M. Petrie had found organic deposits dating back to Zone II outside the last ice limit in Gleann Shieldaig.

D. The Geological Survey memoirs.

The Geological Survey memoirs and accompanying maps include the earliest attempts to map some of the glacial landforms of the Highlands systematically and in detail. Most of the field-mapping was done at the 1:10,560 scale but the published maps are at the 1:63,360 scale. These attempt to show the distribution of different varieties of drift (e.g. boulder clay, alluvium) and indicators of the direction of ice movement, namely striations and roches moutonnées. The memoirs include description of these, as well as of erratics and rock basin lakes, and attempt to deal with some of the implications of the evidence regarding the nature and extent of successive glaciations.

Three memoirs deal with parts of the thesis area. The

Blair Atholl Memoir is the earliest (L.W. Hinxman et al., 1905). The adjacent Rannoch area was surveyed slightly later but published much later (Hinxman et al., 1923). The neighbouring areas to the south were mapped but on two 1:63,360 sheets (sheet 47, Crieff, 1888; sheet 46, Balquhidder, 1900). No memoirs were written for these areas and neither map was published. Both maps are available for consultation but unfortunately the distribution of drift is not shown on them. The Stirling area has been resurveyed and a new memoir and map produced (E.H. Francis et al., 1970). However, as far as the parts of the thesis area included are concerned, the quality of detail and explanation is very similar to that in the earlier memoirs mentioned above.

The authors of the early memoirs found evidence in the Tummel - Tay area which they believed showed that there had been an earlier and a later glaciation (Hinxman et al., 1905). The broad uplands flanking the Loch Tummel and river Tay valleys are largely covered by till and there is a pattern of striations oblique to the alignments of these two valleys. Over most of the uplands the striations point south-eastwards and can only have been produced by an ice sheet whose surface overtopped the hills and whose movement largely ignored the presence of the valleys. The later glaciation, according to Hinxman et al., (1905), was confined within the main valleys. It left 'moraines' or sands and gravels in the Loch Rannoch - Loch Tummel valley, the Garry valley, and the river Tay valley. Its striations parallel the valley axes and lie within the valleys. Various features in these valleys were said to indicate retreat stages, although few details on supporting evidence were quoted.

Although modern interpretations based on contoured maps and more advanced geomorphological knowledge often conflict with these older accounts, they do have and did have considerable value. It was on such evidence from a large part of Scotland that authors such as the Geikies (1894, 1901) and Wright (1914) contended that there had been several phases of glaciation in Scotland. The present-day usefulness of the older memoirs is principally in their identification of striations, roches moutonnées and indicator stones. In particular, the accounts of the transportation of erratics into and from Rannoch Moor (Hinxman et al., 1923), are most useful in identifying the directions of movement of former glaciers.

The memoir on the Stirling district (Francis et al., 1970) will be discussed separately in detail in the chapter dealing with the Teith valley.

E. Other literature.

Amongst the published literature there are three other groups of papers that are relevant to the interpretation of the Pleistocene or the last glaciation in the thesis area. D.L. Linton has probably contributed more than any other to the knowledge and understanding of glacially eroded landforms in the area. His series of papers (1949, 1957, 1959, 1962) contains explanations of the origins of many features, some of which bear directly on the interpretation of the former pattern of glaciers, as for example around Rannoch Moor. His discussion of ice-moulding in the Callander area illuminates the interpretation of certain forms there (Linton, 1962). And his reflections on the distributions of corries, rock basins and types of glaciated landscape in Scotland (1959) help to clarify the pattern of landforms in the thesis area as a whole.

Secondly there are two papers produced independently, though made public in the same year, that describe the 'Parallel Roads of Loch Tulla'. The authors, J. Mathieson and E.B. Bailey (1925) and J.C. Gregory (1926), recognised a series of lake terraces on the southern side of Rannoch Moor and were struck by the similarity they bear to the famous 'Parallel Roads of Glen Roy'. The Loch Tulla terraces will be discussed in chapter 6.

Thirdly the Forth valley and part of the Teith valley contiguous with the southern part of the thesis area were studied in great detail by D.E. Smith (1965) and D.D. Kemp (1971). Their identification of terraces and other features in the lower Teith valley and the changes of sea-level in the Forth valley have been most useful in relation to the interpretation of the last stage of glaciation of the upper Teith valley.

F. Summary.

It has long been recognised that there was a distinct phase of glaciation, more or less confined within the Highlands, that created a 'morainic' landscape. Simpson (1933) identified the limit of this stage at the southern end of Loch Lomond and at Lake of Menteith, calling it the Loch Lomond Readvance limit. Other glacier limits on the west coast have been correlated with the Loch Lomond Readvance on account of their proximity to the main West Highland watershed, or former iceshed, and of their relationship to a relatively low sea-level thought to have occurred at this time. Relative dating and radiocarbon dating have confirmed that the Loch Lomond stage was a distinct readvance in Zone III in the South-western Highlands. The ice limits north-east of

Menteith remained largely unknown however, apart from one suggested for the western end of Loch Tay. Other information regarding striations, _roches moutonnées_, erratics and glacial troughs assists the identification of the routes taken by former glaciers.

Chapter 3. Physiography and Geology.

The function of this introductory chapter is to outline the general character of the thesis area and particularly to discuss the glacial drift. It is not intended that the physiographic history should be explored and description of the topography of each valley system will form the introductions to subsequent chapters.

A. Topography.

The thesis area lies almost entirely within the Highlands, between the Trossachs in the south and Glen Garry in the north, and between Rannoch Moor in the west and Glen Almond in the east. Only the Teith valley, which drains the Trossachs lochs, extends into the Lowlands below the Highland edge (fig.1.1). The largest area of high ground, with numerous summits exceeding 3000 feet (915 m), is between Rannoch Moor and Loch Tay (sheets 47, 48). Over most of the remaining area the summits exceed 2000 feet (610 m), with fewer and widely separated groups of hills exceeding 3000 feet (915 m). The thesis area lies immediately to the east of the highest and wettest part of the main Highland watershed and is largely separated from it by the great basin of Rannoch Moor, much of whose undulating floor lies as low as 1000 feet (305 m).

A number of major valleys, each with its system of tributaries, are included in the thesis area. Each major valley is directly connected to its neighbours by one or more major glacial breaches. In some instances these are at low levels; for example Strathyre at about 500 feet (150 m), which connects the Loch Voil and Loch Earn valleys (sheet 54), or the three valleys (1200 - 1400 feet, 365 - 425 m) through the hills at the western end of Glen Lyon that connect it with Rannoch Moor and Glen Orchy (sheet 47). In many more instances valleys with breached watersheds hang well above the main troughs, generally cutting across divides almost at right angles. D.L. Linton (1949) has shown that much watershed breaching was accomplished by diffluent ice flow across existing cols between major troughs. Numerous examples of modification of these passes exist in the area, ranging from slight lowering to major deepening. A most impressive example is the Loch Lubnaig valley (sheet 54), which was considered by Linton and Moisley (1960) to have been cut right through the pre-existing watershed (Ben Ledi - Ben Vorlich).

On a broader scale Linton (1957, 1959) has suggested that each of the major valleys in the thesis area formed part of a system of troughs radiating outwards from "the most powerful centre of ice dispersal in Britain" (1957, p.303) centred on Rannoch Moor and the surrounding mountains. All of these troughs, except Glen Lochay and Glen Almond contain substantial rock basin lakes which testify to the erosive power of the outflowing glaciers during the Quaternary period. On the bases of the depositional evidence and of the inferred ice surfaces, it will become apparent in this thesis that all but three of the major valleys in the area were interlinked by a continuous spread of glacier ice during the last stage of glaciation. (The exceptions were Glen Almond, Glen Artney and Glen Garry . In the cases of Glen Artney and Glen Garry only narrow watersheds separated their glaciers from neighbouring glaciers.) The availability of major and minor breached watersheds between the valley systems during this last stage was of primary importance in allowing most of the major glaciers to become linked with one another, and thus to leave continuous spreads of characteristically fresh hummocky drift passing from one valley system to the next. This continuity is one of the principal reasons for postulating that the fresh hummocky drift in each of the valley systems in the thesis area was formed during the same lateglacial period.

B. Geology.

With the exceptions of the Menteith Hills, south of Loch Venachar, and of the south-eastern side of Glen Artney, the thesis area lies entirely within the zone of Highland rocks (sheet 54). The Loch Rannoch and Garry valleys are largely developed on the Moinian flaggy gneisses, and most of the other valleys on the more complex and slightly younger Dalradian series. In general both series have been eroded into big bold rounded hill masses from which both spectacular rocky mountain scenery and gently undulating plateau surfaces tend to be absent. There are however certain formations upon which distinctive landscapes have developed. In the north the Schichallion quartzites form the rugged conical mountain of Schichallion (sheet 48), which is enveloped by its own blocky scree. The Ben Lawers calcareous schists are more easily weathered and eroded than many of the more massive surrounding rocks yet, because they lie along "the structural axis of the country" (Hinxman _et al._, 1905, p.1), they form a most impressive ridge of high ground. This runs from Meall Glas - Sgiath Chuil (over 3000 feet, 915 m), between Glens Lochay and Dochart, east-north-eastwards parallel to Loch Tay and includes the crest of the jagged Farragon ridge between the Tay valley and Loch Tummel (fig.8.1). The highest part of the schist ridge consists of the Meall nan Tarmachan - Beinn Ghlas - Ben Lawers - Meall Gruaidh hill mass, out of which a number of fine corries have been excavated. The irregular lime content and numerous and often contorted planes of cleavage are held to be responsible for the ruggedness of the scenery developed by glaciers on these schists (P. Macnair, 1908, chapter 15; F. Walker, 1961).

A multitude of striking rocky forms has been developed on a belt of pebbly grits that runs parallel and close to the Highland edge. In places the grits form massive blocky outcrops, as in the rock bar across the mouth of Loch Katrine, or in the hills and rock bar at the eastern end of Loch Earn. In others they are associated with towering cliffs, as at the mouth of Glen Almond (the Sma' Glen), or as in the corries of Ben Vorlich - Stuc A'Chroin. Yet the hills formed of the pebbly grits are no higher and often considerably lower than many less craggy hills in Glen Lyon.

The great basin of Rannoch Moor in the north-west of the thesis area is largely based on "a medium-grained grey hornblende - biotite granitite or tonalite" which is normally called granite (Hinxman et al., 1923). The ease with which the granite weathers into rounded boulders and fine gravel and the numerous joints may partly account for the frequency of low rounded rock knobs and hills on the floor of the Moor. The rock knobs are often all but indistinguishable from the mounds of drift.

There are five major fault lines within the thesis area. Four of these, the Ericht-Laidon, Tyndrum, Brig o'Balgie and Loch Tay faults, have exerted some influence upon topography, as can be seen in the marked linearity of some valleys (for example Loch Garry, Glen Ample). However the form and alighment of most valleys seem not to have been affected by either faults or the regional strikes of the rock formations (predominantly west-south-west to east-north-east). Only lower Glen Lyon, Glen Dochart, the River Tay valley, and the south-western and north-eastern thirds of Loch Tay have been excavated along the strike of the bedrock. (The last three are parts of one valley; fig.1.4). The fifth and most important fault is the Highland Boundary Fault, which runs through Loch Venachar in the south-west, along the length of Glen Artney, and on north-eastwards past the mouth of Glen Almond at the south-eastern corner of the thesis area (sheet 54). It does not correspond exactly to the topographic margin of the Highlands, for the resistant Old Red Sandstone conglomerates of the Menteith Hills, the south-eastern side of Glen Artney and the hills around lower Glen Turret reach considerable heights. The only part of the Lowlands to be included in the thesis area is the Teith valley below Callander where the gently sloping interfluves are developed on the comparatively easily eroded Old Red sandstone beds.

C. Hummocky drift.

Throughout the following chapters great emphasis is placed on the implications of the distribution of hummocky drift. On occasions description and explanation of sediments and structures are necessary, in particular of lateral moraines and eskers. With these exceptions, comments on the sediments would be repetitive and, taken individually, somewhat inconclusive. Accordingly the general characteristics of the hummocky drift and their possible implications are set out in this chapter. Only a sample of the plethora of separate observations can be quoted, yet they can be summarised without loss.

Lateral moraines, the Teith terminal moraine and various eskers are discussed individually in later chapters. Nevertheless certain conclusions can be drawn from their presence, even though this anticipates the subsequent consideration of each feature.

The fresh hummocky drift of many Highland valleys, often termed 'hummocky moraine' (chapter 2A; W. B. Wright, 1914), is widespread in this thesis area. Its distribution corresponds closely with the inferred distribution of the last glaciers in the area. The mounds of drift are exceedingly numerous, fresh in appearance and reasonably consistent in composition. "They are largest and most abundant on and near the valley floors but often also extend hundreds of feet up the valley slopes" (Sissons, 1967a, p.95.) In places they form a continuous spread from one major valley system to the next via tributary valleys (chapter 14). In general "the margin of the moundy area is not marked by any distinctive feature" (Sissons, p.95), lateral moraines being comparatively rare. Normally "the moraines appear to form a sea of chaotic mounds lacking any systematic arrangement" (Sissons, p.97). "Most of these mounds are more or less rounded in form with no very definite direction of axis" (L.W. Hinxman <u>et al.</u>, 1923, p.84). The sharpness or freshness of the mounds seems to be related to their height, to their composition and possibly to their age. Low mounds, even with steep sides, tend to appear less clear than mounds whose crests rise higher above surrounding hollows. "Mounds of coarse debris are usually sharp with slopes as great as 30 or 40 degrees, while those composed largely of sand are often quite smooth and rounded with less abrupt slopes" (Sissons, p.108). Where mounds merge together or where peat has infilled the intervening hollows the mounds may seem less sharp. On parts of Rannoch Moor, for example, small mounds are flanked by or are partly submerged by a sea of peat, the mounds themselves often supporting a peaty top. The alluvium of wandering streams here and elsewhere complicates the apparently random scatter of peat and moraine.

Another factor contributing to the relative sharpness of many moundy deposits formed in the last stage of glaciation is the absence of periglacial modification. Within the limits of the last glaciers "solifluction has not operated at all on low ground ..... with the consequence that ..... features such as kames and moraines are extremely sharp and clear" (Sissons, p.222). Outside these limits during the last glacial stage it is possible that many areas of moundy drift of the preceding glacial stage were modified by solifluction. In lower Glen Garry, Glen Errochty, the River Tummel valley, parts of the River Tay valley, Glen Lednock, the Loch Earn valley and lower Glen Artney virtually all the mounds are remarkably subdued and smooth, so that the areas occupied by such mounds are normally difficult to delimit precisely.

Within the mounds of the last glacial stage there are numberless exposures of "loose unsorted debris, the stones being angular or sub-angular, mixed indiscriminately and of all sizes" (J.K. Charlesworth, 1955, p.778). "The surfaces of the mounds are often littered with angular boulders and similar boulders are plentiful in the mounds themselves. The boulders are usually mixed with an assortment of stones of all sizes, as well as with finer material" (Sissons, p.95). In Glen Lyon and Glen Lochay, for example, the mounds are composed of an "open-textured, rubbly deposit of earthy or clayey sand, full of angular and sub-angular pebbles and boulders, ... fairly pervious, ... loose, unconsolidated ..... unstable" (geological report, North of Scotland Hydro-Electric Board, 44/01/5).

The examples that follow show the range of variation and common characteristics of mounds of the last glacial stage. In each there is a substantial exposure of drift but in most cases only of the surface layers.

The material in some low mounds in Auch Gleann (326351, sheet 47) ranges from silt to coarse gravel. The numerous boulders are angular in comparison with the rounded cobbles of the adjacent river but less angular than the frost-shattered blocks on neighbouring summits. Slightly rounded stones are common in the mounds, whose average height is 2-3 m. Very similar observations were made in mounds around Loch Tulla (especially 3044, 3144, 3143, 3042), including shores of the loch. Even in the river bed at Bridge of Orchy (2939) the average boulder has some angular and some rounded edges, there being very few rounded boulders.

On the valley bench south of Loch Rannoch (sheet 48, hundred-km square 55) almost all the gently sloping land supports forest of varying ages. Consequently access is restricted to the marked tracks and to the belt occupied by linear mounds (5353 - 5652 - 5953). Drainage ditches through the latter area expose sand, rounded gravel and rounded boulders. Exposures along the track in squares 5353 - 5453 - 5452 are of sand and markedly angular surface gravel. In square 5953 the mounds thought to have been deposited by meltwater draining parallel to the ice margin include fines whose bedding is contorted (chapter 5). In nearby Coire Carie (6156 - 6253) there are many exposures of sand, sometimes bedded, and gravel, including rounded pebbles and slightly rounded boulders.

Near the head of Loch Garry (6473, sheet 48) at Dalnaspidal station one mound just above the flood plain contains bedded sand, rounded pebbles and gravel. In contrast just above the road the surface of a larger mound consists of sand and angular gravel. Directly to the north at 634750 one of the very large mounds above the road has sand, gravel, angular, sub-rounded and well rounded boulders. Sand is bedded at various angles and in one part steeply dipping sand beds surround a boulder almost 0.5 m in diameter.

In Glen Ogle (579256, sheet 54) the top 2 m of one low broad mound contains gravel and angular boulders, some of which are striated. Here, as is usual in the thesis area, the large boulders tend to lie near the tops of the mounds and to litter their surfaces. In Glen Dochart (sheets 54 - 48) there are numerous exposures of sand, angular gravel and boulders in the valley floor mounds.

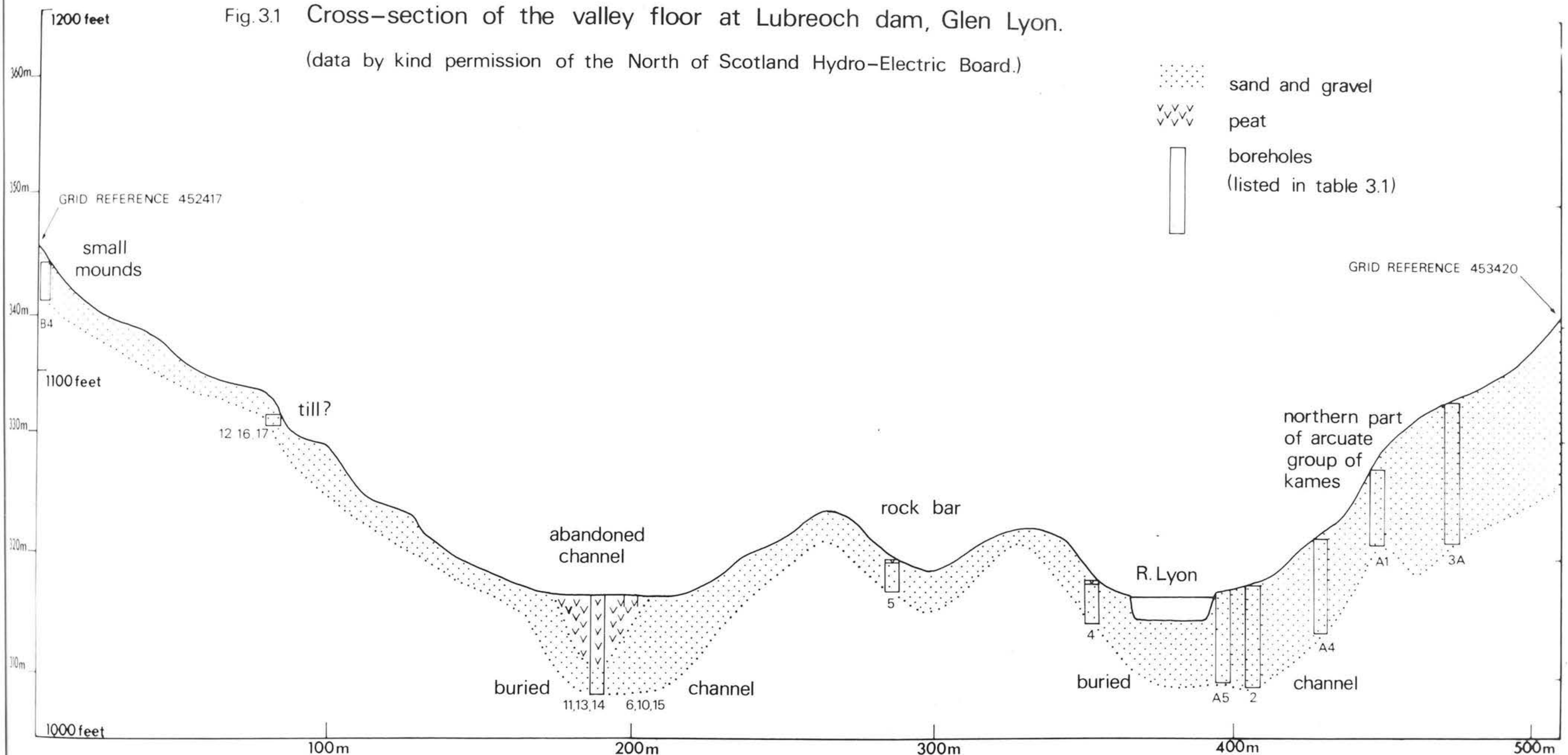
The examples quoted so far are representative of the great majority of available exposures, in which there is generally a sand and angular gravel mixture, a scattering of boulders especially near the ground surface, and on occasions some beds of fine material. These beds tend to be insufficiently exposed or developed for more than tentative explanations of their origin to be made. However, much firmer conclusions can be drawn from the following examples. In lower Glen Lyon at Slatich (6347, sheet 48), in mounds banked against the foot of the steep hillside, there are horizontally bedded sands, with gravel, including rounded pebbles. To the east at Inverinain occasional kames above a kame terrace exhibit slumped sand and well rounded gravel. Westwards at Innerwick the cores of a pair of mounds standing isolated in the flood plain (591471) have beds of silts and sands dipping gently eastwards and much rounded gravel. Just to the west of Innerwick bridge (587475) the upper part of a mound has roughly horizontal bands of fine sand and silt, about 20 cm thick and c.1m long, which are slightly contorted. These abut and lie on sub-angular and angular gravel. 1 km to the west another quarried mound has similar deposits (579471).

North of Loch Rannoch numerous mounds on the low interfluve in squares 6061 - 6161 - 6060 - 6160 furrowed by drainage ditches or gullied by streams exhibit sand and rounded gravel. The debris in local streams is remarkably similar. A large deeply-sectioned mound by Loch Garry (626704) has a small area of bedded sands, in one part horizontal, in the adjacent part dipping steeply. On one flank of the mound beds of gravel dipping parallel to the ground surface may represent an original constructional slope (R.P.K. Clark, 1969). Sand, gravel and boulders make up the remainder of this mound. Many other mounds in the valley show similar materials without sign of bedding, but on most only the angular surface debris is exposed. Far to the south-east in Glen Almond (8233), amongst the large mounds at Auchnafree, a steep 10 - 15 m high section includes a prominent load cast in sand-silt amongst masses of sand and rounded gravel(cf. Ph. H. Kuenen, 1953, p.1058). Elsewhere in the thesis area load casts have been observed in an esker (chapter 10).

Investigations in connection with the dam at Lubreoch in upper Glen Lyon have yielded useful information (4541, sheet 47). An arcuate belt of mounds swings across the

Fig. 3.1 Cross-section of the valley floor at Lubreoch dam, Glen Lyon.

(data by kind permission of the North of Scotland Hydro-Electric Board.)



valley, from c.1200 feet (365 m) at each end down to c.1040 feet (315 m) in the middle of the valley (fig.3.1). Mounds without apparent pattern occupy the lower slopes of the valley west and east of this group. Boreholes through the mounds have revealed that considerable thicknesses of drift occupy the lower slopes and valley floor. On fig.3.1 seventeen of the twenty-nine borehole records have been projected on to an axial plane following the line of the dam. It is apparent that 6.0 - 11.0 m (20 - 36 feet) of sand, gravel and boulders cover the bedrock where the dam ends in the arcuate group of mounds on the northern valley side. On the southern hillside drift thickness is variable, generally being 3.0 - 4.5 m (10 - 15 feet) but in places as much as 9 - 12 m (30 - 40 feet) above 1150 feet (350 m) O.D. (It is not clear whether the boreholes on each hillside were through mounds or were in the intervening hollows). Between the foot of each slope and the rock bar or island are flanking hollows, the northern infilled with drift and occupied by the present river (prior to construction of the dam), the southern partly filled with drift into which a now abandoned channel had been cut.

Whilst it is possible that the sand, gravel and boulder drift is till, a number of sections in the arcuate group of mounds on the northern hillside suggest a fluvioglacial origin. A section in a small mound at the northern end of the dam mostly consists of angular debris, but near the top is an approximately horizontal bed of banded silts covered by gravel, including rounded stones, and this in turn by angular blocks. Another includes considerable amounts of fine sand, rounded pebbles and angular debris. A third exhibits approximately horizontal beds of rounded gravel, sand and fine rounded gravel, sand, and coarse rounded gravel, with about 2 m of coarse angular gravel on top. Rounded gravel was noted in neighbouring exposures. The arcuate plan of the group of mounds, being concave up-valley, suggests that they may be some type of kame deposited by meltwaters flowing through the highly crevassed and stagnant snout of the receding Lyon glacier. Westwards, in squares 4441 to 4141, almost a dozen similar groups of mounds exist on the southern or northern valley sides, or on both. Although some are now submerged and no sections have been found in the accessible ones, it is tempting to suppose that they record successive periods of deposition along the retreating ice margin.

The most informative section in a mound discovered in the thesis area is at Ledcharrie in lower Glen Dochart (5028, sheet 54). Here, in a small group of mounds, separated from the valley floor spread by an abandoned channel and a fan, a pair of coalesced mounds 6 - 9 m (20 - 30 feet) high have been quarried right to their centres. At the base of the mound there are 2 - 3 m (7 - 10 feet) of fine sands and silts occurring as steeply sloping beds, almost horizontal beds and current-bedded layers, separated by unconformities, occasionally folded or faulted. Above the bedded fines are about 2 m of sand and well rounded coarse gravel. The top 2 m of exposed material is quite different, being an unstructured mixture of sand and angular to sub-angular coarse gravel, including many substantial boulders.

This topmost deposit is the ubiquitous 'morainic drift' noted by Charlesworth, Sissons and others in many Highland valleys. Sissons has classified the Glen Dochart mounds as kames, apparently on account of their sand and gravel content. The Ledcharrie section, which is clearly in a kame, illustrates his point that "a section through a single mound may show that it is in part composed of unsorted morainic debris and in part of water-laid deposits" (Sissons, p.110). The preceding examples of mounds containing water-washed bedded and angular unstructured deposits are of this type. It is significant that virtually all the exposures of water-worn gravel and bedded fines occur where quarrying has stripped away the surface layers and possibly reached the core of a mound, whereas angular debris occurs on the surfaces of the mounds. Mounds containing water-washed material have forms and patterns of distribution in no way different from those in which only angular material is exposed. "Rigid distinction between" mounds of 'morainic drift' and kames seems not only impracticable but possibly misleading (cf. Sissons, in the press; quotation from Sissons, 1967a, p.110). The 'morainic drift' and angular unstructured surface coverings of kames are most probably ablation till "let down on to the ground as the glaciers finally decayed, probably associated with considerable redistribution of the material by meltwater streams" (Sissons, 1967a, p.97). Short-lived stream action may account for the slight rounding of otherwise angular material noted above. It is equally possible that some rounded material was initially formed by meltwater during the glaciers' advance or in an earlier period. The common absence of fines from the angular surface debris is reminiscent of Okko's observation that the lack of fines in ablation till of contemporary Icelandic glaciers is due to their removal by meltwater (V. Okko, 1955).

In most areas of hummocky drift there is no recognisable order in the distribution of mounds. However there are two varieties of feature that reflect the presence of a controlling factor. Firstly there are groups of mounds whose shape or arrangement has been influenced by protruding bedrock. For example, on southern Rannoch Moor (Black Mount, hundred km squares 24 - 34, sheet 47) the hummocky drift mantle is rarely more than 3 - 4 m (10 - 13 feet) thick. Around Lochan na h-Achlaise (3048 - 3148) some mounds are rock-cored, some are roughly aligned south-west to north-east, and others are roches moutonnées. In square 4338 there are elongated parallel mounds, probably rock-cored and with rock cropping out on their north-eastern ends, that seem to record north-eastwards flow of the Coire Ban Mor glacier. In most cases, however, bedrock influence has brought no apparent order, the mounds being chaotically distributed but rock-cored: for example, the head of Glen Ogle (5527, sheet 54), lower Glen Lednock (hundred km square 72, sheet 54), south of Lochan na Lairige (5938, sheet 48), the drift-covered rock bar in Glen Lyon (5344, sheet 48).

The second type of 'controlled' feature has been found extensively in Glen Garry (hundred km squares 66 - 67, sheet 48) and the Orchy - Kinglass district to the west of the thesis area (hundred km squares 13 - 23 - 14, sheet 47), and in two other small areas, a tributary of Glen Almond (square 7932, sheet 48) and in the Allt Ollach valley above Glen Artney (7013, sheet 54). A photograph of the Allt Ollach mounds (fig. 10.1) shows that they are small, varying little in size, and are arranged in closely spaced parallel lines that usually descend obliquely downslope. Occasionally they run directly downslope (e.g. 6167, 6168, 6268, 6372, sheet 48) and in one area the lines run downslope and then turn until almost parallel with the river (square 6068 - 6067, sheet 48). Such features have been observed elsewhere in the Highlands. For example, B.N. Peach and J. Horne described them as being "distributed in parallel lines" (1910, vol.II, p.45). Although linear ridge patterns have been mapped in the Cairngorms by D.E. Sugden (1970, p.206-9), the two sets of features do not have the same characteristics. Unlike the Cairngorm ridges, those in western Perthshire do not descend downslope from kame terraces or meltwater channels and are individual mounds rather than esker-like ridges. "The origin of the [lines of mounds in western Perthshire] is not established , but their straightness and V-shaped pattern in plan, along with their regularity, make formation along an ice margin rather unlikely and suggest the possibility of subglacial accumulation in relation to crevasse systems in the ice at a time when the ice had become stagnant" (Sissons, 1967a, p.97-8). No sections were discovered in any of these mounds but in one place a subglacial meltwater channel system on one valley side includes possibly sub-marginal channels that descend the valley side at the same angle as lines of mounds on the opposite valley side (6771, sheet 48). Both sets of features might have been controlled by transverse crevasse systems.

D. Eskers.

The identifiable eskers in the thesis area are discussed individually in later chapters. Nevertheless certain common features are worth noting so that each may be seen in context. They have been discovered on the valley benches above Loch Rannoch, in Glen Artney and at Callander. At Callander they were produced by subglacial drainage through the thinning stagnant snout of the Teith glacier (6307-6306-6406, sheet 54; chapter 12). In Glen Artney (Srath a'Ghlinne 6717, sheet 54) well-preserved bedding of silt, sand and gravel in an esker at the terminus of the last glacier indicates that stagnation of the snout had set in while the esker was forming (chapter 10). The majority of the identified eskers lie above Loch Rannoch. In square 5353 a single esker is fresh, sinuous and undisturbed. A belt of linear mounds between 1200 and 1300 feet (365-395 m) (5452 - 5953) includes exposures of fluvioglacial material and terminates at the beginning of a meltwater gorge (5954 - 6156). In square 6360 a pair of eskers at about 1150 feet (350 m) parallel the inferred ice margin, and further south four eskers run down to the Annat Burn. The approximate concurrence of their upper ends suggests that there was here an englacial water table at about 1000 feet (305 m) that controlled deposition by streams flowing downslope under the ice. It is unlikely that the movement of water could have been eastwards in square 6360 irrespective of topography and under hydrostatic control, for the ice margin appears to have lain at about 1100 feet (335 m), just above the eskers. In squares 6061 - 6161 eskers run obliquely downslope parallel to the ice margin. In squares 5662 - 5661 - 5762 the eskers run downslope but across the present drainage lines, indicating that the glacier influenced the direction of subglacial drainage but did not control it completely.

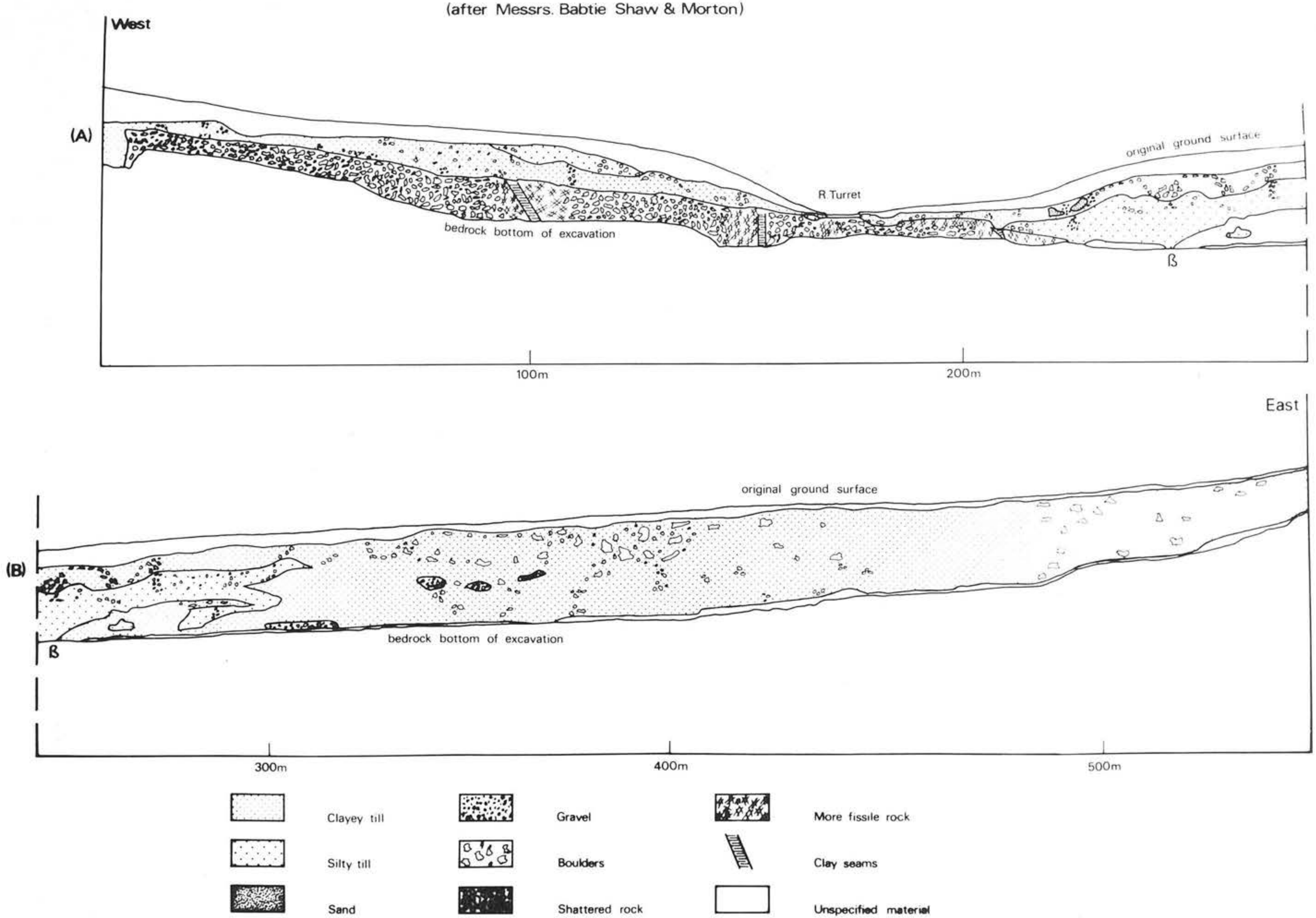
Excluding the Glen Artney and Callander eskers, which formed under stagnant ice tongues, the remaining eskers occur in localities that might be expected to have had impeded drainage during deglaciation. The eskers south of Loch Rannoch lie on very gentle slopes, as do some to the north, whilst the remainder run transverse to the present drainage lines. The undisturbed form and distribution of the eskers imply that glacier ice on the Loch Rannoch valley benches had become immobile by the time the eskers were formed. Examples (quoted in section C) of fluvioglacial material in the valley bench hummocks also imply that deglaciation here was by widespread stagnation.

E. Lodgement Till.

Lodgment till left by the last valley glaciers and by earlier ice is widespread in the thesis area. Often it is a smooth cover obscuring the bedrock surface of a hillside above the zone of hummocky drift. Occasionally hummocks are developed on top of the till. Very thick deposits of till, with one exception, are found in localities not covered by the last valley glaciers. This need not imply that none of the thick deposits of the last glacial stage are till, for good exposures are uncommon. Lodgment till may be distinguished from ablation moraine (ablation till) by being much tougher. The latter is associated with the hummocky drift, whereas lodgement till is not.

The following examples illustrate the character of the material. A shallow embayment on the southern side of Beinn a'Chuallaich (6759, sheet 48) is plugged with till consisting of angular pebbles in a matrix of clay, which is soapy when wet and like concrete when dry. The term 'boulder clay' would be apt here. In the Invergeldie a thick till sheet infills the 2 km of hanging valley mouth between the last glacier limit (7529) and Glen Lednock (7427, sheet 54). The till is a silty, gravelly matrix including large angular boulders, some of which are striated. The majority of small

Fig. 3.2 Till section at Glen Turret dam.
(after Messrs. Babtie Shaw & Morton)



exposures of till in the thesis area are similar, though striations are not usually preserved. For example, around Loch Rusky (Teith valley, sheet 54, 6204) angular blocks of various lithologies are mixed into a silty or sandy gravelly till. Where bedrock almost reaches the surface the blocks in the till are restricted to this rock type. A deep cut made for a dam at Loch Turret (8027 - 8127, sheet 54) showed that the distribution of particle sizes is very irregular (fig.3.2). There are masses of silt, of clay, of silty clay, and of gravel, varying from less than 1 m to several hundred m in length. Boulders are haphazardly scattered through the till, whilst one bed of boulders 200 m long at the base of the till might better be described as shattered bedrock (information by courtesy of Messrs. Babtie, Shaw and Morton, and the Central Scotland Water Development Board). Some clay bands in this shattered bedrock are reminiscent of a temporarily exposed road-cut between Killin and Glen Ogle (5528, sheet 54). The bedrock is well-jointed blocky slates and schists into whose joint planes fine sand appears to have been injected. There is a gradation from bedrock into rocky till in which fissures of sand also occur. Boulders in the till are plastered with stiff silty sand that adheres more tightly to them than does the remainder of the sandy matrix. On top of this lodgement till the drift in the mounds is looser and gravelly. The angular blocks in till were presumably quarried from the bedrock by the ice, as for example the shattered rock layer at the Glen Turret dam shows. The large angular blocks that can be seen passing from the bedrock into sandy till in a deep gully just above the hummocky drift of Glen Dochart (5629, sheet 54) demonstrate quarrying 'in action'. Fine materials were presumably produced by abrasion. However there is some evidence that water-laid deposits may be intimately associated with till in such a way that it is difficult to classify the deposit in terms of a single origin. A thick till sheet outside the lateral moraine of the last Loch Rannoch glacier (5451 - 5551, sheet 48) has c.0.5 m of crumpled laminated clay beds near the top, into which a large boulder protrudes downwards. Most of the c.30 m of drift underneath is rounded gravel, with occasional beds of sand. 8 km to the east there is a thick till sheet in Coire Carie (6252 - 6253) which must have been covered, if not deposited, by the last glacier there. At the top are sand and rounded gravel, and underneath a great thickness (perhaps 20 m) of layered fine and coarse debris. These beds are discontinuous and tend not to be well-sorted. One bed of fine material about 1 m thick stretches for the 30 m width of two neighbouring sections that are about 100 m apart. It includes laminae crumpled and overfolded during deposition, as well as planar laminae and beds. At one point in this bed the cross-bedding of a stream channel is exposed. Despite such features, this and the previous section lack the characteristic structures and more or less continuous sorted beds associated with outwash or kames. The ground surface above the sections undulates gently and, lower down Coire Carie, the mounds of the last glacier lie on top of this thick deposit. It is suggested that the crude sorting, rounding of gravel and discontinuous bedding were produced by meltwater activity, when the glacier was also depositing till, at a stage prior to final decay when the hummocky drift was laid down.

Many of the valleys in the hills between Loch Tummel and the River Tay (hundred km square 85, sheet 48) are deeply plugged with till. A section in the Frenich burn (8258?), recorded in the Survey memoir, contains 8 feet (2.4 m) laminated silts, 30 feet (9 m) brown till, 2 feet (0.6 m) fine soft yellow sand, and 10 feet (3 m) yellow clay (L.W. Hinxman et al. 1905, p.136). Perhaps the bedded fines were produced by subglacial meltwater activity. (Unfortunately the writer was unable to find this section, though there is no doubt that till thickly fills this valley).

F. Periglacial Landforms.

In chapter 1 it was mentioned that, whereas all types of landforms were mapped during the earlier part of this research, subsequently only hummocky drift was mapped. Throughout the emphasis was on identifying glacial features. Consequently ground occupied by periglacial forms was studied only to ascertain whether glacial deposits were present. Thus any information gathered about periglacial forms is incidental but is thought to be worth recording.

By far the most common periglacial form is the uniform solifluction sheet. Except where rock outcrops are numerous or slopes are too steep or hummocky drift is present, these sheets extend down to 2200 feet (670 m). Characteristically the ground is smooth, gently undulating, dry, stony and covered with vegetation that becomes more stunted at higher levels. In upper Glen Lyon it is only above c.3000 feet (915 m) that there are patches of bare ground within any solifluction sheet that has been traversed by the writer. Lower down, perhaps only below 2500 feet (760 m), the sheets are often veneered with a peaty top that probably stabilises them (cf. R.W. Galloway, 1961, p.78). Thick easily identifiable peat layers are well developed only below c.2200 feet (670 m). It will be demonstrated in chapter 7 that the Glen Lyon valley system was thickly filled with valley glacier ice whose surface level exceeded 2200 feet (670 m) in Upper Glen Lyon (sheet 47). In the valleys above Loch Lyon the ice surface seems to have been not less than 2500 - 2600 feet (760 - 790 m) and in the valley heads probably 3000 feet (915 m). The existence of periglacial features even here down to 2200 feet (670 m) shows that periglacial forms have developed since the slopes were revealed during deglaciation. For example, on the northern side of Beinn a'Chreachain (3744, sheet 47) smooth solifluction sheets (down to 2200 feet, 670 m) and terraces (down to 2800 feet, 855 m) have developed on ground covered by the last glacier in Coire an Lochain. Around Beinn Heasgarnich (4040 - 4440), where the Lyon glacier reached 2500 feet (760 m) and the Heasgarnich corrie had its own corrie glacier, smooth sheets and other features descend to 2200 feet (670 m).

On occasions lobes and terraces are associated with smooth sheets. For example there are turf-banked terraces on the steeper slopes of Beinn Heasgarnich over 2200 feet (670 m), as there are on the Sow of Atholl (6273 - 6274, sheet 48) and on Ben Lawers (6340 - 6441, sheet 48). On Ben Lawers they are actively moving down moderately steep slopes, with 'risers' up to 0.5 m high and 'treads' up to 1.5 m wide (the vegetation on them includes arctic plants). Some of these terraces are almost horizontal, whilst others are oblique to the slope. On Beinn a'Chreachain (3744 - 3745, sheet 47) for example terraces down to about 2600 feet (795 m) are at as much as a 45° angle to the hillside. Lobes are apparently uncommon in the thesis area. They have been tentatively identified on aerial photographs on the steep southern spur of Beinn Dorain (3237, sheet 47), on the slopes below the summit ridge of Meall Breac (6354 - 6454 - 6555) and above 2500 feet (760 m) on a ridge above Loch Ericht (5672 - 5671). Only the first locality was ice-covered in the last glacial stage. The latter two also have turf terraces. There are two localities that may have stone-banked lobes. These are above 2000 feet (610 m) and lie not far outside the margin of the last Loch Rannoch glacier (5651 - 5751, and 6562 - 6662). The latter area may also have stone streams. Stone streams do occur on the Sow of Atholl just below 2500 feet (760 m, squares 6273 - 6274) and at 2200 feet (670 m) overlooking Glen Artney (6819, sheet 54). The upper slopes of Schichallion (7154, sheet 48) are covered with boulders, some of which above c.2500 feet (760 m) seem to form crude stone-banked terraces. This mountain lies outside the extent of the last glaciers.

The best developed non-vegetated features are blockfields. Well developed blockfields are confined to summits that were not covered by the last glaciers. The summit ridge of Ben Lawers - Beinn Ghlas (6240 - 6443, sheet 48) overlooked valley glaciers draining to Glen Lyon and possibly corrie glaciers on its south-eastern side. Blockfields and tors of calcitic schist occupy much of the ridge between 3000 and almost 4000 feet (915 - 1220 m). It is suggested in chapter 8 that the ridge crest and summits were not covered by glacier ice at this time. If tors are at least partly periglacial in origin (C. Embleton and C.A.M. King, 1968), it follows that they and the blockfields may last have been developed during the last glacial period.

It is difficult to generalise from such scanty evidence. Galloway has concluded that major forms (solifluction sheets, stone-banked lobes or terraces, and blockfields) were produced during glacial times and that they occur widely in Scotland above 1800 - 2000 feet (550 - 610 m). Evidence in the thesis area accords with this view for, though stone-banked features and blockfields can be found outside the margins of the last glaciers and though some solifluction sheets occupy valley sides overrun by the last glaciers, none of these features has been found in any corrie or valley head that was an ice source in the last glacial stage. Where hummocky drift occupies a former ice source above 2200 feet (670 m) it does not seem to have been modified by solifluction. It is suggested that major features were last active during deglaciation when much ground had been vacated but when the much reduced glaciers still occupied their sources. The presence of a substantial vegetation cover and of peat above 2200 feet (670 m) suggests that features down to 2000 feet (610 m) are fossil and that the lower limit of present-day solifluction is higher. This limit is probably below 3000 feet, though more detailed study would be needed to distinguish features of periglacial origin from those of non-periglacial mass movement. The turf-banked terraces (and probably the turf-banked lobes) are quite small features and may be forming under present-day conditions.

Table 3.1. Lubreoch borehole records.

Feet		
3A.		
1090.4	ground level	332.4 m
1054.4	bedrock	321.4 m
36.0	drift thickness	11.0 m

0.0-0.5	soil
0.5-6.0	sandy clay and boulders
6.0-6.8	boulders
6.8-14.0	green gravel and boulders
14.0-29.0	gravel

29.0-34.5	boulders
34.5-36.0	gravel

A1.

1074.5	ground level	327.5 m
1053.0	bedrock	321.0 m
21.5	drift thickness	6.5 m

A4.

1054.5	ground level	321.4 m
1028.5	bedrock	313.5 m
26.0	drift thickness	7.9 m

2.

1039.6	ground level	316.9 m
1014.1	bedrock	309.1 m
25.5	drift thickness	7.8 m

0.0-0.5	soil
0.5-2.0	sand
2.0-9.0	sand and heavy gravel
9.0-9.7	boulders
9.7-11.0	sand and heavy gravel
11.0-24.5	boulders, sand, gravel
24.5-25.3	boulders
25.3-25.5	sandy clay

A5.

1035.7	ground level	315.7 m
1015.2	bedrock	309.4 m
20.5	drift thickness	6.3 m

4.

1042.6	ground level	317.8 m
1031.1	bedrock	314.3 m
10.5	drift thickness	3.5 m

0.0-1.0	peat
1.0-6.0	sandy clay and gravel
6.0-6.8	boulders
6.8-9.0	gritty gravel
9.0-11.0	boulders
11.0-11.5	clay and gravel

5.

1048.7	ground level	319.6 m
1040.2	bedrock	317.1 m
8.0	drift thickness	2.5 m

0.0-0.5	peat
0.5-4.5	gravel
4.5-5.5	boulders
5.5-8.0	gritty gravel
8.0-8.5	boulders

10.

1040.4	ground level	317.1 m
1035.4	bedrock	315.6 m
1.0	drift thickness	0.3 m

0.0-4.0	peat
4.0-5.0	soft clay

6.

1041.6	ground level	317.5 m
1035.6	bedrock	315.7 m
0.5	drift thickness	0.2 m

0.0-5.5	peat
5.5-6.0	gritty gravel

15.

1037.9	ground level	316.4 m

0.0-3.0	peat

11.

1038.3	ground level	316.5 m
1012.3	bedrock	308.6 m
8.0	drift thickness	2.4 m

0.0-18.0	peat
18.0-26.0	coarse gravel

12.

1087.7	ground level	331.5 m
1084.7	bedrock	330.6 m
3.0	drift	0.9 m

0.0-3.0	sand clay and stones

16.

1088.2	ground level	331.7 m
1084.2	bedrock	330.5 m
4.0	drift thickness	1.2 m

0.0-4.0	sandy clay and stones

17.

1087.0	ground level	331.3 m
1081.0	bedrock	329.5 m
6.0	drift thickness	1.8 m

0.0-6.0 sand clay and stones

B4.

1129.67	ground level	344.3 m
1119.07	bedrock	341.1 m
10.6	drift thickness	3.2 m

From the evidence in available sections the author suggests that "clay" is more probably silt. Secondly it does not seem possible to correlate the stratigraphies of the various boreholes. This is to be expected for the drift exists as kames rather than as outwash.

Chapter 4. Glen Garry.

A. Previous literature.

Glen Garry lies within the area included in the Geological Survey memoir for the Tummel-Tay district (Hinxman et al., 1905, sheet 55). Very little description or explanation of the glacial landforms of Glen Garry appears in this memoir. The Loch Garry valley lies within the area described in a later memoir for Rannoch Moor and its environs, but again little mention is made of the Loch Garry valley (Hinxman et al., 1923, sheet 54). The main sources of information are the 1:63,360 maps and the unpublished 1:10,560 maps upon which the memoirs were based.

Most of the measured striations shown on the maps occur on the hills well above the valleys and show that when the hills west of Loch Garry were last covered by an ice sheet it was moving eastwards (sheet 48). As this ice sheet reached the Garry-Tummel interfluve it turned more towards the east-south-east. These directions conform with the general trend of the principal valleys of the district, the Allt Shallainn-Glen Errochty and Glen Garry. The Loch Garry valley however lies at right angles to these valleys and appears to be a glacial breach which presumably was formed during various stages in the Pleistocene when thick ice in the Allt Shallainn-Errochty valley was forced to spill northwards into Glen Garry.

The ice sheet glaciation may also have been responsible for the deposition of blocks of Rannoch Moor granite on the hills and in the valleys east of Loch Ericht (Hinxman et al., 1923, 83). This is part of a wider distribution of granite erratics north and east of the Moor. The source of at least some granite erratics may have been within the Ericht - Garry area, for there are several outcrops of granite there, two small ones in the Garry (5767, 6271) and one large one by Loch Ericht (5369 - 5471). There may also be some unmapped occurrences hidden under drift, for granite erratics occur frequently in the Garry valley, though not with the abundance displayed in the Loch Rannoch valley.

Hinxman et al. showed that the striations and granite erratics on the hilltops around Rannoch Moor were the products of ice sheet glaciation. They further identified moundy deposits in the valleys and on the Moor which they believed were formed during the subsequent and most recent stage of the Pleistocene when valley glaciers moved along the valleys. Although they did not refer to the Garry in particular, the impression is given that the moraines in the Garry were deposited during the last valley glaciation. P. Macnair had earlier concluded that moundy drift in the Garry valley north of Dalnaspidal (c.6374) could be ascribed to this period (Macnair, 1908).

J.K. Charlesworth (1955) virtually neglected the Garry in his discussion of glacier recession, apart from the Forest of Atholl which lies immediately to the north of Glen Garry, outside the thesis area.

B. Introduction.

The principal headwaters of the Garry surround Craiganour Forest (5967 - 6167), and include the drainage from three relatively enclosed valleys (5766, 5969, 6070) and three valleys whose watersheds have been breached (5667, 5668, 5769). The hills surrounding these valleys reach 2500-2750 feet (760-840 m) in most cases. They are bounded on the east by a fault line that has been eroded to form a broad pass southwards

Fig.4.1

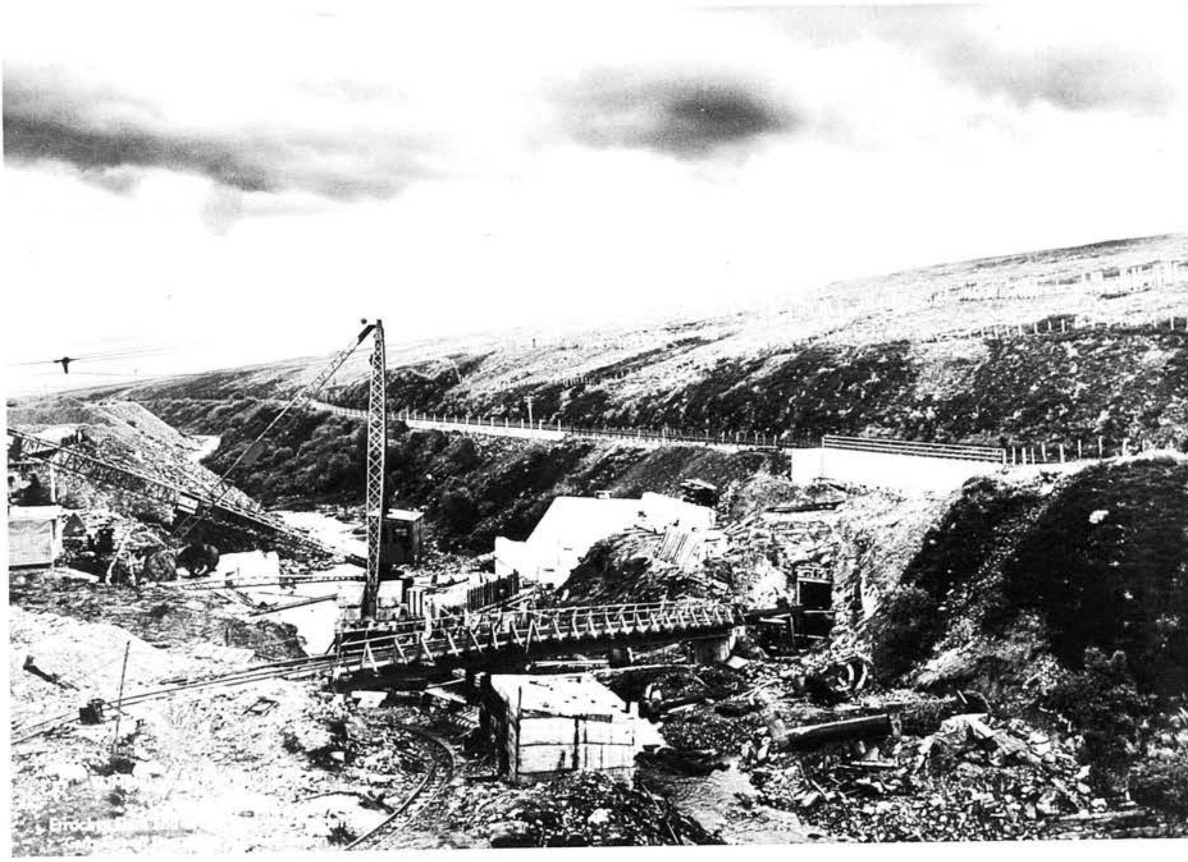


Fig.4.2

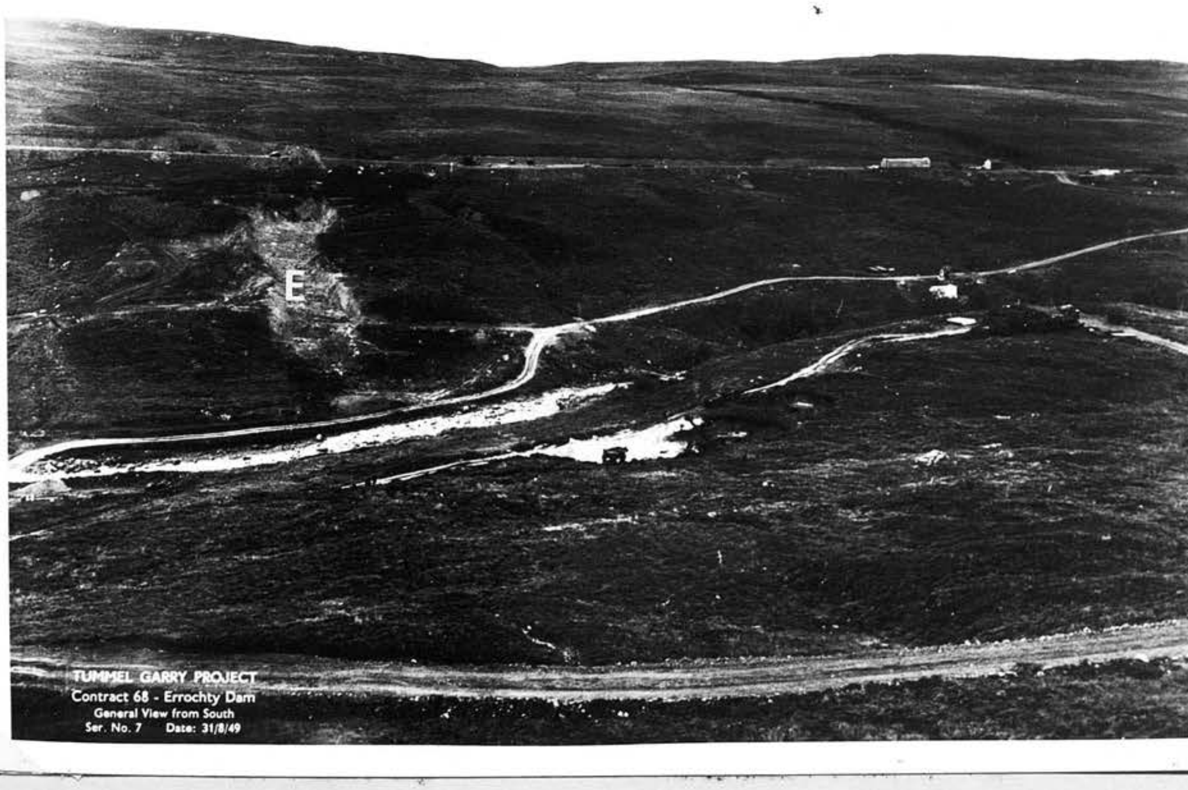

E
TUMMEL GARRY PROJECT
Contract 68 - Errochty Dam
General View from South
Ser. No. 7 Date: 31/8/49

Fig. 4.1. Glen Garry.

The foreground is now occupied by a small dam across the river Garry. Above it the gently undulating, smooth, till-covered hillside stretches south-eastwards (square 7070, sheet 48) away from the limit reached by the last glacier which is immediately upstream from the dam.

Fig. 4.2. The Errochty valley.

The hillsides in this area tend to be gently undulating and smoothly covered with till. The excavation (E), now occupied by the hydro-electric dam (square 7165, sheet 48), shows that bedrock lies close to the surface.

Photographs by permission from the North of Scotland Hydro-Electric Board.

into the Loch Rannoch valley (5964 - 6065) and northwards into the narrow trench of Loch Garry (6269 - 6371) where another fault joins the first. Beyond the southern end of Loch Garry a broad pass connects it eastwards with the Errochty (6366 - 6566). This pass, the Craiganour Forest and the Errochty may have constituted an original west-east valley, approximately parallel to the Rannoch-Tummel valley and to Glen Garry. Loch Garry cuts across this alignment at right-angles. Its valley clearly owes its present form to glacial overdeepening along the fault line and may even be entirely the consequence of watershed breaching by glaciers (cf. Linton, 1949, 12-13).

Northwards the valley of Loch Garry is joined by only one further tributary valley, the Allt Coire Luidhearnaidh (6372). At this point both join the broad west-north-west to east-south-east valley that is called Glen Garry. The Loch Garry valley is clearly only a tributary of this greater valley. The latter is connected with Glen Truim and the Spey by the major glacial breach, Drumochter Pass, only 3 km to the north of Loch Garry. East of Loch Garry the Garry valley receives only minor tributaries until the confluence with Glen Errochty is reached. This point marks the north-eastern limit of the thesis area. The hills and valleys east of Loch Garry (figs. 4.1, 4.2) show much less evidence of glacial erosion than do the upper reaches of the Garry valley (including Loch Garry), where truncated spurs, overdeepened valleys and breached watersheds are numerous. The hilltops immediately above the Loch Garry fault reach 2600 - 2700 feet (800 - 825 m) but eastwards the broad undulating uplands lie below 1700 - 1800 feet (520 - 550 m). Consequently, whereas corries and corrie-like valley heads are numerous to the west of the Garry valley, there are none tributary to Glen Garry to the east of Loch Garry within the thesis area (sheet 48).

C. <u>The features.</u>

Abundant hummocky drift fills the main tributary valley of Loch Garry, the Allt Shallainn (5667 - 6167), and most of the smaller valleys of the Craiganour Forest tributary to the Allt Shallainn. At the western end of the valley of the Allt Shallainn (5667) mounds commence 1 km to the east of the broad pass that leads westwards and then south-westwards and northwards to Loch Ericht. The glacier responsible for the deposition of these mounds must have had its source to the west of the thesis area, as there are no sources in the vicinity of square 5667. From this locality the upper limit of the mounds in the Allt Shallainn falls eastwards, but the width of the valley and the area covered by mounds increases. Secondly, the mounds in the southernmost 1 km of the Coire na Garidha (6068) rise as high as 2100 feet (640 m), only about 100 feet (30 m) lower than those in the western end of the Allt Shallainn (5667), 3.5 km to the west. This small difference in the minimum ice level suggests that glacier ice was also nourished locally in the Craiganour Forest.

It will be shown later in this chapter that the tributary valley at the northern end of Loch Garry must have been occupied by a valley glacier originating in the upper part of the valley (6072). The neighbouring valley, Coire na Garidha, has very similar altitude and dimensions, and it is therefore not inconsistent to conclude that it also supported its own glacier. The occurrence of abundant mounds at the southern end of this valley up to 2100 feet (640 m) implies that in the adjacent valley westwards ice may have attained a similar altitude. Considering that the minimum glacier altitude at the western end of the Allt Shallainn appears to have been about 2200 feet (670 m), the ice at the southern end of the

Coire na Feithe Bige (6968) must have reached between 2100 and 2200 feet (640 - 670 m). Some may have moved southwards from the upper part of this valley to join the main eastward-flowing Allt Shallainn glacier. Two neighbouring passes north-west of these two localities lie at about 2200 feet (670 m). Both have drift-covered floors but lack mounds (5768, 5769). As they lie at the edge of the thesis area it is not known whether any ice was contributed to the Allt Shallainn by way of these passes. The ice-flow map (fig.13.1) for this area must therefore remain incomplete here.

A different question concerns the source of the ice that must have filled the Allt Cro-cloich (5766), the only southern tributary of the Allt Shallainn. The valley head (5666 - 5765) is only 350 feet deep (105 m) and is much less enclosed than valley heads to the north thought to have sustained glaciers. On the other hand the plateau area (5565 - 5665) could have acted as a source of wind-blown snow. Yet, if any glacier was formed in the valley head, it must not have overtopped the back of the valley (5764 - 5765) for the slope above the Loch Rannoch glacier (5764) appears to have been ice-free (chapter 5). An alternative explanation is that the Allt Shallainn glacier moved into this valley. Deposits from this glacier reach 1950 feet (595 m) in square 5967, implying that ice reached a similar height in the Allt Cro-cloich.

It is noticeable that both the maximum altitudes of moundy drift and the implied minimum ice surfaces in the Craiganour Forest are higher on the northern side of the east-west trunk valley than along its southern side. This contrast is consistent with the previously inferred existence of one, or possibly two, valley glaciers tributary to the

the northern side of the trunk valley (5968, 6068). The contrast is maintained eastwards around the southern end of Loch Garry for here the Coire Easan (6169) is filled with hummocky drift, indicating that a corrie glacier was formed in this small hanging valley. However there is evidence around the confluence of the Allt Shallainn and Garry valleys that ice from the Coire Easan may have moved northwards, away from the bulk of the Allt Shallainn ice.

Moundy deposits occupy most of the low ground around the Allt Shallainn-Garry valley confluence (c.6167). On the southern side of the Allt Shallainn the upper limit of mounds declines from about 1900 feet (580 m) to 1500 feet (460 m) in 2 km (6067 - 6165), a gradient of 200 feet per km (60 m/km). This is a much steeper gradient than that farther up-glacier (80 feet per km, or 24 m/km, from 5667 to 5967). The greater declivity was apparently made possible by the lateral spreading of the Allt Shallainn glacier in a piedmont lobe as it reached the wide extent of low ground at the valley confluence. The extent of this lobe is clearly delimited by the distribution of mounds. They run across the mouth of the Allt na Duinish pass (6166 - 6165) at 1500 feet (460 m) but do not enter it, although the sides and floor of this valley are gently sloping. Peat now covers the floor and the lower slopes possess only a thin cover of till. There are apparently no glacial or proglacial deposits in the Allt na Duinish contemporary with the Allt Shallainn mounds. Precisely the same situation occurs in the adjacent pass eastwards (6265) where the Allt Shallainn mounds fail to enter the valley.

On the north-eastern side of the confluence area (6267 - 6367) the upper limit of mounds again occurs at about 1500 feet (460 m). In square 6367 the very gentle slopes above

1500 feet (460 m) are completely devoid of mounds. The 1500 feet (460 m) level is the eastern limit of mounds in the Garry valley, for they do not occur anywhere in the Errochty valley. This supports the inference that the 1500 feet (460 m) contour delimits the extent of the Allt Shallainn glacier on the north-eastern and southern sides of the confluence area. The south-eastern margin of the glacier must have extended from square 6265 north-eastwards into square 6366 a little above 1450 feet (440 m). Most of this margin is still marked by moundy deposits, except where they have been submerged under the edge of an extensive raised peat bog (6366).

The inferred extent of glacier ice in the confluence area contrasts to some degree with that in the Loch Garry valley, which has moundy deposits along its entire length. It would be illogical to imagine that the Allt Shallainn glacier was responsible for the deposition of these mounds, because their upper limit appears to be at least 100 feet (30 m) above that of those formed by the piedmont lobe. The most likely origin for the ice in the Garry valley must therefore have been the Coire Easan (6169). It may be supposed that the Coire Easan glacier moved away from its source by the easier of two routes. The southerly route, into the confluence area, would already have been filled with the Allt Shallainn glacier, at least during the conditions of maximum ice advance. In particular, the Coire na Garidha tributary would have been dropping down steeply towards the piedmont lobe in the square 6167 area. The Allt Shallainn lobe could therefore have deflected the Coire Easan glacier northwards into the Garry trough and indeed may itself have spread some distance into the trough. The curve of the moundy drift limit eastwards and northwards out of the Coire Easan (6169) from 2150 feet (655 m) down to 1650 feet (500 m) in the Garry valley, compared with the higher limit of 1900 - 2000 feet (580 - 610 m) at the confluence (6168), appears to uphold the suggestion of deflected ice flow.

The upper limit of mounds in the Garry valley descends northwards into square 6270. Yet near the northern end of the valley it rises into the Coire Luidhearnaidh, attaining 1900 feet (580 m) on the southern side of this corrie and 2000 feet (610 m) on its north-western side (6172). The Coire Luidhearnaidh glacier appears to have had two probable routes of escape, one southwards into the Loch Garry valley, and the second eastwards down Glen Garry. A third, in the opposite direction up Glen Garry, is uncertain for reasons given below. As Coire Luidhearnaidh is three times the area of Coire Easan and as its headwall rises to 2500 feet (760 m) compared with 2200 feet (670 m), it would have been a considerably larger source of ice.

It is therefore probable that a considerable part of the ice in the Garry valley was a transfluent branch of the Coire Luidhearnaidh glacier, and the other part the deflected Coire Easan glacier, the two meeting perhaps in square 6270 where the upper limit of the mounds descends to its lowest level in the Garry valley (1650 feet, 500 m). The total absence of mounds from the eastern wall of the Garry trough is due to the remarkable steepness produced by glacial erosion along the two concurrent fault lines on this side of the valley.

The blocking of this route by the opposing Coire Easan glacier must have emphasised the greater importance of the route eastwards down Glen Garry. Around the mouth of the Coire Luidhearnaidh the mounds reach 1750 - 1900 feet (530 -

580 m) (6272) and in Glen Garry, on the opposite hillsides 1750 - 1800 feet (530 - 550 m) (6573 - 6672, 6471 - 6571). Northwards their margin is lower but, as the northern limit of the thesis area occurs there, it is not possible to discover whether the mounds there (6373 - 6374) were deposited by ice from the north or by a transfluent branch of the Coire Luidhearnaidh glacier.

Along the route eastwards down Glen Garry the upper limit of abundant fresh hummocky drift gradually declines from about 1800 feet (550 m) in the squares 6571 - 6672 area to about 1650 feet (500 m) (6770) in 2 km. On the southern side the upper limit drops more steeply thereafter, being 1400 feet (425 m) 2 km farther on (6971). The upper limit on the northern valley side descends similarly, though less regularly owing to the variations in slope angle, a factor affecting the preservation of deposits on the slope. In square 6971 the upper margin drops more steeply still to 1200 feet (365 m) where the mass of hummocks abruptly ceases in the centre of the valley. The north-eastwards orientation of a group of possibly submarginal drainage channels (6771) that run obliquely downslope only 3 km back from this limit concurs with the eastward declivity of the upper limit of mounds in implying that the glacier's motion was eastwards.

To the east of the very sharp down-valley limit of the mounds, no similar landscape exists anywhere in either Glen Garry or in its tributary Glen Errochty. Scattered subdued mounds occur spasmodically on the lower hillsopes but not in sufficient numbers or with sufficient clarity to be mapped as landform units. (The approximated boundaries for moundy deposits in lower Glen Garry and Glen Errochty reflect this). The great majority of the landscape east of the Glen Garry limit, as well as to the south of and above the extent of the former Glen Garry glacier, consists of smooth undulating till-covered slopes (fig.4.1). Apart from the rockier Beinn a'Chuallaich (6861), the landscape of Glen Errochty is strikingly similar (fig.4.2). The very clear contrast between the presence of abundant hummocky drift up-valley and its absence farther down-valley therefore verifies the conclusion that the down-valley limit of the hummocks marks the down-valley limit of the Garry glacier.

D. Summary.

During the period of maximum glaciation the ice sheet or sheets moved eastwards across the Garry, submerging the higher hills and leaving granite erratics, some of which were derived from Rannoch Moor. Glacial diffluence hollowed out the weak fault line zone to create the Loch Garry valley. The glaciers of the last stage of glaciation were confined within the valleys in which they deposited abundant hummocky drift. At least one glacier entered the Craiganour Forest from the Ericht district, but the remainder of the ice was nourished locally within Craiganour Forest, mainly in the higher northern valleys. This ice formed an eastward-moving glacier that proceeded down the east-west trunk valley, the Allt Shallainn, to the broad confluence with the Garry valley where it spread out and terminated in a piedmont lobe.

The Garry valley was occupied by convergent glaciers, one from the south deflected northwards by the piedmont lobe, and the other a transfluent branch from the north. At the northern end of the Garry valley the other transfluent stream moved eastwards down Glen Garry until at 6 km distance it attained its limit. To the east of the Glen Garry and piedmont lobe limits there does not appear to have been any glacier ice for comparable abundant moundy deposits are entirely absent.

Chapter 5. Loch Rannoch.

A. Previous literature.

The principal early sources of information on the Loch Rannoch area are the maps and commentaries produced by officers of the Geological Survey. J.S. Grant Wilson (1888) described the profiles ~~of~~ and sediments in Loch Rannoch and the probable extent of the rock basin, in part of which the present loch lies. In 1905 a survey memoir on the Blair Atholl area described many glacial features from the eastern end of Loch Rannoch eastwards into the Tummel, Garry and Tay valleys (Hinxman et al.). The 1:63,360 map, accompanying the memoir, was found useful in this thesis for it portrays the distribution of various types of deposit and measured striations over a large area. Together with the distribution of erratics from Rannoch Moor and from Ben Vuroch (north-east of Pitlochry), the striations and deposits were believed by the authors of the memoir to show that an ice sheet had once moved east-south-eastwards across the region from the Rannoch Moor area.

Detailed evidence regarding the occurrence of erratics, striations, exposures in drift deposits, and the character of types of deposit in numerous areas was often checked by the present writer and found to be accurate.

In 1910 B.N. Peach and J. Horne briefly described all the lochs of the area, classifying all of them as rock basin lakes. They noted that, of all the large valleys radiating from Rannoch Moor, the Loch Rannoch valley is the widest and that it must have acted as a major outlet for ice from Rannoch Moor when ice sheets were centred on the Moor. Rannoch Moor and the major part of the Loch Rannoch valley were described by Hinxman _et al._, in 1923. The evidence they presented is of major importance in interpreting the glacial history of the area. They discovered that erratic blocks of grey Rannoch Moor granite are widely distributed on the hills and in the valleys for as much as 60 km round Rannoch Moor, being especially abundant eastwards. On the mountains of Glen Coe to the west of the Moor, granite erratics were found perched at altitudes of 2000 - 3000 feet (610 - 915 m), high above the Moor whose surface lies mostly at about 1000 feet (305 m). Many more were found widely dispersed at high altitudes north, north-east and east of the Moor. The authors considered that these boulders must have been eroded from the Moor and carried by a thick ice sheet streaming radially outwards from the Rannoch Moor basin at high levels.

On the western part of the Moor, at 1000 feet (305 m), near the base of the high western mountain rim, they detected blocks of Glen Coe volcanic rock that had been transported eastwards into the Moor from the north-eastern part of Glen Etive (sheet 47). It was also noted that others had similarly been carried eastwards on to the floor of the Moor from corries in the western mountains (Hinxman _et al._, 1923, quoting E.B. Bailey _et al._, 1916). They concluded that the glaciers at the last stage of glaciation flowed eastwards into the Moor. Furthermore the striations on the floor of the Moor and along the Loch Rannoch valley showed that the glaciers had moved across the Moor and eastwards out of it at relatively low altitudes, being confined within the valleys as valley glaciers. In brief, the evidence from erratics and striations demonstrated that in earlier periods Rannoch Moor was the centre of radiative dispersal of an ice sheet and that later the Moor was occupied by valley glaciers moving into and across it eastwards.

In addition to mapping the distribution of drift deposits, Hinxman _et al._, (1923), noted a series of conspicuous lateral moraines that run along the southern side of the Loch Rannoch valley, in places blocking the mouths of tributary valleys. The present writer found many of these observations to be accurate, except that hummocky drift was discovered to be much less widely distributed than the Survey map suggests.

J.K. Charlesworth's history of glacial retreat (1955) is of little value, but it is interesting to note his suggestion that two diffluent ice tongues moved southwards from the Loch Rannoch glacier to Glen Lyon (5651, 5951, sheet 48). Charlesworth rarely invoked glacial diffluence in his discussion of western Perthshire. He also apparently ignored the large lateral moraine barriers that block both valleys (5651, 5951), although these had been described in the Survey memoir (Hinxman _et al._, 1923).

B. Introduction.

The area to be discussed in this chapter extends from about the western end of Loch Rannoch eastwards for 30 km to half-way along the Loch Tummel valley (sheet 48). From the watershed in the hills south of Loch Rannoch it is 15 km northwards to the watershed north of the loch. Eastwards the hills and watersheds are lower in the Tummel valley section, and the distance north to south only about 7 km. The Loch Rannoch valley may be considered as the eastward extension of the Moor of Rannoch basin (sheet 47). Only at the eastern end of the loch do hills approach the centre of the valley and restrict it to a width of 1 - 1.5 km.

On the southern side of the Loch Rannoch valley the hilltops form a dissected plateau surface between 2000 and 2600 feet (610 - 795 m). Four of the valleys in these hills are connected southwards by breached watersheds with valleys tributary to Glen Lyon (5449, 5651, 5951, 6150). To the east of this area the hills become much more extensive and in places much higher. Directly east of the four breached watersheds the Carn Gorm - Meall Garbh - Carn Mairg hills rise above 3000 feet (915 m) where resistant calc-sericite schists and quartzites appear. Northwards the hilltops lie below 2600 feet (795 m). In this area (hundred km square 65) south of Loch Rannoch the pattern of valleys is more dendritic, is much less glacially modified than are the valleys to the west. The hills sweep down to the south-eastern end of Loch Rannoch and are continued north-eastwards by the broad mass of Beinn a'Chuallaich, most of which lies below 2500 feet (760 m).

North-west of Beinn a'Chuallaich two low hills (6165, 6365) partially separate the Loch Rannoch valley from the Garry and Errochty valleys.* Two passes, at 1600 feet (490 m) (6064) and 1500 feet (460 m) (6264), connect the Garry and Loch Rannoch valleys. A third much broader pass at 1200 feet (365 m) (6362) leads from the Loch Rannoch to the Errochty valley. West of these passes the hills of the Talla Bheith Forest culminate in a plateau area about 2500 feet (760 m). These hills extend south-westwards, beyond the area of sheet 48, into the north-eastern corner of Rannoch Moor.

*(In this thesis the term 'Errochty valley' applies to the valley now flooded by the Errochty dam. Down-valley from the dam the valley is called 'Glen Errochty', as on the Ordnance Survey map. Similarly the name 'Glen Garry' is used for the Garry south-east of Dalnaspidal, and the term 'the Garry valley' for the valley headwards, including Loch Garry).

Between the hills bounding the Loch Rannoch valley to north and south is a broad valley bench. On the southern side this is bounded by the steep crags of Cross Craigs (5352) at 1250 feet (381 m) and eastwards by gentler hillslopes at about 1500 feet (455 m). North-eastwards the bench narrows and lies below 1100 feet (335 m) as the hills curve down to the eastern end of the loch. Drainage is markedly impeded on the gentle slopes of the bench, except where the Camghouran, Dall, Bogair and Carie burns are engorged in the bedrock. North of the loch the valley bench undulates much more, yet there is still a very large area of gentle slopes below about 1750 feet (535 m). The major streams are incised in drift but only in part engorged in the bedrock.

Loch Rannoch is a rock basin lake which is shallow at its western end and deepens eastwards, where it is mostly about 300 feet (90 m) deep. It has been eroded 800 - 1000 feet (245 - 305 m) below the valley bench. At its eastern end the loch shallows rapidly, its floor rising from about 380 feet (115 m) to the shore at about 670 feet (205 m) in 1 km. Although no bedrock appears in the outflowing river Tummel until Dunalastair is reached (7058), steep rocky crags overlooking Kinloch Rannoch (6658) narrow the valley to a mere 1 km. They are developed on steeply dipping resistant schists which cross the valley northwards here. 1 km west of Kinloch Rannoch the western ridge of Beinn a'Chuallaich is composed of felsite dykes which reappear on Meall Dearg (6457 - 6557) on the southern shore. In view of the continuity of these rock outcrops and the upstanding ridges that they form, it is very likely that the rapid shallowing of the eastern end of the loch reflects the existence of a buried rock barrier on the valley floor commencing 1 km west of the eastern end of the loch.

From this point (6558) eastwards for 7 km, northward-striking resistant strata cross the valley and probably form a continuous buried rock bar. At Dunalastair the rock reaches ground level as an impressive barrier of metamorphosed limestones and quartzites that southwards form the isolated mass of Schichallion. Dunalastair overlooks the eastern extremity of a belt of water-laid sediments that commences at the eastern end of Loch Rannoch and forms a relatively flat valley floor infill. These sediments terminate at Dunalastair where the river Tummel cuts deeply through the rock and makes its way eastwards by waterfalls and rapids.

From Dunalastair the Tummel valley opens out eastwards. The northern side of the valley is the lower, for the low gently undulating ridge separating the Tummel from Glen Errochty rarely exceeds 1500 feet (455 m). The southern side, east of Schichallion (7154), often exceeds 2000 feet (610 m) in the broader, steeper Farragon ridge, lying between Loch Tummel and the Tay valley. This ridge shows abundant evidence of glacial erosion, even on its highest parts, being rugged with jagged rock.

C. Features of the Loch Rannoch valley.

The subject of this chapter is the Loch Rannoch valley system, its continuation the Loch Tummel valley system, and the Errochty valley. The boundaries of the area have been selected on several bases. The western boundary is entirely artificial, the western edge of sheet 48. Northwards, to the north and north-west of the Loch Rannoch valley, the Ericht - Garry watershed was selected, though this is more relevant to the study of the Garry valley. Its neighbour the Errochty appears not to have been occupied by ice during the last glacial stage but, as it is physically part of the Glen Garry drainage system, only the upper section of the valley is included in this chapter. On the southern side of the Loch Rannoch valley the hills form a natural boundary eastwards into the Loch Tummel valley. The latter is included within this chapter in order to clarify the contrasts in landscape inside and outside the limit of the last stage of glaciation.

C.1. <u>The southern side of the valley.</u>

The hummocky drift that extends widely across the Loch Rannoch valley is part of a larger spread that occupies the Rannoch Moor basin (sheet 47). Although the author has only mapped Black Mount and the south-eastern flank of the Moor, it seems clear from the Geological Survey maps and from checking easily accessible areas that the distribution of moundy drift is continuous. In the Loch Rannoch valley (sheet 48) mounds extend from the base of the hills on the southern side across to those on the northern side (hundred km squares 55 and 56). On the southern side there is a series of lateral moraines from Cross Craigs (5451) to Meall Druidhe (6356), evidently deposited along the margin of the Loch Rannoch glacier.

In two of the diffluence channels that run southwards towards Glen Lyon, the Lairig a'Mhuic (5650) and the Lairig Chalbhath (5951), there are hummocks. In the Lairig a'Mhuic they occupy the part of the valley that is clearly tributary to Glen Lyon. In the Lairig Chalbhath the mounds occur immediately south of the col (c. point 5951) and in the southern part of the valley. As there are no forms in or tributary to these two lairigs that could have supplied corrie glaciers, the ice that deposited the mounds must have come either from the Loch Rannoch valley or from Glen Lyon. The available evidence is of three types. Some suggests a southward flow of ice, some a northward flow, and some evidence could suggest either.

In the Lairig Chalbhath low mounds run from the col (5951) southwards below 1750 feet (535 m) for 1 km until the sides of the valley become too steep. Farther south more mounds occur (5849) near the valley confluence below 1500 - 1600 feet (455 - 490 m) on quite steep slopes above the engorged burn. On the gentler slopes at the valley confluence (5848) much larger clearer mounds commence and maintain their size, sharpness and abundance down into the trunk valley of Glen Lyon. Overall, the gradient of the upper limit of mounds falls southwards. This is to be expected as the valley descends southwards. (In narrow valleys throughout the thesis area the upper limit of mounds tends to descend in the same direction as the valley, irrespective of the direction of ice movement in the valley). The southward descent of the mounds therefore does not necessarily indicate southward ice movement. In the Lairig a'Mhuic (5650) the evidence is equally ambiguous, although the mounds here commence (or terminate) 1.5 km south of the Loch Rannoch valley and some 300 feet above the floor of the lairig (5649, 5749). Between 1500 and 1800 feet (455 - 550 m) the linear features marked are faint and the upper limit marked may in consequence be inaccurate.

In the Lairig Chalbhath the mounds on the western side of the col (5951) include occasional erratics of Rannoch Moor granite. These are few in number, as are the granite blocks that occur spasmodically in Glen Lyon, as for example around Keltneyburn where the Lyon meets the Tay (c.7749). Such erratics are however super-abundant in the Loch Rannoch valley, including the lateral moraine at the northern end of the Lairig Chalbhath. This distribution suggests that at some time or times diffluent ice moved southwards through this lairig. There is no proof that this happened during the last stage of glaciation, which was by valley glaciers. It is just as likely to have occurred when much thicker ice submerged the hills and left Rannoch granite erratics on Schichallion (7154) and Carn Mairg (6651) at about 3000 feet (915 m) (Hinxman et al., 1905). The Rannoch Moor granite bedrock lies immediately to the west of the area of sheet 48. Erratics from there are abundant in the Loch Rannoch valley within the area undoubtedly occupied by the Loch Rannoch glacier. But in the Lairig Chalbhath, only 1.5 km south of the Loch Rannoch valley, there are very few granite erratics. Although this contrast has not been quantified, it is striking. As the granite crumbles easily into gravel when weathered, it may be that the last southward-moving diffluent in the col preceded the last stage of glaciation and that its granite erratics have mostly weathered away, just as have those discovered in Glen Lyon. On balance it appears more probable that the mounds in the col were deposited either by ice of the penultimate stage of glaciation or by a diffluent from Glen Lyon, rather than that they were left by a diffluent from the Loch Rannoch glacier during the last stage of glaciation.

The distribution of the mounds in the two lairigs, rather than the gradients of their upper limits, also suggests that the last ice in the lairigs came from Glen Lyon. Apart from the subdued mounds on the col of the Lairig Chalbhath, which were discussed above, the abundant clear mounds lie well south of the watershed and pass without a break into Glen Lyon. They do not join up with the Loch Rannoch mounds.

From the evidence in the Loch Rannoch valley it is evident that during the last stage of glaciation the Loch Rannoch glacier was 12 km or so wide and in the middle at least 1300 feet (395 m) thick. However, all but the central 2 - 2.5 km lay over the valley bench where it must have been about 500 feet (150 m) thick. The Glen Lyon glacier, south of the two lairigs, was less than 5 km wide and up to 1200 feet (365 m) thick in the middle. But Glen Lyon is narrow and steep-sided, suggesting that the glacier could have had only limited possibilities of evacuation. By contrast the Loch Rannoch glacier had ample space in which to spread out. It is consequently more likely that the Lyon glacier would have sent diffluent branches northwards into the two lairigs, which did not possess their own corrie glaciers, than that the Loch Rannoch glacier did so.

The pattern of lateral moraines in the Loch Rannoch valley is one of the clearest indicators of a former glacier margin anywhere in the thesis area. The largest of these features are the three that block the mouths of the two lairigs (5952, 5651) and their western neighbour (5551). In the mouth of the last, the small stream breaks through the moraine at 1900 feet (580 m), and the top of the moraine at its extreme ends is 2000 - 2100 feet (610 - 640 m). At the mouth of the Lairig a'Mhuic the equivalent figures are 1700 and 1850 feet (520, 565 m). Eastwards, the highest lateral moraine reaches about 1750 feet (535 m) (5852), and across the mouth of the Lairig Chalbhath the moraine barrier lies between 1500 and 1550 feet (455, 470 m). These features imply that the ice margin must have been about 150 - 200 feet (45 - 60 m) high across the valley mouths. Furthermore, being such large impressive features, the glacier must have taken a long time to build them. Consequently it may be inferred that they were built up more or less continually throughout the active life of the glacier on the valley bench.

From this viewpoint it would therefore be difficult to argue that the diffluents in the lairigs came from Loch Rannoch because it would be necessary to suppose that diffluents moved into the three valleys (5551, 5651, 5952) and were then abandoned, even although the surface of the trunk glacier still lay 150 - 200 feet (45 - 60 m) above the floors of these valleys. It is more logical to suppose that the Loch Rannoch glacier maintained continual lateral moraine construction and did not require to branch southwards into these valleys. It follows that the ice in the two lairigs was derived by diffluence from the constricted Glen Lyon glacier. The distribution and character of the glacial deposits are entirely in harmony with this deduction.

In the Loch Rannoch valley the series of lateral moraines that runs from the Dall burn (5451) to the Lairig Chalbhath (5952) is considered to represent the position of the Loch Rannoch ice margin during its period of maximum activity. Across the mouth of the valley of the Dall burn (5451 - 5551) the western end of the moraine barrier reaches 2100 feet (640 m). Here it is about 30 m thick, but as it meets the eastern hillside (5551) it suddenly diminishes and is continued without a break by a narrow lateral ridge only 2 - 3 m high at about 1850 feet (565 m). At the Lairig a'Mhuic the top of the moraine barrier reaches 1850 feet (565 m) and is about 20 m thick. To the east of the lairig the same sudden diminution in size is repeated where the moraine leaves the valley mouth and becomes confined to the hillside at 1850 feet (565 m).

Between the two lairigs the upper limit of the lateral moraines decreases to about 1750 feet (535 m) in square 5852, and the moraine barrier across the mouth of the Lairig Chalbhath drops from 1650 to 1500 feet (505 - 455 m) (5952). To the north-east (5953) the upper limit of undoubted moundy deposits is about 1500 feet (455 m).

These altitudes enable estimates of the ice surface gradient to be made. The highest lateral moraines occur immediately west and east of the Lairig a'Mhuic at 1850 feet (565 m), 150 feet (45 m) below a solifluction sheet at 2000 feet (610 m) (5751). It is quite possible that the periglaciation took place whilst the glacier lay immediately downslope, and it is very unlikely indeed that the glacier could have occupied the slope above 2000 feet (610 m) because it does not appear to have entered the Lairig a'Mhuic. The downslope limit of the soliflucted sheet appears to have been determined by the concave break in slope. It is consequently logical to suggest that the ice surface lay at about 1850 feet (565 m) in square 5751 and that it rose westwards. On the basis of ice-marginal forms on the northern side of the Loch Rannoch valley a gradient of 40 feet per km (12 m/km) is suggested, giving an approximate altitude of 1950 feet (595 m) at the mouth of the Dall burn (5551) and of 2050 feet (625 m) against Cross Craigs (5352) (cf. C.M: Son Mannerfelt, 1949*; who estimated 10 - 20 m / km for a decaying ice sheet).

In the Lairig Chalbhath around the present stream confluence (5952), up-valley from and contiguous with the

* Mannerfelt's calculations are derived from the measurement of the gradients of meltwater channels that he believed to have been marginal. Later research has suggested they may have been submarginal, in which case the ice gradients would have been even less (C-G. Holdar, 1957).

moraine barrier, there is an area of terrace remnants dissected by these same streams(T). They appear to the unaided eye to belong to a common level as their slope is down-valley and in towards its axis. This latter gradient is steeper than would be expected of river-deposited terraces, and the terrace is much too extensive at c.250 m diameter to be due solely to deposition by the present streams so close to their sources. The true extent of the terrace is concealed by thick peat growth on its surface. The gentle slope of the peat continues all the way to the col, obscuring the headward portion of the terrace. However it is clear that the terrace thickens rapidly down-valley to the moraine barrier, so that its surface gradient northwards is much less than that of the present streams.

Parts of the left bank of the northward-flowing stream are undercut, particularly at 595524 where the least slumped of all the exposures occurs. Under the top peat layer is approximately 7 m of sands and gravels. The upper half of the section consists of graded beds of sands and rounded gravels, up to the size of small boulders, alternating with thinner bands of sands and silts, but the predominant materials are coarse. The lower half of the section consists of predominantly finer deposits, silts to coarse sand, also as graded beds. The junctions between the coarser base of a bed and the much finer top of the underlying bed appear always to be abrupt and horizontal. The grading is from a coarse base upwards, with the predominant grade becoming finer upwards. The beds of fine sand or silt are much thinner than the coarser beds. In one bed festoon cross-bedding occurs; the length of each wave is c.20 cm, and the amplitude c.5 cm. Due to the looseness of the sand. in which these festoons occur, it was not possible to determine their direction of dip.

The deposit has most of the diagnostic characteristics of graded bedding as defined by F.J. Pettijohn (1957): uniformity of thickness along a bed, abrupt interfaces between strata, the appropriate distribution of particle size concentrations, and the virtual absence of cross-bedding. The consensus of opinion, as given by Pettijohn and by Ph. H. Kuenen (1953), is that graded bedding is produced either during settling in comparatively still water or by a river whose competence is decreasing. However, Kuenen states that "graded sands deposited by streams are characterised by steep, large-scale cross-bedding of variable direction, wash-outs, irregularity of bedding ....." (1953, p.1045).

The presence of virtually horizontal, uniform, graded beds suggests settling in still water. On the other hand, the coarseness of some beds, the sharp junctions between beds, the alternating coarser and finer beds, the rounding of the gravel and the festoon cross-bedding indicate the action of running water. Consideration of the topographic situation may allow reconciliation of these requirements.

The lateral moraine barrier (5952) shows that the Loch Rannoch glacier moved eastwards across the valley mouth, thereby presumably damming it. The lateral moraine rises steeply above the left bank of the present-day stream at an unstable angle and is absent from the right bank, where however there is a thick drift sheet. The terrace continues without a break into the moraine, which is predominantly sandy till with angular gravel, with numerous boulders on its top surface.

The merging of and sandy nature of both terrace and moraine imply a common source of deposits, at least to some degree. (Unfortunately the exposure in the moraine is steep and dangerous, so it was not possible to search under its slumped face for structures). Meltwater drainage was evidently from west to east beside, on or in the glacier (this matter is discussed later). It seems necessary to postulate meltwater contribution to account for the large volume of water-sorted sediment and for the high percentage of sand in both the moraine and the terrace. The coarser particles in the moraine are not rounded however.

The consequence of the valley mouth being blocked by the glacier would presumably be the build-up of an ice-marginal lake into which glacial meltwater, snowmelt and groundwater would drain (from squares 5951, 6051 and adjacent ground). The sediments brought in down-valley towards the glacier and also directly from the glacier would presumably form a layer of drift that would at present resemble neither a delta sloping southwards nor a stream terrace sloping northwards but rather a mixture of the two. It is suggested that large volumes of inflowing water were responsible for the alternations of silt, sand and gravel and for their rounding and that the graded bedding was produced by these streams flowing into a lake. Bottom currents or temporary drainage may have created the festoon cross-bedding, and sudden heavy periodic influxes may have laid down the gravel beds. Such an explanation may account for this combination of indicators of running water and still water.

To the north-east of the Lairig Chalbhath the upper limit of the glacial deposits is about 1500 feet (455 m) as far as the Creagan na Corr (6054). Here linear ridges below the western side of the crag may be the expression of the bedrock.

Fig. 5.9

Fig. 5.9. <u>The southern shore of Loch Rannoch at Carie.</u>

The apparently chaotic spread of moundy drift is interrupted by a number of upstanding porphyrite dykes (d-d, p-p, r-r) that run north-north-eastwards down to Loch Rannoch. Most of squares 6056 (background) and 6156 (foreground) are shown. Large boulders of ablation till can be seen in the foreground (b,b).

Unfortunately most of the valley bench on this side of the loch, the hill south of Creagan na Corr (6053, 6153, 6054, 6154), and the Coire Carie (from 6253 northwards) were planted with coniferous trees during the later 1960's. Only the steeper slopes above 1500 feet (455 m) (5552 - 5752) or 1250 feet (380 m) (5353 - 5452) are free of trees. Most of the lateral moraine system was still accessible and visible during 1970, but the Creagan na Corr area was not. Therefore the suspicion that the ridges there may not be moraines cannot be verified. However the 1:63,360 Geological Survey map indicates the presence of a porphyrite dyke on the western side of Creagan na Corr with the same alignment.★ The conspicuous narrow straightness of these ridges, as seen on the aerial survey photographs, further suggests the geological explanation (fig.5.9).

If this is accepted, it follows that the upper limit of deposits (1500 feet, 455 m) north of Lairig Chalbhath represents the maximum level of the ice. This implies that the ice surface must have steepened from a gradient of 40 feet per km (12 m/km) west of the Lairig to 100 feet per km (30 m/km) east of it. Projection of the latter gradient would imply that the Loch Rannoch glacier passed north-eastwards below the mouth of Coire Carie (6155), reaching about 750 feet (230 m) at Kinloch Rannoch. Ice marginal evidence here confirms that this surface gradient estimate is reasonable.

In the Coire Carie (6351 - 6254) drift deposits occur on the valley floor from source to mouth. The streams are

★These dykes are very common in the terrain north and south of the eastern part of Loch Rannoch (fig.5.9). In the Loch Rannoch - Errochty pass, for example, there are almost exactly twice as many dyke outcrops as are marked on the Survey map.

incised into the drift, thus making its presence apparent, from 2200 feet (670 m) just below the steep backwall of the valley head. The incision of the Carie burn deepens down-valley until, from about 1100 feet (335 m), the Carie is cut into the bedrock (6155). A thickening layer of till is revealed from square 6351 to square 6253; down-valley it does not thicken further. The head of the Coire Carie is relatively enclosed by hills. This and the presence of fossil periglacial deposits down to 2000 feet (610 m) on Meall Droilichean (6152) make it very unlikely that Loch Rannoch ice could have overridden the Meall Droilichean - Creagan na Corr ridge (6152 - 6054). Therefore the Coire Carie must have acted as an ice source in its headward parts (6351). Its mounds commence in square 6253 between 2000 feet (610 m) and the valley floor at 1650 feet (505 m) for no apparent reason. They are concentrated on the eastern side of the valley, whilst west of the river till blankets the lower slopes. The upper limit of the mounds descends towards 1500 feet (455 m) where the Loch Rannoch and Carie deposits converge (6255). North-eastwards the upper limit is about 1250 feet (380 m) until it curves rapidly down towards the loch (6457).

Along the most easterly 2 km of the southern side of Loch Rannoch (6457 - 6557) hummocky drift occupies the lower slopes. These slopes are almost all wooded, rock outcrops are frequent, and consequently mapping is difficult. There is no doubt that the mounds that stretch up to 1250 feet (380 m) in square 6356 pass eastwards at decreasing altitudes into square 6457. The boundary ascribed to the latter was derived from aerial photograph interpretation and could not be checked in the field because of dense woodland. To the east (6557) the slopes steepen but the woodland is thinner. Hummocky drift definitely occurs below a maximum of 900 feet (275 m), above which rock lies at or near the surface. Exactly above the south-eastern corner of the loch the mounds give way to a single kame terrace at about 720 feet (220 m) which merges eastwards into channelled outwash deposits just below 700 feet (215 m) on the valley floor (6657, 6658). Much of the western margin of the outwash is kettled, showing that its western edge lay against the glacier whilst rivers flowed off the ice eastwards and deposited the outwash spread. (The outwash features will be discussed in more detail in section C.3 of this chapter). It will also be shown in sections C.3 and D that there are no other deposits in the Loch Rannoch valley to the east of the Kinloch Rannoch area that could have been deposited by the Loch Rannoch glacier. Consequently it is apparent that the outwash deposits, which commence at the eastern end of Loch Rannoch, mark the position of the terminus of the Loch Rannoch glacier.

It has already been shown that the highest lateral moraines along the southern side of the Loch Rannoch valley delimit the ice edge at about its maximum thickness. They are however only the top-most of a series of parallel ridges. These lie in the 300 feet (90 m) or so below the highest lateral moraines from the Dall burn (5552) eastwards to the Allt na Bogair (5952). Small meltwater channels (5752) and larger channels (5852) show that drainage in the vicinity of the ice margin paralleled the direction of ice movement. These features evidently were created whilst the glacier remained active but was thinning in stages by some 300 feet (90 m). Each lateral moraine marks a period of deposition whilst the ice margin

Fig. 5.8

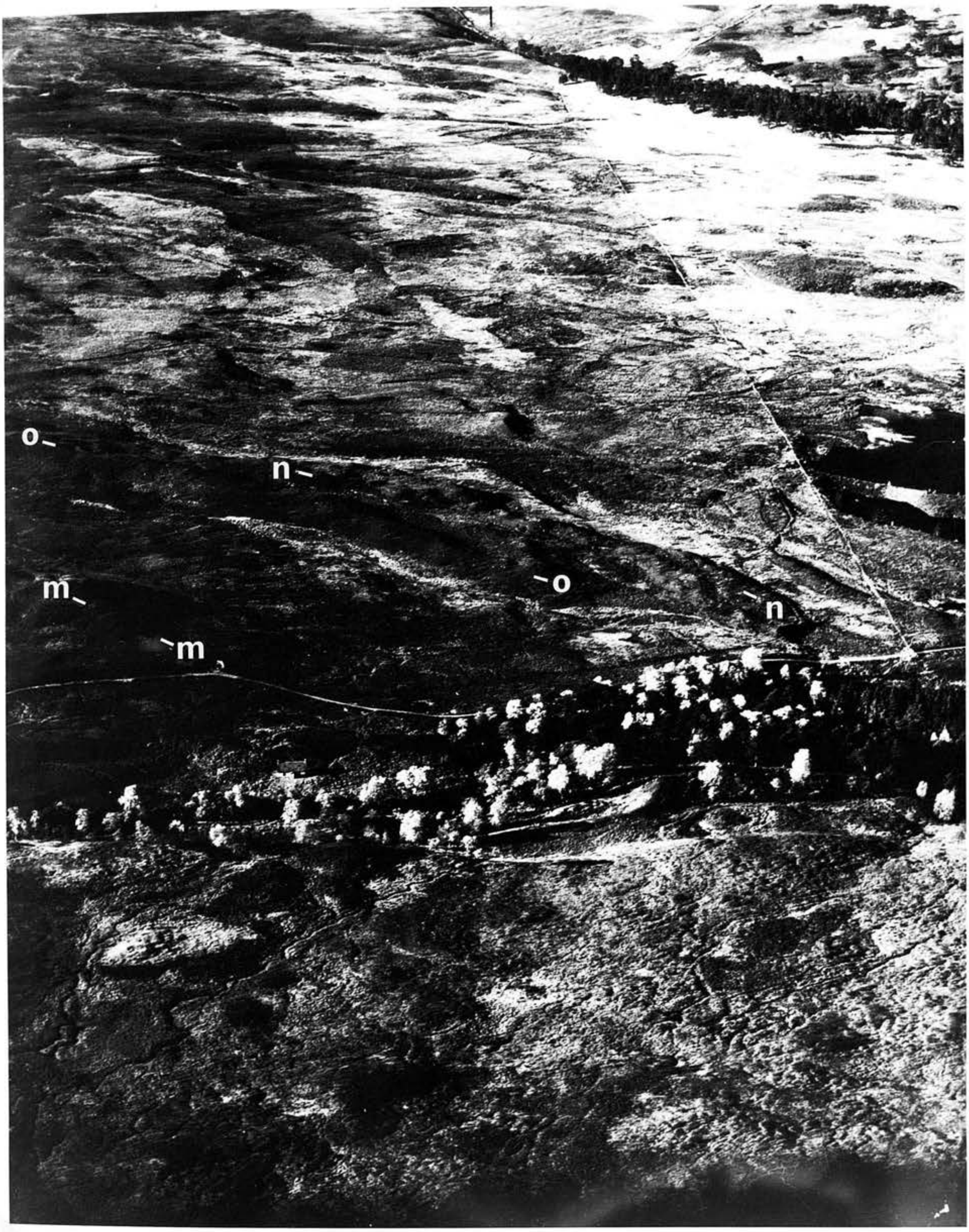


Fig. 5.8. The Loch Rannoch valley bench.

Numerous small mounds, thought to be kames, occupy this part of the valley bench (south of Loch Rannoch) between the Allt na Bogair, in the foreground, and the Dall Burn in the distance. The reservoir on the right of the photograph lies in square 5954 (sheet 48). Linear mounds (m-m, n-n, o-o) that stretch east-north-eastwards towards the reservoir may have been formed by subglacial drainage parallel to the ice margin.

maintained a more or less constant position against the hillside.

Meltwater drainage is delineated also by the esker in square 5353, which descends from 1250 feet (380 m) to less than 1150 feet (350 m) north-eastwards, and then climbs back to 1250 feet (380 m) south-eastwards. Its fresh, sinuous, undisturbed shape implies that the glacier, at least on the valley bench below 1250 feet (380 m), did not move after the formation of the esker subglacially. The fresh hummocks on the valley bench contain a high proportion of sand, rounded and partly rounded gravel and small boulders, surmounted by angular ablation debris. These characteristics confirm that the ice on the valley bench appears to have stagnated after the period of lateral moraine formation. The more conspicuous and linear of these mounds run in a group eastwards to a bend in the Allt na Bogair (5954). (Fig. 5.8 shows the mounds at this locality). Here the river channel suddenly deepens from an incision in drift to a deep narrow gorge in bedrock. This gorge runs quite straight for 3 km to within 1 km of the loch, where it fades out at the present fan. A major fault crosses the southern end of the gorge (5954) but runs north-north-eastwards to square 6057. A number of dykes lie between the fault and the gorge, and another is marked on the Geological Survey map as occurring for about 300 m in and following the gorge (c. point 6156). Although most dykes in the Loch Rannoch valley are upstanding features (fig. 5.9, for example), it may be that there is an eroded dyke along the length of this gorge that is less resistant than its neighbours. This is certainly the deepest channel anywhere in the Loch Rannoch valley. Its depth may be partly due to the fact that it coincided with the direction of meltwater drainage. Other channels transverse to this north-easterly direction are less engorged.

South of Kinloch Rannoch the Inverhadden valley is an isolated tributary whose glacial deposits are not physically joined to those of the main part of the Loch Rannoch valley. In the higher eastern branch of the Inverhadden valley the Coire Cruach Sneachda has abundant large mounds for a km or so above its confluence with Glen Sassunn (6654, 6754). The mounds evidently were deposited by a glacier originating in the Coire Cruach Sneachda (6752, 6753). Glen Sassunn, however, does not contain any mounds but is floored with till that thickens down-valley until it meets the mounds of the Coire Cruach Sneachda (6654). The head of Glen Sassunn (6453) and its two tributary valleys (6552, 6653) are much more open than the relatively enclosed head of the Coire Cruach Sneachda (6752, 6753). Consequently it is possible that there was a valley glacier in the Coire Cruach Sneachda and not in Glen Sassunn.

Below the confluence of these two valleys mounds are absent for about 2 km. The till layer here clothes the lower slopes above the incised Inverhadden burn. In the most northerly 1 km of the valley (6757) mounds recur but, because this area is wooded, it is difficult to discover whether they occur with the same frequency as in the Coire Cruach Sneachda. The valley glacier of the Coire Cruach Sneachda may have terminated just below the valley confluence (6655) or it may have moved down to the mouth of the Inverhadden valley (6757). Beyond the valley mouth there is a large fan but this appears to be the product of the present river. It is possible however that outwash from the Loch Rannoch glacier destroyed or buried any forms that existed at the mouth of the Inverhadden valley. Therefore the termination of the mounds at the mouth of the Inverhadden valley does not necessarily imply that the responsible glacier terminated there. On the other hand the area of mounds in the last 1 km of the Inverhadden valley is limited and does not conflict with a suggestion that the glacier terminated at about the valley mouth.

C.2. The northern side of the valley.

Hummocky drift is as widely distributed on the valley bench north of Loch Rannoch as south of it. Its outer margin is just as clearly delimited, although lateral moraines are much less well developed. On the other hand there are two systems of eskers on the valley bench which cross the present drainage lines and are clearly related to the period of deglaciation.

On the part of the valley bench south of the Talla Bheith Forest (5564 - 5763) the northern edge of the moundy deposits is sharply delimited by a narrow, slightly curving ridge at 1650 - 1700 feet (505 - 520 m). In squares 5563 - 5663 it is continuous for over 1 km, and in square 5763 for about 300 m. Between these places it is a series of shorter mounds rather than a continuous ridge, yet it still forms a sharp outer margin to the moundy deposits. At 567638, where a stream breaks through this feature, sandy gravels including rounded pebbles and boulders are the dominant size fraction; sand and silt, cross-bedded, are a minor part. This section was badly slumped and so the nature of the structure of the ridge could not be determined, except in so far as it was apparent that the flanks of the ridge had slumped, and that the cross-bedded sands and silts lie in the centre of the cross-section of the ridge. This is the only good exposure in the ridge but may well not be representative of the whole feature. The present stream probably follows the same course as its ancestor did in glacial times when the glacier occupied square 5663. This stream may well have carried rounded and fine sediments down to the glacier where they could easily have become incorporated into the ice-marginal deposits.

The ridge is probably not an esker, as the numerous eskers to the south branch and wind sinuously downslope (5663, 5763, 5662, 5762). Nor does it have the profile that should be expected of an ice-marginal water-laid deposit. The valley bench slopes gently so that any ice-marginal river would have formed a kame terrace, not a symmetrical ridge. The ridge shape more probably was produced by the deposition of material along the ice edge by debris sliding off the ice and by the release of englacial-subglacial debris from upward-curving thrust planes (cf. J.F. Nye, 1952). In other words, the ridge appears to be a lateral moraine. This possible origin fits with the relationship of the ridge to the hummocky deposits whose margin it forms. North of the ridge the smooth till-covered slopes are entirely devoid of mounds and show no sign of having been covered by the Loch Rannoch glacier.

To the east of square 5763 the margin of the abundant moundy deposits is quite clear but not marked by any distinctive individual landforms. There is simply the contrast between numerous drift mounds to the south and gently undulating peat-covered slopes to the north and north-east. The boundary between these two landscapes descends constantly from about 1650 feet (505 m), where the lateral ridge ends (5763, to about 1100 feet (335 m) on the flanks of Beinn a'Chuallaich (6360), and thence down towards the eastern end of Loch Rannoch. Furthermore its gradient parallels and its position mirrors the limit of deposits on the southern side of the loch (section C.1). Consequently it is reasonable to regard this boundary as the approximate marginal extent of the Loch Rannoch glacier on the northern side of the valley.

The pass that runs north-eastwards from the Killichonan burn area to the Garry valley (5863 - 6165) is floored with peat for about 5 sq.km. The till on the hillsides above thinly conceals the bedrock (5864 - 6066; 6165). Only at the entrance to the Garry valley (6166) do moundy deposits occur, and these are quite clearly part of the group that extends eastwards from the Craiganour Forest. There are no drift mounds in the pass. Therefore there is no evidence to suggest that ice from either Loch Rannoch or the Garry travelled through this pass, although the altitudes of the deposits in squares 5863 - 5962 suggest that the Loch Rannoch ice only just failed to do so.

The evidence in and around the eastern pass (6264) is less clear. A few scattered mounds, with no exposures of their material, lie between the path and the burn south of the col (6264) at about 1500 feet (455 m). North of the pass the abundant mass of mounds of the Garry valley (6265) is 1 km distant and lies below those south of the col. In square 6062 the Loch Rannoch deposits reach 1500 feet (455 m). Between here and square 6163 their limit falls 50 - 100 feet (15 - 30 m) and re-ascends to 1500 feet (455 m). The mounds have a clear limit (6162 - 6163) but this does not seem simply related to any conceivable glacier margin. Mounds are completely absent from the area east of the burn at any altitude north of grid line 62. The trend of the upper limit of the mounds to the west of grid line 61 is however quite consistent with that east of grid line 62 in suggesting an ice margin constantly descending for 10 km. The mounds in squares 6264, 6163 and the north-eastern half of 6162 could be remnants of the preceding stage of glaciation. Other remnants occur in the Errochty valley nearby (6665, 7066).

In squares 6261 and 6360 the limit of the mounds descends from 1250 feet to about 1100 feet (335 m). On the western slope of Beinn a'Chuallaich their limit is vague, but they are certainly absent above 1100 feet (335 m). Four eskers run downslope from about 1000 feet (305 m), two being on each bank and almost opposite each other. Up-valley two other eskers near the path appear to merge into small terraces above the present drainage lines. These forms appear to indicate that meltwater drainage here during deglaciation was down the ground slope under the ice. The approximate concurrence of the upper ends of the four southerly eskers suggests that in the southern part of square 6360 there was an englacial water table below about 1000 feet (305 m) that controlled deposition by streams flowing downslope under the ice. It is unlikely that the movement of water could have been eastwards in square 6360 irrespective of topography and under hydrostatic control, for the ice margin appears to have lain at about 1100 feet (335 m), just above the eskers. The Annat burn and its tributary (6360; 6359) have destroyed much of the deposit in the valley bottom as downcutting proceeded. As a 300 m length of the burn (6359) uses a meltwater channel, it is evident that meltwater erosion took place at a stage later than the deposition of the eskers when the ice had greatly thinned and its englacial water table had ceased to exist here. This erosion fragmented the valley bottom deposits (6360) into scattered terraces.

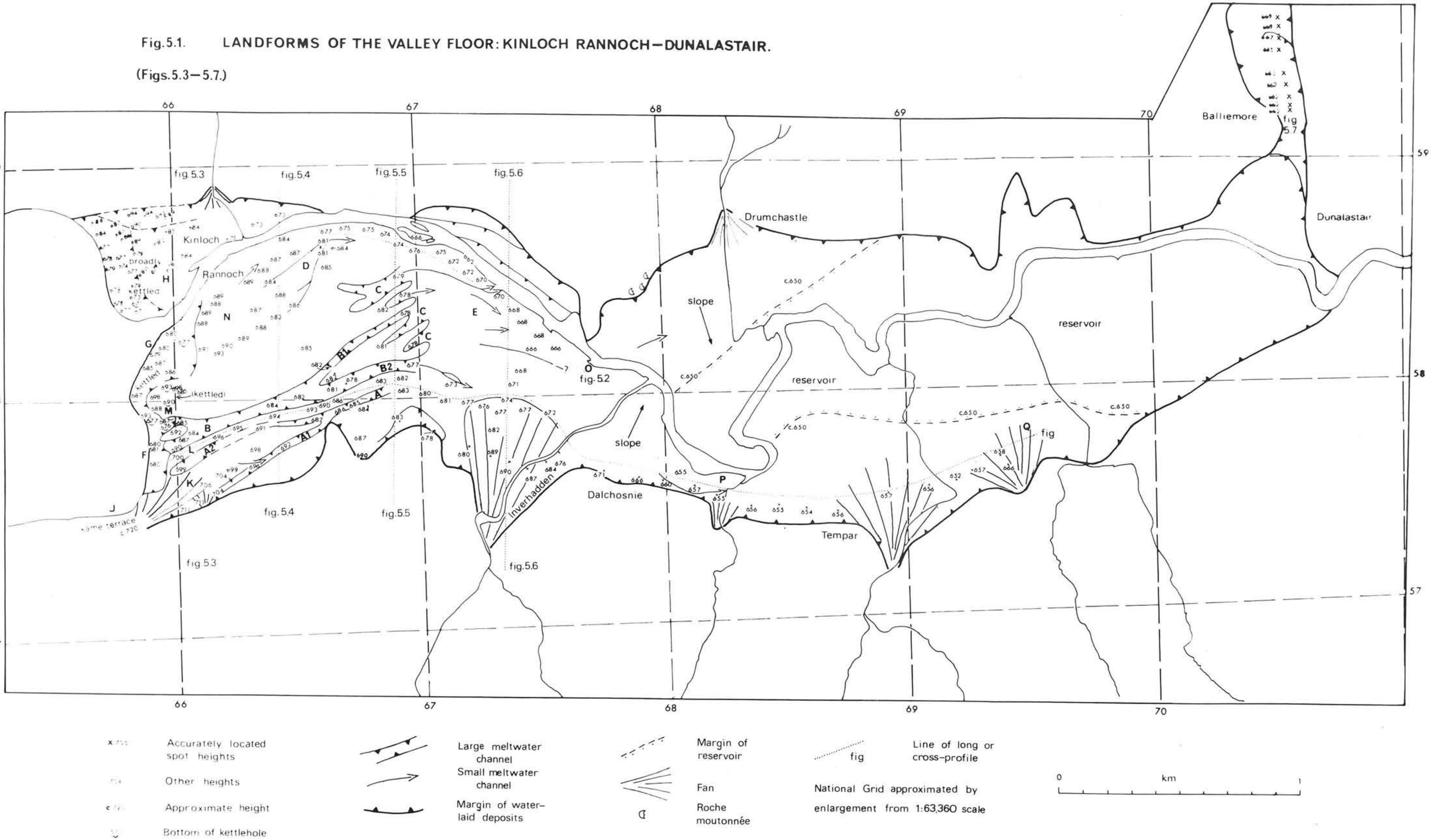
Viewing the evidence on the northern side of the Loch Rannoch valley as a whole, and excepting the anomalous evidence of the square 6163 area, the glacier margin appears to have descended gradually eastwards from about 1700 feet (5663) to about 1500 feet (455 m) (6062) in 6 km and more steeply thereafter for a further 6 km. As on the southern side of the valley the evidence along the last 2 km of hillside above the loch is fragmentary. Deposits are absent from the steep slopes of the 6459 - 6559 area, as they are from all but the lowest slopes on the opposite side of the loch. Where gentler slopes occur eastwards, as for example around Dunalastair (c.7059), the distinctive hummocky landscape of the Loch Rannoch valley does not recur. The evidence along the last 2 km of the northern side of the Loch Rannoch valley is entirely in accord with that on the southern side and with the outwash deposits that occupy the valley bottom below 700 feet (215 m) around Kinloch Rannoch (6658). This altitude accords with the calculations already given, which show that the ice margin declined quite rapidly in its last few km from about 1100 feet (335 m) in square 6360 (northern side) and 1250 feet in square 6355 (southern side) to its snout at about 700 feet (215 m) (c.6558).

Elsewhere, to the west, meltwater drainage took various routes. In the 6061 - 6161 area the eskers run obliquely downslope parallel to the ice margin, but stop where they reach the Allt Chreagain Odhar. Evidently this valley must have provided an easy escape route southwards under the ice for the esker-forming streams. The valley of the Allt Chreagain Odhar is just as deep in its last 2 km as the last 2 km of the Aulich burn (6060 - 6160 - 6159), although only the latter is clearly cut into the bedrock. The Geological Survey map is rather generalised here, but the rock in the 6160 - 6159 area seems to be rather fissile and weak, which may explain why upstanding craggy rock does not appear in the river channel. The engorged section of the Aulich burn (6060) lies west of a major fault that runs north-north-eastwards 200 m west of the Allt Chreagain Odhar. The lowest 1 km of the Aulich burn follows the fault line. In the 5663 - 5662 - 5862 area two trends are apparent. The meltwater channels (5862) appear to have been formed by water running parallel to the ice edge and then downslope, perhaps via crevasses. The eskers run downslope but across the present drainage lines. This indicates that the glacier influenced the direction of subglacial drainage but did not control it completely. Therefore there is a contrast with the glacially directed drainage of the 6061 - 6161 area, where the water flow was in the direction of decreasing hydrostatic pressure, that is towards the glacier terminus (J. Gjessing, 1960). In each of these two areas the topographic situations and proximities to the ice edge were similar, so there is no apparent reason for the contrast between them.

One other matter of interest, regarding the calculated gradients on the Loch Rannoch glacier, is the cross-profile of the ice. As the loch and presumed axis of the glacier lie along a west-east line, points along the margin equidistant from the terminus, lie directly north or south of each other. Reference to the ice-flow diagram (fig.13.1) shows that the ice edge on the southern side was about 200 feet (60 m) higher than on the northern side in the western half of the valley,

Fig.5.1. LANDFORMS OF THE VALLEY FLOOR: KINLOCH RANNOCH—DUNALASTAIR.

(Figs.5.3—5.7.)



and about 100 feet (30 m) higher in the eastern half. Some of this is probably attributable to the greater ablation there would have been on the northern side, as the ice-free ground by the margin faced the sun and, being inclined southwards, would have received the greater concentration of insolation (per unit area of ground). No part of this northern side lies in shadow. By contrast the steep hillsides of the southern side would have cast a shadow over the glacier margin there. Also the ice-free ground of the southern side is inclined away from the sun for most of the daylight hours. The glacier certainly must have been thickest in the middle, where it buried the Loch Rannoch rock basin. From sheet 47 it will be seen that the exit from Rannoch Moor into the Loch Rannoch valley is punctuated by a number of low hills with intervening valleys. These are disposed so as to have directed the outflowing Rannoch Moor ice towards the head of Loch Rannoch (c.5157). Consequently the principal line of flow was most likely to have been along the easiest route, the Loch Rannoch rock basin. Much of the ice on the valley bench therefore would have been lateral spillage from the rock basin as the basin became overfilled with ice. Another ice stream probably moved on to the valley bench from Rannoch Moor via the deep valley (5153) that lies between the main body of the hills (c.5050) and Loch Rannoch. This ice stream may have been higher than the ice on the northern side of the valley.

C.3. Kinloch Rannoch - Dunalastair.

The general character of the valley between Kinloch Rannoch and Dunalastair has already been described in sections B and C1 (sheet 48). More detailed information is presented in figs.5.1 - 5.7. From the bathymetrical form lines on sheet

48 it is evident that Loch Rannoch shallows very rapidly at its eastern end, its floor rising from 500 to 670 feet (150 - 205 m) in 0.5 km. As has been explained in section B, there is good reason to believe that a submerged rock bar commences 1 km west of the eastern end of the loch and that it continues eastwards under the water-laid sediments until it reaches the ground surface at Dunalastair (7058). Accordingly, despite the fact that there are no bedrock outcrops at the eastern end of the loch or in the bed of the outflowing River Tummel it may be said that the loch is dammed by buried bedrock and only to a minor degree by the sediments that conceal the rock. This deduction should be borne in mind when referring to fig.5.2.(Certain matters relevant to the limits of accuracy in figs.5.1 - 7 are discussed in Appendix 2).

A low undulating strip of ground fringes the entire eastern end of the loch (F-G-H). The width and altitude of this strip are quite irregular, ranging from 100 to 350 m and 671 - 693 feet (204.5 - 211.2 m) respectively. The southernmost section (F), at 680 - 681 feet (207.3 - 207.6 m), lies below the main spread of deposits (L-M) and the channels incised in them (B, A2). (Refer to figs.5.1 and 5.2). The altitudes of these channels range from 685 feet (208.8m) in channel B to 700 feet (213.4 m) at L. To the north of F the altitudinal difference between the main spread of deposits (M-N) and the kettled area (G) is similarly about 5 - 10 feet (1.5 - 3.0 m), except where the kettles in G are adjacent to the unkettled parts of M when the relief is as much as 20 feet (6.1 m) (fig.5.1). Area M is the only locality within the main spread of deposits that is kettled, but it has been separated from area G on the map (fig.5.1) because its unkettled parts constitute a portion of the gently sloping surface of the deposits (L-M-N) (fig. 5.3). To the north of the outflowing river Tummel the broadly kettled area (H) slopes southwards from 684 to 677 feet (208.5 - 206.4 m), and thus even its highest parts lie at least 4 feet (1.2 m) below the main spread of deposits at N (figs. 5.1, 5.3). It is unfortunate that the village of Kinloch Rannoch has obscured the topography directly north of N. Consequently it was not found possible to delimit the eastern edge of the kettled area (H) or measure the elevation of the deposits underlying the village.

To the east of the kettled areas (F, G, H, M) the surface slope of the deposits is more regular and ice-contact features attributable to the last stage of glaciation are entirely absent. Yet the deposits of the valley floor from the edge of the loch for at least 1 km eastwards are apparently unvarying sand and well-rounded gravel (fig. 5.2). As the slope of these deposits eastwards and the presence in them of large meltwater channels clearly indicate that they are outwash features, it can be concluded that areas (F, G, H and M) are the kettled proximal margin of the outwash deposit. Consequently it may be inferred that the kettled outwash was deposited upon the terminus of the Loch Rannoch glacier (fig. 5.2) and that, at the cessation of deposition, the margin of the tongue corresponded to the presently kettled area (F-M-G-H). The position of the tongue may well have oscillated but there is no visible evidence that could indicate the extent of any such movements. If the magnitude of relief between the kettled and unkettled outwash surfaces, 4 - 10 feet (1.2 - 3.0 m), is a measure of the thickness of the glacier's snout, it follows that the ice at (F-M-G-H) must have been too thin to be other than dead when deposition there ceased. Furthermore, as it was inert when the eskers at Annat were formed between 1000 and 850 feet (305 - 260 m) (square 6360, sheet 48), it is possible that considerable parts of the glacier's margin became stagnant after it had advanced to its maximum position in the Loch Rannoch valley.

The mounds that occupy the lower part of the southern valley side above the eastern end of Loch Rannoch give way to a narrow kame terrace (J) whose surface lies at about 720 feet (219 m) (fig. 5.1). Just beyond the south-eastern corner of the loch this feature terminates where the ground slopes down to K at 710 feet (216 m). K is a fan between the kame terrace and channel A1. The close proximity of the three features suggests they were probably deposited by one meltwater stream, the fan perhaps when the water supply finally diminished. It is therefore suggested that the fan largely post-dates channel A1 and that the fan infilled the proximal section of the channel.

To the east-north-east and north of the fan (K) the valley floor slopes down gently, the fall east-north-eastwards being the greater, namely from 704 to 682 feet (214.6 - 207. 9 m) over 750 m distance, compared with 704 to 688 feet (214.6 - 210.0 m) northwards in the same distance (fig. 5.3). The gradient across the outwash is not completely uniform, as for example the cross-profile (fig. 5.3) shows, yet it is clear that within squares 6657 and 6658 the outwash surface is higher along its southern edge (figs. 5.3, 5.4). It is therefore surprising to find that the deepest, longest and widest meltwater channels occupy the higher southern side of the valley.

The highest channel (A1) has already been mentioned as being the probable continuation of the route followed by the meltwater that deposited the kame terrace (J). The present western end of channel A1 is only 2 feet deep (0.6 m), but for most of its length it is 4 - 6 feet deep (1.2 - 1.8 m). It descends from 704 feet (214.6 m) to 687 feet (209.4 m) where it joins a lower channel (A2). Channel A2 evidently operated at the same time as A1, at least towards the end of their lives, for at their confluence their beds merge at the same altitude. The combined channel runs for a further 300 m east-north-eastwards before fading out at 683 feet (208.2 m) where its floor merges with the general outwash surface.

The largest channel (B) is incised about 10 feet (3.0 m) into the outwash surface between L and M and its branched head commences 10 feet (3.0 m) above the kettled area F (fig. 5.2). Both branches merge into each other at a common level of 684 feet (208.5 m), suggesting as with A that both operated simultaneously, at least towards the end of their lives. As channel B lies 6 - 10 feet (1.8 - 3.0 m) lower than channel A2 and is approximately twice as deep as A2 (figs. 5.3, 5.4) it may be deduced that channel B was the principal meltwater route towards the end of the period of outwash formation of which there is record. The positions of the proximal ends of channels A2 and B clearly indicate that they were created by meltwater emerging from the body of the glacier, probably from an englacial or subglacial tunnel. The streams may have flowed out across the thin stagnant frontal zone of the glacier, depositing the gravels supraglacially and then proglacially. Subsequent kettling (F) may explain the abrupt beginnings of channels B and A2 (fig. 5.2) and their absence from area F (fig. 5.1). It is tempting to conjecture that F is a depression relative to all the ground contiguous with it because it corresponds in location with the former channel courses across the ice. Channel A1 has been shown to have operated at the same time as A2. It follows that, when A2 had been more or less abandoned, ice-marginal drainage forming the kame terrace (J) and channel A1 was also more or less abandoned as the much lower channel (B) became the main outlet from the presumably lowered englacial water table.

It is quite probable that the majority of the outwash deposits east of Loch Rannoch were laid down by water whose channels are no longer to be seen (cf. C. Embleton and C.A.M. King, 1968, chapter 18). As the proximal 1 sq. km or so of the outwash is in the form of a fan, sloping east-north-eastwards and northwards from the kame terrace (J), it is evident that the principal outlet for meltwater lay on the southern side of the glacier, approximately where the kame terrace now exists. It may be imagined that the outwash fan was furrowed by shifting anastomosing channels, presumably including those at D and conceivably those at C.

The channels at D are about 3 feet (0.9 m) deep, narrower than A and B, and apparently have been infilled, for they start and fade out quite gradually and have gently sloping sides. The proximal ends of the channels at C may also have been infilled by sediment dumped by water flooding across the fan, presumably from their neighbour, channel B (fig. 5.5). Some of the channels in group C as well as channel B1 fade out along a line, approximately grid line 670 (fig. 5.1). To the east of grid line 670 the floors of the remaining channels become the general level of the outwash surface, but the northernmost two of groups C and channel B2 continue eastwards as shallower, narrower features. B2 fades out where it encounters the Inverhadden fan, while to the north there are three other channel fragments (E) that may have been continuations of the channels at C. However it is considered that the features at C and E are too fragmentary to allow even a tentative reconstruction of the possible connections between them, or explanation of the change in their character between C and E (compare figs. 5.5 and 5.6).

In the vicinity of Dalchosnie, on the southern side of the valley, the long-profile of the outwash steepens for 500 m and thereafter flattens out in the vicinity of 655 feet (199.6 m) to the east of P (fig. 5.2). In addition, the cross-profile of the outwash changes east of grid line 677 (Dalchosnie) from being a slope down to the north right across the valley to a slope down into the middle of the valley from both valley sides (fig. 5.1). East of area P this results in most of the valley floor being submerged under the waters of Dunalastair reservoir. Nevertheless enough measurements have been obtained to allow some discussion of the valley form east of Dalchosnie. Whereas the gradient eastwards along the outwash as far as Dalchosnie is 1:180, and that from Dalchosnie to P is 1:120, that from P to Q is 1:700. Another contrast between the ground up-valley and down-valley from Dalchosnie is that the coarse well-rounded gravel to the west gives way to fine gravel and sand to the east (fig. 5.2). Thirdly, channels entirely attributable to meltwater rivers do not occur east of Dalchosnie. The two small channels intersected by grid line 680 appear to be remnants of the river Tummel's wanderings across the almost flat valley floor.

One further piece of evidence must be introduced before these facts can be placed in perspective. Adjacent to the exposed portion of the rock bar seen at Dunalastair there is a small valley called Balliemore that runs northwards from the reservoir for about 1 km (fig. 5.1). Boreholes, whose positions were levelled, were made along the axis of the valley. They revealed that 1.8 - 2.4 m of light grey silt with fine sand lies upon the rock floor at the southern end of the valley. Northwards the top surface of the silty sand ascends gradually from about 661 feet (201.5 m) to 667 feet (203.3 m) where the silty sand ends against a break of slope on the valley floor (fig. 5.7). North of the break of slope the ground surface becomes much less smooth and sand or peat on top of gravel replaces the silty sand. This gravel is very similar to the gravel in the immediate vicinity of and in the channel of the stream that drains this valley.

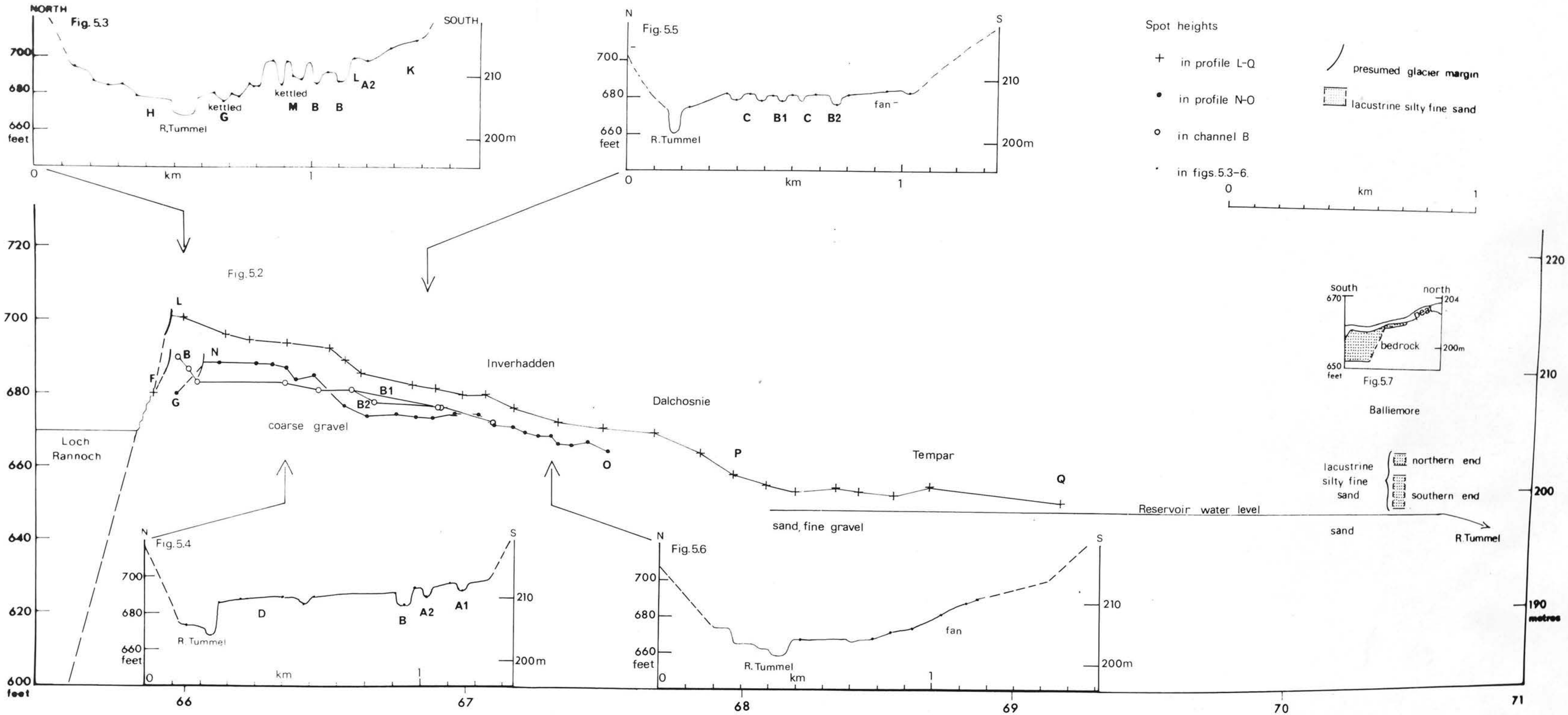
The silty sand in the Balliemore valley thus lies between 661 and 667 feet (201.5 - 203.3 m) (fig. 5.2). The complete absence of sand and gravel layers suggests that this is neither a flood plain nor a stream channel deposit. The homogeneity and fineness of the silty sand imply that it accumulated in settled, quiet water, not subject to periodic drainage and stream action. Therefore it is concluded that the deposit is lacustrine.

For several reasons it appears that the lake stretched as far as Dalchosnie. Firstly the deposits are not coarse gravel but sand with fine gravel at Dalchosnie and fine sand at Dunalastair. Secondly the long-profile of the valley floor between Dalchosnie and Dunalastair is exceedingly gentle (1:700 from P to Q, fig. 5.2). Thirdly there is no sign of any solid obstruction that could have dammed up the southern end of the Balliemore lake. Therefore the Balliemore lake must have been part of a larger lake that occupied the main valley. If the headward extent of the Balliemore silty sand to 667 feet (203.3 m) be taken as the minimum level of the lake, when the silty sand accumulated to that altitude, this provides a measure of the extent of the lake in the main valley. Altitudes of 667 feet (203.3 m) or less occur from area E, north-west of Dalchosnie, in a widening zone eastward until to the east of Dalchosnie the whole valley floor lies below 667 feet (203.3m) (fig. 5.1). It is tempting to associate the dying out of the channels at E with their descent to this altitude. It is also conceivable that the steeper gradient of the long-profile (fig. 5.2) at Dalchosnie between 670 and 655 feet (204.2 - 199.6 m) represents a delta laid down as the outwash rivers arrived at and flowed into the lake. The absence of appropriate channels between area E and Dalchosnie may be due to the spread of the Inverhadden fan (fig. 5.1, fig. 5.6) and to the postglacial activity of the river Tummel before it established its present course.

In brief, it may be said that the evidence for a lake in the main valley and at Balliemore is the presence of the lacustrine silty sand, the fineness of the deposits held to have been laid down in the lake, and the contrasts in sediments, in long - and in cross - profiles between the lake floor area and the outwash plain.

One point remains to be introduced to complete the discussion. The outlet at the eastern end of the lake was a channel cut through the Dunalastair rock bar. The aerial photographs of this locality reveal that a deep rocky gorge occurs there, which however has been submerged by the waters of Dunalastair reservoir. Given the evidence that a lake was held up above this gorge, it is evident that the gorge at that time was insufficiently deep or wide to permit complete drainage of the lake. In addition, the geological map

Figs.5.2-7. PROFILES OF THE VALLEY FLOOR: KINLOCH RANNOCH—DUNALASTAIR.



portrays a number of vertical quartzite, metamorphosed limestone and epidiorite - hornblende schist beds exactly at the point of outflow. These rocks form this part of the rock bar and the walls of the gorge. There must therefore be a rock lip at the present day between the flat valley floor to the west and the gorge to the east. During the lateglacial period this lip is likely to have been higher than it is today. Presumably it was sufficiently high to limit the outflow from the lake so that the lake level lay at about 667 feet (203.3 m) for long enough to allow silty sand to accumulate up to a thickness of 2.4 m. As the bulk of the sediment brought into the lake must have been dropped quite quickly, the outflowing water could have possessed only a limited erosive power. Consequently the lowering of the rock lip, and with it the lake level, must have taken a considerable period. In conclusion it is suggested that the gorge acted as a valve, able by virtue of its volume and altitude to evacuate just enough water so that a lake was maintained at about 667 feet (203.3 m) for a certain period until erosion of the gorge, possibly aided by diminution of the meltwater supply, allowed the lake to empty. As the lake floor remains relatively intact, it is apparent that the meltwater subsequently contributed by the glacier during its eventual decay did not possess enough erosive power, while crossing the flat valley floor, to rework the lake floor sediments to any recognisable extent.

C.4. Summary.

The series of events visualised to account for the landforms between Kinloch Rannoch and Dunalastair may be summarised as follows. During its period of advance to and stillstand at the eastern end of Loch Rannoch, the Loch Rannoch glacier contributed a considerable volume of outwash-carrying meltwater. For at least the later period of stillstand the main outlet for water from the glacier lay at or near its southern edge. This resulted in the outwash accumulating as a sand and gravel fan whose apex lay at the south-eastern corner of the glacier. The major meltwater channels run from this point east-north-eastwards for over 1 km, after which they become indistinct. They may have terminated in a lake whose water surface lay at about 667 feet (203.3 m). Finer sediments accumulated on the lake floor, which is almost flat. The outlet of the lake was a narrow gorge whose elevation and restricted volume appear to have caused the formation of the lake and to have allowed its eventual drainage once the gorge had been eroded further and the meltwater supply diminished. Since the retreat of the ice from its limit, there appears to have been very little alteration of either the outwash or the lake sediments by the river Tummel.

D. The Tummel valley and Glen Errochty.

The areas to be described in this section are the continuation of those discussed in section C of this chapter. They have been grouped separately because they have a landscape quite different from that of the Loch Rannoch valley. The abundant mounds of drift, that characterise the Loch Rannoch valley are totally absent from the Errochty and Tummel valleys (sheet 48). Furthermore the deposits in these latter valleys occur in localities that could not have been covered by a valley glacier such as the one that terminated at Kinloch Rannoch. Over most of the Errochty-Tummel area it was found very difficult to define precisely the limits of hummocky glacial deposit landscapes because these features are often very subdued or intermixed with till-covered rock knobs. Both this landscape type and the difficulty encountered are contrasts with the clear hummocky character of the Loch Rannoch valley features.

It has already been shown that the distribution of lateral moraines in the Loch Rannoch valley and the outwash deposits at Kinloch Rannoch are consistent with each other in showing that the Loch Rannoch glacier achieved a major stillstand at Kinloch Rannoch. There are however patches of moundy deposits in the valley to the east of Kinloch Rannoch. Most of these are in a small group around Tempar (6857 - 6957) between 850 feet (260 m) and 650 feet (200 m) on the gentler slopes. This is the only such occurrence between Kinloch Rannoch and Dunalastair (7058). No deposited mounds exist on other equally gentle slopes at similar altitudes in squares 6758 or 6958 - 6959; these localities have only a thin coating of till on bedrock. It could be argued that the Loch Rannoch glacier advanced to a maximum position around Tempar and deposited the mounds there, and then receded about 3 km to its main stillstand. However the absences of any ice-marginal outwash features from the valley at Tempar and of moraines in the 6758, 6958 - 6959 areas do not support this idea. It is more likely that the mounds at Tempar (6857) belong to the same stage of glaciation as those scattered widely north, east and south-east of Dunalastair (c.7261, c.7358, c.7453).

North of Dunalastair there is a broad shallow valley tributary to the river Tummel. Scattered drift mounds do occur spasmodically in the area delimited by the three roads that join in a triangle (7163 - 7059 - 7559). These mounds are intimately mixed up with eroded rock knobs. In the

7259 - 7159 - 7160 area, and in the 7359 - 7360 area these landforms are almost indistinguishable from each other and, as exposures are often lacking, it was not found possible to distinguish the extent of each type. No groups of abundant drift mounds occur in this area. In fact, from Beinn a'Chuallaich eastwards (6861) into the upland north of Loch Tummel, both the general and the detailed appearance of the landscape are determined by the presence of bedrock at or near the surface. On Beinn a'Chuallaich and the steeper slopes on the northern side of Loch Tummel there are numerous bedrock outcrops. On the former hill the resistance of the Schichallion quartzites and associated rocks is the cause, whereas along Loch Tummel the steepness of the hillside and attendant outcrops of the bedrock are the consequences of the hollowing out of the Loch Tummel rock basin by successive glaciers. Elsewhere the slopes are smoother and gentler, often with a till or peat covering, although bedrock is revealed along much of the upland above Loch Tummel.

The landscape on the southern side of the Tummel valley is much more obviously rocky. The hill that terminates eastwards in the Craig Kynachan (7257 - 7657) is devoid of deposits. South of the river Tummel scattered moundy deposits are mixed up with rock knobs (7258 - 7658). As most of this area is forested, it was not found possible to map this part (7257 - 7657) in detail. Nevertheless its general character is not in doubt and there are certainly no conspicuous moundy deposits. The hill that terminates eastwards in Craig Kynachan (7257 - 7657) is developed on Schichallion quartzites, as are Schichallion (7154) and the hillside above the southern side of Loch Tummel. Eroded bedrock outcrops dominate these areas, except where till clothes the slopes below about 800 feet

(245 m) along Loch Tummelside. The valleys of the Fremich burn (8257) and Allt Tarruinchon (7956) are plugged with till, down through which the burns have become engorged, but moundy deposits are absent.

There is also a group of low linear mounds at the head of Loch Tummel (7758) that runs downslope from 800 feet (245 m) for up to 1 km. The longest is both wider and longer than even the largest lateral moraine in the Loch Rannoch valley. The facts that the longest widens downslope and that all the mounds run downhill, rather than along the hillside, suggest that they are not simply glacial deposits, although their surfaces are made entirely of loose angular blocks. Furthermore these linear mounds lie on the leeside of the Craig Kynachan. Taken together these characteristics suggest that the linear mounds may be the ice-moulded bedrock tail of a crag-and-tail feature, whose crag is the hill that stretches from near Dunalastair (c.7157) to the Craig Kynachan. The bedrock for 1 sq. km around Foss (c.7857) is clearly grooved in the same east-north-easterly direction. To the south of Schichallion Gleann Mor contains scattered subdued hummocky deposits from the valley confluence (7053) eastwards and then southwards towards the Tay valley (via 7650). South-east of square 7453 they are intermixed with till-covered rock knobs (7552 - 7550 - 7551) in the valley of the Keltney burn. Elsewhere around Schichallion (6956 - 6852) bedrock lies at or near the surface.

The striations marked on the Geological Survey 1:63,360 map (sheet 55) clearly demonstrate that the last ice movement in the Schichallion area and on the uplands north and south of Loch Tummel was east-south-eastwards. The movement must have been that of an ice sheet for it was across the uplands and was not confined within the valleys. The distribution of till high on these uplands, in the Keltney burn - Gleann Mor area, as well as north and south of the river Tummel, implies just such an extent of ice. The distribution of till and striations in the Garry and Tay regions is very similar too, and gives a very wide spread of evidence indicating that an ice sheet was responsible for the glacial deposits of these areas. This ice sheet was clearly very much thicker and more extensive than the glacier that terminated at Kinloch Rannoch.

Glen Errochty is connected directly with the Loch Rannoch valley by a broad low pass that runs from the valley bench (6362) north-eastwards. From squares 6263 - 6262 - 6361 - 6461 north-eastwards to the Loch Errochty reservoir there is a swarm of felsite or porphyrite dykes that forms the dominant part of the landscape for about 9 sq. km. Approximately half of these are marked on the Geological Survey maps (sheets 54 and 55); the other half were apparently considered to be 'moraines', but careful examination of their composition, form and pattern shows this to be mistaken. They are distinctly linear ridges, of varying lengths, and arranged in lines oriented towards east-north-east or north-east. One of the longest and most prominent is not marked on the Survey maps. It is the ridge that runs north-eastwards through squares 6462 - 6563, which is the continuation of that marked in squares 6159 - 6260 - 6361. In a few places the ridge has been eroded down to rock knobs, yet its base is continuous and the straightness of the whole is not disrupted. Along its length fragments of dyke rock are littered, and the same parent rock is occasionally exposed. At the western end of the reservoir there are numerous hillocks, but the rock outcrops of dyke rock on them and the complete absence of drift from them demonstrates their igneous origin.

There are two areas in the Errochty valley with substantial drift deposits. At the south-western end of the reservoir a layer of drift occupies the valley bottom below 1200 feet (365 m), but there are no exposures in it. At point 663644 there is a small group of kames which rises above this drift layer. Another very small group of mounds occurs in the valley of the Allt Chon (6966); these were not investigated. However two isolated small groups of mounds scarcely provide enough evidence for it to be suggested that they could have been deposited by a diffluent branch of the Loch Rannoch glacier that terminated at Kinloch Rannoch. They are much more likely to be part of the fragmented set of deposits that occurs throughout Glen Errochty and Glen Garry which were left by the last ice sheet.

E. Summary.

The last glacier to occupy the Loch Rannoch valley moved eastwards into it from Rannoch Moor. The ice occupied both the rock basin of Loch Rannoch and the valley bench on each side of it up to the hills that margin the bench. On the southern side and to a lesser extent on the northern, the edge of the ice at its maximum thickness is marked by a series of lateral moraines. These show that the surface gradient of the ice was slight until the final 4 km or so of the glacier where its surface sloped down much more steeply to its terminus at the eastern end of Loch Rannoch. Two smaller valley glaciers existed on the southern side of the main valley. The more westerly was confluent with the Loch Rannoch glacier, but the more easterly existed independently to the east of Loch Rannoch and was of limited extent. It does not appear to have left any deposits in the main valley east of Loch Rannoch. On the northern side of the Loch Rannoch valley the glacier on the valley bench was insufficiently thick to flow through either of two passes leading to the Garry valley or the broader pass into the Errochty.

The terminus of the Loch Rannoch glacier is indicated by a substantial spread of channelled outwash whose proximal zone is kettled, indicating the position of the inert snout towards the end of the period of outwash deposition. Between 1.5 and 2.0 km from the glacier the outwash streams entered a shallow lake which was held up by the constricted outflow at Dunalastair rock bar. When this drained there was no longer sufficient meltwater to destroy the outwash or lake deposits, and it is therefore probable that the glacier was in retreat.

Beyond the limits of the Loch Rannoch glacier the evidence of striations, till and occasional moundy deposits shows that an ice sheet from a previous stage of glaciation had submerged the Rannoch-Tummel and Errochty valleys and the hills on each side of them to a much greater altitude than that attained by the more limited Loch Rannoch valley glacier.

Chapter 6. Loch Tulla and Black Mount.

A. Previous literature.

The Geological Survey memoir accompanying sheet 54 (Rannoch) deals with both Black Mount and the Loch Tulla - Water of Tulla district. Much of the latter is presented on an earlier map (sheet 46, 1900), which does not have an attendant memoir. The Rannoch memoir is of more than usual value to this thesis as it presents useful evidence about the role of Rannoch Moor in glacial history. This evidence was described in detail in the preceding chapter (5, sections A, B). Therefore it should suffice to note that whereas the Moor was a centre of radiative dispersal during maximum glaciation (Linton, 1957), it became a route of through-flow during the last stage of glaciation (Hinxman et al., 1923). At the latter time, the principal movement was from the western mountain rim eastwards into the Moor, across it and out by the eastern exit, the Loch Rannoch valley.*

J.K. Charlesworth (1955) followed the Rannoch memoir in his review of ice movement. He further suggested that various glaciers from the hills west, south-west and south of Loch Tulla moved into the Moor, without however giving relevant evidence (p.843).

The series of terraces, called the Parallel Roads of Loch Tulla by J.C. Gregory (1926), was first noted by D. Milne-Home (1847, 1849). He correctly visualised them as lake terraces,

* Further evidence for this movement is given by D. Milne-Home (1871) who reported that particular white boulders scattered around Loch Tulla and the Water of Tulla valley had been transported eastwards from Stob Coir'an Albannaich (1743), 13 km west of Loch Tulla (sheet 47).

whereas R. Chambers (1848) imagined very high sea-levels to have been their cause. Milne-Home gave altitudes of 725, 819 and 1016 feet for three terraces. Chambers suggested eight levels from 611 to 1044 feet, including 726 and 819 feet levels. Although both authors compared the Loch Tulla terraces with those in Glen Roy, neither accepted L. Agassiz' revolutionary interpretation of the Glen Roy features as evidence of an ice-dammed lake (1840).

J. Mathieson and E.B. Bailey (1925) and J.C. Gregory (1926) did not however find any difficulty in applying Agassiz' hypothesis, as developed by T.F. Jamieson (1863), to their interpretations. Their papers will be discussed in detail later in this chapter.

B. Introduction.

Rannoch Moor is a broad basin whose slightly undulating surface generally lies at about 1000 feet (305 m). Four low hills rise above this floor. Two, Beinn Chaorach (2950) and Meall Beag (2947 - 3047), stand near the mouth of Coire Ba in the Black Mount district of the Moor. Meall Beag and its flanks form a low watershed between the main part of the Moor to the north and the Loch Tulla drainage to the south. The remainder of this watershed consists of the Glas Bheinn - Leathad Mor ridge (3247 - 3851). There are four passes from the Loch Tulla drainage to the Rannoch Moor - Loch Rannoch drainage between and around these hills, namely in squares 2846, 3147, 3448, and 4049 (sheet 47). They lie between about 1000 and 1150 feet (305 - 350 m). A pass westwards to Glen Kinglass (1941) and the present-day drainage southwards along Glen Orchy lie at much lower levels. The Water of Tulla lies in a valley of its own well below the level of the Moor and drains through Loch Tulla (water level 543 feet O.D., 165.5 m) into Glen Orchy.

The hills along the south-eastern border of the Moor are broken by only one major breached watershed, Glen Meran (3944). Otherwise these 2500 - 3500 feet (760 - 1065 m) hills form an effective divide between the Moor and Glen Lyon. Hinxman et al. deduced that corrie glaciers emanating from this watershed area must have descended to the Moor, so more or less precluding Rannoch Moor ice from Glen Lyon, for boulders of Rannoch granite are almost absent from Glen Lyon and completely absent from its southern side (1923, p.82, 87).

C. The features.

This chapter is exceptional within the thesis, for it cannot deal with a major valley system and the movement of glaciers within the system. The flow of glaciers into and out of Rannoch Moor can be discussed only to a limited extent because only the southern part of the Moor and one major outlet, the Loch Rannoch valley, have been studied. The chapter will mainly concentrate on the Parallel Roads of Loch Tulla and on their relation to the former extent of glacier ice.

In the preceding chapter it was shown that the surface of the Loch Rannoch glacier at the western end of the Loch Rannoch valley lay at about 2000 feet (610 m). The Black Mount - Loch Tulla district lies about 25 km to the south-west, that is up-glacier from the Loch Rannoch valley. The surface gradient of ice on the Loch Rannoch valley bench was calculated as possibly 40 feet per km (12 m per km). The gently undulating surface of the Moor could have influenced the glacier gradients to approximately the same extent as this gently sloping valley bench. Therefore a projection of the 40 feet per km (12 m per km) ice gradient south-westwards across the Moor to 3000 feet (915 m) provides a useful assessment of the possible altitude of the ice surface in the Black Mount area. The corries in this area are both numerous and at high levels, the tops of their backwalls frequently exceeding 3000 feet (915 m). This does not conflict with the deduction that they were a source of the Loch Rannoch ice (Hinxman et al., 1923).

Since the general level of the Moor is approximately 1000 feet (305 m) the moundy drift on it can suggest only the horizontal extent of the ice, not its thickness. Detailed field mapping of the Black Mount, Loch Tulla and Water of Tulla areas has shown that mounds are widespread. (An example of such a map, fig. 1.3, is included). Reconnaissance mapping on aerial photographs of much of the Moor north and north-east of Black Mount, as well as south-westwards and southwards into the Glen Kinglass and Glen Strae valley systems, has indicated that moundy deposits are widespread and continuous for hundreds of sq. km. around Black Mount.

With the exception of some localities along the Water of Tulla only a few exposures of material in the cores of mounds were found. Most exposures are of surface material, which ranges from a small proportion of silt to a much larger proportion of sand with coarse gravel, without anywhere showing bedding. The edges of gravel fragments are usually angular or slightly rounded, except for granite pieces which crumble easily into rounded rocks and fine gravel.

In many places in Black Mount the mounds are rock-cored or rock lies within 3 - 4 m of the ground surface. Frequent patches of peat, which often partially submerge rock or drift forms, further diversify the landscape of the Moor. In brief, this landscape consists of a chaotic assemblage of drift mounds, including many bedrock protrusions or rock-cored mounds, interspersed with patches of peat and small lochans.

South-west to north-east trending bedrock makes its appearance around Loch Tulla. On the northern side of the Loch is a suite of four rock ridges, some of which will be discussed in the next section of this chapter. South of the loch drift-veneered rock ribs between 700 and 1100 feet (215 - 335 m) in squares 3042 - 3143 do in places superficially resemble terraces (fig. 6.4). However the multiplicity of these ribs up the hillside and their lack of continuity along the hillside do not suggest that they have been terraced. This conclusion conflicts with Gregory's, who included the features as Parallel Roads (fig. 6.1). Much of the remainder of the valley of the Water of Tulla contains drift mounds without trace of rock cores (sheet 47). Although most exposures in them are of angular gravel, there is an area of kames near Gorton (3747 - 3848) that may be related to the Parallel Roads (section D).

D. The Parallel Roads of Loch Tulla.

In the past these features have been described principally in two contemporaneous publications, by J.C. Gregory (1926) and by J. Mathieson and E.B. Bailey (1925). Their work will be reviewed before the writer's own results are presented.

Gregory provides an excellent description of the appearance of the terraces and associated features. "The hillsides are covered with morainic mounds, across which each

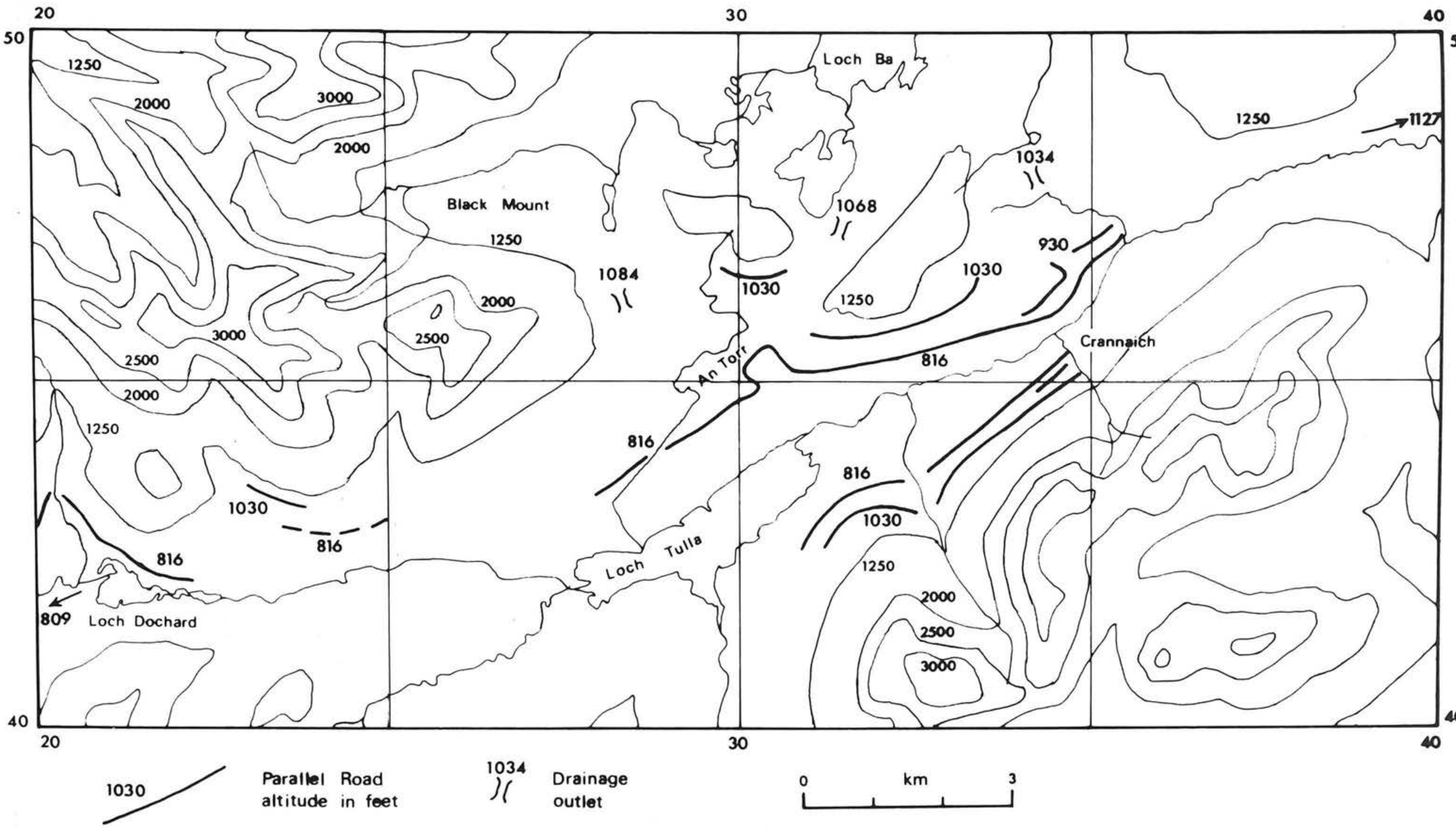


Fig. 6.1 PARALLEL ROADS OF LOCH TULLA according to J.C.GREGORY (1926).

terrace cuts, forming a small ledge. These ledges vary in breadth from a few feet up to 20 or 30 yards; their slope is commonly about 10° on a hillside sloping at 20°. The moraines generally have flat or rounded tops, but they are local, and although several mounds may often be found together with their tops at nearly the same level, they appear only as projections from the hillside, and the shelf thus formed does not curve into re-entrants. The terraces on the other hand follow round the moraine mounds and give the appearance of being completely later. Although the terraces are difficult to see from close at hand, and are often invisible, yet they appear distinct from a distance. They are seen as very faint horizontal lines running among and across the moraines with very frequent interruptions, but appearing again at the same level further on" (p.93-4). (In the lower left quadrant of fig. 6.4 some Roads are visible).

Gregory identified five groups of terraces (fig. 6.1) :-

816 feet (249 m)

930 feet (284 m)

1030 feet (314 m) including two or three terraces.

1090 feet (332 m)

1150 feet (350 m)

He considered the 816 feet (249 m) and 1030 feet (314 m) terraces the best developed and the others much less so. He claimed that the lowest terrace is the most extensive and that he had traced it as far west as the Loch Dochard - Glen Kinglass pass, though he did not determine its height there. Consequently his correlation of features near this pass with the 816 feet (249 m) terrace is suspect, particularly in view of his error in tracing it around "the top of the long low ridge of An Torr" (p.96), which lies north of Loch Tulla.

The upper parts of this ridge lie between 900 and 1000 feet (275 - 305 m).

At about 1030 feet (314 m) he detected "three or sometimes only two faint parallel lines" (p.98). As with the 816 feet (249 m) terrace, he accepted the heights surveyed by Mathieson and Bailey. These are 1041 feet (317 m), obtained by theodolite, 1030 and 1020 feet (314 m, 311 m) obtained by visual estimation. (Gregory correctly allowed that his own estimates by aneroid barometer were insufficiently accurate). He believed that one or more of these higher terraces existed away to the west near Loch Dochard but "was unable to trace them in detail" (p.98). However he was in no doubt that the railway line crosses the 1030 feet (314 m) terrace immediately to the west of Crannaich wood (3444). Unfortunately the railway lies at only 900 feet (275 m) there and descends to progressively lower altitudes as it approaches Loch Tulla. It is possible that Gregory was thinking of the 816 feet (249 m) terrace which is shown on his map as crossing the railway west of the wood.

He described the 930 feet (284 m) terrace as "quite distinct" but recognisable "over only a surprisingly short distance" (p.97), and those at 1090 feet (332 m) and 1150 feet (350 m) as "obscure" (p.98) (they are not shown on his map).

Gregory was so impressed by the similarity of the Loch Tulla features to the Parallel Roads of Glen Roy that he found it "impossible to doubt" that all were formed in the same way, that is as the shorelines of a glacial lake. He envisaged that glacier ice lay near its sources west of Black Mount, west and south of Loch Tulla and in Coire Achaladair (3341) and Coire an Lochain (3644). He supposed that water

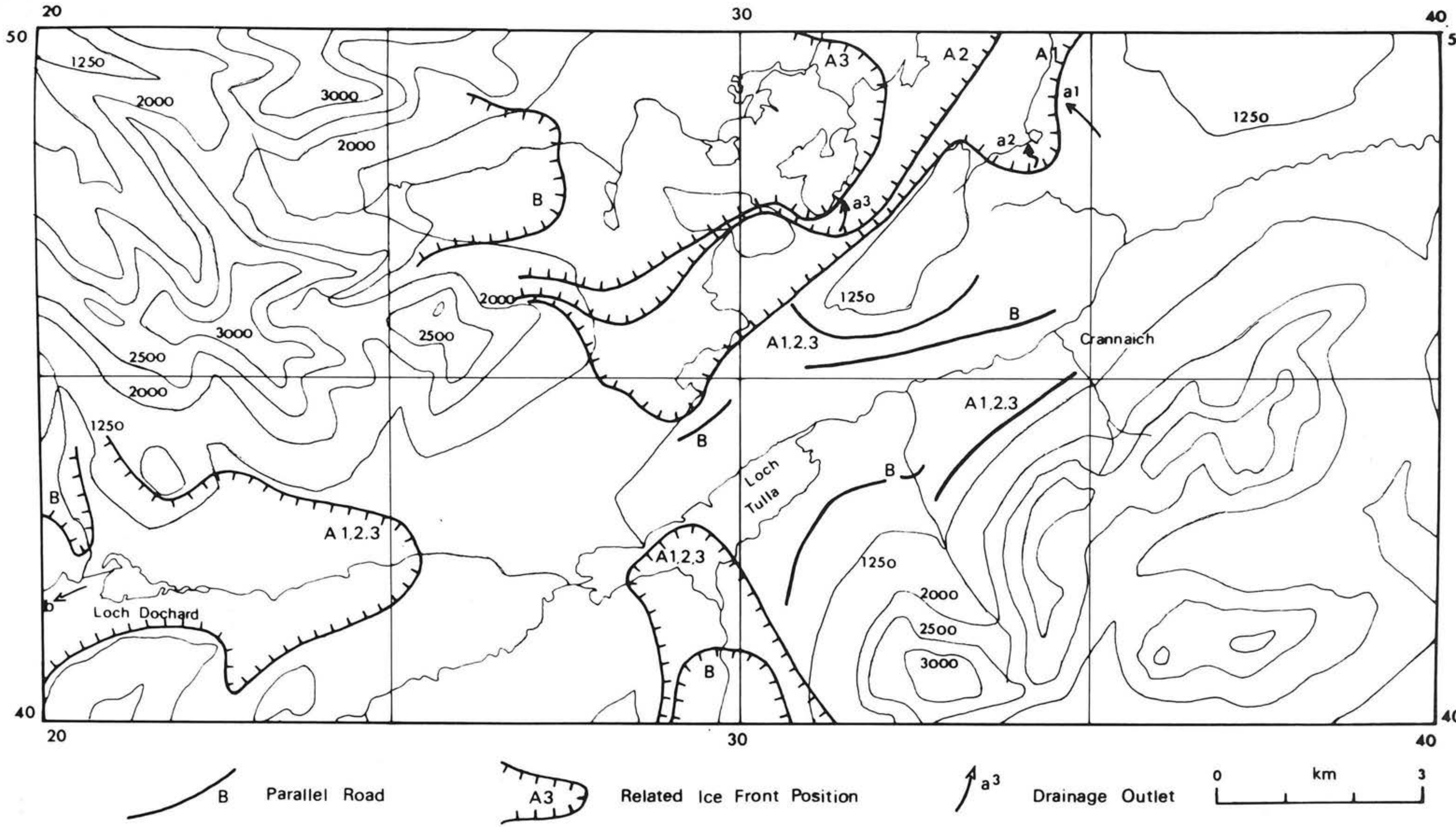


Fig.6.2 PARALLEL ROADS OF LOCH TULLA according to J.MATHIESON and E.B.BAILEY (1925).

was held up in the Loch Dochard - Loch Tulla - Water of Tulla valley by ice on Rannoch Moor, west of Loch Dochard, and south of the Dochard - Tulla valley. From spot heights marked on Ordnance Survey maps, he judged that outlets to the north and east into Rannoch Moor could have been vacated by ice retreating westwards across the Moor, the opening of each route controlling the falling lake level. He suggested that the highest pass, which lies to the east-north-east at 1127 feet (344 m), could have held up a lake to the 1150 feet (350 m) level (fig. 6.1). The 1090 feet (332 m) water level could have succeeded it as a pass at 1068 feet (326 m) to Loch Ba was opened. The 1041 and 1030 feet (317, 314 m) lake levels could have been controlled by a 1034 feet (315 m) pass north-east to Loch Laidon, and the 1020 feet (311 m) level by an outlet towards Loch Ba near the 1068 feet (326 m) one. This latter point was suggested by Mathieson and Bailey and incorporated by Gregory.

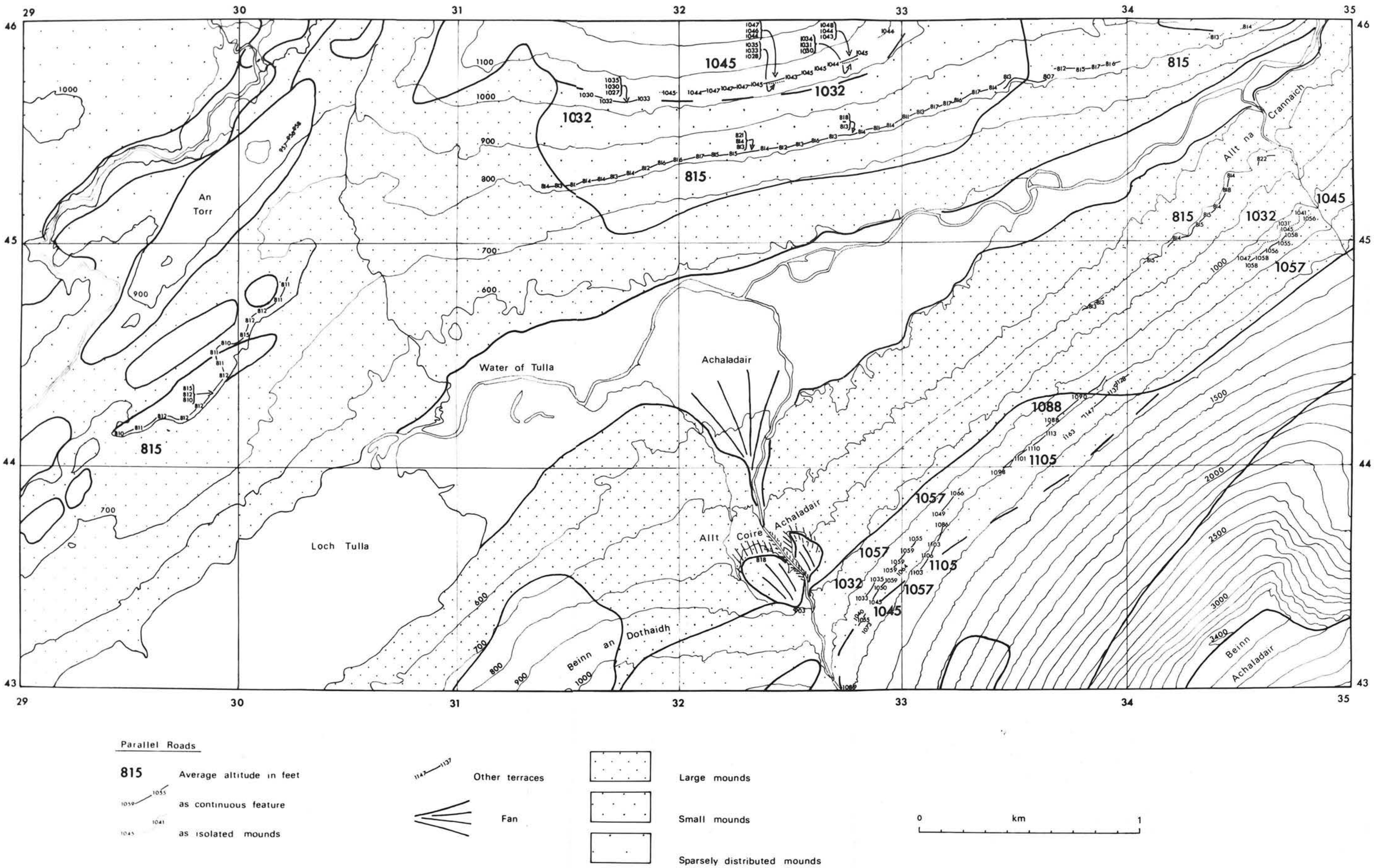
The 816 feet (249 m) terrace was mapped by Gregory as extending almost to the Loch Dochard - Glen Kinglass watershed, which lies at 809 feet (247 m). As it is the clearest and most extensive terrace, Gregory believed that the lake level must have persisted longest at this level. As this terrace is absent from the southern side of the Dochard - Tulla valley on the hillsides west of Glen Orchy, Gregory supposed that ice occupied these hillsides and Glen Orchy whilst the Dochard - Glen Kinglass pass at 809 feet (247 m) was opened by ice recession.

In conclusion there are three reasons why it must be recognised that Gregory's results have only a limited value. Firstly, with two exceptions, his height measurements were made by aneroid barometer or taken from the very limited spot height content of the second edition 1:10,560 Ordnance map. Secondly his visual correlations of terrace fragments have been shown to be incorrect in some instances. Thirdly there is no mention in his paper of how many heights he obtained along the length of each terrace or whether his heights refer to the back, middle or front of each feature. It will be seen from the present writer's diagram (fig. 6.3) that the altitude varies along the lengths and across the widths of the terraces by as much as 15 feet and 8 feet (4.6, 2.4 m) respectively. This makes it impossible to accept completely the suggested association of terraces with various passes, particularly as recent Ordnance maps give different altitudes for some of the passes.

J. Mathieson and E.B. Bailey (1925) considered that there were only two groups of terraces (fig. 6.2); a set of two or three (A 1,2,3) whose highest member lies at 1041 feet (317 m), and a lower (B) at 816 feet (249 m). They obtained these heights by careful triangulation, but only estimated the two other terraces of the upper group as lying at 1030 and 1020 feet (314, 311 m). Like Gregory, they do not specify where their measurements were made, but they do mention heighting two points, one on each of the highest and lowest terraces. Their map (fig. 6.2) shows that they discovered fewer and less extensive features than did Gregory. However they came to more or less the same conclusions about the presence of ice west and south of Loch Tulla and the implied overflow of the ice-dammed lake to the north and north-east. They obtained additional altitudes for these outflow passes with an aneroid barometer that expressed their distrust of its accuracy and of the Ordnance Survey spot heights. Yet they concluded that "fortunately the uncertainties involved

Fig. 8.3.

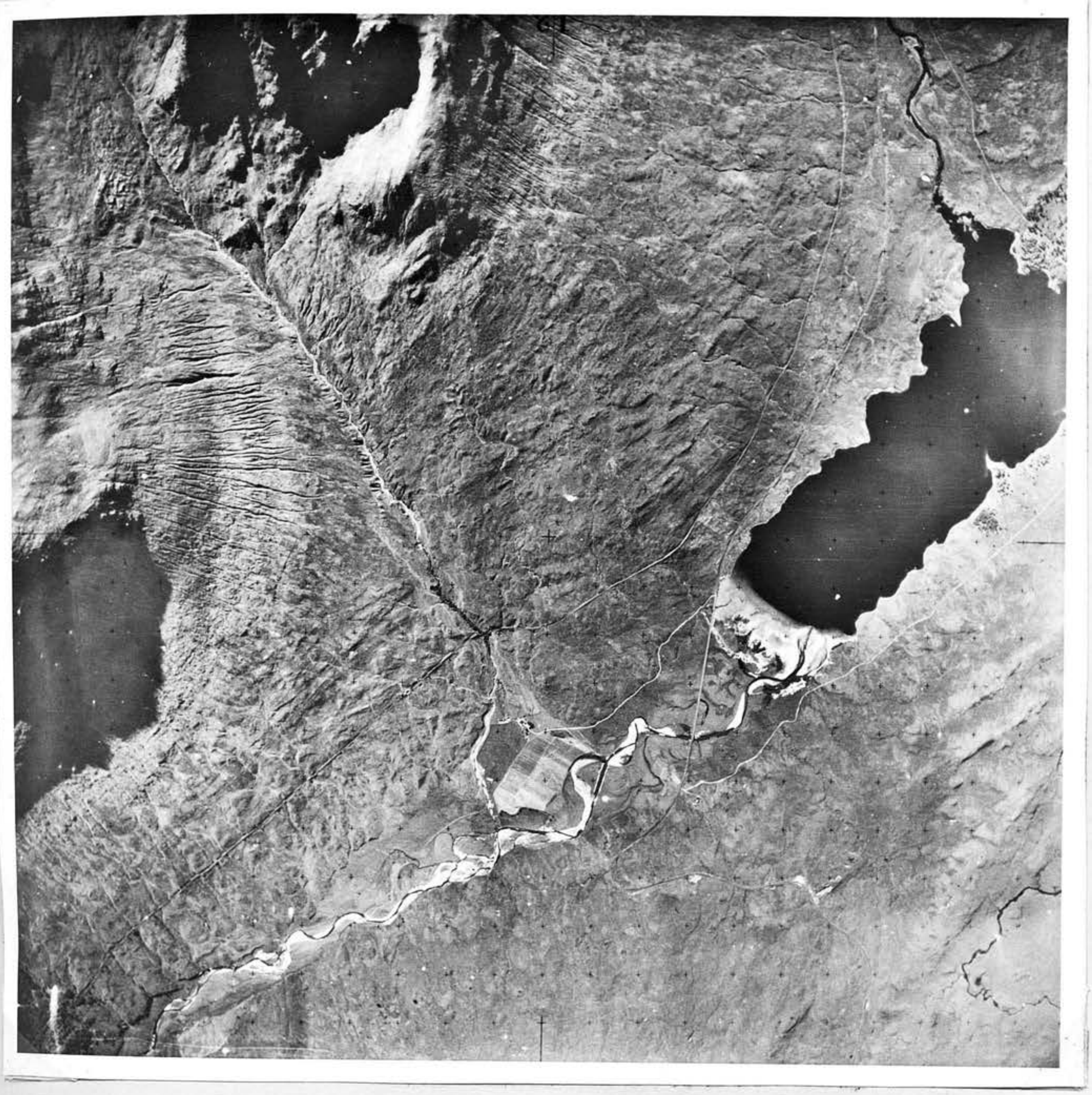
PARALLEL ROADS OF LOCH TULLA.



in this connection only affect points of very secondary importance" (p.199).

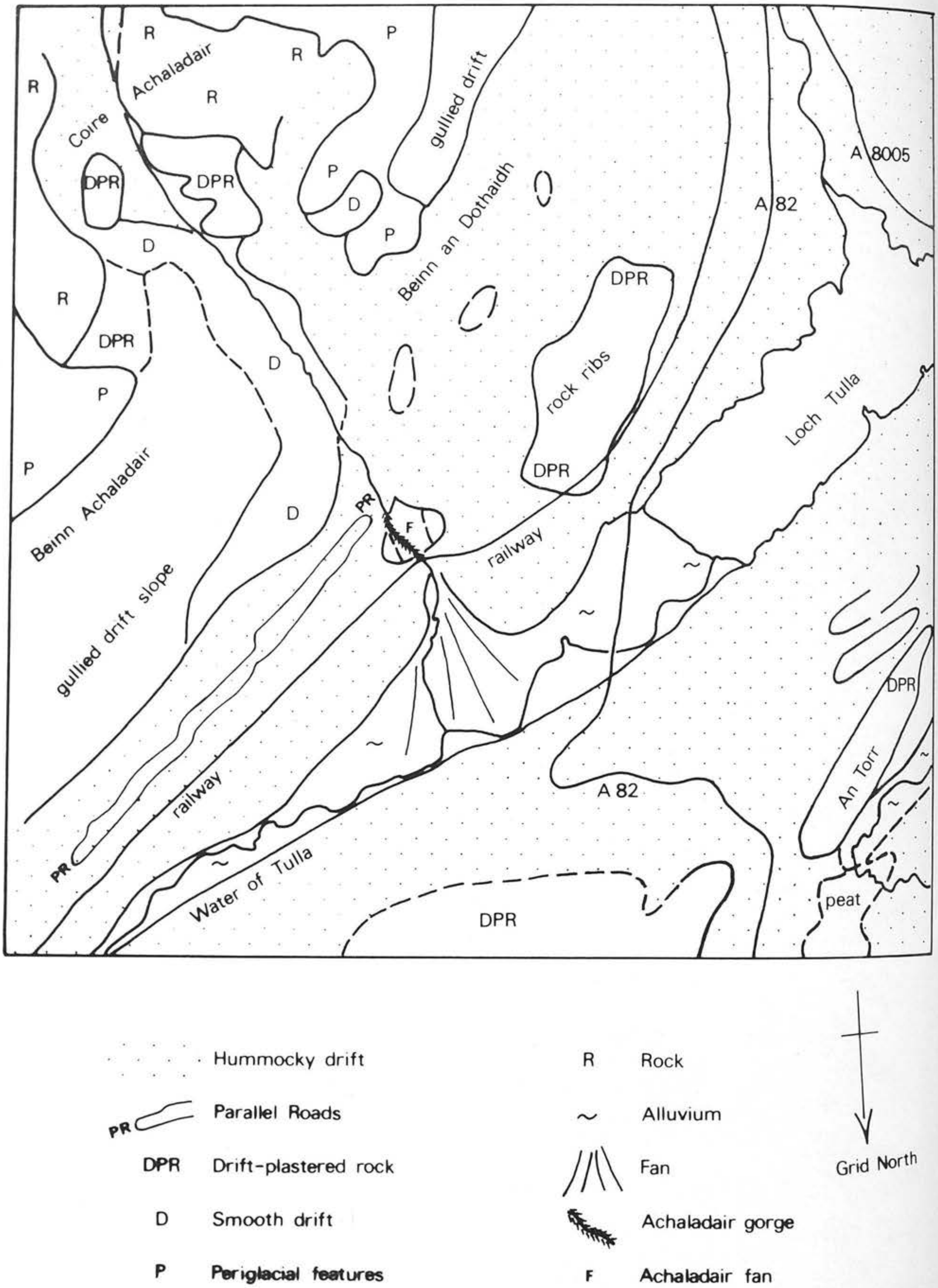
The present writer has mapped at a scale of 1:25,000 Black Mount, the Water of Tulla valley from Gorton (3748) and Dun Laoghan (3747) westwards to the western end of Loch Tulla, and the hills towering above the south-eastern side of the Tulla valley. (A sample of this mapping is given in fig. 1.3 (NN34NW) and the content of the maps is summarised on 1:63,360 sheet 47). Identification and measurement of the Parallel Roads proved to be very difficult. For reasons of time, it was decided to concentrate on fully studying the more accessible features first. Unfortunately it was not found possible to survey the more remote features from Crannaich wood (3545) north-eastwards or any to the west of Loch Tulla. However, during earlier 1:25,000 mapping, it was discovered that some terrace-like features occur immediately north-east of Crannaich wood (3545 - 3646) between 1000 and 1200 feet (305 - 365 m) to the north of the wood (3547) below 1000 feet (305 m), and along the course of the Water of Tulla for 1.1 km north-east of the wood. (These have still to be studied). In addition to these there are two groups of features mentioned in the literature that, for the same reason, cannot be considered here. The first is "a conspicuous series of sand and gravel terraces" along the Water of Tulla valley for 4 km upstream from Crannaich wood (3547 - 3948) between 800 and 1050 feet (245 - 305 m) (Hinxman <u>et al.</u>, 1923, 87). These probably include what appear to be three river terraces noted by the writer (3547 - 3647). The second group of features includes the Parallel Roads seen by Gregory near Loch Dochard (1942, 2142, 2343, 2442).

Fig. 6. 4



Ordnance Survey photograph. Crown copyright reserved.

Fig.6.4 Coire Achaladair and Loch Tulla.



Nominal scale c. 1:32,000

These could not be studied owing to lack of time. Therefore it should be borne in mind that the Parallel Roads may be more extensive than fig. 6.3 suggests. Investigations in the future may require revision of the present interim account, which can offer only a partial explanation for those Parallel Roads that have been surveyed.

Under favourable light conditions it is possible to see a double or triple terrace high up on the southern hillside between the Allt Coire Achaladair and Crannaich (fig. 6.4, PR-PR; fig. 6.3) and a single or double feature facing it on the northern side of the Tulla valley. At a lower level there is a large prominent fan on the hillside below the Coire Achaladair (fig. 6.4, F; fig. 6.3, 3243). Gregory mentions this fan as being near the 816 feet (249 m) terrace but his estimation of the altitude of its apex is 100 feet (30 m) too low. The lower terrace (816 feet - 249 m) is more clearly visible on the northern valley side from Loch Tulla north-eastwards for 4.5 km than it is on the southern side near Crannaich wood. Each of these features was marked out along its length with surveying poles after the whole of each hillside had been very carefully examined three or four times. Other reasonably level and continuous forms were also marked out in order to find whether or not they correlated with similar forms elsewhere on the valley sides. Every feature was instrumentally levelled from Ordnance Survey bench marks. (This and the methods of representation used in fig. 6.3 are discussed in appendix 2). The greatest error in levelling was 1.14 feet (0.35 m) in ascending from 751 feet (229 m) on the railway to 1163 feet (355 m) on the highest feature on Beinn Achaladair. This hillside is covered with moundy drift which is everywhere exceedingly wet and unstable. These factors produced this sort of error in levelling as well as changes in the altitude of the terraces. Fortunately the northern hillside is both gentler and drier and the drift masking it appears to be more stable in the vicinity of the terraces.

In the majority of instances on the southern hillside the backs of the terraces have been blurred by mass movement and their fronts degraded. Accordingly the heights were measured midway between the front and back of each terrace in order to be consistent. On the northern valley side, where the edges of the terraces are clearer, a few heights for the front and back edges were obtained in addition. On fig. 6.3 the extent of individual terrace-like features is portrayed diagrammatically because each is much too narrow to be represented in any other way. Sometimes a terrace consists of a continuous level surface along which representative altitudes have been measured. On other occasions there is a series of mounds whose top surfaces at worst slope less steeply outwards than does the hillside in general or which at best are more or less level-topped. These mounds are often separated by streams that appear on some occasions to have created the mounds from a pre-existing terrace.

In assessing the implications of the surveyed altitudes it was decided to regard as Parallel Roads those terraces that recur at two or more localities at about the same altitude, provided that they possess a terrace-like form. Individual flat-topped mounds or isolated sloping benches that do not recur on the hillside at similar altitudes have not been regarded as Parallel Roads.

Description.

There are five instances of such dubious features. In square 3344 a small terrace lies at 1163 feet (355 m) but has no counterpart elsewhere as far as is known.* A short distance to the north-east another slopes down from 1147 feet (350 m) to 1128 feet (344 m) but nowhere approaches the horizontal. In squares 3343 - 3243 there is a single section of gently sloping hillside at about 1064 feet (324 m) and nearby a set of three terraces at 1073, 1055 and 1040 feet respectively (327, 322, 317 m). Only the one at 1055 feet (322 m) is repeated elsewhere on the hillside and so it alone has been considered to be part of a Parallel Road.

The remaining feature is the rock bench that runs "close to the top of the long low ridge of An Torr" (Gregory, p.96) but which lies at about 957 feet (292 m), not 816 feet (249 m) as Gregory imagined (square 3045). There is certainly a 100 m length of horizontal rock bench near the north-eastern end of the ridge but it dies out abruptly south-westwards against crags and more gradually north-eastwards as it is replaced by smoothly sloping bedrock. It may recur west of square 3045, as Gregory suggests (p.97), but the writer has not so far studied this area. If the surveyed feature were a Parallel Road eroded in bedrock by lake waters, as Gregory believed, then it could be expected to have developed clearly or extensively in drift elsewhere in the Tulla valley. Yet no comparable feature in the 950 - 960 feet (290 - 293 m) range has been discovered. It is therefore considered more likely that the bench at 957 feet (292 m) on An Torr was created by glacial erosion. Numerous similar short benches, both horizontal and sloping at various angles lengthwise,

* This may be Gregory's dubious 1150 feet (350 m) terrace.

exist on the southern face of the neighbouring hill in square 3046 (fig. 1.3). These appear to have been eroded by ice moving north-eastwards across this hill and across Meall Beag (2947, sheet 47), striating the rock and fashioning the two hills into roches moutonnées in this direction.

Gregory, Mathieson and Bailey believed that Parallel Roads exist on the south-eastern side of Loch Tulla, that is on Beinn an Dothaidh (c.3142 - 3143). Gregory suggested that the 816 feet (249 m) and 1030 feet (314 m) triple series existed on this hillside, but Mathieson and Bailey portrayed only the lower terrace on their map here. However, careful examination of this hill revealed that the bedrock has been grooved by the ice so that a series of thinly masked or exposed rock ribs exists between 700 and 1100 feet (215 - 335 m). It has already been suggested that none of these seems to form a Parallel Road, that is a reasonably level terrace that curves into re-entrants and recurs at the same altitude in two or more localities (fig. 6.4).

However there are six sets of features surveyed by the writer that do qualify as Parallel Roads. The two best developed lie at about 815 feet (248 m) and 1045 feet (319 m), and others of lesser extent at 1032 (315 m), 1057 (322 m), 1088 (332 m) and 1105 feet (337 m). The clearest and most extensive is the lowest one. In the vicinity of Loch Tulla it is a narrow bench whose altitude hardly varies from 812 feet (247.5 m) over 1.2 km. It consists entirely of bedrock and is for most of its length backed by low rock outcrops. Although missing from the much steeper basal slopes of An Torr (3045) and from the vicinity of the road, it reappears east of the road in squares 3145 - 3445 as an almost continuous feature 3.4 km long. Its altitude ranges from

812 to 817 feet (247.5 - 249.0 m), with its front edge at about 813 feet (247.8 m) and its inner edge at about 821 feet (250.2 m), where such measurements have been taken. This 3.4 km stretch is developed across thin moundy drift on moderately sloping hillside. The eastern end of this terrace dies out against much steeper rock outcrops opposite Crannaich Wood (3445). On the southern hillside a terrace at the same altitude (814 feet, 248.1 m) emerges from the wood and continues as a series of almost flat-topped mounds for 1 km until it intersects the railway, beyond which it cannot be traced.

The 1032 feet (315 m) Parallel Road is composed of five fragments. On the northern side there are two isolated terraces and a 250 m long bench that dies out at each end against moundy drift. Above Achaladair farm (3244) a set of flat-topped mounds only 150 m in length is conspicuous, as is a single flat-topped mound near Crannaich wood (3445). In these two cases the 1032 feet (315 m) feature is quite clearly the lowest of a number of 'steps' on the hillside. The repetion of the feature in three places suggests that the fragments can be correlated together.

At four places the much longer 1045 feet (319 m) Road is visibly higher than and therefore to be distinguished from the 1032 feet (315 m) Road. At the Allt na Crannaich these are clearly the two lower of a set of three steps, and near the motor road to Loch Ba (3145) there is only a short break between the ending of the lower and the beginning of the higher terrace. Eastwards the 1032 feet (315 m) Road recurs twice as a short terrace or bench below the main 1045 feet (319 m) one. Above Achaladair there is one further fragment 150 m long at about 1045 feet (319 m). As with the lowest terrace the Parallel Road on the northern side is formed in thin drift and on the southern on much thicker moundy drift.

At about 1057 feet (322 m) there are four fragments. At Crannaich wood this Road is the highest of three but near Achaladair it consists of three portions amongst a number of short terraces. The multiplicity of admittedly quite clear terraces here may well have made Gregory, Mathieson and Bailey uncertain whether there are two or three high terraces (cf. fig. 6.4, PR-PR). The surveyed features at about 1088 and 1105 feet (332, 337 m) are also restricted in extent. At one point they even merge with each other as a sloping bench (3344). Like the remaining southern Roads, they are formed across moundy drift.

More conspicuous than any of these is a large fan around the Allt Coire Achaladair whose apex lies at 903 feet (275 m). Its top surface is approximately planar down to its sharp front at about 818 feet (249 m), except where it is moundy or degraded along some edges. As the Allt Coire Achaladair reaches the fan it leaves a course incised deeply into drift and plunges down into a precipitous rock gorge which ceases abruptly after a distance of 300 m. Thereafter the stream descends gently across a lower fan that merges with the flood plain of the Water of Tulla. In this lower section it has hardly cut into bedrock at all, just as it has hardly done so above the higher fan. Clearly the higher fan and gorge are anomalous with respect to the existing stream. Gregory stated that he found "washed and rounded morainic material" where the railway cuts across the base of the fan, and that "three feet of finely laminated clay rests in a small channel on top of" the fan (p.96). The writer found only angular gravelly debris on top of and below the fan. Unfortunately the exposure of laminated clay, which was important evidence for believing that a lake had existed, no longer seems to exist.

Examination of the contour pattern below Coire Achaladair reveals that a shallow valley 300 - 400 m wide descends from this corrie down to the flood plain. The lower portion of this valley appears to have been infilled as much by moundy deposits as by the fan. Indeed the front face of the fan, between 700 and 800 feet (215 - 245 m) and the north-eastern and western edges of the fan consist of moundy deposits. To a great extent the planar part of the upper surface of the fan appears to be the reworked version of formerly more extensive mounds. The gorge, which cuts through both the fan and a much greater depth of bedrock, may be younger than the fan. Yet it is equally, if not more, probable that the gorge is a much older route for meltwater escaping from ice in the Coire Achaladair during various periods in the Pleistocene.

Discussion.

As a whole the Parallel Roads show a clear pattern, within the area so far investigated. There are three virtually horizontal terraces or benches that occur on both sides of the valley, namely those at 815, 1032 and 1045 feet (248, 315, 319 m). Above these there are three fragmented terraces on the southern side at 1057, 1088 and 1105 feet (322, 332, 337 m). No terraces have been identified west of the Allt Coire Achaladair on the southern valley side, and only the lowest has been found anywhere west of the Water of Tulla (approximately grid line 31). The most obvious explanation that can be given for the formation of the Parallel Roads is that adopted by Gregory, Mathieson and Bailey, who believed that they should be explained as the shorelines of ice-dammed lakes in the same way as the classic Parallel Roads of Glen Roy (cf. T.F. Jamieson, 1863).

It may be imagined that the Dochard-Tulla valley, Black Mount and the southern part of Rannoch Moor were occupied during the last stage of glaciation by ice flowing from the numerous corries west of Black Mount and Loch Tulla (Hinxman <u>et al.</u>, 1923). In Glen Orchy (3040 - 3235) the apparent absence of Rannoch granite erratics and the presence of corries high on Beinn an Dothaidh and Beinn Dorain (3244 - 3344, 3343) suggest that more ice advanced northwards into Loch Tulla. The upper limit of mounds left by this glacier varies according to the hillslope angle, reaching as high as 1700 feet (520 m) west of Coire Achaladair (3242). Yet, as has been noted, the ice at or near its maximum may have reached as high as 3000 feet (915 m) in the Loch Tulla district. The three north-facing corries, Coire Achaladair, Coire Crannaich (3543) and Coire an Lochain (3644) almost certainly nourished glaciers, for the lowest (Coire Achaladair) contains abundant hummocky drift.

Towards the end of the last glacial stage the glaciers in this area presumably thinned, allowing nunataks to appear or become enlarged. These probably included the progressively exposed summits and ridges above the corries and, at later stages, parts of the low hills on the Moor, such as Meall a' Ghortain (3749) and Glas Bheinn (3247). The downward surface gradients of the various glaciers were presumably east-north-eastwards along the Water of Tulla valley, northwards in Glen Orchy towards Loch Tulla, and eastwards from the Coire Ba across Black Mount. During the ablation season there was probably a considerable quantity of meltwater along the margins of and within the body of the ice in the Dochard-Tulla valley in particular, for this is the lowest part of the Rannoch basin. In the Loch Dochard - Loch Tulla valley the direction of meltwater-drainage ought to have been eastwards for both the valley and the ice surface descended in this direction. Although the present drainage from Loch Tulla is southwards into Glen Orchy, the northward-flowing Glen Orchy glacier could have provided an effective barrier against both marginal and englacial drainage southwards from Loch Tulla, so long as the ice remained relatively unbroken. Similarly, so long as glacier structures exerted more control over drainage than did the gradient of the valley floor, the flow of meltwater in the Water of Tulla valley would have been east-north-eastwards in the direction of minimum hydrostatic pressure (J. Gjessing, 1960).

As ablation reduced the volume and level of the ice, it is possible that meltwater drainage in the Loch Dochard - Water of Tulla valley could have become restricted by various cols. In the light of present knowledge, which indicates that the higher roads occur for only a short distance on the southern side of the valley, it seems that the Roads are more likely to have been created by ice-marginal drainage than formed in a proglacial lake. Furthermore, because the levels of most of the Parallel Roads correspond to the levels of a series of cols, it is envisaged that, if and when a given col controlled the level of meltwater, each lower col was still blocked by ice.

11 km east-north-east of Loch Tulla there is a broad pass, now largely occupied by peat and alluvium (probably fans and flood deposits), on which the watershed lies at just over 1106 feet (337.1 m) (square 4048). The middle of the highest Parallel Road has been surveyed at 1105 feet (336.8 m), but

it must be remembered that the inner edge of each feature is generally 4 - 7 feet higher (1.2 - 2.1 m). Ice-marginal drainage along (the southern side of) the Water of Tulla valley could have been held at about this level by the col in square 4048 long enough to deposit or erode a terrace on the southern hillside but not long enough to notch the bedrock on the northern side to a recognisable degree. (With reference to this and each succeeding Parallel Road, it may be noted that it should not be presupposed that each is horizontal throughout its length as far as its associated col. Although Rannoch Moor and its environs are thought to have been the centre of isostatic recovery, it is possible that portions of Parallel Roads in the areas excluded from this thesis may have been slightly tilted).

The durations of the water levels at a little over 1088 feet (332 m) and 1057 feet (322 m) may have been brief also, for the Roads at these levels occur only on the southern side in drift. No passes at appropriate altitudes exist however. Only the col between Loch Tulla and Black Mount (2846) at 1075 feet (328 m) lies at a suitable altitude for the 1088 feet (332 m) Road. Yet if this col had been made available by ice recession, then two lower cols farther east would also presumably have been available (3147, 3447) and would have allowed the water table to drop well below 1050 feet (320 m).

Alternatively, if a process of downwasting is envisaged, in which the gradient of the ice surface down towards the east-north-east was maintained, then the cols between the Water of Tulla and Rannoch Moor would have been revealed in order from east to west. In this way, the 1050 feet (320 m) pass (3447) would have been the second to become available. Since the 1088 (332 m) and 1057 feet (322 m) Roads were presumably the second and third to be formed, the meltwater forming them could have drained northwards in the vicinity of the 1050 feet (320 m) pass, presumably by englacial routes.

The three Parallel Roads so far discussed are different from the lower three in that they are each of limited length, occur only on the southern side of the Water of Tulla valley, and are formed of moundy drift. For these reasons it is suggested that, during their formation, glacier ice still occupied the Water of Tulla valley and neighbouring parts of Rannoch Moor. The three higher Roads are not uniformly horizontal, suggesting that they may have been formed between the ice and the hillside in narrow lakes, or stream courses, or both. Small features, such as those surveyed but not considered to be Parallel Roads (3243 - 3343 - 3344), may conceivably have originated in this way.

The lower three Roads, including the two most extensive, occur on both valley sides. The 1045 feet (319 m) Road on the northern side of the Water of Tulla is about 1 km long and formed in thin drift or perhaps bedrock (lack of exposures here precludes more precise identification). As its altitude is consistent it may be supposed to have been formed in an ice-marginal lake whose level was controlled by the pass to Loch Laidon at about 1050 feet (320 m) in square 3447. Further retreat of the ice westwards revealing the pass to Loch Ba (3147) and /or withdrawal north-westwards of ice in Black Mount may subsequently have opened the pass to Loch Ba at above 1025 feet (312 m), allowing the water level to fall so that the 1032 feet (315 m) Road was formed. Both Roads are absent from the vicinity of Loch Tulla, suggesting that ice, whose surface exceeded the levels of the Roads as they were formed, still existed immediately west of these Roads.

In accordance with feasible glacier gradients it is suggested that the Tulla glacier tongue probably extended some distance east of Achaladair and that at least the western ends of the 1045 and 1032 feet (319, 315 m) Roads were ice-marginal.

The lowest Road is the most extensive but, like the others, is absent from Beinn an Dothaidh (3143), that is from the south-eastern side of Loch Tulla. This tends to suggest that the Glen Orchy glacier persisted in and around the site of Loch Tulla in such a way that none of the Roads was able to form, or perhaps to be preserved, on the southern side of the valley west of the Allt Coire Achaladair (3243). The 815 feet (248 m) Road does exist above the eastern end of the Loch on the northern side, suggesting that the ice had withdrawn southwards into the Loch Tulla hollow from the vicinity of the pass to Loch Ba. It follows that the developing 815 feet (248 m) Road, which now overlooks Loch Tulla, would have been formed near the ice margin, and that ice thickness probably diminished eastwards.

11 km west of Glen Orchy there is a pass at approximately 809 feet (247 m) leading south-westwards from Loch Dochard into Glen Kinglass (1941). Gregory and Mathieson and Bailey were in no doubt that this pass controlled the level of the water at this stage. As Gregory claimed to have found the 816 feet (249 m) Road near the pass, he supposed that a lake stretched 18 km from there to the same altitude north-east of Crannaich wood (3647) (fig. 6.1). As the present writer has been unable to examine the ground west of Loch Tulla it is not possible to confirm Gregory's observations. Accordingly either of two circumstances may be envisaged. Firstly there may have been, as Gregory believed, a lake 18 km long with valley glaciers debouching into it from north and south,

preventing the lake from notching the southern valley side in particular. Alternatively the Dochard - Tulla valley may have been largely occupied by glaciers through which an englacial water table was maintained in the vicinity of 815 feet (248 m) by the pass to Glen Kinglass. The glaciers involved may have included ones from Glen Orchy, Gleann Fuar (2540), Fionn Leirg (2240), Glen Kinglass (1741 - 1839), the Allt Dochard area (2044, 1943), and the corries of Stob Ghabhar (2244, 2444, 2345 - 2445). Conceivably the second set of circumstances may have given way to the first as deglaciation proceeded. It seems likely that the water was in places deep and wide, for example to the east of Achaladair, in others a narrow pond between ice and hillside, and in other pools within walls of ice.

Much of the ground below Coire Achaladair was apparently no longer occupied by the Coire Achaladair glacier by the time the higher Parallel Roads had started to form, as parts of these lie directly below the corrie. The meltwater from this glacier very probably poured down the present course of the Allt Coire Achaladair, widening and deepening the course until it met some obstruction. During the formation of the higher Roads the Glen Orchy glacier may have lain across the slope below the corrie. Lowering of the ice surface with time would have resorted any deposits laid on or under the ice by the Coire Achaladair meltwater. However if, by the time the 815 feet (248 m) Road was established, the Glen Orchy ice had withdrawn west of the Allt Coire Achaladair, then the meltwater could have flowed directly into the 815 feet (248 m) lake. Although the north-eastern and western margins of the fan appear to be the remains of moundy drift, and although no structures have been found in the deposits, it may be that the feature should be classified as a delta (cf. Embleton and King, 1968, p.433).

Subsequent ice recession and drainage of the water, possibly southwards via Glen Orchy, would have removed the cause of deposition of the Achaladair fan or delta. Further meltwater from the corrie would have cut down through the fan or delta until the gradient of the stream suddenly diminished at about 700 feet (215 m), below which the existing lower fan may have started to accumulate.

E. Conclusion.

Much fieldwork has yet to be done on the Parallel Roads of Loch Tulla, from Loch Tulla westwards and from Crannaich Wood eastwards. This may reveal the existence of further features, including portions of Parallel Roads. It may also show whether drainage channels exist in any of the cols; none has so far been discovered. Although such work might require considerable revision of this account, there are three reasons for believing this to be a reasonable interpretation. Firstly, for the maintenance of most of the lake levels, there is a controlling col at an appropriate altitude and location. Secondly, the clearer development and greater extent of the lower three Roads fit with the idea of a change in terrace formation from ice-marginal to proglacial situations. Thirdly, other terrace-like features that were surveyed, but which do not occur more than once at the same altitude and are short in length, are not considered to be Parallel Roads. In contrast to the recognised Parallel Roads these other features do not correspond to the levels of cols.

In interpreting the mode of formation of the series of terraces known as the Parallel Roads of Loch Tulla, the hypothesis set out contemporaneously by Gregory and by

Mathieson and Bailey has been accepted. During deglaciation meltwater drainage from the Water of Tulla valley appears to have been impeded by a number of cols as the level of drainage fell. During the maintenance of the water at three higher levels short, approximately horizontal terraces were formed in drift on the southern side of the Water of Tulla valley between the Allt Coire Achaladair and Crannaich wood. As ice in the Dochard - Tulla valley thinned and receded, lower cols controlled the water level, which appears to have fallen in three stages. During these a much larger lake appears to have existed in the Water of Tulla valley (extending at the third stage westwards to or beyond the vicinity of modern Loch Tulla), for the three lower Roads are the most extensively developed. Whereas the five higher Roads appear to have been drained by cols leading into Rannoch Moor, the lowest was controlled by a col to the west of Loch Dochard.

Glen Lyon.

A. Previous literature.

The whole of Glen Lyon is included within three Geological Survey 1:63,360 sheets. The earliest of these, the unpublished manuscript sheet 46 (Balquidder, 1900), covers the western half of the glen, for which the only glacial information given is the record of striations. These are sufficient in a few localities to assist in the interpretation of ice movement but are too few and too unequally distributed to mirror the evidence of an earlier ice sheet and a later valley glaciation contained in the remainder of the thesis area. The same comment can be fairly applied to the even more limited striation records on the two later maps that cover the remainder of Glen Lyon. Sheet 54 (Rannoch) covers the glen from the confluence with the major tributary, Gleann Daimh, to the vicinity of the Ben Lawers group of hills. The remaining easterly portion of the area is presented on sheet 55 (Blair Atholl). Each of the latter two accompanies a memoir by L. W. Hinxman et al. (Blair Atholl, 1905; Rannoch, 1923).

These memoirs are particularly valuable for they describe the distribution of Rannoch Moor granite erratics that "are found plentifully on the hills that form the watershed between Loch Rannoch and Glen Lyon" (sheets 47, 48) but hardly at all on the southern side of the glen (1923, p.82). This contrast implies that "the Moor of Rannoch ice on its passage eastwards and south-eastwards over the hilly ground between Loch Rannoch and Loch Giorra (Gleann Daimh) was not able to cross into the Lyon valley" (1923, p.87). Therefore it is presumed (p.86) that "the Lyon valley was ..... filled by ice emanating from the high ground round Loch Lyon and [received] tongues from the many tributary glens opening on it from north and south" (sheet 47).

J.K. Charlesworth's (1955) account of ice recession in Glen Lyon is of less use because it does not mention any evidence on which his interpretation is based.

On the other hand the geological reports and engineering drawings commissioned by the North of Scotland Hydro-Electric Board in connection with dam sites and other works in Gleann Daimh and upper Glen Lyon have proved of considerable value in the interpretation of drift deposits at these localities (chapter 3, C).

B. Introduction.

Glen Lyon is the longest glen in the Highlands, being 43 km in length from the Abhuinn Ghlas watershed (3635), south-west of Loch Lyon, to Macgregor's Leap (7247), at the narrow, deeply gorged mouth of the glen. Throughout this distance the valley is a deep U-shaped trough, except at its mouth where the rock bar of Ben Lawers schists restricts the valley to a narrow V-shape (sheet 48). Gleann Daimh, containing the twin rock basin lakes, Loch Daimh and Loch Giorra (4645 - 5046), is the only major tributary within the Glen Lyon valley system (sheet 47). Most other tributary valleys are less well developed and either hang above the main Lyon trough, as does Gleann Daimh, or descend steeply and evenly to it. There are two major glacial breaches connecting the glen at low levels with Rannoch Moor, by Gleann Meran (3943), and with Glen Orchy, by Auch Gleann (3539) (sheet 47). Other passes at varying higher levels connect Glen Lyon with Glen Lochay, with Loch Tayside (the Lochan na

Lairige), and with the Loch Rannoch valley (sheets 47, 48).

The hills of Glen Lyon are consistently high, with almost every summit in excess of 2000 feet (610 m) and nearly a score exceeding 3000 feet (915 m). The groups of hills at the head of the glen, in the Tarmachan - Lawers belt, and in the Carn Gorm - Carn Mairg group near the mouth of the glen form the largest area of very high ground in the thesis area, that is in the zone south, south-east and east of Rannoch Moor. This concentration requires emphasis for it is not immediately apparent from the 1:63,360 O.S. maps.

Numerous well-formed corries and deep valley heads scallop these hills, the former being concentrated particularly near the head of the glen and around the Daimh - Lyon confluence (sheet 47). Although no consistent lithological factor appears to account for the presence of these corries, it does happen that most seem to occur in high ground where the strata or planes of foliation dip down into the hillside, rather than up into it.

C. The features.

In this thesis the bulk of the discussion of each valley system is directed towards an assessment of the elevation and gradient of the ice surface in each valley, the sources of glacier ice, and the limits of the principal glaciers. For certain reasons deductions about the ice surface in upper Glen Lyon cannot be made in as much detail as normal. The principal reason is that fresh moundy deposits in lower Glen Lyon, in the valleys north-west and south-west of Innerwick (c.5748), indicate that the surface of the trunk glacier there exceeded at least 2000 feet (610 m, fig. 13.1). Calculations of the minimum ice surface gradient projected westwards towards the principal areas of snow accumulation, as well as consideration of the effects of glaciers flowing into or out of the trunk valley, suggest that the ice surface in the valleys west of Loch Lyon must certainly have exceeded 2500 feet (760 m) (fig. 13.1). Such thick ice would have largely submerged the trunk valley, hanging valleys and corries, leaving only the highest peaks to a greater or lesser degree as nunataks. Because moundy deposits survive on the gentler slopes, which are mostly the lower slopes, the upper limits of mounds in upper Glen Lyon lie well below what was the probable ice surface during the height of the last stage of glaciation (sheet 47). Therefore calculation of the ice surface in upper Glen Lyon has to be based on extrapolation westwards from the Innerwick area (c.5748). (The depositional evidence around Innerwick will be discussed later).

The assumption that the ice surface descended eastwards towards Innerwick accords with the distribution of probable ice sources and in no way conflicts with the implications of the depositional evidence in both Glen Lyon and neighbouring valley systems. These statements will be justified once the evidence has been presented.

The majority of the former ice sources lie in upper Glen Lyon (sheet 47) in three groups, west of Loch Lyon, on the southern side of the valley east of Loch Lyon, and around Gleann Daimh (Glen Lyon's main tributary). Amongst the first group, only the Coire a'Ghabhalach (3339) contains hummocky drift which, in two small rocky corries above the valley head, reaches 2750 feet (840 m). Although the major direction of ice flow was probably down-valley eastwards, the roche moutonnéed form of the col between this valley and

Coire an Dothaidh(3239) is evidence of a westward transfluent ice flow from presumably the more westerly of Coire a'Ghabhalach's rocky corries (3239). Moundy deposits recur at the lower end of the Coire a'Ghabhalach (3539), passing from there to the shores of Loch Lyon (3839) but for no apparent reason not south-westwards down Auch Gleann to Glen Orchy (3235). Ice from the two corries on the east side of Beinn Dorain (c.3338) no doubt contributed to the flow into Glen Orchy (chapter 6) and may have encouraged the Coire a'Ghabhalach glacier to use the outlet eastwards to Loch Lyon.

There are three small rocky corries high on Beinn a'Chreachain (3743, 3744) which may be supposed to have supported corrie glaciers, as may the equally high valleys betwen this mountain and Beinn Achaladair (3643, 3543, 3442). It has not been possible to look for erratics of Rannoch Moor granite in Gleann Meran (3946 - 3942) but, as only a very few have been found in Glen Lyon, it is likely that ice from these corries and valleys around Beinn a'Chreachain prevented Rannoch Moor ice from entering Glen Lyon by way of Gleann Meran.

The second group of ice sources in upper Glen Lyon extends from Coire Heasgarnich, overlooking Loch Lyon (4139), to the flanks of Meall Ghaordie (5139). There are two large corries on Beinn Heasgarnich. The flow of ice from the steep rocky Coire Ban Mor (4238) appears to have bifurcated twice. Between the corrie and the Allt Lairig nan Lunn (c.440390) the rocks knobs that protrude through the drift have been streamlined by ice moving north-eastwards down into Glen Lyon. It may be inferred from this that the mounds in the neighbouring Allt Chall valley (4340) result from a similar north or north-eastward movement, implying that the ice bifurcated in square

Fig. 7.1

Fig. 7.1. <u>Creag Laoghain in upper Glen Lyon.</u>

A stream of boulders derived from Creagh Laoghain (L) crosses the mouth of the hanging Coire Laoghain valley (C) and passes along the drift - mantled face of Creag an Tulabhain (T). The distribution of boulders indicates that the north - eastward - flowing Lyon glacier (moving from right to left in this photograph) was joined by a tributary glacier from Coire Laoghain and also that, during deglaciation, the corrie glacier did not descend to the floor of Glen Lyon after the Lyon glacier had ceased to occupy this part of the valley. The triangular area of debris (f-f-f) may have been deposited on or beside the Lyon glacier by meltwater from Coire Laoghain (square 5141, sheet 47).

Geological Survey photograph.

4339. Secondly, the continuous spread of mounds across the col (4438) and down to Glen Lochay (4636) suggests a further divergence. It is less likely that Glen Lochay ice entered Glen Lyon, for the greater concentration of ice sources appears to have been in Glen Lyon. (In 1908, on account of striations or deposits in this area, P. Macnair suggested that either the Lyon or Lochay glacier was sufficiently thick to override the intervening watershed).

The neighbouring Lairig Liaran (4738) is a shallow breached col at the back of the hanging corrie-shaped Allt Rioran valley (4739). The distribution of mounds in the valley and col show that the Lyon and Lochay glaciers were here connected, perhaps by transfluent flow northwards from the hanging valley and southwards across the lairig. To the east of this lairig the watershed rises up to the peak of Meall Ghaordie (5139). The northern side of this hill mass contains a further three ice sources, the valleys of the Allt Chiorlaich (4839), Allt Laoisich (5040), and Allt Laoghain (5240). The prominence and abundance of boulders portrayed on the map and on the accompanying photograph (fig. 7.1) of the Allt Laoghain (5141) are remarkable. Their source is the steep ice-quarried cliff, Creag Laoghain, from which one train of boulders descends across the hanging lip of the Coire Laoghain to join a second running along the steep side of the trunk valley. These two merge as a single spread of boulders passing north-eastwards and are reinforced by a third train of boulders emanating from Creag an Tulabhain (5241 - 5242). This distribution indicates that the north-eastward - flowing Lyon glacier was joined by a tributary from Coire Laoghain and also that, during deglaciation, the corrie glacier did not move down to the floor of Glen Lyon after the Lyon glacier had ceased to occupy this part of the valley (fig. 7.1).

The distribution of prominent boulders around the mouth of the Lairig Luaidhe (5242 - 5342) and the continuous spread of mounds through the lairig into Glen Lochay (5336) show that the Glen Lyon and Glen Lochay glaciers were here directly interconnected. For four reasons it is probable that a diffluent ice tongue moved southwards from the Lyon glacier through the lairig. Firstly the greater concentration of ice sources lay in Glen Lyon. Secondly the Lyon glacier extended very much farther east than the Lochay (cf. chapter 8). Thirdly the boulder train passes some distance up into the lairig and fourthly the only other source of ice for this lairig could be the shallow embayment on the south-eastern side of Meall Ghaordie (5239), which however was probably much less powerful than ice from the deeper north-facing Coire Laoghain (5240). The branching of the Lyon glacier southwards through the Lairig Luaidhe was very likely encouraged by the entry close by of additional glaciers from Gleann Daimh and the corries in the confluence area (5044 - 4943) (fig. 13.1).

At the head of Gleann Daimh (4346) moundy deposits extend up to 2300 feet (700 m), a level higher than that of the watershed with Rannoch Moor. It has already been suggested (chapter 6) that thick ice occupied Rannoch Moor; a surface gradient estimate, when extrapolated south-westwards from the Loch Rannoch lateral moraine system, suggests that the Rannoch ice surface near Gleann Daimh might have lain at about 2500 feet (760 m). Moundy deposits reach 2150 - 2250 feet (655 - 685 m) on the Rannoch side of the col with Gleann Daimh (4246 - 4347), 2300 feet (700 m) on the Gleann Daimh side, and 2500 feet (760 m) in neighbouring Coire Eoghannan (4144). In the latter the presence of the mounds by the northern col to

Rannoch (4145) and on the western col above the corrie (4044) implies that ice extended beyond the bounds of the corrie. Thus the depositional evidence substantiates the concept of ice in this area thick enough to have spread across the cols between Coire Eoghannan, Rannoch Moor and Gleann Daimh (fig. 13.1). The only indication of the direction of ice flow is in the eskers pointing north-eastwards (4146 - 4247), which suggest ice flow in this direction and so perhaps into Rannoch Moor from Coire Eoghannan (4145) but out of the Moor eastwards into Gleann Daimh (4246 - 4346).

The plateau-like upland between Coire Eoghannan and the Daimh - Lyon confluence, which rises to over 3000 feet (Stuchd an Lochain, 4844), could have provided a considerable source of wind-blown snow for the corries that scallop its perimeter. Only the unnamed corrie south of Loch Daimh (4644), the Coire an Duich (5044) and its southern neighbour (5043) contain abundant moundy drift. The remaining three corries are virtually drift-free (4745, Coire an Lochain 4845, Coire Cashlie 4843). The addition of glaciers from these corries to the Gleann Daimh glacier, and from Coire Cashlie to the Lyon, must have created a large body of ice which would have greatly enlarged the already powerful Lyon glacier as they joined forces in the valley confluence area (c.5244).

It is in the valleys north-west and south-west of Innerwick that the significantly high-level moundy deposits occur (sheet 48). Below Cam Chreag and in Coire Odhar (5448) mounds lie at up to 2100 feet (640 m) and in the Lairig a'Mhuic (5649) and Lairig Chalbhath (5849) on hillsides at up to 1750 feet (535 m). In chapter 5 the northern ends of these three valleys were discussed in detail. It was argued from the presence of large lateral moraines across the mouth of each valley that it is very unlikely that the Loch Rannoch glacier could have penetrated southwards into any of the valleys. It has been calculated that the edge of the Loch Rannoch glacier lay at about 1950 feet (595 m) across the mouth of the westernmost valley (5451 - 5551), 1850 feet (565 m) at the Lairig a'Mhuic, and 1750 feet (535 m) at the Lairig Chalbhath. It is clear from the map that both through-valleys, the two lairigs, could not have nourished their own glaciers and therefore that the ice responsible for depositing mounds there must have come from Glen Lyon. Unfortunately the case of Coire Odhar (c.5548) is ambiguous. It may be that the head of the valley (square 5548) was the source of a glacier that moved eastwards down-valley, and that the crags in square 5448 nourished a small glacier that moved down on to the col above Coire Odhar (5448). On the other hand it may be that the Lyon glacier was thick enough to completely overtop the Ben Meggernie ridge, flow down to the col (5448), fill up Coire Odhar and spread into the two lairigs. The Ben Meggernie ridge and the narrow entrance to these valleys at Innerwick (5847) probably restricted the quantity of ice entering the valleys so that the ice tongues were able to proceed only 2 - 3 km before reaching their limits.

Further support for the suggestion that thick ice occupied this part of Glen Lyon is given by the altitudes of moundy deposits to the south of Innerwick (5844), in the Lairig Breisleich (5641), and in the Lairig Luaidhe (5340). In the lee of the crags in square 5844 the mounds reach 1950 feet (595 m), although some ice may have been derived from this side of the crags. At the entrance to the Lairig Breisleich (5642) mounds on one side of the valley reach 2000 feet (610 m) and, on aerial photographs at least, seem to possess a parallel alignment reminiscent of fluted moraines as described by Sissons (1967a) and by J.D. Peacock (1967). The extent of these features from about the stream confluence (5743) south-south-westwards for nearly 2 km suggests that the ice in contact with the ground moved parallel to this alignment. If diffluent branches of the Lyon glacier were able to spread out northwards into the three valleys above Innerwick, there attaining about 2100 feet (640 m), and southwards through the Lairig Luaidhe, depositing mounds there at 2200 feet (670 m), then it follows that a further branch would have descended south-south-westwards through the Lairig Breisleich depositing mounds there at up to 2000 feet (610 m) (5641, 5439). All this evidence points to an ice surface in Glen Lyon (c.5645) at an altitude of perhaps 2200 feet (670 m), and to an even higher ice surface up-glacier near the Daimh - Lyon confluence. It is on account of all this evidence that it was suggested at the beginning of this section that the ice in upper Glen Lyon was sufficiently thick to submerge both the trunk valley and many of the hanging valleys and corries. The assumed ice surface elevations for upper Glen Lyon calculated upon this basis will be discussed at the end of this chapter (also fig. 13.1).

Adjacent to the Lairig Breisleich the huge north-facing Coire Riadhailt was probably a very considerable ice source. The low roche moutonnéed crags on its eastern spur (5840) show that ice did move northwards to the corrie mouth, but the obvious route down to Glen Lyon would have been blocked by the Lairig Breisleich diffluent. Accordingly the Coire Riadhailt glacier would have been forced to branch in probably two directions, south-south-westwards into the Lairig Breisleich, and eastwards towards the cols with the Lochan na Lairige valley and with Gleann Da-Eig (5941).

In neighbouring Gleann Da-Eig (c.5942) mounds run from about 2200 feet (670 m), near the head of the valley (6041), descending northwards below the col (5941 - 5942) before rising again to 2000 feet (610 m) in square 5943. This col may perhaps have been just low enough to permit a diffluent branch of ice from Coire Riadhailt to join a presumably small glacier flowing northwards from the head of the Gleann Da-Eig valley. Northwards the sources of the mounds high up on the western side of the valley may be sought in the two small north-east-facing rocky corries in squares 5944 and 6044. Prominent boulders lie scattered down-valley from the more northerly corrie. Near the northern end of Gleann Da-Eig the mounds at 1750 feet (535 m) show that ice, possibly derived from this corrie, lay at about this level. Nearby in the trunk valley the upper limits of mounds are generally very low, owing to the steepness of the valley sides. Therefore calculations of the level of the Lyon glacier surface have to be based on extrapolation from the Innerwick area down-valley towards the ice limit, some 9 km distant.

It has been suggested that, in the vicinity of squares 5645 - 5646, the ice surface lay at about 2200 feet (670 m). As a result of the massive outflow of ice from this area northwards and southwards (fig. 13.1) it follows that the ice surface would be expected to have dropped rapidly eastwards in squares 5947 - 6047, doubtless becoming deeply crevassed in the process. In the vicinity of Camusvrachan (6147 - 6247) the incoming supply of tributary ice would have countered this trend but, from about square 6347 eastwards and with the exception of the Invervar tributary glacier (6648), the lack of further supply would probably have allowed the ice surface to drop rapidly towards its limit (6747), where the highest mounds reach about 750 feet (230 m). Such behaviour would be expected both theoretically and from the limited evidence available. The suggested ice margins have been calculated accordingly.

In lower Gleann Da-Eig mounds reach 1750 feet (535 m) but do not occupy the adjacent col (5945) at 1900 feet (580 m). This may imply that the Lyon glacier on the western side of the col lay below 1900 feet (580 m). As the small corrie on the eastern side of the col (5945) rises from 1750 feet to 1850 feet (535 - 565 m), the distal part of the Gleann Da-Eig glacier presumably lay no higher than, say, 1750 feet (535 m) in square 6046. The surface of the Lyon glacier could well have descended to this level by the time it reached square 6046. (The gradient envisaged is only 110 feet per km, or 33 m/km). At the mouth of the Allt a'Chobhair valley (629462) mounds enter Glen Lyon at about 1500 feet (455 m). If this figure is adopted as a reasonable estimate of the ice surface at the confluence, it yields a gradient estimate of 90 feet per km (25 m/km), succeeded eastwards, where there could have been only one minor tributary, by a steeper gradient averaging some 160 feet per km (50 m/km). These are by no means the only possible estimates but they do conform tolerably to the requirements set out above.

The distribution of corries and valley heads in the Allt a'Chobhair valley parallels that in Gleann Da-Eig, with two small north-east-facing corries on the western valley side, and two valley heads reaching 3000 feet (915 m). Although the upper limit of mounds on the eastern side rises down-valley from 1600 to 1900 feet (490 - 580 m), the existence of these potential ice sources in the valley makes it improbable that these mounds could have been deposited by a diffluent of the Lyon glacier. The boulder train, that descends east-north-eastwards from the roche moutonnéed rock knobs on the col between Gleann Da-Eig and the Allt a'Chobhair valley (6146), does in fact show that a diffluent from Gleann Da-Eig converged with the Allt a'Chobhair glacier as it entered the main valley.

Tributary glaciers from the northern side of Glen Lyon at Camusvrachan probably contained a much smaller volume of ice than did the Gleann Da-Eig and Allt a'Chobhair, for the three valleys (6049, 6149, 6249) are narrow and descend steeply to the main valley.

In the main valley abundant fresh mounds terminate on the southern side at Roromore (6346) because the hillside eastwards is too steep to support mounds. On the northern side small groups of kames do occur between rock knobs along the base of the steep hillside (6247 - 6347). The most easterly group of mounds is near Invervar on gentle slopes in the lee of a rocky spur (6647 - 6747). There is good reason for regarding this group as the down-valley limit of the mounds left by the last Glen Lyon glacier and for not accepting the cessation of widespread moundy deposits at Roromore as the limit (6346).

On the southern side of the valley near Invervar, that is at Dericambus (6647 - 6747), there are four well-developed outwash terraces, the lowest of which lies well above the flood plain. The highest terrace contains at least one deep kettlehole (c.670477). On the northern valley side there are again four terraces at Invervar (6648) and in the Balintyre area (6847). The most westerly portion of the four terraces is at Invervar (6648) where they are being truncated by the distributaries of the Invervar burn as it crosses the degraded wooded part of its fan. At Invervar the terraces are much higher above the present river than are any to the west and are also higher than the lowest mounds immediately west of Invervar. To the west of this locality, near Slatich (6447) and at Milton Roro (6247), there are only two terraces, much less elevated above the river than the higher ones beyond Invervar.

The abrupt appearance of high terraces and termination of moundy deposits in the Dericambus area (6747) are very likely to represent the down-valley limit of the Lyon glacier. As the ice receded and down-wasted, the highest terrace at Dericambus would have been formed, either as a kame terrace or as proglacial outwash in which a large detached block of ice was included, thereafter creating the aforementioned kettlehole. Without detailed levelling there is no way of discovering whether the highest of the terraces at Invervar, Dericambus and Carnbane formed a single outwash surface, or whether each was deposited separately against the ice front during stages of recession. Further recession would have occurred before the hillfoot kames and kame terrace at Inverinain (6547) were formed. This kame terrace is less elevated above the river than the Dericambus one, and consists of a terrace merging downwards distally into kames and kettles. However, as terraces are fewer and less well developed west of Invervar, it can be said that the main phase of outwash deposition was accomplished while the glacier stood in the vicinity of Invervar.

In the valley of the Invervar Burn (6450 - 6648) mounds run from the valley head right down to 1000 feet (305 m) in Glen Lyon. The manner in which at their southern limit they are spread across the hillside cannot represent the edge of the former glacier, so the implication is that the Invervar glacier could have made contact with the Lyon glacier. What is less clear is whether or not the Invervar glacier was joined by others from the adjacent valleys below Carn Mairg (6651, 6750, 6850). The mounds high in the westernmost valley (6651) suggest that a glacier there was restricted to the valley head. However, the complete absence of such deposits from the two neighbouring valleys (6750, 6850), from Gleann Muilinn (7050), and from the hanging valleys on the southern side of Glen Lyon (6444. 6544 - 6644, 6744) neither proves nor disproves the possible existence of glaciers in these valleys. Although the two north-facing valleys (6444, 6544 - 6644) are the most likely to have supported their own glaciers, it does not seem possible to assess their possible extent by morphological mapping.

Now that the evidence and the deductions about directions and limits of ice flow have been presented, it is possible to explain the assumptions that have been made about the level of the ice surface in upper Glen Lyon west of Innerwick (fig. 13.1). Because the majority of the ice sources lay in upper Glen Lyon, it is logical to assume that the Lyon glacier moved down-valley eastwards from its sources. (Every other major glacier within the thesis area appears to have moved eastwards). The highest available indication of the minimum level of the ice in upper Glen Lyon occurs at the head of Coire Eoghannan (4144), where mounds cross the col at 2500 feet (760 m). Although at its maximum the ice surface nearby in Glen Lyon may well have exceeded this level, a conservative estimate of 2500 feet (760 m) has been adopted for this part of Glen Lyon and for the adjacent head of Gleann Daimh. On fig. 13.1 and sheets 47 and 48 it has been assumed that the ice surface declined gradually eastwards from about 2500 feet (760 m) in these localities to some 2200 feet (670 m) around Innerwick. Naturally the glaciers in the higher corries and valley heads would have lain at higher levels, especially around the head of Glen Lyon, where they may have constituted a broad area of high-level ice that descended steeply to form or add to the trunk glacier below. It has been assumed that in the source areas the ice could extend right up to near the top of the back and side walls of the valley heads and corries that nourished glaciers. Lastly, in support of the hypothetical glacier pattern outlined above, it is worth noting that it was argued in the preceding chapter that very thick ice probably occupied the Loch Tulla - Black Mount district to the west of Glen Lyon. An approximate surface level of 3000 feet (915 m) was suggested, which broadly agrees with the hypothesis that high-level ice occupied the corries and valley heads in the hills at the head of Glen Lyon.

D. Summary.

During the last period of glaciation in Glen Lyon a major glacier flowed eastwards from sources in the upper part of the valley system. On account of the high level of deposits in lower Glen Lyon, it is suggested that in upper Glen Lyon the main glacier was sufficiently thick to transgress the cols and passes into Rannoch Moor in the north and Glen Lochay in the south. To the east of its confluence with the Gleann Daimh tributary glacier, several diffluent branches appear to have diverged from the Lyon glacier. In this way a group of three valleys north of Innerwick and two to the south-west are thought to have been invaded by the Lyon glacier.

Immediately east of this area of outflowing glaciers it is probable that in consequence the ice surface dropped rapidly. In the Camusvrachan area a number of tributary glaciers entered the main valley.

Abundant moundy deposits cover most of the gentler slopes in the valleys occupied by the system of glaciers from Camusvrachan westwards. To the east of this locality such mounds exist only on the base of the very steep valley sides. However, abundant mounds recur near Invervar where they are associated with the abrupt beginning of a series of high outwash terraces. As no further mounds occur below Invervar, the appearance of the terraces and termination of the mounds is interpreted as the down-valley limit of the Glen Lyon glacier.

Chapter 8. Glen Lochay, Glen Dochart and Loch Tay.

A. Previous literature.

Two Geological Survey unpublished 1:63,360 sheets cover Glen Lochay, Glen Dochart and the portion of the Loch Tay valley with which this chapter is concerned (sheet 46, 1900; sheet 47, 1888). From the striations recorded on these sheets it appears that the predominant direction of ice movement during at least the most recent stages of glaciation was directly down each of the three valleys. To the south-east of Loch Tay striations and roches moutonnées indicate that thick ice at one time submerged the uplands between the Loch Tay and the Earn valleys. The south-eastward movement of the last ice sheet here may or may not have been contemporaneous with the down-valley flow of the last Loch Tay glacier (see chapter 9, Glen Almond). P. Macnair (1908) was of the opinion that the two movements were part of an ice sheet glaciation and he contrasted this with a later period of valley glaciation when abundant 'moraines' were deposited in Glen Dochart.

The studies of pollen and mineral deposits in Lochan nan Cat (6442) by J.J. Donner (1962) indicate that the last glacier to occupy this corrie of Ben Lawers may have post-dated the last Loch Tay glacier and thus have existed during the last stage of glaciation. This matter is discussed in section C.

In his discussion of the Loch Lomond Readvance J.B. Sissons (1967a, p.141) suggests that "the limit of the abundant fluvioglacial deposits and moraines" at Killin in Glen Dochart (5732) marks the terminus of the last glacier to occupy Glen Dochart. It will be shown in chapter 14 that his ascription of this limit to the last stage of glaciation fully accords with the evidence in the remainder of the thesis area. Furthermore it will be demonstrated in this chapter that his identification of an ice limit at Killin is thoroughly justified by the evidence.

B. Introduction.

This chapter is principally concerned with the area between the confluence of Glens Lochay and Dochart at Killin, where they combine as the Loch Tay valley, and the corries of Ben Lawers (6341) (fig. 8.1). (This area is represented on sheet 48, whereas peripheral parts of Glen Lochay and Glen Dochart are shown on sheets 47 and 54 respectively). The Killin - Ben Lawers area has been studied in considerable detail on the ground with the aid of 1:10,560 and 1:63,360 maps and with 1:25,000 aerial photographs. In addition a much wider surrounding area was included in the preparatory examination of aerial photographs. Most of the valleys tributary to Loch Tay and the River Tay to the east of Ben Lawers in the area of sheet 48 have been checked in the field and so are included within the thesis area. Several parts of Glen Dochart included on sheet 54 (and on sheet 53) have been examined but the majority of Glen Dochart has not been investigated in the field. Too many problems of identification of landforms in the valleys between Glen Dochart and Glen Lochay (sheets 47, 53 and 54) exist for detailed deductions concerning the movement of glaciers in these valleys to be made. Consequently the portions of Glens Lochay and Dochart outside sheet 48 (Loch Tay) lie outwith the thesis area. Nevertheless enough is known about the extent of moundy deposits in these valleys for the detailed studies of lower

Glen Lochay and lower Glen Dochart to be viewed in a wider context.

C. <u>The features.</u>

The first of the four areas to be considered in this chapter is Glen Lochay. Although most of the upper part of the valley (shown on sheet 47) lies outside the thesis area, part of the northern side of the valley (east of Beinn Heasgarnich, 4137) has been studied on the ground and enough is known about the remainder for the general pattern of moundy deposits to be recognised. Numerous mounds occupy the lower gentler slopes of the glen from its head continuously to its mouth, a distance of 23 km. At the head of the glen they spread without a break along the valleys flanking Ben Challum (3832) into Strath Fillan (i.e. upper Glen Dochart). (The appropriate sheet - 53 - is not included). From Strath Fillan the area continuously occupied by mounds of similar appearance stretches westwards to Glen Orchy, north-westwards to Rannoch Moor and eastwards along Glen Dochart to Killin. It has already been shown that in the Lairig nan Lunn and Lairig Liaran (sheet 47) mounds of drift were left by glaciers that were formed in the high valleys between Glen Lyon and Glen Lochay. Ice from the Coire Ban Mor (4238) appears to have branched at about square 4439, sending a diffluent south-south-eastwards to Glen Lochay. In neighbouring Lairig Liaran it has been suggested that ice spilled southwards from the Allt Rioran valley (4739). In the vicinity of these two lairigs it has been calculated that the surface of the Glen Lyon trunk glacier lay no lower than about 2400 feet (730 m). About 10 km to the east (sheet 48) the ice in Glen Lyon was still thick enough to be able to send diffluent branches southwards through Lairig Luaidhe (c.5340) and Lairig Breisleich (c.5540). As Glen Lyon ice entered the Lairig Breisleich (5643) it appears to have caused the Coire Riadhailt glacier (5739) to diverge south-westwards into the Lairig Breisleich and eastwards towards Gleann Da-Eig and Lochan na Lairige.

From the confluence of the Lairig Luaidhe and Lairig Breisleich (5338) thick moundy drift spreads down to Glen Lochay. These numerous mounds are absent from the opposite steep rocky valley side (c.5234, sheet 47), from the rock bar (5334 - 5435), and from much of the craggy northern side of the valley below the rock bar (5435 - 5634). However the southern side of the glen east of the rock bar contains numerous mounds whose upper limit is particularly clear between square 5433 and the mouth of the glen. This margin declines gradually from about 950 feet (290 m; 5433) to 850 feet (260 m; 5533) in 1 km, and then more steeply to below 500 feet (150 m; 5633) in the following 1 km. Between the rock bar and square 5433 the boundary between drift mounds below and rock knobs above is ill-defined. Accordingly the gradient of 100 feet per km (30 m/km) between squares 5433 and 5533 has been projected westwards. When a parallel gradient on the northern side of the valley is projected up-valley it fits exactly into the upper margin of the mounds in square 5337 at the valley confluence. Consequently this estimate of the possible ice margin has been adopted.

The down-valley limit of the mounds is exactly at the mouth of the glen (5634). The rock bar at Finlarig (5734) and the northern side of the Loch Tay valley (excepting the Lochan na Lairige area c.6038) are completely devoid of comparable moundy drift deposits. Only to the east of grid line 69 does hummocky drift reappear but the forms here are very smooth and subdued. These continue intermittently eastwards along the River Tay valley to at least the margin of the thesis area and are thought to belong to the preceding more extensive stage of glaciation. Between the Ben Lawers area and the Glen Lochay limit (5634) the lower gentler slopes are diversified by numerous low rock outcrops that protrude from a thin till cover. The distinctive hummocky landscape of Glen Lochay is clearly absent.

Whereas the floor of the Glen Dochart valley is covered with gravelly mounds the slopes above the southern side of Loch Tay are dominated by bedrock lying at or near the surface (sheet 48). Superficially it might be anticipated that the margin of moundy deposits, and hence of the Dochart glacier, could be traced on the more gently sloping south-eastern side of the valley south of Killin. However, for reasons that will be given later, this has not proved possible. Accordingly, within the area of sheet 48, the position of the Dochart glacier margin has had to be estimated from evidence on the north-western side of the valley.

Full evidence relating to the presumed ice margin near the head of Glen Ogle (sheet 54) will be presented in chapter 11. It is sufficient here to note that the margin of the Dochart glacier declined eastwards from about 1650 feet (505 m) in square 4927 to about 1250 feet (380 m) in square 5428. Glen Ogle appears to have been invaded by a diffluent branch of the Dochart glacier which moved 6 km south-south-eastwards to terminate at the head of Loch Earn. Immediately opposite the entrance to Glen Ogle (5331) the upper limit of thick valley-side drift lies at about 1250 feet (380 m), which is the same altitude as that of the uppermost mounds in square

Fig. 8.1

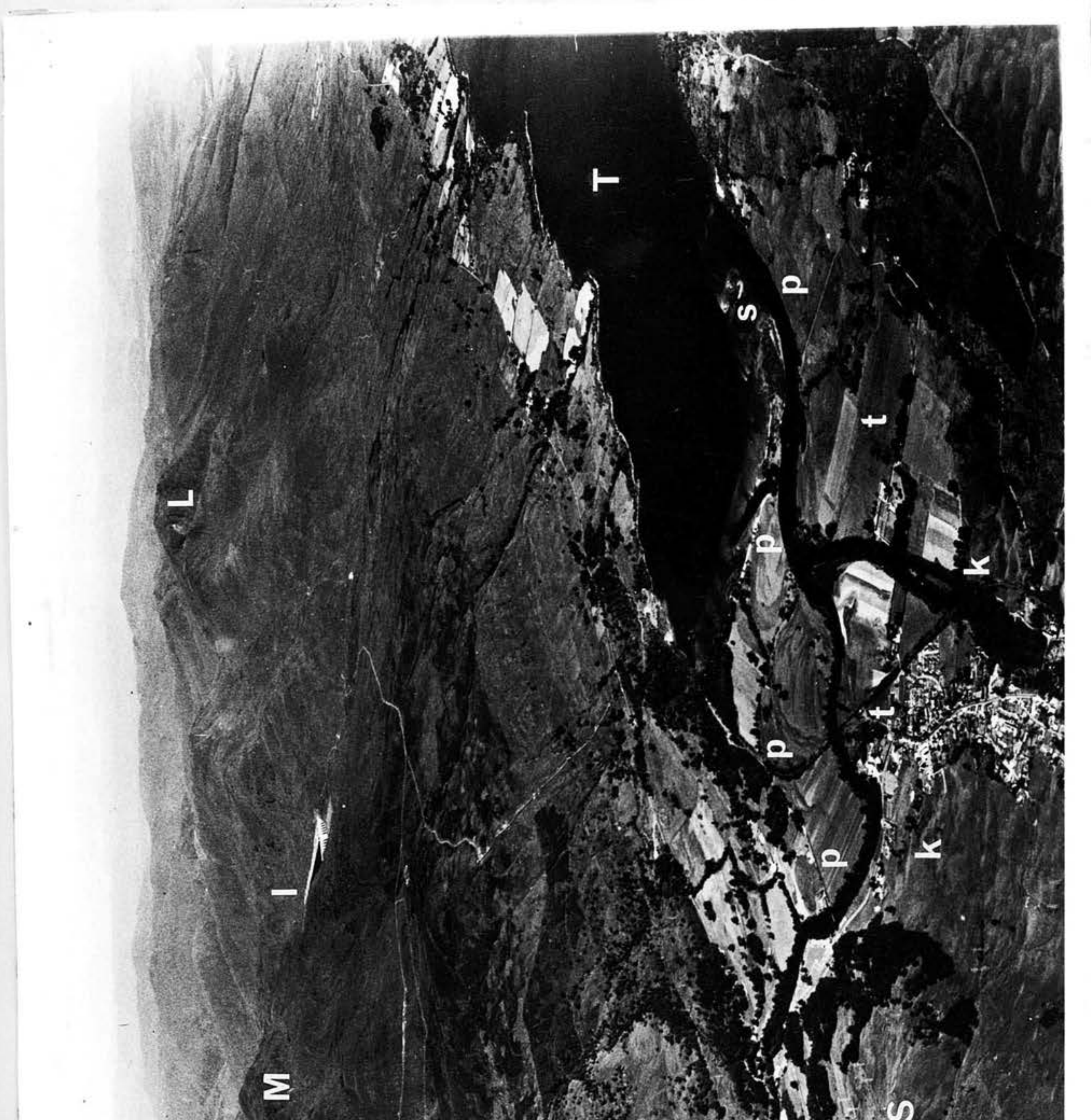


Fig. 8.1. <u>Ben Lawers and Loch Tay.</u>

Glen Lochay and Glen Dochart join at Killin, where they combine as the Loch Tay rock basin (T). The limit of hummocky drift left by the last Glen Dochart glacier is at Killin (k - k) and in Glen Lochay deposits of the last glacier end near the mouth of the valley (h). The head of Loch Tay is being infilled by alluvium (flood plain 'p', spit 's'), some of which is terraced (t). To the north-east the highest summit in western Perthshire, Ben Lawers (L; 3984 feet, 1214 m), is separated from Meall nan Tarmachan (M) by a glacial breach, occupied by the Lochan na Lairige (I).

Photograph by Planair.

5428. The north-western side of the valley above about 800 feet (245 m) is too steep to support moundy drift. The much higher drift limit, which is revealed by the headward extent of incised stream courses, gradually declines north-eastwards to 750 feet (230 m) near Killin (5632), where it merges with the clear upper margin of numerous mounds. Over the ensuing 1.3 km this margin drops to 400 feet (120 m) and is there abruptly truncated by a sloping terrace in Killin village (fig. 8.1). No mounds exist between here and the mouth of Glen Lochay, for the deeply cleft hillside (5633) is too steep to support any (fig. 8.1, S). The flood plain of the combined rivers Lochay and Dochart has not only replaced any forms that may have been created by the last Dochart glacier but is still actively growing (fig. 8.1, p). For example, Grant Wilson (1888) mentioned that the sand spit at the mouth of the rivers advanced 600 m into Loch Tay between 1861 and 1888 (fig. 8.1, S). A borehole where the railway bridge spans the Lochay (5733) recorded 22 m of drift without reaching bedrock. Clearly therefore the head of the Loch Tay rock basin is being infilled with fluvial deposits. The true head of the basin probably lies directly below the steep rocky slope that faces eastwards in square 5633 (fig. 8.1, S) and below the rock bar that the River Dochart crosses in Killin (5732).

5 km south-west of Killin near the head of Glen Ogle (5329) the Dochart glacier was at least 230 m thick. In Killin village the margin of the hummocky drift is crossed by the 500 feet (150 m) contour at a point directly upslope from the low rock bar (the Falls of Dochart), where the bedrock surface is about 400 feet (120 m). These figures imply that the thickness of the glacier on top of the rock

bar was not less than 30 m. A decrease of minimum thickness from 230 m to 30 m in 5 km signifies that the glacier snout probably reached its maximum not more than 1 km beyond the present limit of the hummocky drift in square 5732. Within that 1 km the glacier would have begun to descend into the Loch Tay rock basin where the lake water would very likely have caused icebergs to calve off from the ice front, thus effectively limiting the advancing ice.

The location of the glacier margin on the south-eastern side of the valley is less precisely known. Hummocky drift extends from 1150 feet (350 m) in square 5629 right down to the River Dochart. Sections along the road down from Glen Ogle (5528 - 5529), along stream courses (5530 - 5630) and along the railway line down to Killin (5530 - 5631) show that gravel mounds are widespread. On aerial photographs and on the ground this hummocky landscape appears to extend uninterruptedly to the Allt Breaclaich in square 6032 and to be repeated east of this burn in squares 6233 and 6334. However very careful inspection of the ground between this locality (c.6233) and Killin shows that this impression is mistaken. The valley of the Allt Breaclaich and neighbouring slopes of the Loch Tay valley have only a thin irregular mantle of till through which small rock knobs or ribs protrude. Rock ribs are particularly prominent on the higher slopes between squares 6132 and 5629. The Allt Lochan nan Geadas (5930) and the Achmore Burn (5830 - 5831) transect the hummocky landscape and in each of the hillocks and depressions sectioned by these burns only bedrock is revealed. Even the exposures along the course of the smaller burn in the eastern part of square 5731 are of bedrock. Only 1 km to the west cuttings beside the railway are in gravel mounds.

Somewhere between, in square 5731, the boundary between gravel mounds to the west and rock knobs to the east may be expected to exist, but the close similarity of the two varieties of landform has obscured its location. Probing with a soil auger failed to clarify the problem, probably because the surface deposits of till (ablation till when on gravel mounds) are too coarse to permit penetration by the auger. In view of these difficulties the possible ice margin south of Killin has been assumed to descend from its known position at the head of Glen Ogle (5428 - 5629) at the same rate down-valley as the probable ice margin on the north-western side of the valley.

The third area with which this chapter is concerned lies near the southern end of the Lochan na Lairige, the deep glacial breach that cuts through the Meall nan Tarmachan - Ben Lawers ridge (fig. 8.1, I). The area includes the Coire Odhar (6139), the hillsides drained by the Morenish (Mhoirneas) and Edramucky burns(6038/6138 - 6036/6136), and adjacent parts of the Loch Tay valley. It has already been noted that low rocky crags and knolls frequently crop out along the northern side of Loch Tay. These follow the strike of the various beds of rock, each parallel with Loch Tay (between grid lines 58 and 65). As these beds dip into the hillside it is not surprising that ice moving along the Loch Tay valley has picked out the planes of weakness. Over virtually all of the ground between the Creag na Caillich - Meall nan Tarmachan ridge (5637 - 5838) and Loch Tay, and between the Beinn Ghlas - Ben Lawers - Meall Garbh - Meall Greigh ridge (6239 - 6743) and Loch Tay, bedrock lies at or near the surface. For example, over most of square 6037 and all of squares 6036, 6136, 6236 and 6237 low rock outcrops are common and exposures or other signs of significant quantities of drift almost absent.

There are two groups of clear drift mounds. The one at the northern end of the Lochan na Lairige (5941) is separated from that at the southern end (6038) by a gentle drift-covered slope, with occasional subdued mounds, on the eastern side of the valley, and by a steep craggy slope on the western. Beyond the southern end of the lairig the spread of mounds extends across to the neighbouring Edramucky burn (6138), up to the mouth of Coire Odhar (6139) and down to the car park (in the north-eastern corner of square 6037). The upper limit of undoubted drift mounds reaches its highest level around the mouth of the Coire Odhar at 2100 feet (640 m). Here a single drift feature blocks the entire width of the valley. The two principal burns draining the rock-and-peat-floored Coire Odhar (6139) have been forced to turn and run westwards for 180m across the valley floor before being able to break through this barrier. It stands like a rampart facing up-valley, but is continued down-valley without a break by an equal thickness of drift. West of the burn the feature rises upslope above the drift sheet as a series of large mounds until it fades out against a steepening rock slope at 2100 feet (640 m). On the eastern side of the valley the feature thins and narrows upon reaching the valley-side break of slope. Nevertheless it continues unbroken for nearly 200 m as a low ridge curving slightly upwards along the hillside, thinning until it fades out. Taken as a whole this cross-valley ridge is strikingly reminiscent of the highest lateral moraine that crosses the mouth of one of the lairigs tributary to the Loch Rannoch valley (5651, sheet 48). The contrast between the drift-free Coire Odhar (6139) and the thickness of drift below this ridge, combined with the trend of the ridge across the valley (it is convex up-valley), imply that the drift forms were deposited by a glacier moving across the mouth of the valley without entering Coire Odhar. This curving ridge is therefore interpreted as a lateral moraine that, like the series of lateral moraines south-east of Ben Lawers (see below), may mark the margin of the last Loch Tay glacier. Furthermore it may be inferred that no glacier moving southwards from Coire Odhar (6140) has transgressed the ridge since its deposition.

Below the lateral moraine the Edramucky burn is deeply incised into thick drift, and in places into several metres of rock, down to 1500 feet (455 m) where it crosses the margin of the thick drift. The eastern margin of hummocky drift in this vicinity is clear below 1750 feet (535 m) but difficult to identify above this height owing to the very subdued nature of the forms away from the proximity of the burn (6138). To the west of the car park the limit of hummocky drift is equally difficult to identify (5938 - 6037). In the north-eastern quarter of square 5938 occasional small rock knobs, protruding from the drift, merge imperceptibly into drift mounds. For about 1 km downstream from the car park (6037 - 6137) there is a zone of small sandy or gravelly mounds beside the Morenish (Mhoirneas) burn. These extend across to the Edramucky between 1150 and 1250 feet (350 - 380 m). When viewed from below there seems to be a downslope limit of mounds that is followed by the National Trust property boundary (c.1000 feet, 305 m) in square 6137 between the motor road and the Morenish burn. However, careful investigation revealed that drift mounds are confined to the Morenish end of this feature and that, for the remainder of its length, only a thin cover of drift exists. It is suggested that the feature is a drift-covered bedrock ridge, parallel to numerous others in this part of the Loch Tay valley.

There is evidence of meltwater erosion in this neighbourhood. At point 611374 the already incised Morenish burn plunges down into a deep rocky chasm which shallows gradually southwards. Two dry meltwater channels hang above the head of the chasm. Less than 1 km to the east a branched meltwater channel runs downslope for 150 feet (45 m). Another dry channel (6136), with abandoned rock islands and waterfalls, almost connects the Morenish with the Edramucky.

It has been considered necessary to set out this detailed landform description because it does not seem possible to interpret the depositional forms satisfactorily in terms of valley glacier limits. With the exception of the adjacent Ben Lawers corries, the evidence in the thesis area consistently shows a pattern of glaciers flowing out from the high valley heads and corries (chapter 13). In most cases their termini are shown by the down-valley cessation of fresh hummocky topography (and in the remainder by outwash deposits). If the advance of glaciers in the Lochan na Lairige and Coire Odhar were to be visualised in the same way as in the remainder of the thesis area, the expected picture would include a diffluent ice tongue penetrating southwards through the Lochan na Lairige pass and a valley glacier moving down from the Coire Odhar, with each leaving hummocky drift to mark its advance. However, the clear lateral moraine across the mouth of the Coire Odhar shows that such an interpretation would be mistaken. The last recorded ice movement here was across the mouth of the corrie. Furthermore this movement cannot have been of a Lochan na Lairige glacier, for the limit of moundy drift in squares 6038 - 6138, which curves steeply down each valley side, does not conform to any conceivable glacier margin. If a Lochan na Lairige glacier had been thick enough to reach 2100 feet (640 m) across the mouth of Coire Odhar (6139), it would have spread very much farther down towards Loch Tay than the extent of hummocky drift would suggest. On the other hand a coherent interpretation can be made if it is assumed that the barrier across Coire Odhar marks the margin of the last Loch Tay glacier, which is believed to belong to the penultimate stage of glaciation. If at this stage there was a greater build-up of ice in Glen Lyon than in the Loch Tay valley (as was the case in the last stage of glaciation), the Lochan na Lairige would have provided an excellent meltwater route southwards. Deposition on, in and especially under a decaying Loch Tay glacier by such meltwater could produce the spread of mounds in squares 6139 - 6138 - 6038 - 6037 - 6137. Meltwater erosion of the channels in this area could also have resulted from drainage southwards under the Loch Tay glacier.

As a corollary to this hypothesis it follows that the limit of ice during the last stage of glaciation is more likely to have been around the northern end of the Lochan na Lairige (5941). It was suggested in the preceding chapter that, if a glacier was formed in Coire Riadhailt (5739), a diffluent branch of ice would have moved eastwards towards the heads of Gleann Da-Eig (5942) and Lochan na Lairige (5941). For various reasons an ice surface level of not more than 2100 feet (640 m) was deduced for this area. The splitting of the ice into two further branches (Gleann Da-Eig, Lochan na Lairige) would have resulted in the immediate thinning of both. As the main sources of ice in Gleann Da-Eig lay some distance away (6142, 5944, 5945), the Lochan na Lairige diffluent would have been deprived of a further supply of ice. Accordingly it can be expected to have terminated within a short distance, possibly near the head of the Lochan na Lairige rock basin.

The fourth area to be included in this chapter is the Ben Lawers group of corries. This comprises the east-facing corrie occupied by the Lochan nan Cat (6442) and the south-facing corrie between Ben Lawers and Beinn Ghlas (6340), which will be called Coire Ghlas (no name is given for it on the 1:10,560 map). The evidence implying that glaciers existed in these corries during the last stage of glaciation is circumstantial. There is no direct indication of either their presence or absence during this stage.

J. J. Donner (1962) obtained pollen and mineral samples by boring into lake sediments of Lochan nan Cat (6442) at 2350 feet (715 m) (chapter 2, C). From this he concluded that "the formation of organic sediments began during the Pre-Boreal period, Zone IV" (p.26) and that the pollen sequence and mineral deposits represent the entire postglacial period. He found a much higher ratio of mineral to organic matter in this lochan than in some other lower sites (Donner, 1957, 1962). This is a consequence of the sparseness of vegetation cover, which is unable to prevent the delivery of sediment by streams, or by mass movement down scree slopes or, in winter, down snow slopes. Donner considered that "changes in stratigraphy were more influenced by displacement of the streams which carried the material into the lake basin" than by climatic changes. Donner's investigations prove that there was no glacier ice in this corrie during or after Zone IV. However, it should be mentioned that the apparent absence of earlier deposits could as well be due to Donner's failure to find them as to their having been removed by a Zone III corrie glacier. Thus, the absence of lateglacial deposits does not necessarily imply that a Zone III glacier existed in this corrie.

Nevertheless it can be argued that there are two lines of circumstantial evidence that lend some support to the notion of corrie glaciers having occupied the Lawers corries during the last stage of glaciation. The first comprises the morphological evidence in the adjacent part of the Glen Lyon valley system. The last Lyon glacier reached its terminus north-north-east of Ben Lawers and received tributaries from valleys running northwards from Ben Lawers (fig. 13.1). Ice in the Allt a'Chobhair valley (6241 - 6246) could have had four sources, namely the two trough-side corries (6144, 6143) and the two valley heads (6241, 6343). The headwalls of the latter lie at least as high as the headwalls of Coire nan Cat and Coire Ghlas. It is a reasonable assumption that Allt a'Chobhair ice would have come from at least the two higher and therefore colder collecting grounds, that is the two valley heads. It follows that east-facing Coire nan Cat would have been as favourable for glacier formation. Coire Ghlas, facing south towards the sun, may be considered much less favourable.

The second line of argument involves the morphological evidence in the Loch Tay valley below the corries. There is a group of lateral moraine ridges that runs north-eastwards for 2.5 km until it abruptly is truncated by the Lawers burn (6741). These moraines clearly date from the period of the last Loch Tay glacier, thought to belong to the penultimate stage of glaciation. In the vicinity of Lawers burn they do not rise above 1750 feet (535 m). The thick till sheet, of which these are part, extends up the Lawers valley to at least 2000 feet (610 m). It is below 2000 feet (610 m) that the Lawers burn descends into a rapidly deepening gorge, cut almost entirely into the drift sheet. To what extent the huge channel is the expression of the ease of erosion of the till and to what extent the result of glacial meltwater erosion from the corrie remains unknown. Yet it may well be significant that, whereas a very similar gorge has been cut through the till below Coire Ghlas (6339 - 6439), the only other gorge-like channels on this side of the Loch Tay valley lie below the Lochan na Lairige (discussed above) and these are thought to be meltwater channels.

The highest Loch Tay lateral moraines mark the limit beyond which a Coire nan Cat glacier could not have advanced. There is no higher group of forms that might mark a former glacier margin, apart from the few subdued moundy forms between 2100 and 2200 feet (640 - 670 m) in square 6542 whose nature could not be discovered. The outer part of the corrie floor is blanketed with thick peat (6542), and the smooth ridge dividing the Lochan nan Cat into two parts so notably lacks kettling or drift exposures that it must be supposed to be a low rock bar. Accordingly in the absence of ice-marginal deposits, the maximum limit for a Coire nan Cat glacier must be the Loch Tay lateral moraines at 1750 feet (535 m). Alternatively, in view of the apparent lack of disturbance of the till sheet, it may be suggested that the head of the Lawers burn gorge may mark the point of issue of meltwater from a Coire nan Cat glacier (c.665425). A similar inference might be made regarding the gorge leading from Coire Ghlas. Here the gorge begins much nearer the head of the corrie than is the case with Coire nan Cat, perhaps a reflection of the expected smaller size of a south-facing glacier compared with an east-facing one.

In conclusion, it is suggested that the balance of evidence tends to indicate that corrie glaciers of limited extent existed during the last stage of glaciation in Coire nan Cat and Coire Ghlas. Their small size accords with their position on the eastern edge of that part of the thesis area glacierized at this time.

D. Summary.

In Glen Dochart and in Glen Lochay it is apparent from the distributions of fresh moundy deposits that major glaciers moved down these valleys until they terminated near the head of Loch Tay. Comparable deposits are absent from the slopes of the Loch Tay valley except below the mouths of Lochan na Lairige and Coire Odhar. On account of the distribution of deposits here and of a clear lateral moraine across the mouth of Coire Odhar, it is considered that this group of mounds and some associated channels may be meltwater features related to the penultimate stage of glaciation. Accordingly it is suggested that, during the last stage of glaciation, the limit of a diffluent ice tongue from the Glen Lyon valley system (from Coire Riadhailt) may have been at the northern end of the Lochan na Lairige.

There are three principal reasons for conjecturing that the large east-facing corrie below Ben Lawers (Coire nan Cat) may have nourished a glacier during this last stage. Firstly, J.J. Donner has contended that the presence of only postglacial deposits in the Lochan nan Cat signifies that a glacier occupied the corrie during the preceding period (Zone III). Secondly, valley glaciers tributary to Glen Lyon appear to have formed on the adjacent north-western side of the Ben Lawers - Beinn Ghlas ridge. Thirdly, the deep Lawers burn gorge, which cuts through lateral moraines of an older glacial period (moraines of a Loch Tay glacier), is most easily explained as the product of eroding meltwaters derived from a Lawers corrie glacier during the last stage of glaciation.

Glen Almond.

A. Previous literature.

The Geological Survey 1:63,360 map sheet of the Glen Almond area provides minimal information about the evidence of glaciation in the Glen Almond area (sheet 47, 1888). Unfortunately there is no descriptive memoir accompanying this map. The information consists of an indication that 'moraines' exist in a few localities in Glen Almond and neighbouring valleys. However to the south, around Glen Lednock, and to the east-north-east, in Strathbraan, the pattern of striations and roches moutonnées points south-eastwards, indicating that the last movement of ice across the Lednock-Braan district was by an ice sheet flowing south-eastwards. The same ice sheet presumably submerged Glen Almond. The striations along the Loch Tay valley point north-eastwards, and from this it may be inferred that the last ice movement within the valley was in this direction. This movement may or may not have been contemporaneous with the last recorded movement of the ice sheet on the uplands to the south-east. If it was, then it should be regarded as that of a thick ice stream flowing at right angles to the regional ice flow. Alternatively the last ice movement along the Loch Tay trough may have occurred later than the last movement across the uplands.

P. Macnair (1908) attributed abundant moraines in upper Glen Turret, the Highland part of Glen Almond and the Sma' Glen to the last valley glaciers. J.K. Charlesworth (1955) described a possible pattern of ice recession in the Glen Almond district but neither related this to the limits of advance of the ice nor specified the evidence upon which his account was based.

D.L. Linton (1940) interpreted Glen Almond as having been one of the original west-east consequent valleys of Perthshire whose present connection with Loch Tay may have been produced by glacial diffluence outwards from the Loch Tay valley (sheet 48). This hypothesis fits with the pattern of ice sheet flow suggested by the Geological Survey. Linton also considered that the Loch Tay depression has been produced by erosion along the strike of the rocks and in part along the Loch Tay fault. It is probable that these factors were instrumental in the glacial formation and overdeepening of Loch Tay to as much as 150 feet (45 m) below Ordnance Datum. This erosion has left the two valleys around the Shee of Ardtalnaig (7236) hanging high above the Loch, so that their gradient down to Loch Tay is much steeper than their gradient south-eastwards into Glen Almond or that along Glen Almond itself. The steep gradient has clearly been a factor in the engorging of the streams that drain from around the Shee of Ardtalnaig down to Loch Tay. This matter will be considered below.

B. Introduction.

The Highland portion of Glen Almond is a deep, narrow, steep-sided valley 16 km long (sheet 48). The Lowland extension of Glen Almond lies outwith the thesis area. These two major parts of the valley are connected at the south-eastern corner of the thesis area by the Sma' Glen, a constricted rock-walled defile 3 km long (c.8930) and 1000 feet (300 m) deep. Near the northern end of the Sma' Glen, Glen Almond is connected by a low glacially-breached watershed with the Glen Quaich - Strath Braan valley (c.8932 - 9035). 16 km to the west, the head of Glen Almond is joined with the Loch Tay valley by the two glacial diffluence channels around the Shee of Ardtalnaig (Linton, 1940). There are only two other passes of significant size into Glen Almond. The more important is a col 900 feet (275 m) above the floor of Glen Almond that connects it with Glen Turret (7831). The less important, as far as this thesis is concerned, is the 750 feet (230 m) deep rocky ravine of Glen Lochan (8335) which leads into Glen Quaich. This ravine appears to have been cut through the corrie back wall of Glen Lochan by glacial transfluence and perhaps enlarged by later diffluence from Glen Almond.

With the exception of these six passes, Glen Almond and its tributary valleys are enclosed by high rounded hills which attain 2700 - 2900 feet (825 - 885 m) in the west, dropping gradually to about 2200 feet (670 m) near the Sma' Glen and to even lower altitudes east of the Sma' Glen. The western hills of the Glen Almond district are the highest in Perthshire south-east of Loch Tay. On the southern side of Glen Almond a number of well-formed rock-walled corries hang above the trunk valley, their backwalls generally reaching about 2250 feet (685 m). On the opposite south-facing side of Glen Almond the valley heads reach similar altitudes. Although none is cliffed, their shapes generally resemble those of the corries. The most obvious cause of this distinction is the orientation of the corries away from the sun. Another but possibly more important cause is the contrast in rock type between the two sides of Glen Almond. The southern side, from square 7532 via 8433 to 8835, consists of pebbly grits with slate bands.★

★This is the identification adopted on the 1:63,360 'Stirling' Geological Survey sheet (1969). It supersedes the older term 'schistose grit' used on the earlier 1:625,000 and 1:63,360 sheets (46 - 1900, 47 - 1888).

This rock also occurs to the south-west in upper Glen Artney, the Loch Lubnaig and Trossachs districts. In these districts the most prominent characteristic of the higher areas is that the valley sides, valley heads, mountain ridges and summits frequently exhibit well-developed cliffs. The best developed corries and almost the only arêtes (excepting around Ben Lawers) have been formed in the pebbly grits. Although this is not the only lithology in which cliffs have been formed, it is quite clear that the finest rock forms in the thesis area have been developed on the pebbly grits and that equally elevated ground based on most other lithologies does not display cliffed landforms to anything like the same extent (chapter 3).

In Glen Almond the corries occur in the pebbly grits on the southern side of the valley but not in the mica-schists of the northern side. The absence of corries from the pebbly grit area east of squares 8433 - 8835 - 9138 is presumably due to the relatively low altitude of the area (below 2000 feet - 600 m).

Another implication of the lack of cliffing in the valleys on the northern side of Glen Almond is that the absence of the diagnostic characteristics of the corrie (principally rocky side - and back - walls) need not mean that valley heads failed to nourish glaciers. Indeed it will be shown in this chapter that some valley heads tributary to Glen Almond must have supported their own valley glaciers in the same way that the corries supported corrie glaciers.

C. The features.

The western end of Glen Almond consists of a complex of steep-sided, unnamed valley heads (7133 - 7132 - 7332) some

500 - 750 feet deep (150 - 230 m). The top of their back - and side - walls lies in the 2300 - 2500 feet range (700 - 760 m), and the valley floor at their confluence is as low as 1750 feet (535 m). On the northern side of the valley (7133) moundy glacial deposits occur up to 2300 feet (700 m), descending from there towards Glen Almond. Therefore it may be supposed that the minimum surface level of the responsible glacier in square 7133 lay at or slightly above 2300 feet (700 m) and that ice also occupied the neighbouring valley head (7132 - 7232) to a similar altitude. Although mounds are absent from the third valley head in the complex (7332), it has similar shape and elevation to that of the other two. The glacier moving eastwards from the latter deposited mounds up to 2000 feet (610 m) opposite the mouth of this valley head (at point 730332), and so it may be assumed that ice in the valley head (7332) attained at least 2000 feet (610 m), or even 2300 feet (700 m) as in the neighbouring valley heads (7133, 7132 - 7232).

Below this set of valley heads the valley opens out as it becomes Glen Almond proper (c.7433). At this point the two valleys that circumvent the Shee of Ardtalnaig (7234, 7335) make their confluence with Glen Almond. The more westerly of this pair is V-shaped and its watershed lies at 1750 feet (535 m), 2 km from the confluence. The other one is U-shaped and its watershed lies at 1450 feet (440 m), less than 0.5 km from the confluence. Being the steeper-sided, the eastern valley is the wider and its entrance is the more open in comparison with the western valley. These factors appear to have exerted an influence upon the direction of movement of the glacier. Another factor was that the easiest route of egress for the ice must have been eastwards down Glen

Almond. In the following account it will be shown that the depositional evidence indicates that the glacier emanating from the valley heads (7133, 7132, 7332) appears to have used the two easier routes, bifurcating eastwards down Glen Almond and northwards into the more easterly valley below the Shee of Ardtalnaig.

In the confluence area there is an abundance of moundy deposits that spread northwards into the more easterly of the pair of Shee of Ardtalnaig valleys (7335) and also spread eastwards down Glen Almond. In this latter part of Glen Almond (7434 - 7533 - 7633) the mounds reach at least 1750 feet (535 m) over a distance of 3 km on the northern valley side, and lower variable altitudes on the southern. From the confluence northwards however the valley sides are so steep that the thin drift cover is subject to mass movement, producing terracettes along its entire length (7335 - 7237). Consequently the mounds are confined to the lower slopes and cannot in the confluence area be taken to represent the minimum ice surface altitude (c.740350). However mounds are virtually absent from the western valley, except for a small group that appears to be related more to dissection of drift (7136). The mounds in this group do not resemble those in the eastern valley or in Glen Almond as regards frequency, shape and sharpness. As the watershed of this western valley lies at 1750 feet (535 m), which is the same altitude as the upper limit of the mounds in the confluence area, it may be deduced that the glacier probably failed to override the col (7234). Owing to the absence of mounds south-east of the col (7234 - 7334), the extent of such an advance can only be indicated approximately (fig. 13.2). The implication of the apparent absence of ice from the more westerly valley beyond the col is that the ice surface in the eastern valley near the confluence (c.7335) lay below 1750 feet (535 m). The upper altitudes of the mounds in the eastern valley, where the valley sides become less steep (7337), lie below 1500 feet (455 m), and the mounds descend continuously northwards from there to their terminus at 1100 feet (335 m) (7238). These altitudes conform with the above deduction that the ice surface at the southern end of this eastern valley lay below 1750 feet (535 m).

The down-valley limit of mounds in the eastern valley (7238) is not a sharp limit of abundant mounds as occurs in Glen Garry for example. Instead the size and number of mounds gradually decreases from the confluence area (7334) northwards. It is rather the limit beyond which mounds do not occur. At this point (7238) the burn descending towards Ardtalnaig becomes incised into the bedrock but, as the gradient of the valley suddenly steepens here, it is not clear to what extent the initiation of the incision may be connected with the former presence of the glacier tongue.

To the east of the confluence area Glen Almond is joined by seven tributary valleys, each of which hangs above the trunk valley. All but one of these contain moundy deposits that extend without a break down into the mounds that cover the lower slopes of the trunk valley (7634 - 8330). Four other hanging valleys that lie to the east of this group are devoid of moundy deposits (8433 - 8630).

In the westernmost valley of the first group (7635) the mounds on the western side extend almost up to the break of slope with the high uplands (e.g. 2200 feet - 670 m - in square 7634). It may therefore be presumed that this valley was almost completely filled with glacier ice. The ice reached about 2400 feet (730 m) at the valley head (7635) and descended to 1750 feet (535 m) at the valley mouth (7733) where it was joined by a glacier emerging from the Stuck Chapel valley (7834). The highest occurrence of mounds in this valley (7735) is at 2250 feet (685 m), some 250 feet (75 m) below the gently undulating upland surface (7535). Again in square 7834 the highest mounds (2000 feet - 610 m) lie 250 feet (75 m) below the upland surface. This suggests that the Stuck Chapel valley was less deeply filled with ice than was its neighbour to the west. The upper limit of mounds on the western side of the Stuck Chapel valley descends to 1750 feet (535 m) at the valley mouth, merging into those of the Coire Bheilg which also lie up to 1750 feet (535 m) (7733 - 7734).

Slightly down-valley, mounds occupy the lower slopes of an unnamed hanging corrie on the southern side of Glen Almond (7932). Their highest altitude is 1750 feet (535 m) and this must therefore have been the minimum level of the ice in the corrie, although the ice may well have extended towards the col at 1900 feet (580 m) (7831). The level of the ice surface in Glen Almond in the few sq. km near this corrie is hard to identify. On the southern side the upper limit of the mounds varies irregularly without apparent reason (7832 - 7932), except towards the east where it has been determined by the break of slope (8032). On the northern side the upper limit merges imperceptibly into drift-covered rock knobs. However the limit in square 7833 is clearly at 1500 feet (455 m), and again in square 8134 the mounds descending from Glen Shervie reach about 1550 feet (470 m) approximately 1 km north of the trunk valley. As the upper limit of the Glen Shervie mounds descends towards Glen Almond at about 250 feet per km (75 m per km), an estimate of 1300 - 1350 feet (395 - 410 m) for Glen Almond ice surface in square 8133 can be made. These altitudes suggest that the Glen Almond ice surface descended from not less than 1500 feet (460 m) in square 7933 to not more than 1350 feet (410 m) in square 8133. These estimates fit with the trend of the calculated ice surface both to the west and to the east.

In upper Glen Shervie the highest occurrence of mounds is at 2150 feet (655 m) in the valley head (8136), some 350 feet (105 m) below the upland surface. Down-valley the upper margin of moundy deposits descends continuously to 1550 feet (470 m) on the western side (8134) and to about 1300 feet (395 m) on the eastern where it merges with the Glen Almond deposits (8233). The hanging valley that faces Glen Shervie from the southern side of Glen Almond is unusual in this part of the valley system in that it is devoid of moundy deposits (8031 - 8132). Such forms occur only below it in the trunk valley below the break of slope at 1250 feet (380 m) (8132). However the neighbouring hanging coire to the east, the Coire Garbh (8231), is occupied by moundy deposits up to the base of its cliffed backwall at 1750 feet (535 m). As the hanging valley 3 km to the west (7932) also contains mounds up to 1750 feet (535 m), it is logical to expect that glacier ice occupied the middle valley (8031 - 8132) up to a similar altitude.

The Coire Chultrain (8330 - 8431) is the easternmost tributary valley in which there are mounds of glacial drift. These occupy the corrie floor below the rocky back - and side - walls, reaching 1750 feet (535 m) at the head of the corrie. There are two groups of distinctly linear ridges on the eastern side of the valley (8330, 8431). In the upper group (8330) the rough texture of the schistose grit bedrock is visible, and in the lower the north-north-eastward alignment corresponds with that of a number of dykes that crop out in the adjacent stream, the Allt Coire Chultrain. Consequently the linearity may be due to rock control. The mounds of this corrie do not make contact with those in Glen Almond because on the southern side of the river Almond the latter occur only spasmodically to the east of square 8332.

The upper margin of the mounds on the northern side of Glen Almond decreases gradually eastwards from 1250 feet (380 m) in square 8233, to 1200 feet (365 m) in square 8332 and to 1050 feet (320 m) in square 8632. In squares 8731 - 8831 the upper boundary of deposits is a narrow terrace 1 km long. In its western part it is discontinuous owing to dissection by small streams and the steepness of the hillside. But for the majority of its length the terrace surface has been preserved except along its irregular frontal edge. Its gradient lengthwise has not been measured but is certainly small. The terrace ceases abruptly at its eastern end where it abuts against a rock bar that rises from the valley floor at 750 feet (230 m) to about 900 feet (275 m). The terrace surface may therefore be judged to lie in the vicinity of 900 feet O.D. Although no exposures were found in any part of the terrace, the smaller cobbles in the mounds below are frequently rounded, as they are also in a small esker that winds down the hillside less than 1 km west of the terrace. This esker is adjacent to an existing stream but is not the product of dissection as it is a distinct ridge above the mounds of the hillside. From a purely visual inspection the upper end of the esker appears to lie at about the same level as the terrace. These characteristics of the esker and terrace suggest that their deposition may have been to a local englacial water table, causing esker formation by a stream draining down the hillside under the ice, and allowing a kame terrace to accumulate from ice-marginal drainage farther east as far as the rock bar (8831).

The upper limits of the patches of mounds on the southern hillside more or less match those on the northern, descending from 1000 feet (305 m) in square 8531 to about 950 feet (290 m) opposite the rock bar (8831). On the southern side the mounds terminate at the road bridge, whereas on the northern they stretch a further 300 m beyond the bridge before dying out between 700 and 850 feet (215 - 245 m). As the valley sides immediately east of the bridge are relatively gentle, it is possible that the steeper descent of the boundary of the mounds in the last 1 km around the bridge corresponds to the steeper gradient that is typical of an active glacier tongue. The formation of the esker and kame terrace mentioned previously would therefore have post-dated the maximum advance of the glacier as they indicate stagnation of the glacier in the localities at which they occur.

Glen Almond is unusual in the thesis area in that there are three localities within the area covered by the last glacier that possess features marking possible retreat stages of the glacier. These occur within 4 km of the eastern ice limit (8531 - 8831), but each is found on one or other side of the valley, not on both. The first is at 884315 on the southern side of the river where a narrow ridge 2 - 3 m high swings away from the mounds at the foot of the slope across to the river bank. Huge angular blocks are littered along the surface of this ridge, but not on the hillside above it, suggesting that they were placed on the ridge and did not roll down the slope from the cliffs at 1100 - 1250 feet

(335 - 365 m). The ridge is the distal part of a group of mounds and is concave up-valley. As it is separate from the adjacent group of mounds down-valley and as it lies 100 - 150 feet (30 - 45 m) below the kame terrace on the northern side, it is possible that the ridge is a recessional moraine delimiting the first stage of retreat of which there is record.

2 km up-valley, a short distance west of the supposed sub-glacially engorged esker (8631), a low curving ridge extends out eastwards from the mounds at the slope-foot and terminates at the river. Enclosed between this ridge and the river there is a stream fan that merges eastwards into a terrace about 0.5 km long and 1-2 m above the flood plain. It does not appear possible that this terrace could have been formed by the present river Almond because the proximal end of the feature is protected from the river by the ridge, and there is no sign whatever of bedrock in the ridge. If the terrace was not produced by the erosion of moundy deposits, it must be an original depositional feature. Given that it lies in the valley bottom just above the river, and that it slopes down-valley, it can hardly be other than an outwash terrace produced when the glacier was receding but had temporarily attained a stillstand position. The ridge that flanks the proximal end of the terrace may also have been laid down by running water and therefore could be interpreted as a subglacial esker. The distal parts of the outwash must have been destroyed for a wider, longer stretch of flood plain replaced the outwash after 0.5 km (8731).

A short distance up-valley another terrace occurs, this time on the northern side of the river Almond. Again it is narrow and only 1-2 m higher than the flood plain. The terrace commences 2 km west of the terrace discussed previously

(8631), but is not linked to any identifiable ice-marginal ridge. Instead the terrace starts abruptly 2 - 3 m above the undulating drift surface adjacent to and west of it (c.852318). The terrace continues eastwards for about 1.5 km until it fades out where rock crops out on the valley floor (8631). The corresponding tract of ground on the southern side of the river is presently occupied by flood plain (8531 - 8631). The abruptness of the proximal end of the terrace, the elevation of the terrace above the flood plain, and its similarity to the outwash terrace immediately down-valley strongly suggest that this terrace also was deposited by an outwash-carrying river during a stillstand in the recession of the Glen Almond glacier.

In the lowermost 5 km of Glen Almond (8531 - 8931) the mounds of drift are relatively small and tend to occur in scattered groups. Only to the west of Conichan (8432) do more substantial concentrations of larger mounds occur on both sides of the trunk valley. From the Auchnafree area (8133) westwards they are very numerous. In the immediate vicinity of Auchnafree house some particularly high mounds are composed of sand, gravel and well-rounded pebbles or cobbles, with disturbed silt-fine sand beds. Other smaller exposures elsewhere in Glen Almond show similarly rounded pebbles, implying that the mounds are kames.

The former presence of valley and corrie glaciers in the Glen Almond area appears to have been related to the distribution of uplands in excess of 2500 feet (760 m). These exist between grid lines 70 and 85 east, between 30 and 38 north, and also include the environs of Glen Turret (c.7830), part of which is mapped on sheet 54 to the south of Glen Almond. The valleysabove the eastern part of Glen Almond, above Glen Quaich to the north and Glen Lednock to the south are in general cut into uplands whose highest parts lie below 2000 - 2200 feet (610 - 670 m). It is noticeable however that the floors of the valley heads in the latter districts frequently have similar elevations to those surrounded by higher hills: cf. 2000 feet (610 m) in square 8433 with 1900 feet (580 m) in square 8036, or 1500 - 1750 feet (455 - 535 m) in square 8730 with 1500 - 1750 feet (455 - 535 m) in square 8330. Nevertheless the valleys in the area of lower hills (e.g. 8433, 8730) completely lack the abundant moundy deposits that characterise the valleys in the higher hills and that are held to indicate the presence of glaciers during the last stage of glaciation. The absence of deposits does not of course prove the absence of glaciers at this time. But the persistent absence of deposits over a wide area (for example Glen Quaich and Glen Lednock), when compared with the presence of deposits over an adjacent wide area (in this case Glen Almond), suggests a consistency in the factors that determined whether or not a given locality was or was not capable of nourishing sufficient snow for a glacier to form. Unfortunately the majority of glaciers in the Glen Almond district formed in sloping valley heads, and therefore estimates of the snow-line based on the altitude of corrie floors (cf. Manley, 1959) cannot be made or made with any meaning for such a small area (see chapter 13). Valleys apparently not occupied by glaciers may well have supported permanent snow patches, particularly if the valleys lay close to ice-filled valleys, in terms of altitude and location. Therefore it may be imagined that the hanging valleys around the eastern end of Glen Almond (8430, 8630, 8730, 8434, 8633) did not receive quite enough net snow accumulation to create glaciers, but were nevertheless sites of snow accumulation. The inhibiting factor in this district may have been the altitude of the uplands overlooking a given valley, for the elevation of the uplands affects the quantity and temperature of precipitation. (This topic will be dealt with more fully for the thesis area as a whole in chapter 13).

D. Glen Turret and the Invergeldie.

Conspicuous moundy deposits occur in only two valleys that are separate from but in the vicinity of Glen Almond and that can for certain reasons be attributed to the last stage of glaciation. These features are found in upper Glen Turret (7830 - 8029, sheets 48 - 54) and in the Invergeldie valley (7531 - 7529, sheets 48 - 54). These two valleys are flanked by uplands, much of which rise above 2500 feet (760 m) (c.7231 - c.8130). The Glen Turret glacier evidently had two ice sources. The higher was a shallow funnel-shaped hollow on the eastern face of Ben Chonzie (7730). The lower end of this hollow is a rock step at 2000 feet (610 m) which appears to have been sufficient to allow a niche glacier to form between it and the headwall of the hollow at 2750 feet (840 m) (cf. G.E. Groom, 1959). Small mounds of drift occupy this hollow from the base of the backwall down to the rock lip, but do not recur until the floor of the main valley is reached below (7830). The highest occurrence of mounds in the main valley is at 1750 feet (535 m) (7930) over 1 km south-east of the head of the valley. It may be assumed that the ice surface at the valley head lay above this altitude, but there is no depositional evidence to suppose that the Glen Turret glacier was physically connected with its neighbour on the Glen Almond side of the col (7831 - 7932). On fig. 13.2 it has been suggested that the Turret and Almond glaciers were separate, although it must be recognised that transfluent flow north-eastwards and south-eastwards from the col (7831) may well have occurred during the last and previous stages of glaciation.

From point 800300 (see sheet 54) the upper margin of the mounds on the eastern side of Glen Turret declines south-eastwards. Many of these mounds are markedly linear in overall shape, although hummocky in detail. They tend to run obliquely down the slope, paralleling the curving upper margin of the mounds. Some of these ridges have been exposed along a track. Their material is a silt - gravel - boulder till whose coarse fraction is markedly angular. The linear stones clearly point southwards and downwards along the length of the ridges and towards the loch. As the sectioned ridges constituted the margin of the group of mounds, it is very likely that they are lateral moraines formed along the edge of the glacier as it curved downhill towards Loch Turret. As there are a number of these ridges, one above the other, for 1 km along the eastern valley side, it may be imagined that the uppermost mark the maximum thickness of the glacier, and the lower ones successive stages of thinning in the active life of the glacier.

The moundy deposits on the western side and upper part of Glen Turret were not sectioned but are as clearly delimited on the valley side as are the lateral moraines and are particularly numerous. At the northern end of the valley they occupy the gently sloping valley floor below 1600 - 1650 feet (485 - 500 m) (7830). South-eastwards their upper margin descends only gradually until the final 1 km is reached, when they drop from 1500 feet (455 m) in square 7929 to 1150 feet (350 m) at their terminus at the loch (8028).

The lateral moraines on the eastern valley side also terminate quite abruptly around the northern end of Loch Turret, indicating that the glacier reached its maximum position there at about 1150 feet (350 m). Thus the gradient of the ice surface in its lowermost 1 km was about 600 feet per km (185 m per km), a figure comparable with the approximately 650 feet (200 m) of descent in the final 1 km of the Glen Vorlich glacier, a similarly short isolated valley glacier (6222).

The slopes above and south-eastwards from the Glen Turret moraines are smoothly covered with a till whose composition closely resembles that of the till in the moraines. The till on the slopes however is subject to present-day mass movement, for it has in places moved down over the peaty top that usually covers it. To the south of Loch Turret the valley opens out but still is a landscape of smooth till cover on underlying bedrock.

The Invergeldie valley (7531 - 7529) also contains moundy deposits whose down-valley extent is limited. Their highest occurrence is near the head of the valley (7531, sheet 48) at 2000 feet (610 m), implying that the ice surface lay at about this altitude in the valley head. The northernmost part of the valley (7531) is circumscribed by this altitude and there is no sign of the glacier having exceeded it. In square 7531 the mounds on the western side lie below those on the eastern, but southwards (7530 - 7529) there is little difference in the altitude of their respective margins. In their last 1 km (7530 - 7529) they descend from 1650 feet (500 m) to 1350 feet (410 m) at their terminus in the middle of the gently sloping valley floor. At this point (752293) the small meandering Invergeldie burn plunges down into a deep incision in the thick till sheet that occupies the valley for the next 2 km. The dimensions of the incision change very little over 2 km until it ceases where the Invergeldie fan is being deposited on the floor of Glen Lednock (7427). The smoothness of the valley sides above both the incised course (c.7428 - 7528) and above the mounds suggests that the thick till layer exists up-valley as well as down-valley from the onset of the incision. It may therefore be concluded that the cause of the incision was meltwater that poured out from the snout of a valley glacier and cut through the pre-existing till. This deduction supports the conclusion that the Invergeldie valley was occupied by a valley glacier comparable to the neighbouring independent glacier in Glen Turret.

The landscapes of the valleys adjacent to Glen Almond, but not included within the last stage of glaciation, are composed either of till-covered slopes or of moundy deposits whose character and distribution contrast with those in Glen Almond (sheets 48 and 54).

Along Loch Tayside, outside the limit of the ice tongue that skirted the Shee of Ardtalnaig (7238), the slopes are everywhere gently undulating, with rock occasionally cropping out through the smooth till cover (sheet 48). Subdued smooth mounds occur sporadically in the valley above Ardtalnaig (7039 - 7138) but their precise extent could not be mapped. Similar examples are to be found elsewhere on Tayside, and it is in the chapter on that area that they are discussed (chapter 8). They are believed to have been produced during a period preceding the last stage of glaciation.

The uplands around Glen Quaich and Glen Cochill, north-east of Glen Almond, are formed largely of bedrock with a variable till and peat covering. Moundy deposits exist on the uplands at the northern end of Glen Cochill (c.8747 - 8943), as well as across the slopes of the Tay valley from Glen Cochill down to Aberfeldy (c.8747 - c.8548), and throughout the length of Glen Cochill down to Strath Braan (8943 - 9138). Patches of moundy deposits whose extent is exceedingly vague are present in shallow valleys in the uplands east of Glen Cochill (9045, 9044, 9246 - 9244). The continuity of the mounds from Aberfeldy (8548) to Strath Braan (9138) suggests that all the deposits are of the same age and that they are the product of thick extensive ice that submerged both the valleys and the uplands. Perhaps this ice was part of the last ice sheet which moved south-eastwards across the uplands (section B).

Much of the valley floors where Glen Cochill and Glen Quaich become Strath Braan (8836 - 9238) exhibit fluvioglacial landforms. Around the southern end of Glen Cochill for example (9137 - 9238) kames, made of sorted sands and rounded gravels, merge downwards into a kettled terrace, and meltwater channels wind down through the kames to fade out on the terraces. This combination of forms is present only on very gentle slopes, never on even moderate slopes, therefore its distribution is irregular.

In square 8933 there is a former lake site margined by these fluvioglacial forms. It may have been a kettle lake similar to the existing kettle lake immediately to its north (8934). Underneath the raised bog that now occupies the site there is a series of silty clays, including a prominent pink layer resting on grey clay which is underlain by gravel. Preliminary results of pollen analyses suggest that pollen from the interstadial preceding Zone III may be present immediately above the gravel (J.J. Lowe, personal communication;

appendix 1). It is possible that this sequence of deposits is the same as that discovered by J.J. Donner (1957, 1958), in which he adduced palynological evidence to suggest that the pink clay layer was probably formed during the last stage of glaciation, and the underlying clay at an earlier period (see chapter 2, C). The stratigraphical evidence in this former lake therefore concurs with the evidence from the pattern of fluvioglacial deposits in implying that the Glen Quaich - Glen Cochill - Strath Braan area has not been occupied by glacier ice since the penultimate stage of the last glaciation. Furthermore the distinctively fresh hummocky landscape of Glen Almond and the evidence there for the limited extent of the Glen Almond valley glacier system, combined with contrast between the landforms in Glen Almond and the Glen Quaich - Glen Cochill - Strath Braan area and the stratigraphy of the lake site, provide evidence that Glen Almond was most recently glaciated during the last stage of glaciation.

To the south of the Sma' Glen (8931 - 8930) the river Almond leaves the Highlands and in its Lowland section its valley is largely filled with a multitude of outwash terraces and kames, whose accordant and often flat tops betoken kettled outwash. As in Strath Braan, it is believed that these fluvioglacial forms stretch far beyond the thesis area and that they were created prior to the last stage of glaciation (sheet 55 is not included in this thesis).

In the chapter on the Loch Earn valley system it will be shown that the Glen Lednock district appears not to have been glaciated since the last ice sheet submerged the hills (sheets 48, 54). This conclusion will place in perspective the evidence presented above that the Invergeldie valley, which is tributary to Glen Lednock but neighbours Glens Almond and Turret, was occupied by an independent valley glacier during the last stage of glaciation in similar fashion to Glen Turret.

E. Summary.

The abundant clear moundy deposits of Glen Almond and its tributary valleys indicate that this area was a separate centre of valley glaciers during the last stage of glaciation. The principal glacier was formed at the western end of Glen Almond and, on moving out of its source area, it branched in two directions, the minor part flowing northwards to terminate high above Loch Tay, and the major flowing eastwards down Glen Almond. Along its course eastwards the Glen Almond glacier was fed by ice from seven valleys, all of which are surrounded by uplands exceeding 2500 feet (760 m). Tributary glaciers do not appear to have existed in a further four valleys that are surrounded by uplands less than 2500 feet (760 m) in elevation. The Glen Almond glacier terminated in the vicinity of the Sma' Glen. Subsequently whilst its snout stagnated a local englacial water table existed long enough for an esker and a kame terrace to be deposited. Three stages of recession are recorded by a recessional moraine and two small outwash terraces. Isolated valley glaciers also existed during the last stage of glaciation in Glen Turret and the Invergeldie valley, both of which are surrounded by uplands in excess of 2500 feet (760 m).

Outside the limits of these valley glaciers the landscape in the valleys consists of bedrock smoothly covered by till or of fluvioglacial features, both of which appear to pre-date the last stage of glaciation.

Glen Artney.

A. Previous literature.

Almost the whole of the area to be considered in this chapter has been mapped by the Geological Survey, whose maps are available at the 1:63,360 scale. The two earlier maps, which include Ben Vorlich and Glen Artney proper (sheet 47, 1888) and Stuc a'Chroin (sheet 46, 1900), are unpublished and are not accompanied by descriptive memoirs. The maps portray a minimum of information on the drift landforms, but the pattern of striations shown is valuable. If these are interpreted as part of a striation pattern ranging from the Teith valley, across Glen Artney to the Tay valley and Glen Garry, they are consistent with the inference that thick ice had moved across the thesis area during a preceding stage of glaciation. As in the adjacent districts, Glen Almond and the Teith valley, the direction of flow seems to have been approximately south-eastwards. Thus it is clear from striations at up to 3000 feet (915 m) on the Stuc a'Chroin - Ben Vorlich ridge (6016 - 6218) that thick ice overrode this ridge on its passage south-eastwards. Elsewhere on the hills to the east of Ben Vorlich the orientations of the marked striations vary between south (one striation) and south-of-east. The two that occur on ridges point south-eastwards (6518, 6715), but it is not clear whether those pointing south-of-east, all being in the vicinity of the Coire na Cloiche (6520), were found in the corrie or on the ridge above it. They have therefore been omitted from this interpretation. The remaining striations occur within the Strath a'Ghlinne (6620, 6619, 6719) and point south-eastwards or southwards as they follow the line of the valley.

The head of Glen Artney, its confluence with Gleann an Dubh Choirein, and lower Gleann a'Chroin are represented on the most recent Survey map, sheet 39 (Stirling, 1969) and are described in the appropriate memoir (E.H. Francis et al., 1970). Here it is suggested that Gleann a'Chroin, upper Glen Artney and valleys north of Uamh Bheag were occupied by glaciers at some stage late in the Pleistocene (p.261). "A glacier coming down Gleann a'Chroin (6314) ..... may have dammed the valley of a right-bank tributary (the Allt Breac-nic) and caused the accumulation of the gravel terrace near Sron Eadar a'Chinn (632132)" (p.261). Subsequently in the memoir this feature is further described as "a kame terrace, composed mainly of fine gravel with some sand and a little silt and clay. A solitary mound of sand and gravel rises above it." (p.274). However this feature is part of a group of mounds that rise above the remainder of the valley floor and none of which is either flat-topped or abuts the hillside. Although evidence will be presented in section C of this chapter that proves the deposit was water-laid, this feature cannot be a kame terrace formed between glacier and hillside. Nor is it likely to be lake deposit formed by ice damming up the Allt Breac-nic valley as comparable deposits are lacking in this valley.

Again on p.261 of the memoir, it is stated that "a stage in the retreat of the ice in Glen Artney is probably marked by the gravel terrace, with ice-contact slopes to the north, near the head of the glen." Later this feature is said to be "banked against mounds of moraine" near the Callander - Comrie footpath (6614 - 6714), and "its northern limit is a steep slope overlooking lower, moraine-covered ground. This slope probably represents a former contact of the terrace with ice in Gleann an Dubh Choirein" (p.273). Exposures in this so-called gravel terrace are actually of till. The feature slopes down to the south-east from 1050 to 1000 feet (320 - 305 m) in squares 6714-3. Furthermore considerable thicknesses of till are exposed in the banks of the Water of Ruchill, the river that drains Glen Artney. Therefore there is no reason to regard this till layer as either a terrace or proof of a stage in the retreat of ice in Glen Artney. It will be suggested in section C of this chapter that the "ice-contact slopes to the north", which actually face north-east, were produced by erosion and possible re-working of the till by the Gleann an Dubh Choirein glacier as it approached its limit in square 6714.

The third area mentioned by Francis et al. is the pair of valleys north-east of Uamh Bheag (6912, 7013) which they believe contained corrie glaciers "at the time of the Loch Lomond Readvance" (p.261). Although these glaciers deposited hummocky drift, the extent of the glaciers and an assessment of their age are not given. They will be given however in section C of this chapter (fig. 10.1).

Finally the memoir and map sheet (39) omit to mention any of the striations discovered by the Survey. A number of these, all pointing slightly east of south, are shown on the relevant 1:10,560 Survey map. (The only available 1:10,560 sheets for the Glen Artney district relate to the area of 1:63,360 sheet 39). The lowest striation is at about 1700 feet (520 m) on the northern side of Uamh Bheag (6813), and the remainder are on its summit area and eastern face (6811 - 6911) between 1800 and 2000 feet (550 - 610 m). They must have been produced by thick ice moving almost southwards across the Highland edge at a period clearly prior to the last stage of glaciation (when the glaciers were confined to the valleys in the Highlands). The earlier movement was very probably contemporary with the south-eastward flow of thick ice across that part of the Highland edge directly to the south-west of Uamh Bheag discussed in chapter 12 (cf. Linton, 1962).

D.L. Linton (1959) has discussed the valley form of Glen Artney. He stated that it "preserves its preglacial polycyclic form with a lower V-shaped valley below a widely open smooth upper valley, at about 900 feet because its NW-SE direction rendered it ineligible for the role of an avenue of egress for the western ice" (plate 6, p.40). The western ice referred to was the Loch Earn glacier which, in its eastward movement, "strongly moulded" the lower spurs of Mor Bheinn (7121) and Ben Halton (7120). Whilst the numerous roches moutonnées substantiate the latter theory, the presence of numerous glacial breaches and corries in the valley system of Glen Artney conflicts with Linton's opinion concerning the origin of the present form of Glen Artney. The V-shaped form is probably due to relative ease of erosion, for the valley follows the strike of near-vertical beds of both Highland and Old Red Sandstone rocks, between which runs the Highland Boundary Fault complex.

B. Introduction.

The area that is the subject of this chapter comprises Glen Artney and a number of valleys tributary to it or closely linked to it during the last stage of glaciation (sheet 54). The principal valley is known as Glen Artney from the point where the Allt an Dubh Choirein turns a sharp right-angle to flow north-eastwards as the Water of Ruchill (680139). From this point the main valley follows the line of the Highland

Boundary Fault, and so it is convenient mentally to associate Glen Artney with the fault line and thereby to distinguish it from its headstream and other tributaries. Most of the tributaries lie approximately at right-angles to Glen Artney and to the strike of the Highland and Old Red Sandstone rocks. By contrast Glen Artney follows not only the Boundary Fault but also the strikes of the Highland rocks, on the north-western side of the valley, and of the Old Red conglomerates, lavas and sandstones, on the south-eastern side.

The greater resistance to erosion of the Highland rocks appears to have had two contrasting consequences. The first is that the summits of the hills developed on Highland rocks generally reach between 2000 and 3200 feet (610 - 975 m), whereas those on the Old Red Sandstone series do not exceed 2200 feet (670 m) and generally attain only 1600 feet or so (490 m). The second is that the majority of the glaciers and, as a result, the majority of corries and glacial troughs have been formed in the area of Highland rocks. Therefore, with one exception, the deepest valleys have been eroded from the most resistant rocks. The exception is Findhu Glen (7115 - 7313). This valley appears to have been invaded by ice moving south-eastwards from Glen Artney, a movement that caused the watershed to be displaced 1 km south-eastwards and the valley floor to be lowered so that it now merges into the floor of Glen Artney (7115). The original watershed presumably lay in line with the existing summits overlooking it (7213 - 7313 - 7414).

Findhu Glen is the more easterly of two passes that connect Glen Artney with the Lowlands to the south. The other pass is occupied by the Keltie Water (6310) which drains Gleann a'Chroin (6314). The line of hills dividing Glen Artney from

Loch Earn is broken in only two places (6718 - 6719, 7019 - 7020) where there are glacial troughs whose watersheds have been breached. Here the valley pattern is strikingly similar to that of the Loch Voil - Lubnaig - Strathyre - Loch Earn district, with the principal watershed running right across from Ben Ledi (5609), through Ben Vorlich to Mor Bheinn (7121). Following Linton and Moisley (1960), it is easy to imagine that Strath a'Ghlinne (6717) was made into a through-valley by glacial breaching of a watershed at about square 6718, perhaps by transfluent corrie glaciers, and possibly emphasised by south-eastward ice sheet movement.

C. <u>The features.</u>

The valleys of the Glen Artney area are unusual compared with those elsewhere in the thesis area in that they contain some of the most distinctive glacial deposits and the best developed corries but mostly lack sufficient evidence from which the positions of the former glacier margins may be deduced. Therefore it has been found necessary to rely on projected ice gradient values, on comparisons between neighbouring corries and valleys, and on the contrasts of character and pattern of deposits between valleys.

Amongst the larger valleys the clearest morphological evidence and best indications of glacier margins are found in Gleann an Dubh Choirein (6317 - 6714). Large till surfaced mounds commence suddenly near the mouth of the valley head (6316) between 1450 and 1600 feet (440 - 490 m) and continue south-eastwards for 2 km as a narrow band of large mounds on the valley floor. Other much smaller mounds from the neighbouring valley on the eastern side of Ben Vorlich (6417) merge with those in the main valley. About 1.5 km from the valley confluence the mounds on the north-eastern side of Gleann an Dubh Choirein rapidly ascend the slope from 1350 feet (410 m) to 1500 feet (455 m). This is not duplicated on the opposite much gentler valley side. There the upper margin of the mounds continues to descend gradually south-eastwards.

From square 6616 the clear upper margin of mounds on the north-eastern side of Gleann an Dubh Choirein drops at 160 feet per km (50 m per km) for nearly 2 km and thereafter a further 350 feet (105 m) in the final 1 km, terminating at about 900 feet (275 m) in the valley bottom (6714). This upper margin is unusually sharp and as its gradient is comparable with that calculated for the distal portions of former valley glaciers elsewhere (e.g. Glen Ample, Strathyre and Glen Ogle, 12 km to the north-west), it has been assumed that the upper margin of mounds represents the former glacier margin (6616 - 6714). The altitudes of the curving terminal zone of mounds in squares 6614 - 6714 west of the Allt an Dubh Choirein accord with those north-east of the burn (6714). The evidence here will be considered later.

The only estimated gradient for the glacier margin is 160 feet per km (50 m per km), apart from the steeper terminal gradient. If this figure is used in a projection of the inferred ice margin up-valley from square 6616, it gives a figure of approximately 2000 feet (610 m) in the valley heads below Ben Vorlich (6217 - 6418). This is also the altitude of the bases of the four main corries on the Glen Artney side of the Ben Vorlich - Stuc a'Chroin ridge. Therefore it has been judged reasonable to adopt an overall gradient of 160 feet per km (50 m per km) for the Gleann an Dubh Choirein glacier from the vicinity of its headward feeders as far as, but excluding, its terminal 1 km. The ice in the corries would at its maximum have extended well up the cliffed back - and side-walls and so possible ice margins have been suggested on this basis.

On the eastern face of Stuc a'Chroin (6117) there is a funnel-shaped niche from the summit ridge at 3000 feet (915 m) down to a lip at 2400 feet (730 m), below which the main corrie drops down steeply (6217). This niche is reminiscent of similar forms in Spitsbergen that support small glaciers (G.E. Groom, 1959). The lower lip of the niche may be imagined as the site of an ice-fall where the niche glacier descended to the main corrie glacier. Despite their appearances on the map, the cliff-backed embayments well to the south of Stuc a'Chroin's summit ridge (6216 - 6315) are seen on field examination to be much shallower than the true corries to their north (6217 - 6218). It is therefore less likely that they supported additional corrie glaciers. By contrast the valley head in square 6418 is a well-developed rocky corrie composed of two steep funnels within a shallow amphitheatre between 2000 and 2250 feet (610 - 685 m). Like these corries the valley head 2 km east of Ben Vorlich (6518) is devoid of moundy deposits. On account of the altitude of the shoulder of the valley side (c.2200 feet, 670 m), a figure comparable with those immediately to its north (6519, 6619), and bearing in mind the semi-circular plan and 300 feet (90 m) depth of the valley head, it is possible that a valley glacier was formed here and that it was tributary to the Gleann an Dubh glacier.

In squares 6614 - 6714 the abundant drift mounds of Gleann an Dubh Choirein terminate where this glen opens out at the confluence with three smaller valleys. The Gleann an Dubh Choirein mounds are quite distinctly different from other forms in these valleys and in the confluence area (6513 - 6713). The southern limit of the mounds is quite clear as it descends eastwards from 1150 feet (350 m) to 1000 feet (305 m). The ground beyond the limit slopes very gently eastwards. East of grid line 67 there are two channels within 300 m of the limit (c.6713). At first glance their down-valley portions resemble meltwater channels, but it is evident from following the more southerly that the stream presently occupying it is entirely responsible for the depth of the channel. Sections along its length show that the stream has cut down through a sheet of till that rapidly thickens eastwards from only 1-2 m at 670138 to 30 m at the confluence with the Allt an Dubh Choirein (680139). Bedrock is frequently exposed as the base of the stream channel. Although the more northerly channel (671192 - 677188) does not now contain a similar stream it is in all other respects a duplicate of its neighbour and therefore considered to have the same origin. The construction of the path across its upstream end has restricted the drainage through it. The deep sections in the till sheet along these channels and at the confluence with the Allt an Dubh Choirein demonstrate that the till is very easily eroded.

Along its last 1 km the Allt an Dubh Choirein drains 'a valley within a valley'. The burn follows the north-eastern side of the floor of a narrow hollow 200 - 300 m wide whose upper edge is approximately the 1000 feet (305 m) contour on its south-western side. The north-eastern side of the hollow is part of the main valley side. The southern margin of abundant mounds descends eastwards into this hollow, blurring the edge of the till sheet. At 900 feet (275 m) they reach their south-eastern limit, whereupon their margin swings back up the north-eastern side of the valley. This termination at 900 feet (275 m) marks the down-valley end of the hollow. From this point to the confluence the till sheet overlooks the Allt an Dubh Choirein as an unstable 100 feet (30 m) high scarp. From the similarity of till in the mounds and till sheet and from the way in which the edge of the till sheet merges with the mounds it appears probable that the till sheet was formerly more extensive and that part of it was reworked by the advancing glacier to form the present mounds.

In the vicinity of the confluence of Gleann an Dubh Choirein with other valleys in squares 6613 - 6713 erosion of the bedrock has produced somewhat unusual results. The Highland Boundary Fault runs north-eastwards through the area between Druim nan Eilid and Druim Mheadoin (6512 - 6613), across the Allt an Dubh Choirein to the north-west flank of the Monadh Odhar and on to follow the axis of Glen Artney. It appears to have influenced the landscape only where ice and water have flowed along its length. The south-west to north-east valley in square 6613 contains hummocky forms which the burn has cut through. At first sight these forms resemble typical moundy drift but examination of those sectioned by the stream shows that they are eroded Old Red bedrock thinly veneered with weathered debris and till. This characteristic was found repeatedly along the stream course and it contrasts with the absence of drift sections in the hummocks. Only patches of till on the surfaces of a few hummocks were discovered.

Similarly a parallel stream in squares 6612 - 6713 follows the strike of the nearly vertical bands of Old Red rocks and here the landforms and bedrock exposures in the stream closely resemble those 1 km to the west. Above the courses of these streams the low ridges in squares 6513, 6613, 6512, 6612 and 6712 have been eroded so that narrow ribs of Old Red rock protrude slightly, although they can only be distinguished from the larger hummocks when studied on aerial photographs. It is therefore suggested that the hummocks in these valleys (6613, 6612 - 6712 - 6713) are essentially eroded bedrock and not 'moraines' as shown on the Geological Survey map (sheet 39).

There is one other valley in the Glen Artney area in which both corrie ice sources and moundy deposits are as well developed as in Gleann an Dubh Choirein. Srath a'Ghlinne (Strath a'Ghlinne) begins 2 km east-north-east of Ben Vorlich as a rocky valley head with a cliffed northern wall that makes the valley head much more like a corrie than the 1:63,360 map suggests. The northern and western sides of this valley head rise to 2000 - 2100 feet (610 - 640 m) and the southern to 2250 feet (685 m). The rockier, steeper, neighbouring Coire na Cloiche (6619) reaches about 2250 feet (685 m) also. It is below the junction of these two valleys that mounds of drift make their appearance. They constitute a sharply delimited arcuate barrier that almost completely blocks the valley. Up-valley the Allt Srath a'Ghlinne meanders across a broad hollow whose gently undulating slopes are broken by a few small rock outcrops. 400 feet (120 m) above it, from the base of the rockwall at the junction of Coire na Cloiche with the main valley, a slightly winding ridge curves down eastwards into the middle of the valley, thickening from less than 1 m to about 15 m. Here it merges with other equally large mounds but separates from them as it climbs northwards up the other side of the main valley to terminate against a small rock outcrop. The band of large mounds, of which this is the up-valley margin, is equally sharply delimited along its down-valley side. The highest of these lie about 250 feet (75 m) lower on the hillside than the upper western end of the curving ridge. Sections in the ridge and mounds where the burn cuts through them are made entirely of till with large boulders.

The form and position of the upper part of the curving ridge suggest that it was formed as a medial moraine between the main glacier and its Coire na Cloiche tributary when they terminated near the mouth of the corrie. The arcuate form of the remainder of the ridge and its position as the up-valley margin of a band of equally large till mounds further suggest that, below 1250 feet (380 m) or so, the ridge is the edge of a recessional moraine complex. It may be that the medial moraine marks a period of confluence of the main glacier with its Coire na Cloiche tributary, during which the last stage in the creation of a recessional moraine complex was also accomplished, namely the deposition of the curving ridge along the edge of the main glacier. The complex as a whole is so sharply delimited that it must surely represent a prolonged period of deposition along the receding margin of an active glacier that was not subsequently repeated.

To the east of the recessional moraine the mounds are much smaller, at about 5m maximum height, but are equally numerous. The rocky spur marking the eastern side of the Coire na Cloiche projects down to the floor of the main valley, so most of the mounds lie on the northern side of the main valley. Their upper boundary descends eastwards from 1250 feet (380 m) to 1200 and then 1150 feet (365 - 350 m) as it curves round below the pass leading to Gleann Ghoinean (6720). This boundary presumably marks the margin of the Srath a' Ghlinne glacier as it turned southwards towards Glen Artney.

For the succeeding 2 km southwards patches of mounds still dot the narrow valley floor (others have probably been replaced by flood plain), or clothe the lowest hillslopes, although these slopes are mostly steep and rocky. These groups of mounds are too small and the map is at too small a scale for their positions to be accurately represented. Till is exposed in some, and includes lumps of silt with gravel inclusions amongst a generally gravelly mixture.

The abundant mounds terminate in square 6717. For their last 1 km they are particularly large, rising as much as 15 m above the valley floor. Those on the slopes rise to approximately 1050 feet (320 m) in places along this final 1 km and descend to about 900 feet (275 m) at their terminus. The upper surfaces of those on the valley floor are remarkably subdued and broadly accordant in altitude with one another as they slope down-valley. Exposures of the surface material of their tops and flanks reveal gravelly till in which the local clay slates are abundant. Even in the burns these clay slates assume an elliptical disc shape, giving the majority of the stream load an angular aspect not too different from the jaggedness of the till fragments.

There is only one sharp-crested ridge amongst these mounds. It emerged from the smooth-topped mounds and runs for 50 m or so as a high narrow ridge flanked by streams, terminating at the present southern end of the group where a hillside stream fan and the Allt Srath a'Ghlinne floodplain abruptly cut it short. The north-eastern flank of the ridge is surfaced by the same gravelly till as covers the other mounds. This contrasts strikingly with the eastern face of the ridge which has been undercut right to the central axis of the ridge. Approximately 15 m of clearly structured water-laid sediments are revealed in this section, the top half of which is vertical and the lower half less steep. The sediments are worth considering in detail.

Layers of silty sand, fine sand, coarse sand, fine gravel, and coarse gravel dip slightly to the south in normally continuous beds of consistent thickness, mostly a few cm to about 1 m. Each bed is of homogeneous particle size range, implying excellent sorting. No unconformities were seen, except where the occasional gravel layer lies on a finer layer, in which case it could be argued that the gravel was laid down during decreasing flow after a period of erosion. The gravel is not well rounded. In two places load casts occur, although only one was accessible to examination. This consists of a 1m wide by 2m high tongue of gravel and coarse sand that has thrust down from its own stratum into the underlying beds of fine sand and silty sand. Such a structure is alleged by Kuenen (1953) to develop when a heavy arenaceous cover is deposited on top of fine sediments so rapidly that "the interstitial water (in the fine layers) cannot be squeezed out concomitantly with the development of the load" (Kuenen, 1953, p.1058). Near the top of the southern end of the ridge it is possible to observe, though not to examine, some convoluted distortion in fine beds. Kuenen states that "nowhere is more than one bed involved and normally only the upper silty part. Each lamina continues uninterrupted through the (convolute) waves and ..... it is a type of <u>bedding</u> produced during the deposition in the highly mobile sediment" (Kuenen's emphasis, p.1056).

Convolution is "not a post-depositional deformation", and "no horizontal mass movements" are involved (p.p.1056-7). However no ripple marks were observed from which the convolutions could have developed.

Numerous small vertical faults, normal and reverse, were found, but no slumping or folding, except at the southern end of the mound where the unsupported sediments are collapsing. Graded bedding, indicative of slow lacustrine accumulation, and current bedding, produced by streams in channels, fans or deltas, are not present. (F.J. Pettijohn, 1957, chapter 4). Ripple marks formed by streams flowing at a velocity in excess of 25 cm per second are also absent (G.K. Gilbert, 1914).

The excellent sorting, the homogeneity of particle size and thickness in each bed, the predominant fineness of the sediments, their dip southwards, and the absence of grading indicate that the materials were deposited by running water in a channel. The fineness and absence of current ripples show that the stream was mostly slow-moving and relatively incompetent. Considering the 15 m thickness of the deposits above the present valley floor and the relationship of this ridge to the mounds, of which it is part, it must be concluded that the water flowed southwards between ice walls towards the glacier's snout. The fineness of deposits suggests the absence of hydrostatic water pressure. As the section discussed is along the axis of the ridge, it should not be thought illogical that massive contortions produced by removal of the supporting ice walls are not seen. Many small vertical faults are present however. The till on part of the ridge surface that has not been undercut is therefore interpreted as an ablation deposit and the ridge itself as an esker. The distal end of the esker appears to have been destroyed by postglacial river erosion.

The preservation of the esker and its bedding signifies that the snout of the glacier was stagnant while the esker was forming. It was noted above that only the surface materials of the remaining mounds are exposed and that as a whole the tops of the mounds slope southwards. Consequently it is possible to regard the mounds as kames formed from outwash deposited in the decaying terminal zone, perhaps in crevasses. The surficial till covering could have been laid down on top of the kames, as on top of the esker, by subsequent ablation.

To the north of this terminal 1 km the mounds are small and scattered. Presumably the main body of ice occupied this part (6718 - 6719) whilst meltwater formed the kames in the stagnant ice zone beyond. Also it may be supposed that the small mounds represent a subsequent period of rather rapid glacier retreat that ended when the recessional moraine was built up near the head of the valley (6620). The absence of sections in these small mounds and of any ordered pattern of assemblage amongst them does not make it possible to deduce whether the recession northwards was achieved by stagnation or during active flow.

At point 680170 the Allt Srath a'Ghlinne suddenly plunges down into a deep rocky gorge and remains incised, though not so deeply, for the remainder of its journey to Glen Artney. This gorge could have been eroded by the meltwater of the Srath a'Ghlinne glacier. Coincidentally a group of till-surfaced mounds runs from this point south-eastwards, extending gradually upslope from about 800 feet (245 m) in square 6816 to 1000 feet (305 m) in squares 6815 and 6917 as it spreads into Glen Artney. It continues along Glen Artney for 5 km on the valley bench. Around the confluence of Srath a'Ghlinne with Glen Artney (6816 - 6916) and along the Glen Artney valley bench (6917 - 7318/7319) the distribution of these mounds is patchy and their extent is hard to identify precisely, as many of the mounds are very subdued. Only a few are large. Many in the confluence area (6816) are rock-cored or rock knobs thinly coated with till. Four reasons are suggested for regarding these mounds as related to an earlier stage of glaciation. The character of the mounds and their uncertain extent are two. Thirdly their altitude on the valley bench in particular (up to 1000 feet - 305 m) implies that they were deposited by ice considerably thicker and more extensive than that confined within Gleann an Dubh Choirein and Srath a'Ghlinne during the last stage of glaciation. Fourthly, if it were to be argued that this reasoning is false, it would be necessary to produce additional evidence for a greater extension of the Gleann an Dubh Choirein and Srath a'Ghlinne glaciers towards the Keltie and Callander (c.6310) and along Gleann Ghoinean (6820 - 7021) respectively. The latter is quite devoid of moundy deposits and the former has only a very few here and there. It is therefore unjustifiable to propose that the last glaciers in Gleann an Dubh Choirean and Srath a'Ghlinne extended beyond the limits of fresh moundy deposits in these valleys. Concomitantly it is concluded that the valley bench deposits of Glen Artney belong to a preceding stage of glaciation.

The Allt Ollach valley hangs above the southern side of Glen Artney mid-way between and overlooking the two valleys so far discussed, Gleann an Dubh Choirein and Srath a'Ghlinne.

Fig. 10.1

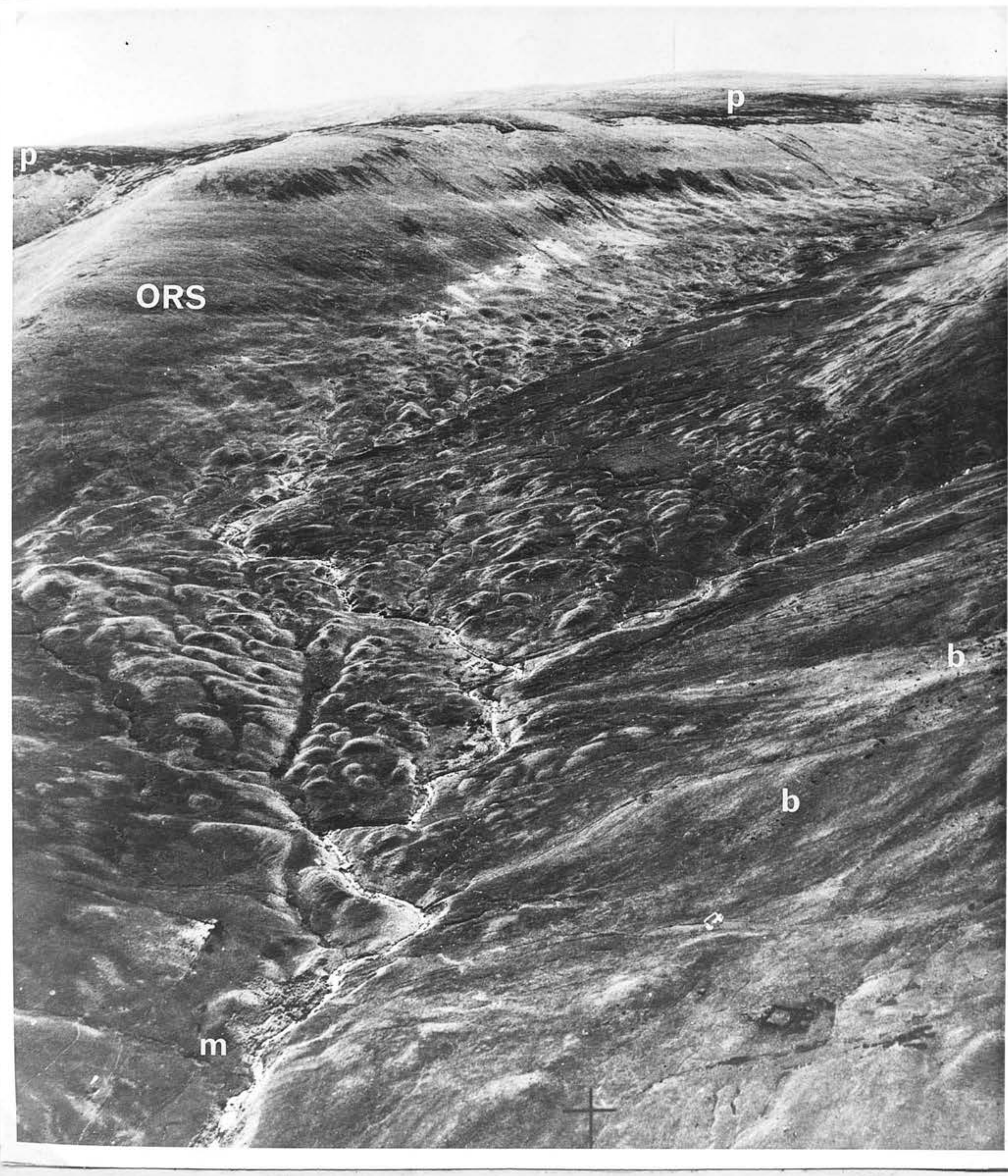


Fig. 10.1. The Allt Ollach valley, Glen Artney.

The abundant, fresh, 'controlled' hummocky drift that terminates in the foreground (m) (south-eastern corner of square 6914, sheet 54) was laid down by a glacier that flowed down from the head of Coire na Fionnarachd (out of the top right corner of the photograph). The western margin of the glacier is marked by a boulder train (or lateral moraine), part of which can be seen to the right (b - b). The drift mounds are small, varying little in size, and are arranged in closely spaced parallel lines that descend obliquely downslope. Perhaps they were formed subglacially in crevassed stagnant ice (J.B. Sissons, 1967a, p.97-8).

Almost horizontal outcrops of Old Red Sandstone (ORS) mark the hillside above the valley and dark spreads of peat (p) blanket the upland above that.

Photograph by J.K.S. St. Joseph.

The Allt Ollach (7012 - 7013) and its tributary (6912 - 6913) contain abundant hummocky drift of astonishing clarity whose extent is sharply delimited (fig.10.1). In the more westerly valley (6912 - 3) they occupy the valley floor from the base of the steep and often rocky walls of the corrie. (The 1:63,360 map gives a false impression of the steep upper slopes between 1500 and 1750 feet) (455 - 535 m). The top of the corrie backwall is 1750 feet (535 m), which may be assumed to have been approximately the upper limit of the corrie glacier. At the mouth of the corrie a boulder train commences at 1600 feet (490 m) at the base of the cliff (6913) and curves downslope northwards, above but parallel to the western limit of the hummocky drift, as far as 1150 feet (350 m). The hillside above the boulder train and between the mounds and the boulder train is virtually devoid of conspicuous boulders or of concentrations of boulders. This strongly suggests that the boulders in the train were carried downslope by the edge of the glacier and that therefore they are a lateral moraine marking the former glacier margin.

The Allt Ollach mounds terminate in the middle of the valleyjust below 1000 feet (305 m). If their clear eastern margin is followed up-valley its altitude can be seen to correspond with that of the boulder train, at equal distances back from the terminus for 1.1 km, that is as far as the 1250 feet (380 m) contour. The margin of the mounds passes just below the col that leads north-eastwards to the neighbouring Allt Mor valley (7014). The total absence of mounds from this col substantiates the view that the extent of the mounds in squares 6914 - 7014 represents the area covered by the last Allt Ollach glacier in this part of the valley.

Headwards the implications of the extent of the mounds are ambiguous. Their eastern boundary runs upslope to about 1600 feet (490 m) in square 7012, which is about the same height as the col at the head of the valley (7011). The ice surface must have reached 1600 feet (490 m) where the mounds now exist, and must also have occupied the ground between them and the col to at least the same level. As there is no sign of moundy drift deposition or meltwater erosion by the glacier in the vicinity of the col, it must be presumed that such activity did not occur there even though the glacier ought to have extended more or less right up to the lip of the col.

So far the discussion has included the three valleys in which fresh hummocky deposits are abundant and from which reasonable inferences about the extent of the last glaciers may be made. There are two other valleys in which the implications of the evidence are unfortunately much less clear. These are the Coire a'Choire, 5 km north of the Allt Ollach, and Gleann a'Chroin, 7 km to the west of Allt Ollach. In the Coire a'Choire there is no lack of moundy deposits; the problem is to ascertain their age. Within the valley (6918) the till-surfaced mounds are numerous and well-defined as they run south-eastwards from the twin corries at the valley head. At the point (707175) where the Allt Coire a'Choire turns eastwards the major concentration of mounds ceases, and only a few spread away from the burn southwards and north-eastwards along the valley bench. It was not found possible to discern any change in the size or appearance of the mounds, between those in the Coire a'Choire and those on Glen Artney's valley bench, but there is a much greater concentration of mounds in the Coire a'Choire. One fact of possible significance is that the Allt Coire a'Choire suddenly becomes engorged in the bedrock exactly at the point where it turns eastwards (707175) and where the abundance of mounds ceases. It is possible that this is where the snout of the last Coire a'Choire glacier attained a prolonged stillstand. This possible terminus at 900 feet (275 m) compares with 900 feet (275 m) for the Gleann an Dubh Choirein glacier, 900 feet (275 m) for the Srath a'Ghlinne, and less than 1000 feet (305 m) for the Allt Ollach. The altitudes along the crest of the corries' backwalls also resemble those nearby (2000 - 2200 feet, 610 - 670 m). Therefore on account of the altitudes quoted and of the abundance of mounds, it is possible that the Coire a'Choire contained a valley glacier during the last stage of glaciation. The restricted extent of such a glacier accords with its position at the south-eastern fringe of the region containing glaciers during the last stage of the Pleistocene in Perthshire.

8 km south-west of this valley Gleann a'Chroin contains only a very limited area of moundy deposits. Most occur over a distance of 1.5 km up-valley from the mouth of the glen but only on the eastern hillside (6314 - 6413). No sections were discovered in any of these mounds but at their northern limit and on the hillsides up-valley from them there are numerous small rock knobs. The band of mounds swings round across the mouth of the glen (6313 - 6413) and terminates beside the western side of the valley. Elsewhere in the valley and outside the valley the landscape is dominated by bedrock. In this context the band of mounds appears to have significance for it can be interpreted as the limit of a glacier moving down Gleann a'Chroin as far as its mouth.

At 633132 there is an exposure 2 - 3 m high by 20 m long in the side of the most south-westerly of these mounds. In it there are three clearly defined layers of fine deposits surmounted by an irregular layer of angular gravel. The upper fine layer consists of thin beds of sand and of silty sand which undulate along the length of the section in short or extended waves. The beds as a whole dip gently south-eastwards and total about 1 m in thickness. The middle layer is less than 40 cm thick and is fine sand folded into monoclines dipping to the south-east. The lowest layer exposed shows ripple bedding in fine sand. All were evidently deposited by running water of limited transporting ability. The structure of the middle layer may be a variety of convolution produced during the deposition of the upper layer. The surface angular gravel so contrasts with the homogeneous fine beds that it must be assumed to have been formed in a different manner, most probably as unsorted ablation debris. This mound does not abut the hillside, nor is it flat-topped. Furthermore no graded bedding was seen in it. Therefore it is not a kame terrace formed in an ice-marginal lake, as was suggested in the Geological Survey memoir (discussed in Section A). As it is one of a number of similar mounds, some of which are surfaced by similar angular gravel, it is more likely to be a kame formed in the decaying terminal zone of the glacier.

The head of Gleann a'Chroin contains two corries. The higher is floored by the hanging rock basin containing Lochan a'Chroin at 2400 feet (730 m) and its backwall rises to 3000 feet (915 m), just below the peak of Stuc a'Chroin. The lower but much larger corrie occupies the remainder of the valley head, rising from 1500 feet (455 m) on the valley floor to 2250 feet (685 m) at the top of cliffed walls. These altitudes are comparable with those for other corries surrounding the Ben Vorlich - Stuc a'Chroin ridge that have been shown (in this chapter) or will be shown (in chapter 11) to have contained corrie glaciers during the last stage of glaciation. For this reason it is inherently probable that the twin corries of Gleann a'Chroin nourished their own glaciers and that they joined forces as a valley glacier whose dimensions should have been similar to those of its neighbours in Gleann an Dubh Choirein and Glen Ample. Possible ice margins have therefore been suggested, descending from the corrie backwalls south-eastwards to the mounds at the mouth of the glen, where the limit lies at 950 - 1000 feet (290 - 305 m). This is the same elevation as has been noted for the clear ice limits in three other valleys in the Glen Artney system, as well as for a possible fourth limit. No other groups of mounds were found to the west, south or east of these that might sensibly be interpreted as the limit of a valley glacier in the same way as limits have been interpreted throughout the rest of the thesis area.

Parts of the landscape outside the suggested valley glacier limits have already been described in conjunction with these limits. Almost all of the valleys between Gleann a'Chroin and Callander are dominated by bedrock which lies at or close to the surface. Away on the north-eastern fringe of the Glen Artney district in the valleys south of Loch Earn, that is the Allt Glas (7020) and Gleann Ghoinean (6921), the landscape consists of smooth peat-covered lower slopes below crags of pebbly grit. Only in Findhu Glen - Corriebeagh, to the south-east of Glen Artney, are there any more drift mounds. The westernmost lie 6 km from and somewhat above the nearest valley glacier limits (Gleann an Dubh Choirein and Srath a'Ghlinne). They appear to be related to a group of meltwater channels in squares 7613 - 7713 that may have been superimposed on the col and hilltop that they cross. It is not likely that such an extensive area of deposits could have been formed by a corrie glacier from Creag Beinn nan Eun (7213). The most easterly of the valley glaciers in the Glen Artney and Loch Earn districts were very much smaller than those farther west (e.g. Glen Vorlich, Srath a'Ghlinne, Allt Ollach). It would therefore be illogical to suggest that the most south-easterly of all the valleys in the thesis area contained a contemporary glacier larger than the three examples quoted. It is concluded that the Findhu Glen - Corriebeagh Burn deposits belong to the extensive set of glacial deposits that characterises the Knaik valley, Strath Allan and Strath Earn outside the thesis area.

D. Summary.

During the last stage of glaciation, valley glaciers were formed in three, and possibly in five, valleys in the Glen Artney district. There is good depositional evidence in three cases, ambiguous evidence in a fourth, and rather less evidence in a fifth, which however ought on climatological grounds to have contained a valley glacier. In each valley the glaciers were nourished in valley head corries from which they moved down-valley for a limited distance before terminating. They left an abundance of moundy deposits that are contrasted with remains of a previous stage of glaciation by virtue of their freshness and proximity to the ice sources. Towards the eastern fringe of the region occupied by glaciers belonging to the last glacial stage there is a noticeable decrease in the size of individual glaciers. This is true both of the Glen Artney glaciers compared with ones farther to the west and north and of the variations in size of valley glaciers within the Glen Artney district.

Chapter 11. Loch Earn.

A. Previous literature.

The valleys of Loch Earn, the river Earn and Loch Lubnaig (sheet 54) contains evidence that was cited by W. Buckland (1840) and C. Maclaren (1849) as proof that glaciers had formerly existed in Scotland. Striations and roches moutonnées in these valleys show that glaciers moved eastwards along the Earn valley and southwards down the Lubnaig valley. Later mapping by the Geological Survey confirmed these conclusions and furthermore showed that an ice sheet had moved south-eastwards across the hills south and east of Loch Earn at a presumably earlier stage of glaciation. (Geological Survey unpublished sheet 46, 1900 and sheet 47, 1888).

P. Macnair (1908) noted moundy drift deposits in the Loch Lubnaig - Strathyre - Glen Ogle area and concluded that those in Strathyre implied that a valley glacier from Loch Voil had been sufficiently thick to transgress the Strathyre watershed and reach Loch Earn. (A similar conclusion is drawn later in this chapter).

J.K. Charlesworth (1955) considered that the Loch Earn area lay well within the extent of the 'Moraine Glaciation'. Although he did not discuss the glacial deposits in the area, he did describe a sequence of retreat stages that, however, are entirely subjective and so cannot be used (chapter 2). D.L. Linton described the characteristics of some of the valleys in the Loch Earn area in a series of papers that deal with glacial erosion (1949, 1959, 1963; Linton and Moisley, 1960).

B. Introduction.

The Loch Voil valley is drained southwards into Loch Lubnaig by the river Balvag. Although the lochs are 7 km apart, Loch Voil's surface is only 2.7 m above Loch Lubnaig's. The river Balvag runs from one to the other over thick alluvial deposits. A borehole near Loch Doine recorded 150 feet (45 m) of drift and organic debris without reaching rock bottom. Since there is no sign of bedrock on the valley floor between Loch Doine and Loch Lubnaig, it appears likely that a rock basin or series of rock basins extends for at least 22 km from the western end of Loch Doine to the southern end of Loch Lubnaig.

The Loch Earn rock basin is separated from the Loch Voil valley by a low pass that rises only 70 feet (20 m) above Loch Voil and descends 170 feet (50 m) to Loch Earn. Each of the valleys between Glen Dochart and Loch Voil and between Loch Voil and the Trossachs valleys has at its head an ice-modified col (Linton and Moisley, 1960), but these were probably less important routes of ice flow than the three major breaches in this area, namely Glen Ogle (c.5726) (Linton, 1949), Strathyre (c.5721) and Loch Lubnaig. Far to the west of this area the head of the Loch Voil valley is connected by several breached watersheds with Glen Falloch. In brief, the Lochs Voil and Earn valleys are connected by ice-modified cols and breached watersheds with other major troughs, Glen Dochart, Glen Falloch, the Trossachs and Loch Lubnaig.

C. The features.

In any attempt to reconstruct the pattern of glaciers, their sources and surface altitudes, the most critical localities in the Loch Earn valley system are the breached watersheds through which mounds pass into or out of the valley system. There are four such places, namely the Monachyle Glen, Glen Ogle, the Invernenty valley and Glen Buckie. The trend of the upper margins of mounds in this valley system, the limits of the area of mounds, and the general distribution of ice sources in the thesis area show that in general the flow of glaciers was into the Loch Earn area from the north-west and west. It will be shown that the evidence in this valley system conforms to this hypothesis. The valleys west of Glen Ogle and Loch Lubnaig within sheet 54 have not been studied other than by the interpretation of aerial photographs. The identification of hummocky deposits in these valleys must therefore be regarded as tentative in many cases, except where mounds are clear and abundant.

The evidence in the valleys between Glen Dochart and Loch Voil is often indistinct or ambiguous. In the Monachyle Glen (4926 - 4720) mounds cross the col at 1500 feet (455 m) from Glen Dochart. There is no depositional evidence to suggest that glaciers were nourished in any valleys tributary to the Monachyle Glen, although it is possible that the head of the glen was itself a source of valley ice. The southward descent of the upper margin of the mounds tends to suggest that a diffluent branch of the Glen Dochart glacier was able to push southwards into the Monachyle Glen.

Gleann Crotha (c.5020), Kirkton Glen (c.5321) and Glen Kendrum (c.5623) are apparently devoid of moundy deposits. However, the Glen Dochart tributaries, Gleann Dubh (c.5326) and Ledcharrie Glen (c.5025), that lie directly to the north of these three valleys contain abundant mounds. The ice-modified cols separating the northern from the southern valleys are at 1750 feet (535 m, Gleann Crotha), 1950 feet (595 m, Kirkton Glen), and 2000 feet (610 m, Glen Kendrum). These are higher than the breached watersheds of the Monachyle Glen (1400 feet, 425 m) and Glen Ogle (950 feet, 290 m). It is probably significant that mounds are continuous through the latter two valleys but exist only on the Glen Dochart side of the intervening valleys (Gleann Dubh and Ledcharrie Glen). The heads of the latter two valleys are shallow and open to an extent that suggests that they may well not have supported their own glaciers. Moundy deposits, sufficiently clear to be identified on aerial photographs, exist only in the lower parts of these two valleys. Accordingly it is suggested that Gleann Dubh and Ledcharrie, like the Monachyle Glen and Glen Ogle (see below) were last occupied by diffluent ice tongues that branched southwards into them from the Glen Dochart glacier. The absence of mounds from Gleanns Crotha, Kirkton and Kendrum and the heights of their watersheds further suggests that, unlike the Monachyle and Glen Ogle branches, the Ledcharrie and Gleann Dubh branches did not penetrate southwards beyond the cols (5023, 5424). It has already been shown that the surface of the Glen Dochart glacier descended east-north-eastwards towards its limit at Killin. Mounds at 1250 feet (380 m) at the entrance to Glen Ogle (c.5428) and at 1600 feet (490 m) near the col of the Monachyle Glen (4925) indicate the minimum levels of the ice surface at these localities. At intermediate points the minimum surface would have been at intermediate levels, which supports the suggestion that diffluent ice did not transgress the cols of Gleann Dubh and Ledcharrie Glen.

The prominent hummocks of the Glen Dochart glacier spread southwards into the northern end of Glen Ogle (5528). For

1.5 km south-eastwards mounds are absent from the rocky sides of the narrow valley. From about 556270 (c.900 feet, 275 m), where the valley floor begins to widen and become gentler, groups of mounds occur more and more frequently south-south-eastwards, being most abundant below 600 feet (185 m) in square 5824 near Lochearnhead. In this area the upper limit of the mounds drops quickly southwards from about 700 feet (215 m) in square 5824 to 330 feet (100 m) in Lochearnhead where the mounds cease abruptly. No further mounds that can be attributed to the Glen Ogle glacier occur beyond this limit.

The irregular lower slopes in square 5823 superficially resemble mounds but bedrock does in fact lie at or near the surface here. Similarly the hillside above Auchraw (5923 - 5924) is devoid of identifiable drift mounds; till covers the bedrock below about 750 feet (230 m). The clear gravelly mounds lying in the northern part of Lochearnhead village are therefore the present limit of the Glen Ogle mounds. Although formation of the flood plain here has probably altered the former limit, the absence of mounds from slopes immediately south and east-north-east of the flood plain confirms that the Glen Ogle glacier terminated at Lochearnhead. It is notable that there are no comparable moundy deposits anywhere along the northern side of Loch Earn or in the valleys tributary to the northern shore.

The ice that occupied the Loch Voil valley probably originated mainly to the west of the thesis area in the deep high valleys north of the trunk valley. There is a continuous spread of mounds through the Invernenty valley, with mounds at up to 1500 feet (455 m) in its col (4514). Already in this chapter it has been mentioned that the flow of glaciers was from the west and north towards the south and east. It follows that the flow of ice in the Invernenty valley is more likely to have been southwards from the Voil glacier than northwards to it. This suggests that the ice surface in square 4518 lay at or above 1500 feet (455 m). 10 km to the east mounds cross the col between Glen Buckie and Loch Lubnaig (5414) and up to 1250 feet (380 m). Since most of the known ice sources lie north and west of Loch Lubnaig, it is much more likely that ice moved south-eastwards down to Loch Lubnaig than north-westwards from it. Local striations support this contention. Therefore ice in Glen Buckie must have been caused to turn southwards in square 5317. The fact that the upper limit of mounds in Glen Buckie is considerably higher than in the Balquhidder area of the Loch Voil valley suggests that it is somewhat more likely that the Glen Buckie glacier branched north to Balquhidder and south-east to Loch Lubnaig than that Loch Voil ice moved southwards through Glen Buckie.

The most likely sources of ice for Glen Buckie are its headwater areas, namely Gleann Dubh (c.4915) and Gleann Fathan (c.4817). The mounds reaching 1350 feet (410 m) in Gleann Dubh (4915) could have been deposited by either a valley glacier moving down-valley or diffluent ice spilling south-eastwards from the Loch Voil glacier via the Bealach Driseach (4918). The former was perhaps more likely as glaciers appear to have formed in similar adjacent valley heads and at altitudes similar to those in Gleann Dubh (i.e. in Glens Finglas, 4911, and Casaig, 5411). To the south of the ice-modified col at the head of Gleann Dubh (c.4713) moundy deposits, other than those attributable to the Invernenty glacier, are apparently absent. This may imply that the Gleann Dubh ice surface was insufficiently high to transgress the col (4714); the possible ice margin has been drawn accordingly. It is equally difficult to judge whether the flow of ice through the Bealach Driseach (4918) was northwards from Gleann Fathan (4817) or southwards from Loch Voil. It has been deduced that at the northern end of the Inverenety valley the ice surface exceeded 1500 feet (455 m). Since the Bealach Driseach col lies at 1250 feet (380 m), somewhat below the probable level of the Voil glacier in square 4919, a southward flow of diffluent ice is possible. On the other hand the corrie-like head of Gleann Fathan rises to over 2000 feet (610 m), possibly giving impetus for ice to flow northwards to the Voil glacier.

The sides of the Loch Voil trough are so steep that it is only near Balquhidder where gentle slopes occur (c.5419) that there is within the valley useful evidence of the minimum surface level of the Voil glacier. The mounds at 900 feet (275 m) in square 5419 indicate the minimum ice level here. Accordingly there is no doubt that the Voil glacier was thick enough to flow into Gleann Crotha and Kirkton Glen (5020, 5321) if these valleys did not support their own glaciers. (Neither valley has been visited and both were completely forested when the only available c.1:10,000 aerial photographs were taken).

The Loch Voil glacier bifurcated at Kingshouse (5520), sending a branch southwards into the Loch Lubnaig valley along the course of the Voil - Lubnaig rock basin(s). This is recorded by the groups of mounds that cover the gentler slopes of this valley, these being in the vicinity of Strathyre village (5618 - 5516), below the Glen Buckie col (5514), and occasionally in very small groups beside the shores of Loch Lubnaig. C. Maclaren (1849) mapped striations pointing southwards near the lochside towards the southern end of the loch. This glacier was probably fed by small tributary glaciers descending from the eastern side of Ben Ledi (5611 - 5610), from whose steep slopes deposits are absent, and from Glen Ample (5915). The series of landslides above 1000 feet (305 m) at the Glen Ample - Loch Lubnaig confluence (5913 - 5914) may have been caused by oversteepening of the hillside by the southward-moving Glen Ample glacier.

It will be shown in chapter 12 that the limit of the last glacier in the Teith valley appears to have been at Callander, downstream from Loch Lubnaig. There is however no proof that the Lubnaig glacier reached Callander. The Callander ice may have come from the Glen Finglas area, west of Ben Ledi, and from Loch Lomond via the Trossachs, as the neighbouring Lake of Menteith glacier must have done (Sissons, 1967a, 99). The lack of depositional evidence along the length of the steep-sided rocky Loch Lubnaig valley therefore makes it impossible to determine the extent of the diffluent glacier that moved southwards from the Loch Voil valley. (Accordingly this part of the ice-flow map, fig. 13.2, has been left blank.) This does not invalidate the hypothesis that glaciers from Glen Ample and Ben Ledi may have occupied at least part of the Lubnaig trench.

The Loch Voil glacier flowed north-eastwards in another diffluent branch towards Loch Earn from its point of bifurcation at Kingshouse (5520). Because the valley southwards to Loch Lubnaig was probably deeper, being a rock basin, the southward-moving branch of the Loch Voil glacier should be regarded as the main one and the north-eastward - moving as a diffluent branch. If the rockhead of the basin at Kingshouse (5520) lies, say, 150 feet (45 m) below ground level, this is only 220 feet (65 m) below the watershed in the pass (5721). (A borehole by Loch Doine recorded 150 feet of drift without reaching bedrock. No other evidence of drift thickness is available). The base of the Voil glacier could easily have ascended 220 feet (65 m), for the ice surface lay at 900 feet (275 m) or more, 400 feet (120 m) higher than the pass.

The mounds left in the pass are larger and clearer than those nearer Loch Voil (5520), the change corresponding with the beginning of the pass at Kingshouse (5620) for no apparent reason. Near the north-eastern end of the pass the mounds descend from 650 feet (5822) towards the loch and fade out in the wood below Carstran farm (595228). On the western side of the valley (5822) their upper limit cannot be traced until they reappear from the woodland on the left bank of the Kendrum burn by the main road. It was shown above that the hillside south of the Glen Ogle glacier limit (5823) is devoid of mounds. This suggests that the margin of the mounds in square 5822 represents the former margin of the Kingshouse glacier. The implication is that the glacier surface descended not less than 300 feet (90 m) in its terminal 1 km; a comparable descent was deduced for the terminal 1 km of the Glen Ogle glacier.

As with the Glen Ogle glacier there is no evidence to suggest that the Kingshouse glacier moved into Loch Earn for any distance. The mounds at the mouths of Glen Ample and Glen Vorlich appear to be attributable to individual valley glaciers formed in these valleys. The four groups of mounds in the mouths of the four valleys, namely Glen Ogle, Kingshouse, Glen Ample and Glen Vorlich, do not merge, and accordingly it is suggested that these groups mark the limits of four separate valley glaciers.

Numerous mounds extend the length of Glen Ample (5915 - 6022). The proximity of this valley to the western end of Loch Earn suggests that at times during the Pleistocene thick glacier ice could have moved southwards from Glen Ogle to branch through the Kingshouse pass, Glen Ample and Loch Earn. Of these three the easiest would have been the deepest, Loch Earn. However, during the last stage of glaciation, ice from Glen Ogle reached its limit at Lochearnhead. The numerous mounds in Glen Ample must therefore have been deposited by a separate valley glacier that presumably issued from the hanging corries on the western side of the Ben Vorlich - Stuc a'Chroin ridge (6118, 6017). Because the extent of the Loch Lubnaig glacier cannot be established, it seems more logical to suggest that ice from Glen Ample moved southwards into the Loch Lubnaig valley than that Lubnaig ice spilled northwards as a diffluent into Glen Ample. If the former was the case, the corrie glaciers descending from Ben Vorlich - Stuc a'Chroin (6118, 6017) probably swung northwards and southwards respectively as transfluent glaciers.

The narrow band of mounds at 1250 feet (380 m) in the pass southwards to Loch Lubnaig (5915) implies that the ice surface must have been somewhat higher mid-way along the valley below the source corries (5818). Here the level of the ice probably fell steeply down from the hanging corries and would have fluctuated as the ice supply varied. Abundant mounds here lie below the break of slope at 1000 feet (305 m). Both they and the former ice limit descend northwards and near the northern end of the glen curve downslope from about 750 feet (230 m) to 450 feet (135 m) in 1 km. The mounds do not extend down to the Burn of Ample fan (6022), nor can any distinctive forms (such as ice-contact slopes) on the fan be found that might suggest a directly glacial origin for the fan. Yet at the Falls of Ample (6022) the burn is incised up to 5 m in rock, despite its gentle gradient and limited length and volume. This incision could be due, at least in part, to meltwater erosion during deglaciation. Meltwater could also have deposited sediment on the fan and as a delta in the loch. However there have been no detailed surveys of the sub-aqueous topography of the loch and so there is no means of determining the presence or absence of deposits in the loch beyond the fan. Neither is there any evidence to suggest that the loch level was either higher or lower than at present.

Glen Vorlich and its tributary Coire Buidhe drain steeply northwards from the high rocky arêtes of Ben Vorlich. Glaciers in these two valleys may have found their sources in funnel-shaped corries on each side of Ben Vorlich's northern spur (6219 - 6319) or to some extent in the lower wider parts of the valleys (c.6219, c.6420). In the western valley a small area of hummocks occurs along the valley axis from 1750 to 1500 feet (535 - 455 m) (6220). In the eastern valley another group lies between 1500 and 1250 feet (455 - 380 m) (6320). Mounds are absent from the moderately sloping interfluve (6320) between these valleys and also from the much more steeply sloping V-shaped valley immediately below their confluence (6220 - 6320). Down-valley below about 1000 feet (305 m) mounds reappear on the less steep slopes within about 300 m of the river. Their upper margin curves downslope to their limit at 350 feet (105 m) at the Vorlich fan although the margin at any given point is indeterminate. Mounds do not occur in the woodland east or west of Ardvorlich

House (6322 and 6222). The river is incised within the V-shaped valley of Glen Vorlich but not where it reaches its fan at about 400 feet (120 m). As with Glen Ample the fan appears to be a simple rather than a composite feature, graded evenly down to the present water level without any breaks of slope that would suggest formerly different depositional conditions or a formerly higher lake level.

To the east of Glen Vorlich the southern side of the Loch Earn valley is steep, with rock at or near the surface. Nowhere on these slopes or by the edge of the loch does hummocky drift occur. Nor is there any along the northern shore of the loch below the steep valley side. In Glen Beich (6329 - 6124) and Glen Tarken (6528 - 6625) the gentler valley sides are covered with till. Occasionally isolated drift mounds are found, mostly in lower Glen Tarken (6625). Nowhere is there any assemblage of features that resembles the profusion of clear mounds in, for example, Glen Ample. Glen Boltachan (7026 - 7224) is entirely devoid of deposited mounds.

Glen Lednock too lacks the abundant clear mounds that characterise the western end of the Loch Earn valley. Smooth gently undulating spreads of drift and craggy rock outcrops dominate the landscape of this valley. Patches of subdued fluvioglacial mounds occur on the valley floor in square 7327 and in square 7624. Till-plastered rock knobs occur widely along the valley floor and right over the broad ridge at the south-eastern end of the glen (7723 - 8024 - 7825). Striations and roches moutonnées, noted by the Geological Survey (sheet 47, 1888), point approximately south-eastwards both within the valley and on the hillsides and ridges above. The south-eastward pointing striations and roches moutonnées also occur on the ridge at the south-eastern end of the glen. This suggests that both the valley and surrounding hills were last covered at the same time by a south-eastwards ice movement, probably by the last ice sheet. This movement is also recorded by numerous striations on the hills south of Comrie (7722). The west to east striations and roches moutonnées in the Loch Earn - River Earn valley, occurring east of square 6322, probably belong to the same period for, during ice sheet conditions, such a major trough would probably be occupied by an eastward-moving ice stream.

There is therefore no evidence to suggest that the valleys of the Loch and river Earn, of the tributaries of Loch Earn east of Glen Vorlich or on its northern side, or of the major part of Glen Lednock were occupied by glacier ice during the last stage of glaciation. The evidence is more in accord with the suggestion that these areas were most recently glaciated by the last ice sheet, a stage thought to have preceded the last glaciation (Simpson, 1933; Sissons, 1967a). Upper Glen Lednock (sheet 48), its tributary the Invergeldie (7529) and Glen Turret have already been discussed (chapters 8 and 9).

D. Summary.

During the last stage of glaciation diffluent ice tongues moved southwards from the Glen Dochart glacier via the Monachyle Glen and Glen Ogle, depositing numerous drift mounds in both valleys. The Monachyle glacier joined a major glacier that moved eastwards into the thesis area along the Loch Voil valley where it was joined by local corrie glaciers. A diffluent branch moved southwards along the Invernenty valley from the Voil glacier to the Trossachs. The volume of Loch Voil ice at the northern mouth of Glen Buckie caused ice from Gleann Dubh to pass southwards over the col at the south-eastern end of Glen Buckie. On descending into the Loch Lubnaig valley, this glacier probably joined the Voil trunk glacier which had turned southwards into the Lubnaig valley. Hummocky drift was deposited in the Loch Voil valley, Gleann Dubh, Glen Buckie and the Loch Lubnaig valley, except on the steep rocky slopes above Loch Lubnaig. Consequently the limit of the glacier in the Lubnaig trench is uncertain, although it is possible that the ice may have extended to Callander.

At Kingshouse the Voil glacier branched, sending a diffluent north-eastwards to the western end of Loch Earn. The Glen Dochart diffluent glacier that moved south-eastwards by Glen Ogle and ice from Glen Ample also terminated at the western end of Loch Earn. Hummocky drift was deposited in Glen Ogle, the pass from Kingshouse, and in Glen Ample. The Glen Ample glacier was transfluent, moving southwards into the Loch Lubnaig valley as well as northwards to Loch Earn. Smaller valley glaciers moved northwards from Ben Vorlich down Glen Vorlich. Their hummocky deposits terminate by the southern shore of Loch Earn. The valleys east of Glen Vorlich and, on the northern side of Loch Earn, east of Glen Ogle, do not appear to have been occupied by glacier ice during the last glacial stage for hummocky drift is absent from them.

Chapter 12. The Teith valley.

1. Previous literature.

Early workers who make mention of glacial landforms in the Teith valley include W. Buckland (1842), the Rev. Thomas Brown (1870), D. Milne-Home (1871), A. Geikie (1894), P. Macnair (1908) and J.W. Gregory (1926). All were interested in particular features that caught their attention, but the first to consider the Teith valley in its geographical relationships was J.B. Simpson (1933), whose identification of the last two glacial stages in the Clyde - Tay region is a highly original and outstanding contribution.

Simpson described large end-moraines at the southern end of Loch Lomond and at Lake of Menteith. The moraines were formed at the limit of a readvance of valley glaciers down Loch Lomond and the upper Forth valley after the retreat of the last ice sheet. The contemporaneity of the moraines is proved by the existence of a large meltwater channel that connects them (fig. 2.2). In the Teith valley he noticed "conspicuous 'moraines' west of Doune that rise above the general ruck", yet admitted that "their exact significance is difficult to assess". He concluded they could as well be the Loch Lomond Readvance limit as merely the products of slower ablation occasioned by climatic change or deep shadowing cast by the valley sides. It is certainly true that the south side of the valley receives very little sunshine in winter, although Simpson's 'moraines' are on the north side.

J.K. Charlesworth (1955) was content to leave Simpson's interpretation as definitive. Charlesworth's 'Moraine

Glaciation' limit is virtually the point at which Simpson's Perth Readvance 'moraines' cease, proximate to a supposed Loch Lomond Readvance which had reached beyond Callander towards Doune.

J.J. Donner's palynological and stratigraphical analyses (1957, 1958, 1962) of lateglacial sites are most significant because they confirm Simpson's interpretation of the lateglacial sequence, and at Loch Mahaick , 8 km east of Callander, show that any equivalent of the Loch Lomond Readvance did not transgress the site. Therefore Simpson's premise that such a glacier was confined within the Teith valley is independently supported.

D.E. Smith's thesis (1965) on the lateglacial and postglacial sea levels of the Forth included detailed mapping and levelling of the Teith terraces from the carse up-stream to 4 km west of Doune, within the area that the present writer has mapped in detail (sheet 54). The terrace profiles and relationships discovered by Smith agree with Simpson's general conclusions. (Smith's evidence will be presented in greater detail in sections 3.D and 5 of this chapter).

The Geological Survey memoir (1970) provides no clearer statement of the glacial sequence in the Teith valley than did Simpson (1933) and Charlesworth (1955). (The memoir is analysed fully in section 4).

D.D. Kemp's thesis (1971) on the buried morphological and stratigraphical phenomena of the northern side of the Forth valley includes discussion of the relationship between the terraces of the Teith valley and the lateglacial shoreline sequence in the Forth basin. It is complementary to the work of D.E. Smith and will be discussed more fully in sections 3.D and 5.

D.L. Linton (1962) included the Teith valley in a paper describing ice-moulding in the adjacent lowlands. He found that grooved bedrock and drumlinoid drift on the Teith interfluves could only have been formed by one or more ice sheets moving south-eastwards across the Highland edge and down over the Lowlands.

2. Introduction.

The river Teith drains two major troughs, from the north Loch Lubnaig and from the west the 'Trossachs' (a convenient term for the valley containing Lochs Katrine, Achray and Venachar). Both connect by low-level breaches with other members of the glacial trough system, the latter with Loch Lomond via Loch Arklet, the former with Loch Voil, Loch Earn and Glen Dochart, as well as with the Trossachs (sheet 54). Corries and valley heads over 2000' partially circumscribe the drainage, yet both high - and low - level breaches must have provided plentiful ingress and egress for glaciers.

The Trossachs and Lubnaig troughs unite into a widening valley at Callander, where the Highland metamorphic rocks are replaced by Old Red Sandstone sediments on the south-eastern side of the Highland Boundary Fault. The steeply-dipping conglomerate beds at Callander are the last to restrict the valley as the Teith enters the Central Lowlands where it flows through a broad valley with gentle slopes.

3.A. The features: Highland tributaries of the Teith.

It has already been mentioned that the land west of Glen Ogle - Loch Lubnaig and south of Glen Dochart has only been studied on aerial photographs. Nevertheless these suffice to indicate the general pattern and continuity of deposits (chapter 11). A continuous spread of innumerable mounds passes along the Loch Voil trench (sheet 54) into the Lubnaig trench via Glen Buckie at 1050 feet (320 m), and Strathyre at 400 feet (120 m). At the western edge of the map area the Invernenty valley connects the Loch Voil trench with Loch Katrine at 1300 feet (395 m). Between the three troughs the floors of the larger valleys are covered with mounds.

The pattern of mounds does appear strangely fragmented in comparison with other major valley systems in the region, yet the reason may simply be that the Voil, Lubnaig and Trossachs valleys are all largely occupied by deep water. In every other part of the thesis area there is a much smaller proportion of water-filled valley floor. And yet the Loch Ard and Loch Lomond valleys only exhibit abundant fresh glacial deposits at their lowland exits, for they too are occupied by lochs (see section 1 above). So too it is only where the Teith is bordered by long gentle slopes, as to the west of Callander, that continuous glacial deposits occur. Up-valley their absence may be explicable by the steepness of the slopes, as along most of Loch Lubnaig, by the jagged rockiness of the Trossachs valley and Menteith Hills, and by the presence of rock basin lakes. However, it may be noted that unpublished 1:10,560 Geological Survey maps and observations by Macnair (1908) indicate that valley glacier 'moraines' occur spasmodically between Loch Lomond and the Trossachs and Loch Ard valleys just outside the thesis area.

3.B. <u>The features: The Teith valley, west of Callander.</u>

At the eastern end of Loch Venachar (sheet 54) the Eas Gobhain, a precursor of the river Teith, issues from a typically narrow Highland valley into a widening, gentler

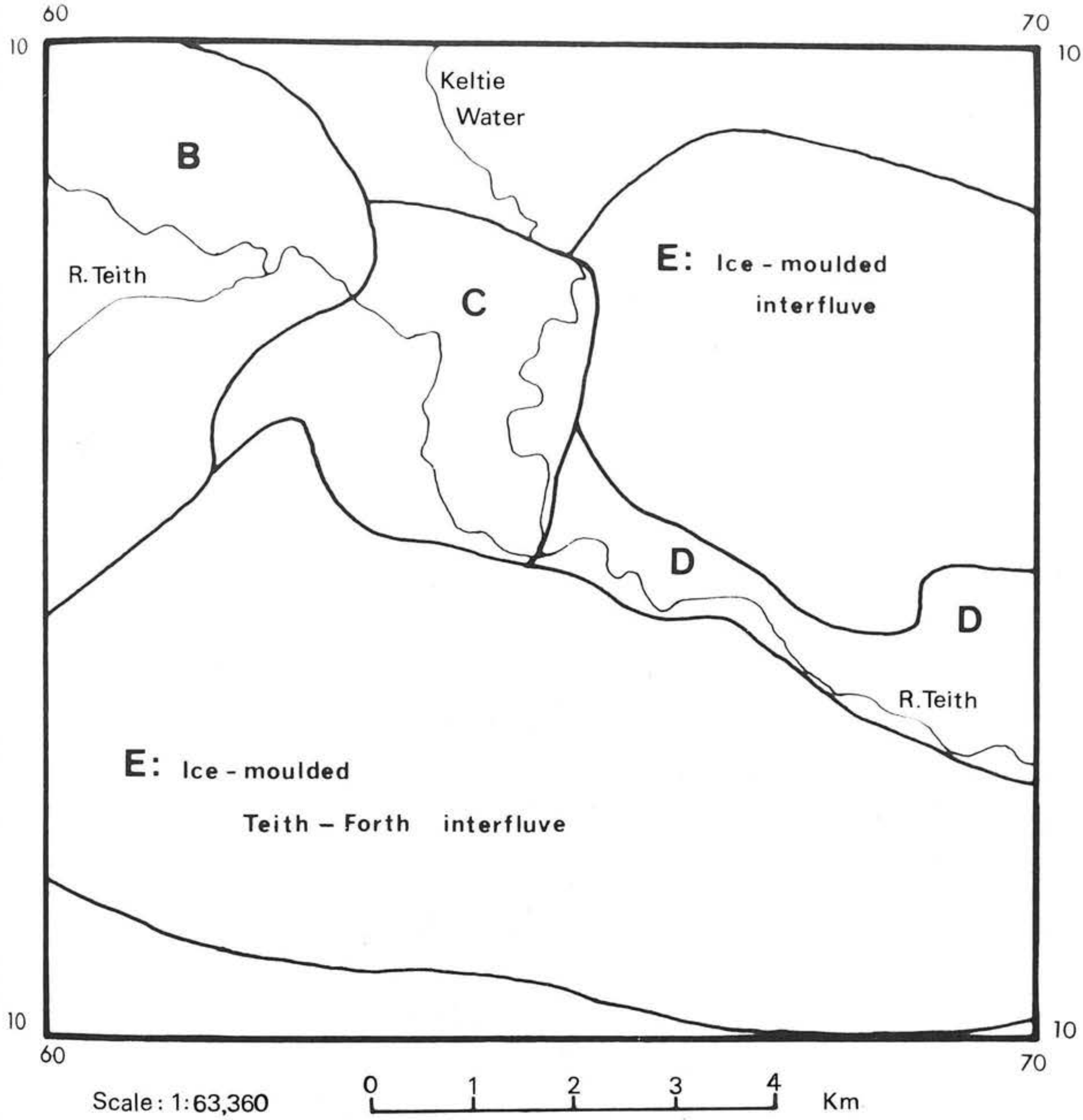


Fig.12.1

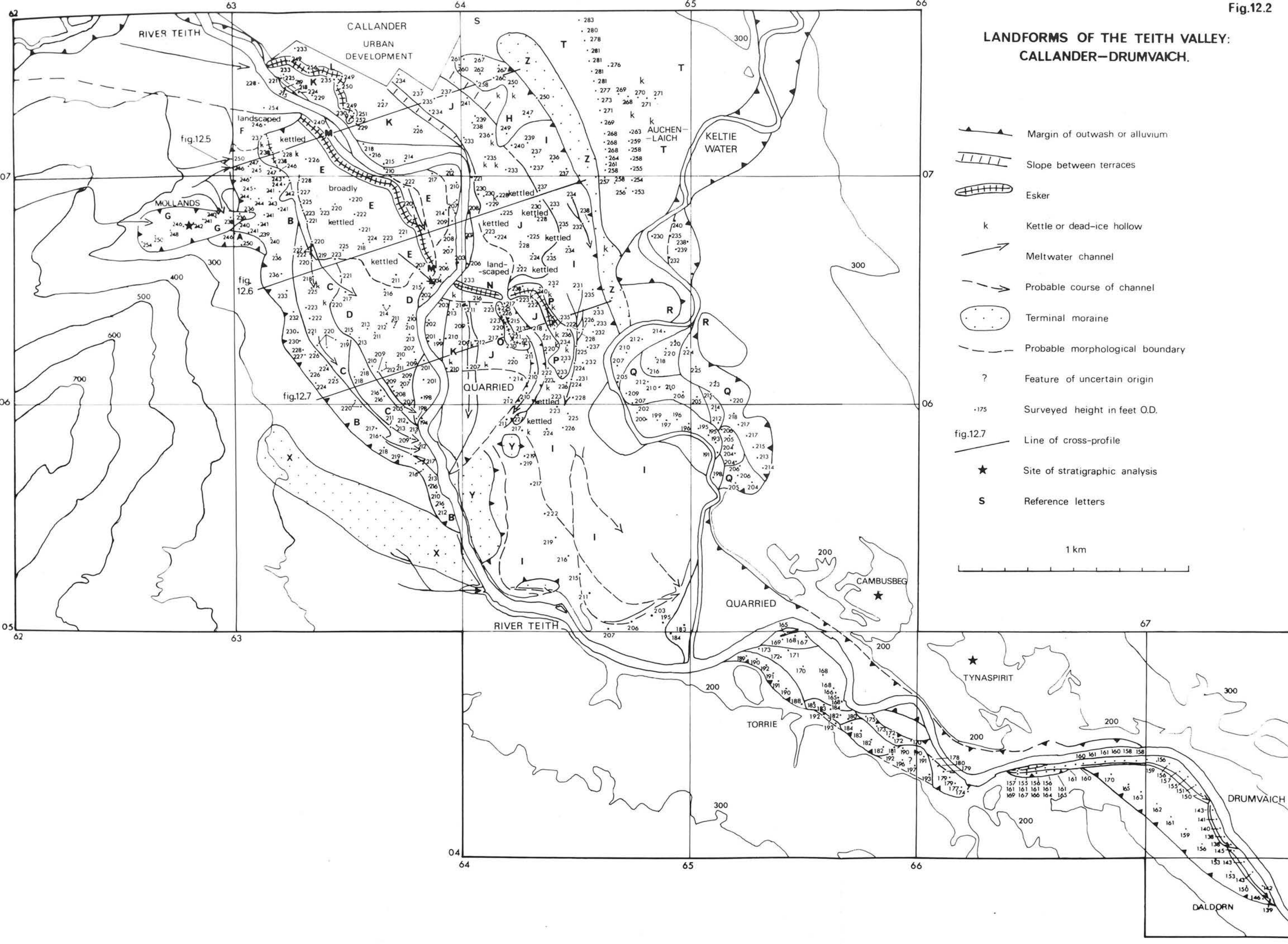
SUBDIVISIONS OF SECTION 3 (SHEET 60)

valley having a Lowland aspect. Below the till-covered slopes of the southern side and the rockier northern slopes are gently sloping terrace-like spreads of well-rounded fluvio-glacial deposits, grooved by discontinuous channels, pitted by dead-ice hollows, and including occasional kames (sheet 54). Eastwards on the southern side these deposits lie below 300 feet (90 m), although in the dense woodland south-west of Callander the forms are as indiscernible as under the built-up areas of Callander and Bridgend.

The Garb Uisge passes southwards from Loch Lubnaig through a deep narrow rocky gorge into the wide valley confluence at Kilmahog, 1.5 km west of Callander (sheet 60). Here a small area of complex terraces reaches up to 300 feet (90 m). The highest and largest (c.610085) is channelled and more extensively kettled than the others. But because they are very fragmented, because the Leny burn has a large fan and has also been artificially straightened, and because roads and buildings have required earth removal, it is not possible to discern whether all of the lower terraces were deposited adjacent to glacier ice. The kettled south-western margin of the highest (c.610085) is probably an ice-contact slope.

All these terraces, around Kilmahog and towards Loch Venachar, are so patchy that their origins can hardly be interpreted in isolation. However they do fit into the pattern beyond Callander (section 3.C; see fig.12.1) and in this light may be explained to some extent. The terraces and channels upon them show that gravel was carried down-valley from the Loch Venachar area and from the Loch Lubnaig valley possibly on to thin stagnant tongues of ice. The ice-contact slope at Kilmahog (mainly in square 6108) suggests that thicker, possibly active ice lay in the valley at Kilmahog whilst this

Fig.12.2



LANDFORMS OF THE TEITH VALLEY: CALLANDER–DRUMVAICH.

outwash was being carried east-south-eastwards away from it on to its thinner terminal zone. As the active glacier receded and thinned, the last at and west of Kilmahog would have been made available for further deposition and erosion. Terraces and channels there probably record this. Gradual melting of the buried ice tongue would have produced the extensive kettling in the earliest, and now the highest, terrace (6108).

3.C. The features: from Callander to the Teith-Keltie confluence.

Description.

On each bank of the river Teith south-east of Callander there are extensive fluvioglacial deposits, attaining a maximum width of 1 km on each side in a sequence of four terraces, in addition to the narrow strips of flood plain which lie 1 - 1.5 m or less above the river (sheet 60). The much narrower terrace suites that lie below the Teith - Keltie confluence are probably genetically related to those nearer Callander but will be discussed separately (section 3.D; fig. 12.1). Furthermore, owing to the number and complexity of forms between Callander and the Teith - Keltie confluence, it will be necessary to deal with the forms systematically, taking the western part first, the terraces east of the Teith second, and other features above these third. Each will be examined in order from north-west to south-east, going down-valley. Thereafter a possible origin for the features as a whole will be described.

Bridgend (6207, sheet 60) appears to have been an island

Fig.12.1 illustrates the division of sheet 60 into the sections relevant to this chapter.

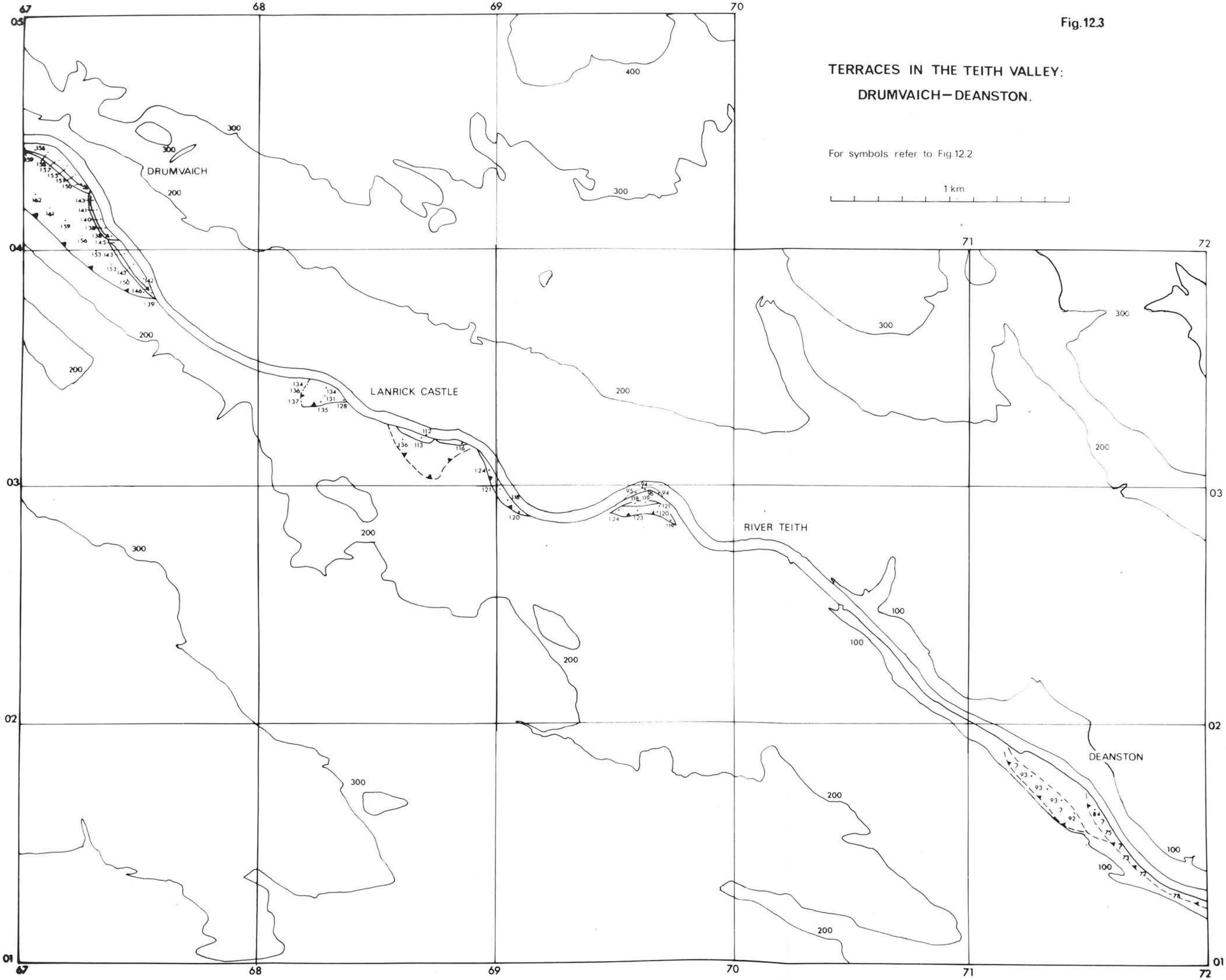


Fig.12.3

TERRACES IN THE TEITH VALLEY: DRUMVAICH – DEANSTON.

between the present course of the river and an older course which lies slightly higher on its southern side. 0.5 km south-eastwards the low ground rises sharply as a north-facing ice-contact slope up to a small irregular feature (F) that has been artificially levelled (630071). (Fig.12.2 will be found useful throughout this section - 3.C; the vertical aerial photograph, fig. 12.13, shows most features). Area F does not seem to have formerly been a terrace. The two eskers issuing from it run south-eastwards through a mass of kames and wide dead-ice hollows (E, fig.12.1, fig.12.13), the longer esker (M) being the inner margin of the kettled, channelled terrace suite. (Fig. 12.14 shows part of esker M and a terraced part of E in square 6306 where the esker is running almost due south). The highest of the three principal terraces (B) commences 4 feet (1.2 m) higher than and to the south of F. Terrace B has the crenulate margins and shallow kettle holes characteristic of a kame terrace. It evidently was formed between the hillside to the west and the glacier occupying area E, area E being approximately 20 feet (6 m) lower than B (fig. 12.2).

Around Mollands farm (6206, fig. 12.2) meltwater channels course down across subdued mounds to the edge of terrace B. One channel splits into two parts, sending a branch southwards into the shallow valley (G). This valley is at present filled with peat whose surface, at its outlet (square 6306), lies about 6 feet (2 m) below terrace B and 10 feet (3 m) below terrace A. In the middle of this valley (G) boring revealed that 24 feet (7.3 m) of peat lie on 4 feet (1.2 m) of homogeneous, soft, light grey clay. This clay contrasts with the fine gravel deposits of the modern stream at Mollands and the coarse sand and gravel of the terraces (A,B).

It is concluded that the site (G) could not have been available for deposition whilst meltwaters were depositing the gravels of A and B. The clay is quite distinct from the local till, which is reddish-brown, tough and stony. Therefore the clay is considered to be a lake deposit formed after terraces A and B.

Terrace A, being higher than B, presumably was formed earlier than B whilst glacier ice was more extensive, occupying the valley G and the area of B. It may be that A was originally more extensive and that parts of it were destroyed by the meltwaters that subsequently deposited terrace B. Meltwater activity during the existence of ice sufficiently extensive to occupy valley G is recorded by small subglacial channels beside Mollands farmhouse and a larger one to the west (figs. 12.2, 12.13). The latter runs down the crest of the hill from 475 feet (145 m) to 375 feet (114 m), there turning to run downslope for 50 feet (15 m) as a subglacial chute, then turning again to join a normal stream channel.

Southwards from this area kame terrace B declines gradually from 240 feet (73 m) to 216 feet (66 m), becoming broadly kettled towards its southern end. Elsewhere its surface is remarkably level and its inner and outer margins are quite sharp (fig. 12.2). (Fig. 12.9 portrays the long-profile of terrace B. Terrace A does in fact slope down-valley; the higher spot height refers to its inner margin, and the lower to its outer margin, hence its anomalous appearance on fig. 12.9). Terrace C is lower than B and slopes slightly more gently. The majority of the meltwater channels in the terrace suite (on this side of the Teith) occupy terrace C. The longest begins in the deeply kettled area (E), it parallels the two eskers (M and area E), and it branches into two parts. One branch rises and falls by two feet and ends in a kettlehole, while the other fades out on a lower terrace (D). This channel shows that areas E, C and D were formerly a single feature and that E and D were lowered after the channel in C had been eroded . This matter is further explored below.

The kame and kettle area (E) lies at the proximal end of terrace D. These two have been distinguished because D is more distinctly a terrace. Nevertheless the spot heights on fig. 12.2, which are profiled on fig. 12.9, show that D is merely the less kettled continuation of E. C, E and D even merge in the vicinity of the aforementioned channel but for the most part D lies about 6 feet (1.8 m) below C. The esker M forms the inner margin of terrace E - D, showing that the esker must have been forming at about the same time as E - D was being built up. (Fig. 12.14 shows terrace E to the right of the esker. Figs. 12.13, 12.2 and 12.9 are also relevant).

The terminal moraine (X) (fig. 12.2), which bounds these terraces to the south, is a belt of till-surfaced mounds with dead-ice and kettle hollows. It swings south-eastwards downhill from 325 feet (99 m) towards the river Teith, thickening and broadening until it is 300 m wide and up to 11 m high. It is continued on the opposite river bank by patches of till-surfaced mounds (Y), and north-eastwards by the ridge - rampart (Z). The soil survey map (fig. 12.11) indicates till in areas X and Y, and test pits dug for gravel indicate that Y and Z are principally gravel with a till surface.

A short meltwater channel system obliquely descends the southern face of the moraine X and also skirts its base for 400 m. The stream now occupying the lowest part of this channel system has lowered it by at least 5 m so that it ends just above the present course of the Teith. Four meltwater channels (B, C, D, and K on the eastern bank) meet the present river course at the northern flank of the moraine (fig. 12.2). It will be shown later that other channels are similarly related to the moraine on the eastern bank (Y, Z). Since there is no other moraine belt anywhere up or down the Teith valley, the existence of one here, with several meltwater channels that break through it and extensive kame terraces within it, indicates that the Teith glacier must have advanced southwards and constructed a terminal moraine (X - Y - Z) as it came to a stillstand. Meltwaters would naturally have tried to escape by eroding a gap through the moraine (Z - Y and Y - X). Once a gap had become established, the flow of meltwater would have become concentrated towards it, hence the creation of the major gap now used by the present-day river Teith.

The town of Callander occupies a gently sloping strip of land 2 km long, which here and there between 225 feet (68.6 m) and 275 feet (83.8 m) seems to be terraced. However south-eastwards and then southwards as far as the Teith - Keltie confluence there is a suite of kame terraces, margined in part by the moraine belt (fig. 12.2).

The highest terrace (H) begins somewhat unexpectedly at 260 feet (79.2 m) part-way along the gentle slope east of Callander, a slope which might well have been expected to support a similar terrace (fig. 12.2). However three facts may help to explain this apparent anomaly. Firstly, the western end of this terrace (H) is intensively kettled;

secondly a large rampart-like moraine (Z) commences beside it and parallels it; and thirdly a similar small feature, the kame terrace A, lies directly opposite on the west side of the river in a similar position.

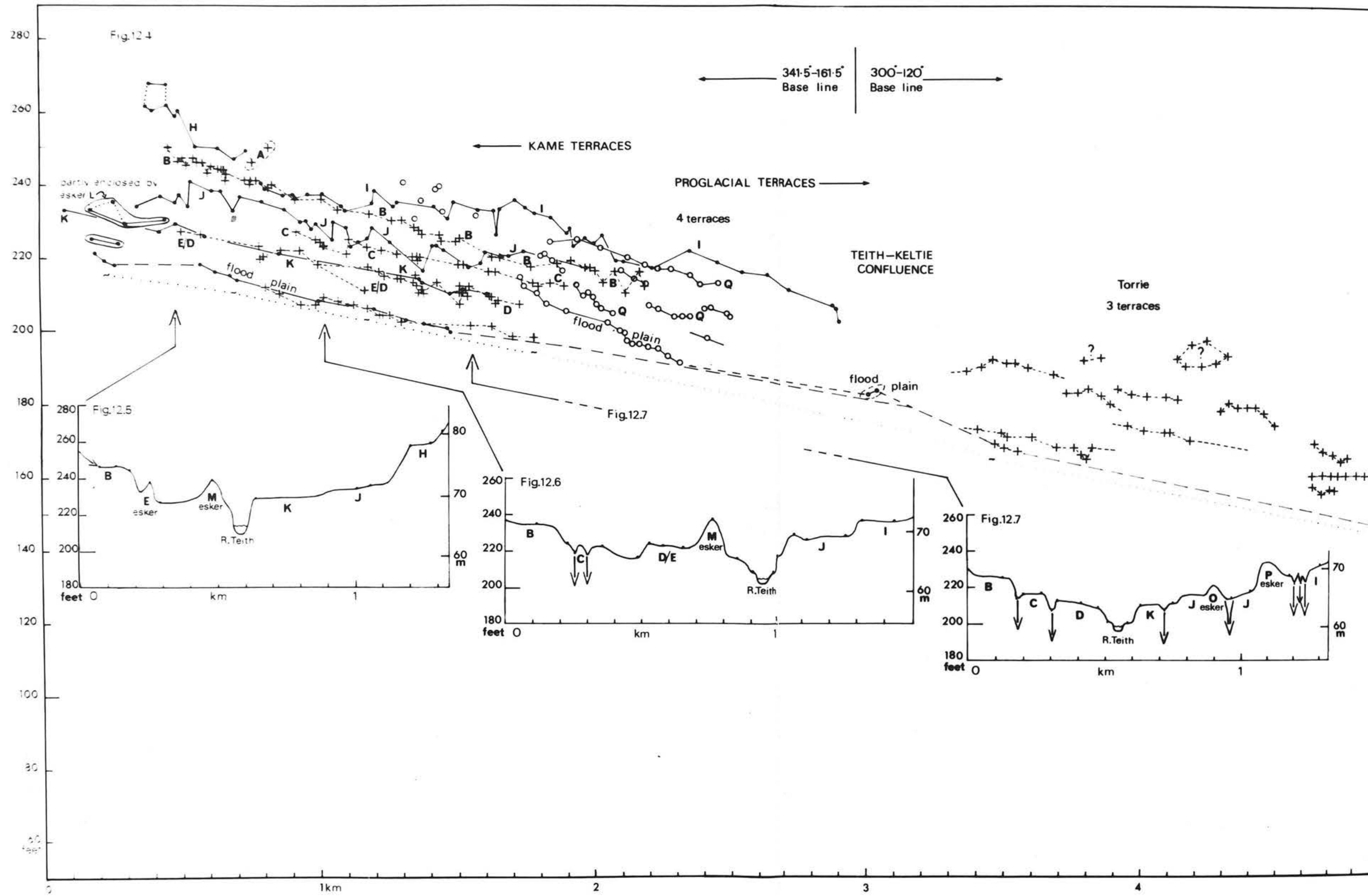
Southwards there is a sharp drop of about 3 m from H down to terrace I at 238 feet (72.5 m) (fig. 12.8). Terrace I is the longest, and in places the broadest, of all the Callander kame terraces. It descends gently for 2.4 km towards the Teith - Keltie confluence, ending there at 203 feet (61.9 m). Two long meltwater channels with shorter tributaries occur within the kettled part of this terrace, that is up-valley from the terminal moraine arc (X - Y). They parallel the rampart section of the moraine (Z) in running southwards. Terrace I is extensively kettled as far south as the area where it passes through the gap in the moraine (between Z and Y). (This kettling is apparent on the photograph, fig. 12.13). Distally from here (square 6405) kettles do not seem to occur. Unfortunately, as this area (6405) is densely forested, the interpretation of landforms is based largely on aerial photographic evidence. The photographs reveal the existence of several meltwater channels crossing the planar terrace, and surveyed spot heights confirm this general impression. Some of the channels break through the morainic mounds (around Y) and continue for 1 km to the present southern margin of terrace I. Evidently therefore terrace I consists of a kettled part (kame terrace) inside the terminal moraine and an outwash terrace outside it. Its long-profile (fig. 12.8) illustrates this point.

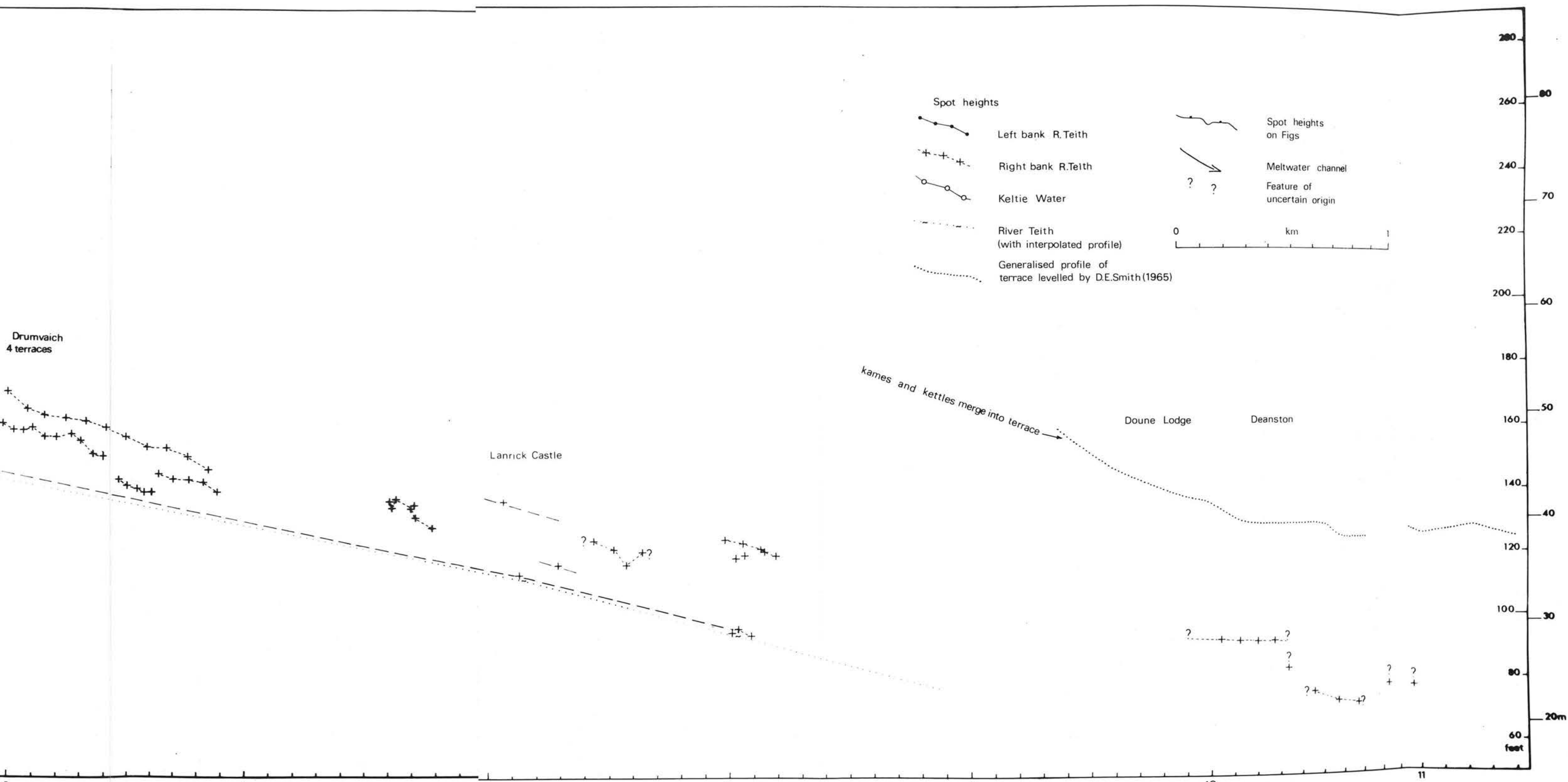
Not only the high terrace(I) but also the two lower kame terraces (J and K) resemble the neighbouring terraces already described on the western side of the river Teith. The middle terrace (J) emerges from the built-up area of Callander, where it is separated by a broad break of slope from terrace K which is about 7 feet (2 m) lower (fig. 12.8; fig. 12.5). South-eastwards the margin between J and K becomes sharper and narrower and remains so to the distal end of these terraces (fig. 12.2). The middle terrace (J) is extensively kettled, as is shown by its long-profile (fig. 12.8). At the southern end of esker P both upper (I) and middle (J) terraces are so kettled that they merge, although they are usually separated by a break of slope varying between 1.2 m and 3.7 m high, depending on the distribution and depth of kettleholes (e.g. to the north of P). The lower terrace (K) lies 10 feet (3 m) or so below the middle terrace (J) in the area south of the eskers N - O - P.

The eskers N - O - P are obviously the distal portion of the eskers L and M, which lie upstream from them (figs. 12.2 and 12.13). Formerly the eskers N - O - P may have been continuous but appear to have been separated by the building of estate roads. Eskers N - O - P and their upstream neighbours L and M should be thought of as a single esker system, now broken into parts by the river Teith. The crest of the esker system undulates and the width continually fluctuates. This is particularly clear along N - O - P (fig. 12.8) for esker P rises out of N and is higher than N, whereas O descends from N and then re-ascends to the same level as N.

Although the esker system has the same general southward trend as the nearby meltwater channels, its sinuous course, undulating crest, varying width and passage from the lowest kame terrace (E - D) to the high kame terrace (I) contrast with the more even width, depth and linearity of the channels

Figs. 12.4–7. TERRACE PROFILES IN THE TEITH VALLEY: CALLANDER–DEANSTON.





Spot heights
Left bank R. Teith
Right bank R.Teith
Keltie Water
River Teith
(with interpolated profile)
Generalised profile of
terrace levelled by D.E.Smith (1965)
Spot heights
on Figs
Meltwater channel
Feature of
uncertain origin
0
km
1
Drumvaich
4 terraces
Lanrick Castle
kames and kettles merge into terrace
Doune Lodge
Deanston
280
260
240
220
200
180
160
140
120
100
80
60
feet
80
70
60
50
40
30
20m
5
6
7
8
9
10
11

(fig. 12.2). The channels have the same trends of height and direction as the kame terraces into which they are cut. The eskers have varying trends of height and alignment, suggesting that they were formed in a different way, perhaps below a subglacial water table rather than above it. The inter-relationships between the kame terraces and eskers can hardly suggest that the terraces pre-date the eskers, or vice versa, firstly because the terraces could hardly be preserved intact by ice advancing over them to deposit the eskers, and secondly because the eskers would have been destroyed had later meltwaters deposited and/or eroded the terraces (E, D, I, J, K). Therefore it seems most likely that the terraces and the esker system were formed contemporaneously.

The eastern terrace suite (I, J, K) has been tested for economic gravel deposits by the Springbank Sand & Gravel Company Ltd. Electrical resistivity surveys and physical test pits over 0.5 sq. km in square 6406 indicated that 9 m or so of gravel lie beneath the high terrace surface (I), and 6 m or so under most of the middle and low terrace surfaces (J, K) (see, for example, cross-profiles figs. 12.6-7). The middle terrace (J) has sand layers on gravel north of the eskers (N - P), with clay under the gravel south of them. The upper terrace (I) has sand layers at various depths within the gravel. Unfortunately there is no record of the exact position of each test, whether on the top surface of a terrace, in kettles, or at the terrace margins. Consequently the details of the stratigraphy cannot be more clearly traced overall. Fortunately however there is a small gravel pit at the southern end of the lower terrace (K) which displays rudimentary bedding parallel to the terrace surface in well - rounded gravel at least 4 m thick.

Above the south-eastern end of the middle and lower terraces (J and K) the area of till-surfaced mounds (Y) overlooks a number of meltwater channels. Some break through the area of these mounds and run along the highest terrace (I). Others occur on the two middle (C, J) and two lower kame terraces (D, K) and run towards the present river Teith. Evidently the meltwaters in these channels must have broken through the terminal moraine on each side of the mounds (Y), perhaps changing the moraine from a ridge to groups of mounds. The outwash terrace (I) beyond the moraine may have been constructed from the debris carried by these meltwaters.

To the east of the moraine rampart (Z) other processes may have been operating. This rampart-ridge runs southwards for 1.1 km falling steeply on its western side to the high terraces (H, I). North of the A.84 road (square 6407) it does not fall at all on its eastern side, for its crest merges at the same height into the till-covered terrace T. South of the road, in square 6406, the crest virtually maintains its altitude, but the terrace below its eastern side drops down so that the rampart becomes a ridge. Also the western side of the ridge becomes markedly crenulate, and a deep kettlehole in the crest causes the ridge to bifurcate. The northern end of the rampart is surfaced by loose gravelly till with angular striated boulders. The soil survey map classifies the feature as fluvioglacial sand and gravel, which need not contradict the presence of the till (fig. 12.11).

Immediately to the north and north-west of the moraine (Z) there is a gently undulating area (S) between about 275 feet (83.8 m) and 375 feet (114.3 m) (presently occupied by the golf course). Despite its moundy appearance S is dominated by vegetated outcrops of bedrock, principally Old Red Sandstone conglomerate, thinly concealed by a loose gravelly till with angular to sub-rounded boulders. Eastwards towards Auchenlaich (T) a thicker drift layer appears to the north-east and east of moraine Z. Most of the land west of Auchenlaich slopes very gently south-south-eastwards and is dotted with broad shallow kettles. Here the surface material is a loose till with angular to sub-rounded boulders, an observation which the soil survey map confirms (fig. 12.11); one angular boulder measured over 2 m in diameter. East of Auchenlaich near the Keltie, and south-eastwards into the north-western quarter of square 6506, the undulations are broader and the till apparently absent. Physical tests for gravel and the soil survey map both suggest that terrace gravels stretch eastwards and south-eastwards from Auchenlaich (fig. 12.11). Furthermore the form of the ground and the physical tests suggest that the same terrace gravels (T) underlie the till west of Auchenlaich. Electrical resistivity tests indicate that most of area (T) between 250 and 300 feet (75 - 90 m) has 6 - 8 m of drift. Unfortunately it is not possible to be sure from the gravel or soil surveys whether or not the kettles lie in the fluvioglacial gravel underneath the till.

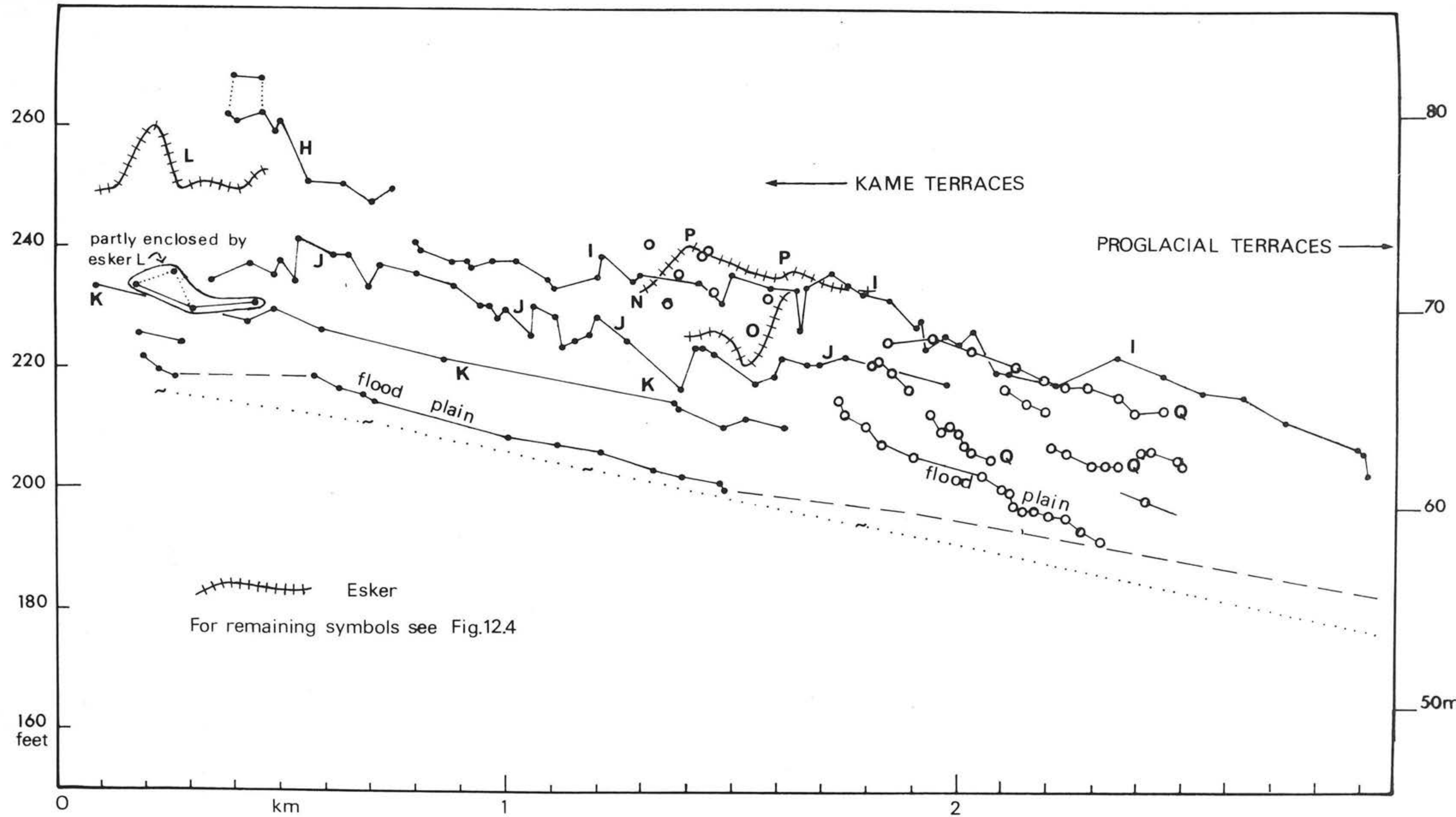
Discussion.

Viewing the evidence in the Callander area as a whole, it appears that a glacier must have advanced south-eastwards from the Highlands for approximately 3 km (sheet 60). On its northern margin immediately to the east of Callander it appears to have deposited only a thin layer of till in area S above 250 feet (75 m) (sheet 60). Similarly the western part of its margin, around point 6306, seems to have left only a thin till layer on the slopes above 250 feet (75 m). However, as the glacier came to a stillstand, it constructed an arcuate terminal moraine (X - Y - Z) along 3.5 km of its margin. The moraine (X) descends from 325 feet (100 m) south-eastwards to about 200 feet (60 m) at Y, then gradually ascends north-eastwards and northwards to 275 feet (85 m) (Z).

During the glacier's advance to this position there may have been outwash deposition down-valley from it in areas I and T. (Fig. 12.10 may be found useful. It attempts to portray the most likely sequence of events). This latter is certainly not a simple terrace however, and it may be that, once the glacier began to construct its terminal moraine (Z), till was able to flow off the snout, across the moraine and on to the recently formed terracefor about 250 m (fig. 12.10 - 1). Cases of large erratics being carried off glacier snouts in flowing muddy till have been recorded, for example by V. Okko in Iceland (1955). A not dissimilar case is recorded by Godwin (1956) where "large angular granite boulders" in a gravelly matrix were soliflucted down "the hillslope under [Zone III] periglacial conditions" (plate III, Hawks Tor Kaolin pit, Bodmin Moor, Cornwall). Another possible origin for the till is that the glacier could have extended on to its outwash terrace T, deposited till subglacially, receded and become stabilised, leaving ablation till upon the terrace, and could then have formed the moraine Z. The absence of meltwater channels from the moraine's distal side does not contradict this suggestion.

The bulk of the outwash deposition appears to have been along the axis of the valley, where the large terrace I is partnered on the eastern side of the Keltie by a series of terraces (Q), whose highest member is at about the same altitude as terrace I. (The profile fig. 12.8 shows this

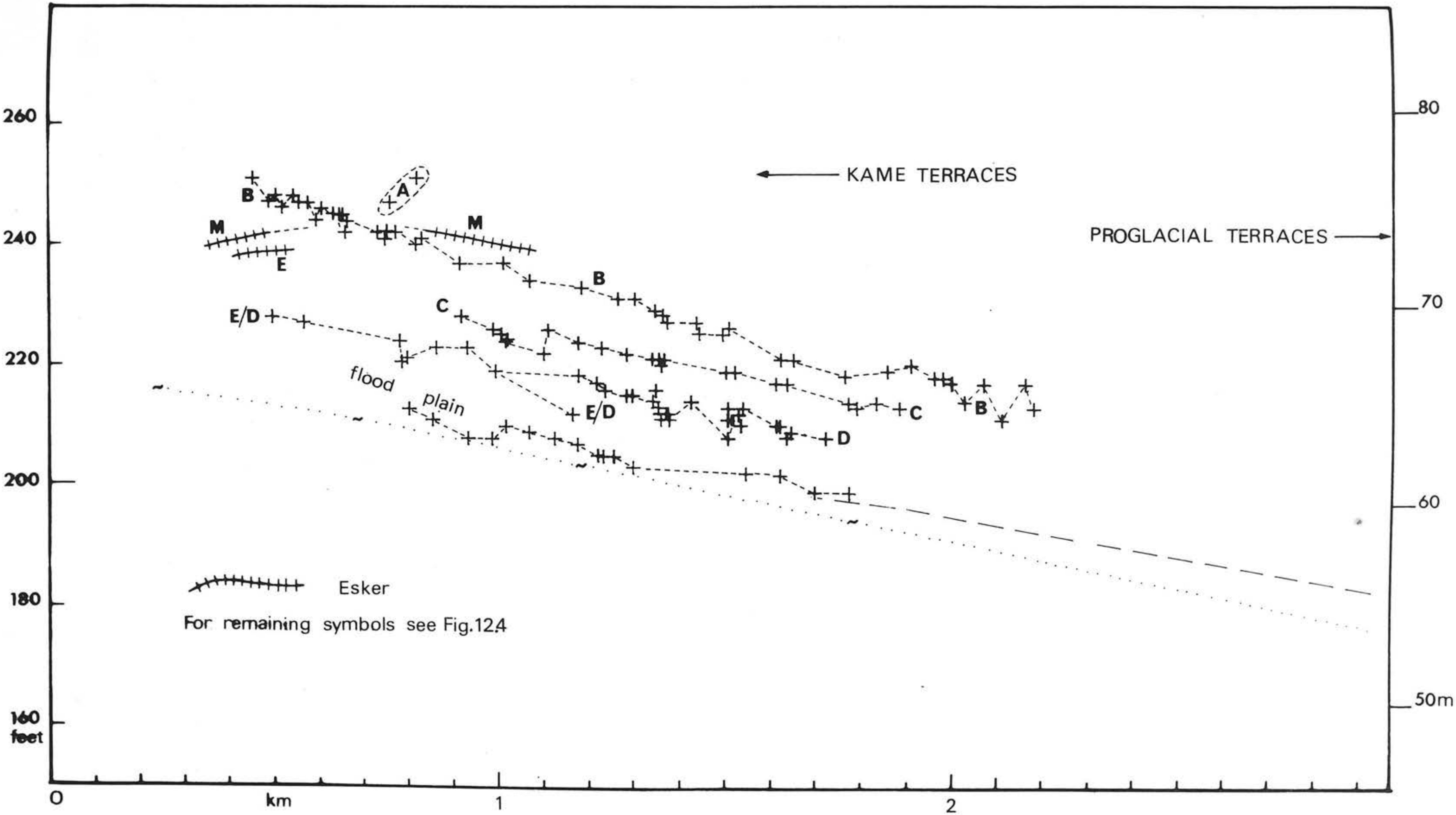
Fig.12.8 TERRACE AND ESKER PROFILES ON THE LEFT BANK OF THE RIVER TEITH.



most clearly). There is no evidence to suppose other than that the Keltie Water lay beyond the glacier, and so should have been free to operate independently. Therefore as the Keltie flowed through the rock barrier R it appears to have met and reworked the outwash being carried across its path south-eastwards (fig. 12.10 - 1). Most probably the deposition of the outwash at I and Q beyond the maximum known ice limit began as the glacier was advancing, continued as it erected the terminal moraine (X - Y - Z) and only ceased at Q and this part of I as the glacier thinned and began to recede inwards and headwards from its moraine. (These stages are shown on fig. 12.10 - 2-3). (It is relevant to note that on fig. 12.10 the kettleholes are first represented when they are thought to have started to appear, that is when deposition at the locality had ceased. Since they take an unknown time to form they are represented in each subsequent stage (cf. G.D. McKenzie, 1969). By contrast, meltwater channels are shown only at the stage during which they are thought to have carried meltwater. Thus no one stage shows all the features that now exist. Such features are shown on fig. 12.2.)

The next stage of deposition, of which there is record, was probably the formation of the highest terraces (A and H). Both are small and H is deeply kettled. It is possible that they were formerly more extensive and have been mostly destroyed by subsequent events. (Accordingly they are not portrayed as a distinct stage of development on fig. 12.10. They presumably were formed between stages 1 and 2). These events were the deposition of the kame terraces B and I, which are about 6 feet (1.8 m) and 8 feet (2.4 m) lower than A and H respectively. They run parallel to the likely

Fig.12.9 TERRACE AND ESKER PROFILES ON THE RIGHT BANK OF THE RIVER TEITH.



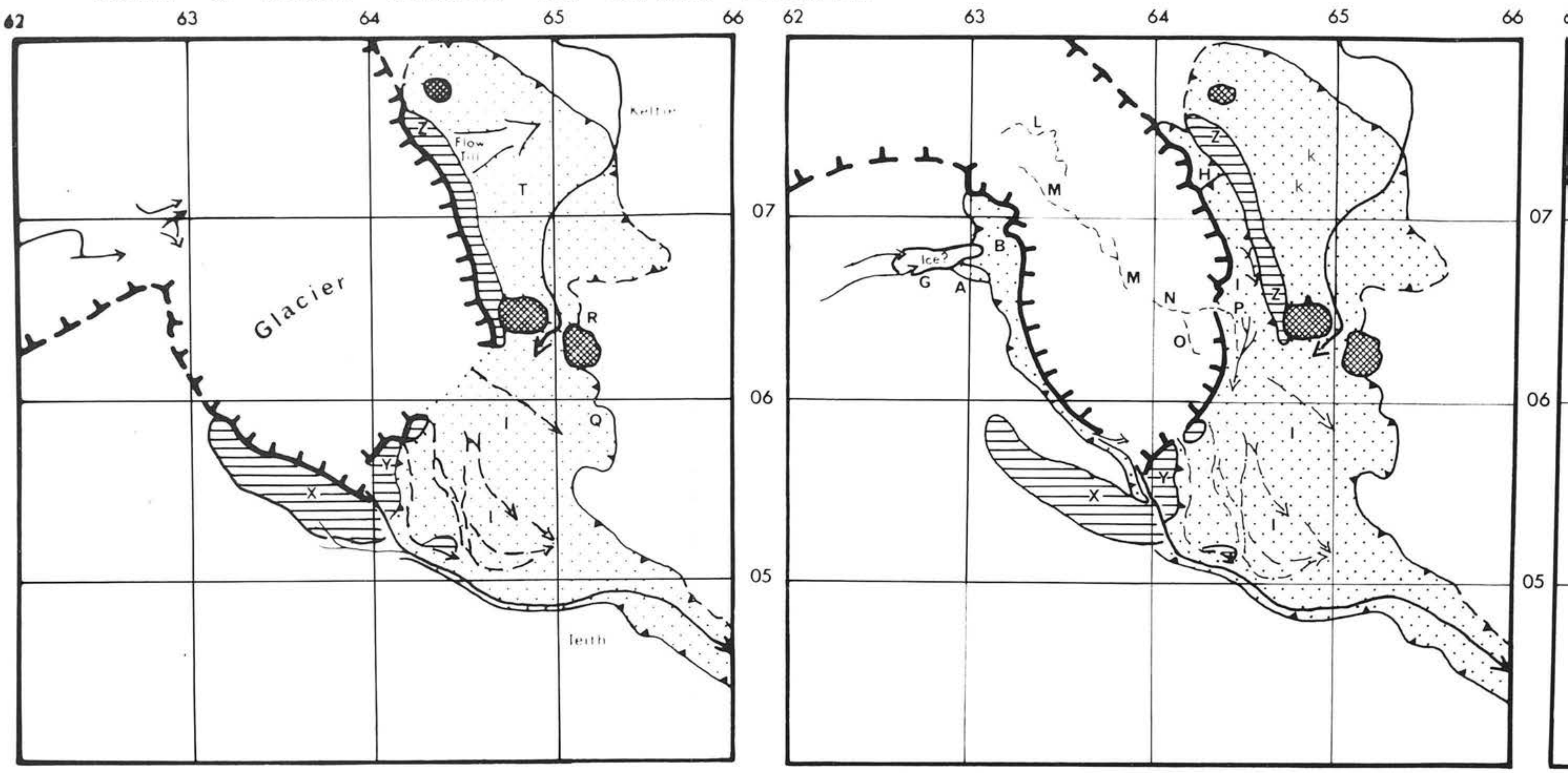
western and eastern margins of the glacier. Since these terraces are extensively kettled and lie within the glacier's maximum extent, they are most simply explained as kame terraces laid down beside and to some extent on the thinning edges of the ice (fig. 12.10 - 2). The ice margin must have been dead, at least towards the end of this phase of deposition, for terraces B and I were not greatly disturbed, even when the many shallow kettle holes appeared in I during final melting (represented on fig. 12.10 - 3 as occurring once material was no longer being deposited on terrace I). Part of the glacier, possibly a detached mass of dead ice, may still have been occupying the valley G, for the bottom of the middle of the valley lies at about 216 feet (65.8 m), some 26 feet below the surface of terrace B, and yet the valley was not infilled by the coarse gravels that constitute terrace B.

At about the same time drainage on, in or more probably under the ice was from the north-west (L - M) towards the south-east, reaching the high terrace I near the southern end of moraine Z, where terrace I was probably forming on top of the ice whilst esker P was building up in a subglacial tunnel beside it (fig. 12.10 - 2). (on fig. 12.8 it can be seen that esker P is now higher than terrace I. Presumably terrace I was lowered below the level of P by melting out of buried ice during stage 3). The esker system is so well preserved that the whole ice tongue in squares 6306 - 6406 must have been immobile and stagnant.

The middle terraces (C and J) have a shape and position similar to those of the high terraces (B and I), and were probably formed in the same way as the ice became thinner and narrower by ablation. Because of disturbance and obscuring

Fig. 12.10

STAGES OF GLACIER RECESSION AND OUTWASH FORMATION.



1. **Terminal** moraine and proglacial outwash.

2. High kame terraces.

3

Glacier margin

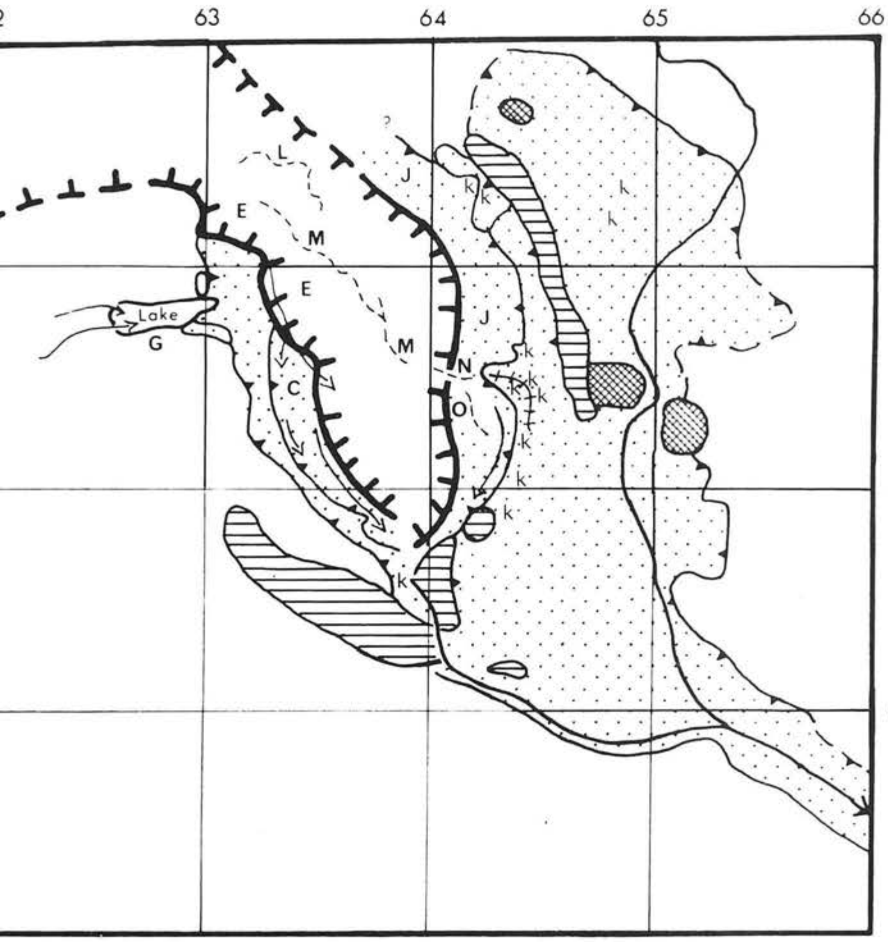
Moraine

Outwash

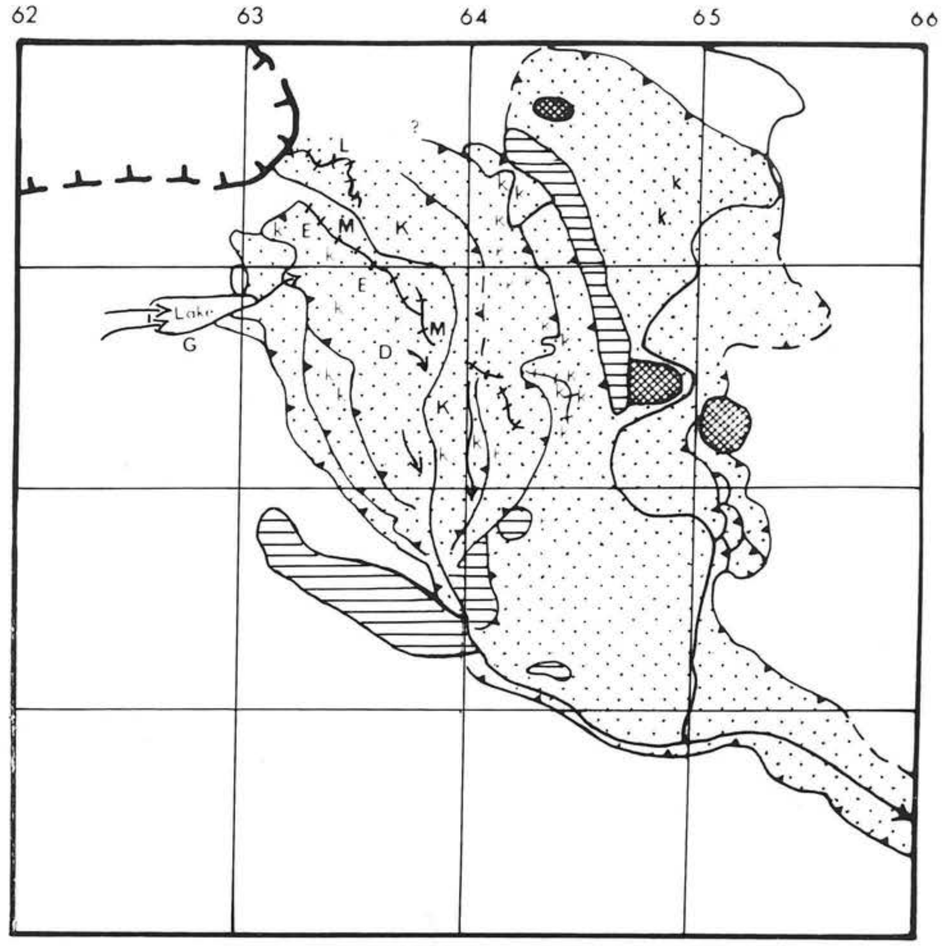
Rock

K Kettle

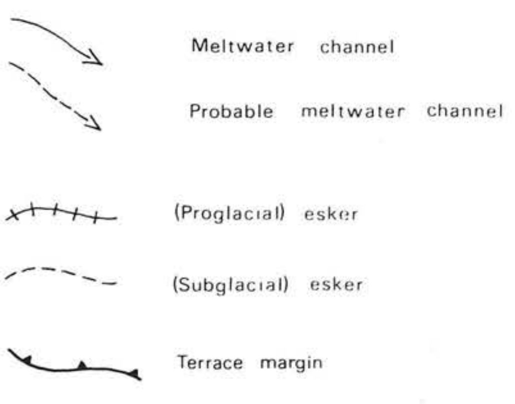
River

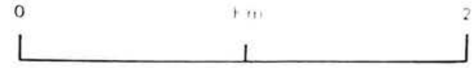


. Middle kame terraces.



4. Low kame terraces.





of the ground in Callander (6307, fig. 12.2), the proximal portion of terrace J cannot be certainly identified. However, west of the Teith the depth of kettling in area E suggests that thicker ice lay around E, contributing the meltwater that was forming C. The meltwater eroded channels along both terraces and must have escaped through the gap in the moraine now used by the present river Teith. The possible ice mass in valley G may have melted away at this time; it must have been quite thin because its meltwaters scarcely affected terrace B. Esker N - O presumably continued to form under the ice, on top of which terrace J was being deposited (fig. 12.10 - 3).

After this stage the glacier seems to have shrunk inwards and northwards, with meltwaters depositing the low terrace (E - D, K) on top of the ice and esker L - M still forming underneath. The kettled proximal end (E) of the low terrace (E - D) continues without a break into the less kettled distal portion D. Presumably this is a reflection of the decreasing thickness of the ice southwards. As the esker L - M shows no constant height relationship to the gradient of the kame terraces (K, E - D), it must be supposed that it was deposited in different hydrostatic conditions, that is subglacially. Melting out of the buried glacier tongue would have lowered the kame terraces down on to and around the eskers, thus achieving the intimate merging of these features which is now seen, and producing the kettling of area E (fig. 12.10 - 4). The bottom of the middle of valley G lies 10 - 12 feet (3.0 - 3.7 m) lower than all but the bottom of the kettles in E. Therefore valley G presumably remained as a lake until deposition and peat growth allowed it to drain.

There is no evidence anywhere farther up the Teith valley to suggest that the receding glacier terminus was stable for long enough to produce comparable deposits. Small terraces have been noted at Kilmahog (6108, sheet 60) and near Loch Venachar (6006), but these are poorly developed outwash features whose detailed origin is not clear. Thereafter the valleys headwards are occupied by Loch Venachar and Loch Lubnaig, with a narrow rock barrier south of the latter.

3.D. Terraces and fluvioglacial forms from the Teith-Keltie confluence south-eastwards (fig. 12.1).

Outside the terminal moraine several flights of river terraces occur that do not exhibit the kettle holes or meltwater channels which characterise the outwash terraces formed beside the Teith glacier (fig. 12.2). Before and during its stillstand at the moraine, and during its recession towards Callander, the Teith glacier probably supplied a great deal of outwash that appears to have filled up the lower course of the Keltie and the Teith below their confluence. The bulk of this was probably deposited within a short distance, as the largest area of river terraces is found immediately outside the moraine beside the Keltie Water at I and Q and just downstream from the Teith - Keltie confluence (at Torrie). Beside the Keltie above the rock barrier (R) there is only a single terrace level above the flood plain; this terrace occurs at 648067 and at 653077. The terrace and the flood plain attain only 200 m width at the most, and yet the total width of the four terraces (Q plus the proglacial section of I) below the rock barrier reaches 1.5 km. Clearly the most likely reason for the

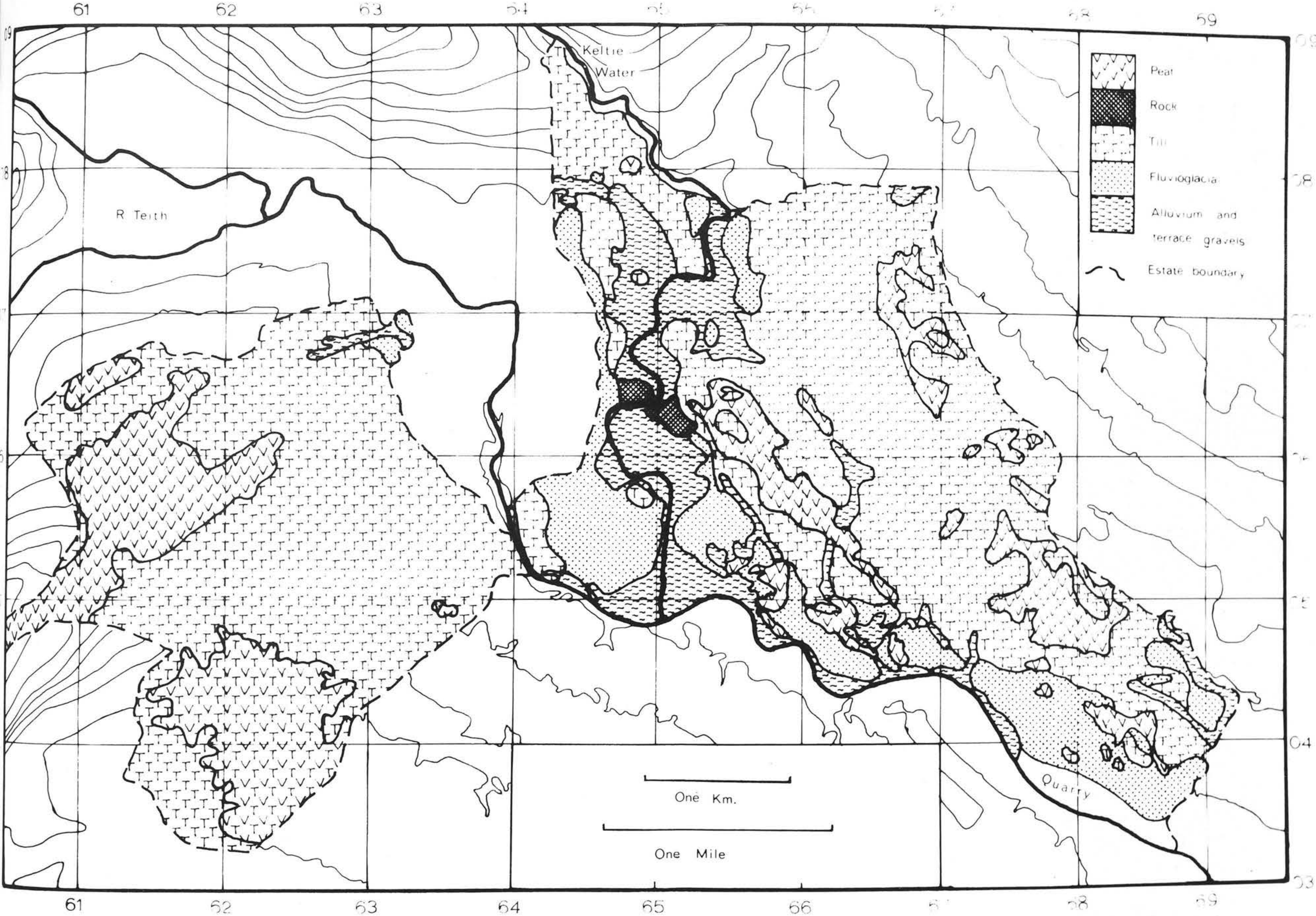


Fig. 12.11

SOIL PARENT MATERIALS OF CAMBUSMORE ESTATE, CALLANDER.

After B.M. Shipley, Macaulay Institute for Soil Research, 1965.

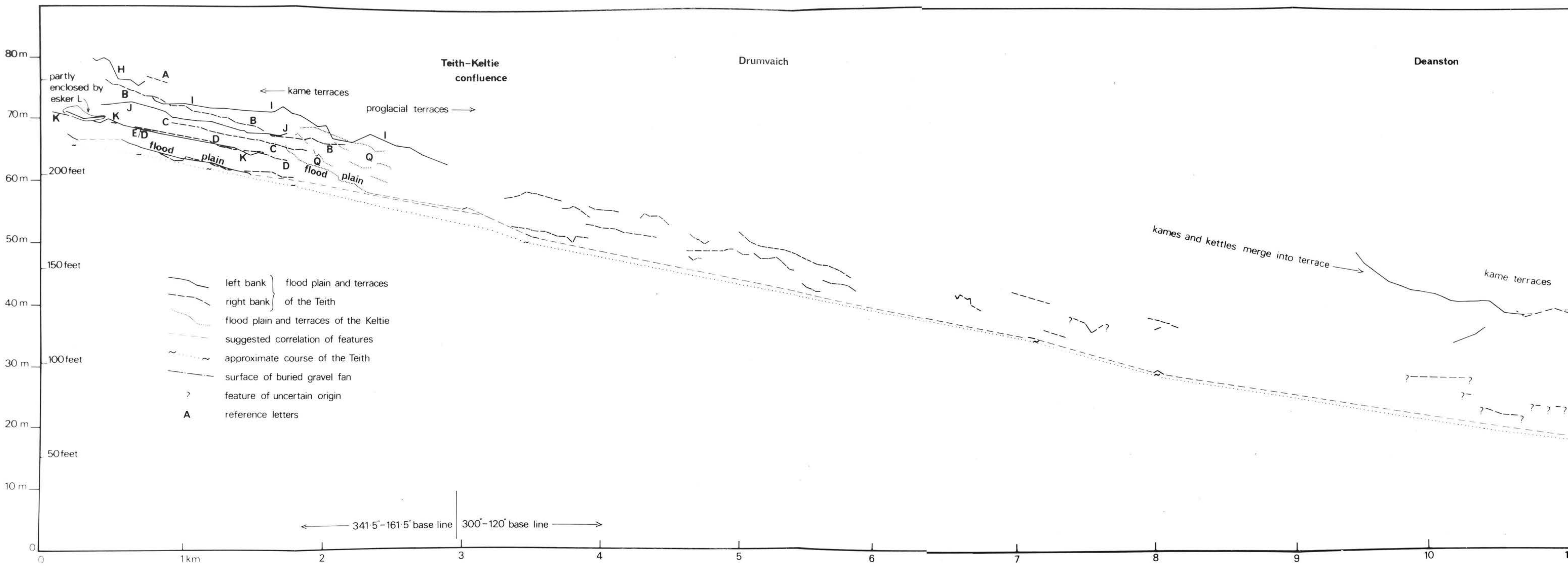
marked change in the behaviour of the Keltie is that, whereas below the rock barrier the Keltie met the full flood of outwash, above the barrier the Keltie was protected.

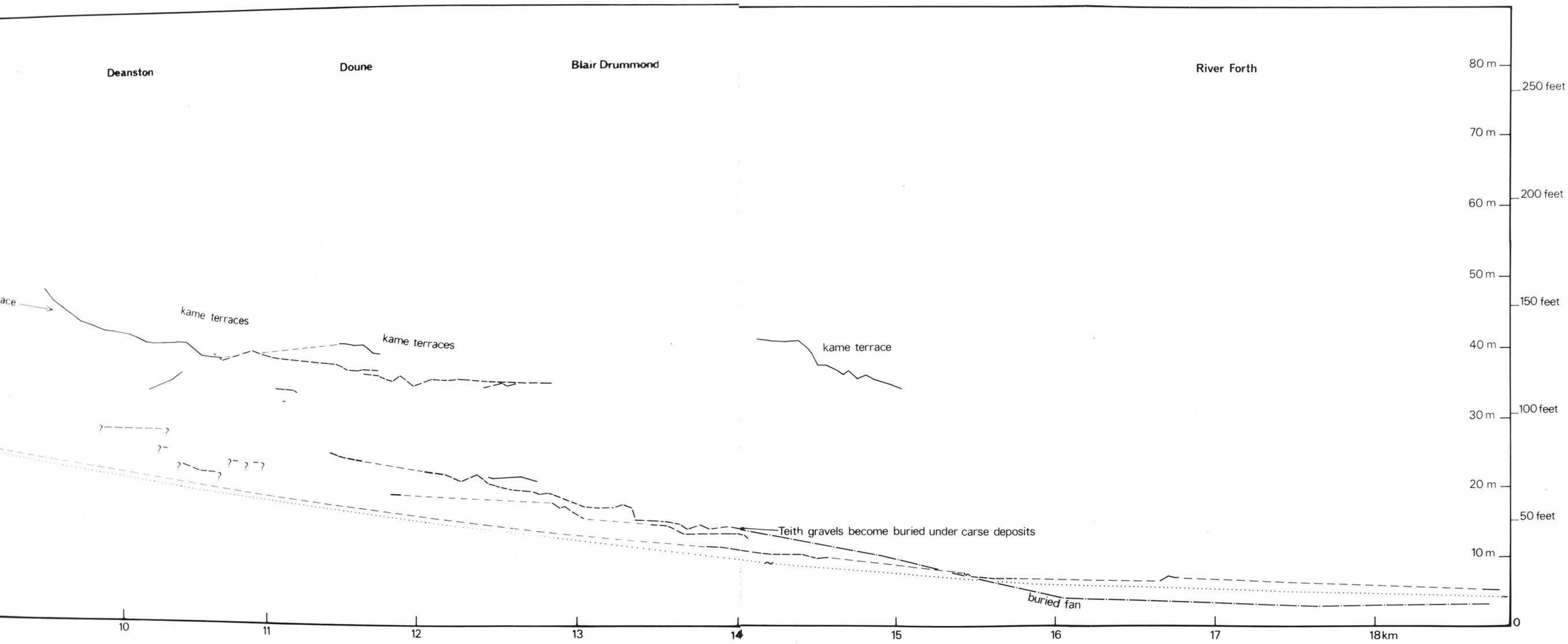
At the confluence, in the south-west corner of square 6505, the outwash that accumulated has since been quarried for gravel and consequently the exact height relationship with the adjacent outwash cannot now be certainly found. However immediately downstream (Torrie) the outwash deposit is 1.2 km long and 300 m wide, if both banks are taken into account (squares 6504 and 6604). South-eastwards the next set of four terraces, on the south bank near Drumvaich (6604 - 6704), is 1.5 km long and 250 m wide (fig. 12.16, t). Thereafter south-east of Drumvaich (fig. 12.3) there are only small terraces, 300 m or less in length and 150 m or less in width, with only one or two terraces occurring at each locality.

Taken as a whole the river terrace remnants beyond the terminal moraine decrease downstream in length, width and thickness, while the number of terraces also decreases. These characteristics suggest that a simple pattern of downcutting along the length of the river was initiated when the source of abundant outwash was withdrawn. This downcutting need not have been caused by any changes of the actual base level which are more likely to have influenced the lower part of the valley near Blairdrummond (c.7399, sheet 54). "The terraces [in valley trains] formed by changes in discharge and load are mainly found in the upper reaches of rivers" (C. Embleton and C.A.M. King, 1968, p.412).

From the eastern edge of this map area (sheet 60) D.E. Smith (1965) mapped and levelled all terraces along the Teith as far as Blairdrummond (7597 on sheet 54). He

Fig. 12.12 Terraced outwash of the Teith valley (after D.E.Smith, 1965, and D.D.Kemp, 1971).





Deanston
Doune
Blair Drummond
River Forth
80 m
70 m
60 m
50 m
40 m
30 m
20 m
10 m
0
250 feet
200 feet
150 feet
100 feet
50 feet
ace
kame terraces
kame terraces
kame terrace
Teith gravels become buried under carse deposits
buried fan
10
11
12
13
14
15
16
17
18km

described two sets of terraces. The higher set lies on gently undulating land above the deep incised river valley. The lower set lies within the incision but above the narrow strips of flood plain. This lower set consists of a single extensive terrace with three small fragments etched into it, the whole being graded from 81 feet (24.7 m) south-east of Deanston (7200) to approximately 42 - 46 feet (12.8 - 14.0 m) at the edge of the carse (7398). The upper altitude is the surface level of the apex of a large gravel fan at the terminus of this terrace. This fan passes beneath the carse estuarine muds. Up-valley the terrace is composed of coarse gravels.

Above the incised valley there is a "multitude" of large outwash terraces intimately associated with a belt of kames and eskers. The majority of the kames and eskers lie north-west of Doune Lodge (7103) in the area mapped by the present writer (fig. 12.15). These pass without a break south-eastwards into terraces, the highest of which commences at 158 feet O.D. (48.2 m) at Doune Lodge and descends south-eastwards (fig. 12.4). Smith found a suite of these terraces extending as far as the carse, where they stop at 110 feet O.D. (33.5 m), and also found that all of the kames, eskers and terraces had been deposited in intimate contact with inert glacier ice lying along the axis of the Teith valley between Doune Lodge and Blairdrummond and in the Forth valley below Blairdrummond.

The belt of kames and eskers continues north-westwards up the northern side of the Teith valley as far as the Teith - Keltie confluence (cf. fig. 12.11). At many localities, notably at the confluence (6505), near Tynaspirit (c.665046; fig. 12.15), at Drumvaich (675043; fig. 12.16 'k'),

Fig. 12.13

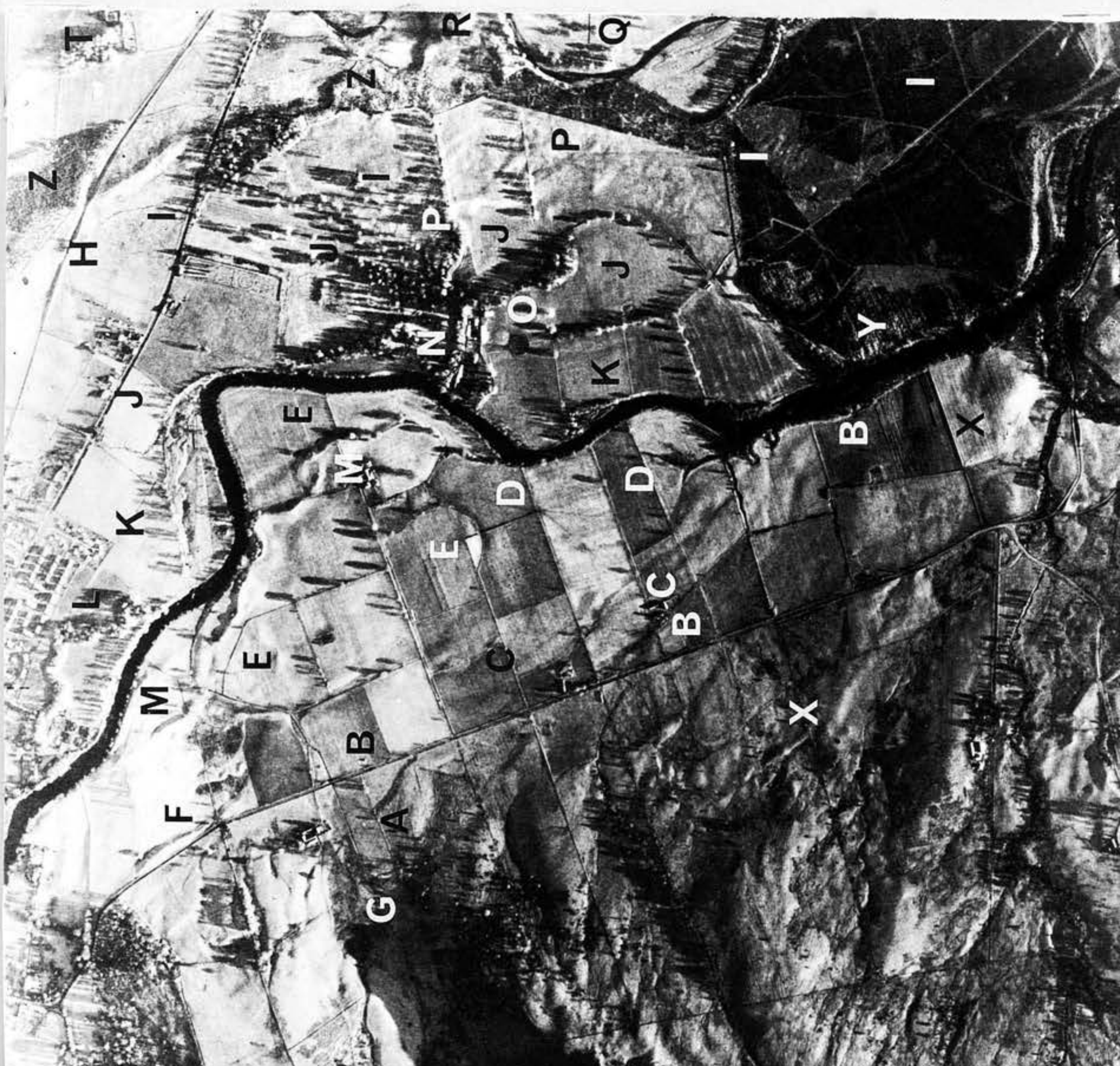
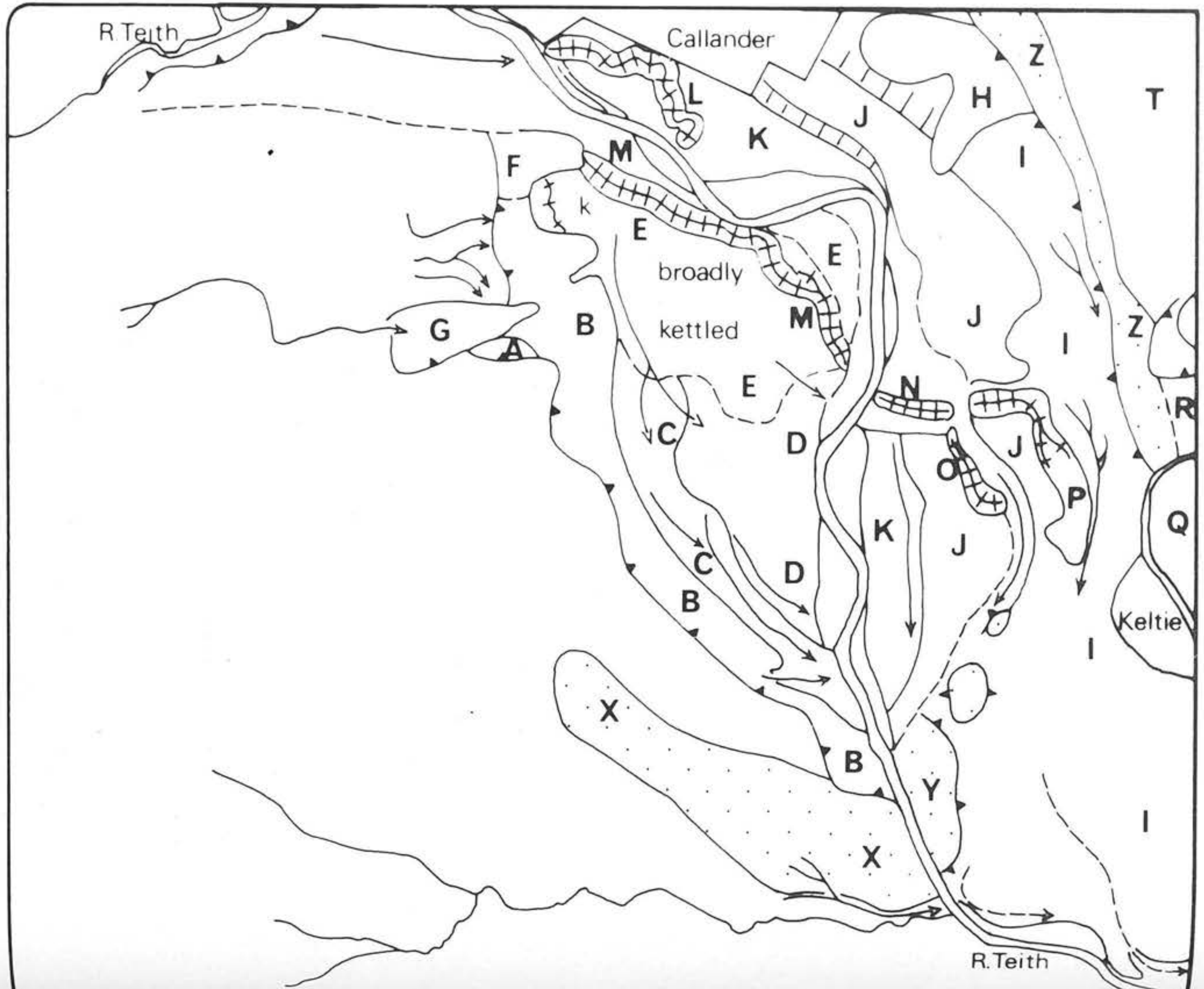


Fig. 12.13 Landforms associated with the Callander glacier limit.



Only features identifiable on the photograph are shown.

Nominal scale c 1:15,000

Symbols as on fig. 12.2

GRID NORTH

Fig. 12.14

Fig. 12.15

Fig. 12.14. Esker M and terrace E at Callander.

Esker M is the inner margin of kame terrace E, which contains broad shallow kettleholes. The view is southwards past Clash farm (square 6306, sheet 60).

Fig. 12.15. Kames and kettles at Tynaspirit.

Kames and kettles, formed during stagnation of the last ice sheet, lie on the left bank of the river Teith outside the Callander terminal moraine. A continuous sequence of deposits dating back to pollen Zone I is present in the kettlehole (k) to the left (square 6604, sheet 60).

Geological Survey photographs.

and at Coilentowie (c.695038), gravel pits show numerous ice-contact structures, frequent changes in dominant particle size, steep current - bedding and considerable total thicknesses of deposits, which are everywhere well-rounded. At Drumvaich and Tynaspirit these deposits exceed 30 m in depth. It is noticeable that, in every case where the terraces of the Teith and Keltie skirt the base of these kames and eskers (within the area of sheet 60), no meltwater channels descend from the kame belt to cross the terraces and no kames or eskers are part of even the highest of the terraces. The terraces always cut off the kames and eskers cleanly at the base. Therefore there is no evidence to suggest other than that the terraces down in the valley proper are later features than the dead-ice forms up above them on the edge of the valley. This relationship is the same as the one deduced by Smith for the downstream portion of the Teith valley.

Smith concluded, from a study of the Forth valley south and south-east of the Teith, that the fluvioglacial forms (kames, eskers and terraces) up on the edge of the Teith valley were formed during the stagnation of the ice sheet that had spread as far as Falkirk. These forms are quite separate from the group of low river terraces within the valley proper (fig. 12.12). Smith suggested that the low terrace, between Doune (7200) and Blairdrummond (7398), was formed later when glacier ice, if any, lay much farther up-valley outside the area he investigated. The present writer has found that the low terrace is continued up-valley by a series of low terraces that lie 12 - 15 m below the ice-contact kames and terraces up on the edge of the valley (fig. 12.12). The low terraces are continued proximally by the outwash and kame terraces near Callander, clearly demonstrating that the group of low terraces down within the valley of the Teith was created from the outwash of the Teith glacier during its stillstand near Callander.

3.E. <u>Ice-moulded interfluves of the Teith valley.</u>

The interfluves that separate the Teith valley from the Forth to the south and from Strath Allan to the east present a totally different configuration to the parts of the Teith valley so far described. The lower slopes are almost entirely covered with till, whilst on the upper the bedrock lies at or near the surface, yet the landforms appear very similar on both types of surface (sheet 60). To the north-east of the Teith the contours on the map and the alignment of the Coillechat and Annet Burns illustrate the grain of the country. Smooth, broad, long mounds and hollows alternate with each other side by side and end to end, in a north-west to south-east alignment from 6506 - 6607 to 6906 - 6905 and beyond (cf. till-based soils, fig. 12.11).

The south-western side of the Teith valley and the northern side of the Forth valley are very similar. Here the broad grooves and ridges begin at the Braes of Greenock (630053), immediately outside the terminal moraine (X), pass through the forested area (6304 - 6404) south-eastwards (fig. 12.16, m) and, at the south-eastern end of the interfluve (c.6901), meet the east-south-eastward alignment of the Forth valley grooves and ridges which begin about squares 6202 - 6101. Going towards the south-eastern end of the interfluve the apparent thickness of the drift increases. The crest of the interfluve, from 6402 to 6801, has a very similar

Fig. 12.1 shows the areas concerned.

Fig.12.16

Fig. 12.16. <u>Terraces, kames and ice-moulded features at Daldorn.</u>

Above the terraced outwash deposits (t) initially supplied by the last Teith glacier, smooth, broad, ice-moulded ridges and grooves (m) record the earlier south-eastward movement of the last ice sheet (from right to left in this photograph, square 6603). A belt of kames and kettles, some of which are seen in the foreground (k), record the decay of the ice sheet (square 6704).

Geological Survey photograph.

appearance although bedrock is at or near the surface, as can be seen in quarries at 650023 and 668026. The undulations along the crest are broader and shallower but the alignment lies between south-east and east-south-east. The ORS bedrock throughout the Lowland part of the Teith valley is folded into a broad syncline which strikes south-west to north-east. Therefore the attitudes of the rock cannot have determined the ice-moulded landforms of the Teith valley.

The consistent alignment and parallelism of these features, whether in rock or drift, suggests that only moulding of the whole area by an ice sheet could have been the cause. The moulding commences so close to the edge of the Highlands and so extensively there that valley glaciers within the Teith and Forth valleys could not have extended so far up the interfluves and still move south-eastwards. Linton (1962) quotes both sides of the Teith valley and the southern side of the Teith - Forth interfluve as ice-scoured slopes, adding that the latter interfluve "becomes increasingly covered by drumlins or drumlin-like forms directed towards its apex." These "distal portions may in part have been ice-moulded from solid rock but appear chiefly to have been shaped by the ice from its own ground moraine. The impression is strongly conveyed that we see here only a remnant of the original Forth - Teith interfluve: formerly it was longer but the distal portions have been wholly destroyed, and only towards the base ..... does a sizeable and recognisable fragment of the pre-glacial divide remain" (Linton, 1962, 251).

This latter area is Lennieston Muir (6103 - 6204 - 6203 - 6303). Here mounds of various irregular shapes occur spasmodically, apparently in no ordered pattern; peat covers the almost flat crest for 3 sq. km. Although till covers much of the area not submerged by peat, bedrock is often at or near the surface as to the west of Loch Rusky, between Lochs Rusky and Dhu, and in the north-east quarter of square 6204. It may be that eroded conglomerate bedrock knobs underly the till. There is certainly no evidence of ice-moulding here. Lennieston Muir's position on the crest of the interfluve in the lee of the Highland edge may account for this absence.

4. The Geological Survey memoir.

At the time of writing, the most recent and authoritative account of the Teith valley was the Geological Survey memoir with its accompanying map. In these documents the authors (E.H. Francis et al.) sought to describe some of the landforms and explain the glacial sequence in the Teith valley. Following upon Simpson's interpretation of a possible lateglacial readvance limit in the Teith valley, it is suggested on p.260 of the memoir that the readvance "might have extended to the vicinity of Drumvaich midway between Callander and Doune. No terminal moraine exists in the area, but there is a noticeable change in the form of the gravel mounds, which have a fresher appearance towards the west" (sheet 60).

For a number of reasons the present writer considers it unlikely that the glacier in question could have advanced quite so far. Firstly while the forms on the lowest slopes east of Drumvaich are subdued those upslope within the same group of forms are sharply defined (6904, sheet 60). No features were found near or at Drumvaich that might suggest a distinct stillstand. Secondly it has already been stated that the belt of fluvioglacial dead-ice deposits, which runs south-eastwards via Drumvaich, is part of an extensive set of features laid down during the melting of an ice sheet that had extended far beyond the Teith valley (Smith, 1965).

Thirdly the authors of the memoir admit that to them the relationship between the eskers and contiguous gravel terraces between Callander and the Teith - Keltie confluence is "not clear", allowing that "it seems unlikely that the ridges (eskers) could have survived if the surrounding terrace gravels had been deposited later". The Survey map portrays some of these terraces as alluvial, whereas in fact ice-contact features abound on them (terraces C, D, K and J in squares 6306 - 6406). Therefore it becomes unnecessary to postulate that a glacier readvanced to Drumvaich over these terraces without disturbing them, the "gravels being deeply frozen and therefore resistant to erosion" (p.260). It is simpler to suppose that the eskers and terraces were formed at the same time. Fourthly it has already been shown that the Teith terraces, which extend from Callander downstream, are directly related to the presence in the Teith valley of a glacier which terminated 4 km north-west of Drumvaich.

The Teith terraces are grouped by Francis _et al._ as one fluvioglacial terrace near Doune and a varied number of alluvial terraces, some of which may "be related to the readvance" (p.260). However reference to Smith's unpublished Ph.D. thesis would have avoided slight but significant inaccuracies, viz:-

(1) the main outwash terrace at Doune is part of a series of high terraces descending from 158 feet O.D. (48.2 m) to 110 feet O.D. (33.5 m) at Blairdrummond, the terrace margins including ice-contact slopes at both localities. They are not river terraces and do not grade to 100 feet

O.D. (30.5 m) at Blairdrummond.

(2) Below Doune Francis _et al._ mention three terraces, the lower two "graded to the level of the carse", passing "into the post-glacial marine deposits near Blairdrummond". (p.288). Smith's levelling and Kemp's borehole stratigraphy clearly demonstrate that these two river terraces pass underneath the carse estuarine muds as a large gravel fan (fig. 12.12). This is particularly significant because the present writer has shown that the Callander terraces grade into these two river terraces.

Between Callander and Drumvaich Francis _et al._ define "two prominent gravel terraces and a more restricted flood plain". In this area the present writer found a maximum of four terraces above the flood plain (fig. 12.4).

In view of these discrepancies the account given by the Geological Survey must be regarded with serious reservations.

5. A lateglacial readvance.

The evidence presented in the third section of this chapter clearly shows that a valley glacier advanced from the Lubnaig and Trossachs valleys to a stillstand position 2.5 km south-east of Callander. In order to create the terminal moraine belt at its limit the glacier must have been active. In view of the known and inferred lateglacial chronology of the surrounding region (Simpson, 1933; Sissons, 1963, 1964, 1967a, 1967b; Smith, 1965), it is essential to discover to which lateglacial stage the Callander terminal moraine belongs. In this matter there are several lines of relevant argument, involving the morphological evidence so far presented, the relationship between the Teith terraces and lateglacial sea-levels, and possible correlations with other lateglacial ice limits.

It was shown by Simpson (1933) that the Teith valley, the Forth valley, and the Strathallan - Strathearn valley were overwhelmed by a Highland ice sheet. The ice-moulded rock and drumlinised drift of the Teith valley and its bounding interfluves (Linton, 1962) demonstrate that the ice sheet must have virtually submerged the hills along the Highland edge above the Teith valley as well as the crests of the interfluves. Subsequently, as the ice sheet thinned, it became confined to the axis of the Teith valley as a stagnant immobile mass and its meltwaters deposited a belt of kames and kame terraces. The kame terraces descend to 110 feet (33.5 m) at Blairdrummond where they appear to have been laid against the margin of ice occupying the Forth valley, for the valley is a rock basin only infilled in postglacial time by estuarine carse deposits. Sea-level had fallen from about 125 feet (38.1 m) to 65 - 70 feet (19.8 - 21.3 m) whilst the Forth valley ice occupied the Stirling area (Sissons, Smith and Cullingford, 1966, p.14). Subsequently, as deglaciation and isostatic uplift proceeded, the Forth valley was vacated by ice and relative sea-level fell to below Ordnance Datum by 11,800 B.P. (Kemp, 1971). Any portion of the Teith terraces laid on the Forth glacier would thus have been redistributed. The Teith was presumably able to flow unimpeded into the Forth valley, there beginning to deposit its large gravel fan (Kemp).

Deposition of pollen in two kettleholes in the Teith valley kame and kettle belt began during Zone I (J. J. Lowe, personal communication). During the milder Zone II period the tundra landscape was invaded by birch trees which also grew in the vicinity of Loch Mahaick on the upland east of the Teith valley (Donner, 1958). By this time local solifluction must have ceased for the Zone II deposits in these sites are of organic mud (gyttja). The decline of birch tree population, the increase of plants tolerant to cold and the reversion to the deposition of mineral matter in these sites, as in Zone I, indicate that Zone III was a cold period.

Glaciers again advanced into the Forth drainage basin and the relative sea-level rose (Sissons, 1967a, chapter 10). A glacier advanced into the upper Forth valley, deposited a terminal moraine at Lake of Menteith, and then poured out meltwater through the moraine to deposit outwash when the sea-level did not exceed 33 - 38 feet O.D. (10.1 - 11.6 m). While ice still occupied the moraine the sea-level rose to 39 - 40 feet O.D. (11.9 - 12.2 m), and a beach was deposited on top of the outwash. This was called the High Buried Beach by Sissons. It extends eastwards along both sides of the Forth valley. "At Blairdrummond it could be expected to stand between 10 and 11 m O.D." (32.8 - 36.1 feet) (Kemp, 1971, p.176). However it is absent from the area of the Teith gravel fan at Blairdrummond, even though much of the fan lies at lower altitudes. Kemp pointed out that, in comparison with the restricted meltwater outlet at Lake of Menteith, the Teith meltwater encountered no barriers in its passage to Blairdrummond. Consequently "any beach form that did develop could have been destroyed or rendered unrecognisable by the changing positionsof distributary streams on the fan" (Kemp, p.177). He admitted that "it has not so far proved possible to obtain an independent date for the final formation of the High Buried Beach, but stratigraphical considerations support the date of 10,300 B.P. postulated by Sissons (1966) for the corresponding beach on the southern side of the Forth" (Kemp, p.177).

At Blairdrummond a slightly younger lower feature, the Main Buried Beach, overlaps part of the western margin of the fan at 29.5 - 32.8 feet O.D. (9 - 10 m). A Low Buried Beach similarly lies on the western margin of the fan at about 28 feet (8.6 m). The Main Buried Beach was completely formed by 9,500 B.P., the Low by 8,800 B.P. (Sissons, 1966), suggesting that deposition on the fan continued well into the postglacial period.

Boring has shown that the fan is 7 - 8 km wide, 25 sq. km in area and usually has about a 40 feet (12 m) thickness of gravels and finer strata. The highest existing altitude on the fan (38 feet, 11.6 m) is a few hundred m west of the apex, because the Teith eroded the apex as it stabilised its course after the main period of fan formation. This altitude is lower than the 47 feet (14.3 m) given by Smith (1965) for the distal end of the Teith's main lower terrace at the point where it dips beneath the carse deposits (fig. 12.12). However Smith points out that downcutting caused a lower terrace to be formed at 43 - 44 feet (13.1 - 13.4 m). Furthermore, Kemp found by boring that these lower terraces "form a continuous unit with the buried fan. The close link between fan and terraces suggests a common origin and it is considered that both were formed initially from fluvioglacial material carried down the Teith. Subsequently the erosion that caused the formation of the terraces probably brought about an extension of the fan ..... while the changing course of the river undoubtedly altered its morphology" (Kemp, p.165 - 7). Consequently it may well be that the outwash, now forming the low set of terraces along the Teith, was laid down beyond the Callander glacier at about the same time as the High Buried Beach was being formed at Blairdrummond and towards Menteith. These relationships suggest that the last glaciers at Lake of Menteith and near Callander may both have belonged to the last glacial period in Scotland, namely Zone III.

Independent confirmation is contained in the stratigraphy of the former lake at Mollands, just within the Callander glacier terminus. Here the lowermost 1.3 m of lake clays rest on glacial gravel and have been dated to a transition period between glacial Zone III and postglacial Zone IV (Lowe). The paucity of tree pollen suggests an early stage of plant immigration but indicators of warmth suggest that climatic amelioration had set in so that climate and glacier were out of phase. A later stage of vegetation development had been reached in the deepest organic samples from Gartmore analysed by Donner (1957), for the earliest recorded period of vegetation development within the Menteith moraine is well into Zone IV when birch trees were widespread. Unlike Lowe, Donner did not analyse the lowermost clays.

After the glacial Zone III period sea-level fell gradually until, in the postglacial marine transgression, the Teith fan and Buried Beaches were covered by the carse estuarine muds. Isostatic readjustment also occurred during and after deglaciation, causing shoreline features in the upper Forth valley to be elevated more than those down-valley. This explains the tilting of the High Buried Beach (Sissons, 1967a).

6. Summary.

The last ice sheet spread south-eastwards from the Highlands, moulding the bedrock and drift of the Teith valley in a south-easterly direction. During deglaciation dead-ice

Fig. 12.17 Symbols on 1:25,000 sheet NN 60.

	Hummocky drift of the last glacial stage
	Margin of outwash or alluvium
	Outwash or alluvium
~	Flood plain
	Fluvioglacial deposits of the last ice sheet
k	Kettle or dead-ice hollows
	Esker
	Meltwater channel
	Probable course of meltwater channel
	Incised stream
	Former stream course
r	Rock
	Clear morphological boundaries
	Probable morphological boundaries
	Possible morphological boundaries
?	Feature of uncertain origin
	Direction of ice-moulding
★	Site of stratigraphic investigation
S	Reference letters

deposits were laid in the Teith valley and outwash was poured along the valley down to Blairdrummond, where thick ice still occupied the Forth valley. Eventually the ice melted and sea-level gradually fell to about Ordnance Datum. Plants migrated into the area and pollen was deposited in lakes as early as Zone I.

Subsequently, during Zone III, glaciers readvanced to the southern end of Loch Lomond, to Lake of Menteith and to Callander. At Callander the Teith glacier created a terminal moraine beyond which outwash accumulated in the Teith valley. The proglacial Teith entered the sea at Blairdrummond, where it continued to deposit gravel, there preventing the accumulation of the High Buried Beach. As the Callander glacier retreated, a series of kame terraces was formed within the moraine limit.

Wastage thereafter appears to have been rapid as no similar features occur within the Lubnaig and Trossachs valleys. Pollen began to be deposited in the lake at Mollands within the moraine limit sometime between glacial Zone III and postglacial Zone IV. Down-cutting by the Teith and Keltie produced a series of river terraces in the proglacial outwash down to Blairdrummond. The Teith gravel fan between Blairdrummond and Stirling was probably greatly augmented by outwash gravels from the Callander glacier. The main postglacial marine transgression covered over the fan and effectively stopped its development.

Chapter 13. Climate and glaciers.

This chapter includes discussion of a series of related topics. The first two parts involve a review and assessment of the literature on the changing climate of lateglacial and early postglacial times, particularly as this is revealed by pollen studies of vegetation. Thirdly the evidence relating to the possible re-establishment of glaciers since the Pleistocene is considered. In the fourth part some tentative calculations of snowlines in the thesis area during the last glacial stage are presented. Fifthly, the distribution of glaciers is related to climatic and topographic influences. This is followed by examination of some aspects of the form and activity of the glaciers. Lastly the possible manner of deglaciation is discussed.

A. Lateglacial climate.

The literature on lateglacial climate as such, rather than on lateglacial vegetation, consists of a series of papers by G. Manley (1951, 1959, 1964). These are based principally on evidence in England but do include some important estimates of conditions in the Ben Nevis area. Because the latter are not supported by any evidence from Ben Nevis and because Manley's estimates differ in two of the papers (1951, 1959), it is necessary to examine Manley's reasoning. In 1951 one of his purposes was to assess the range of climatic conditions in lateglacial Britain. A principal source of information quoted by Manley was W. Pennington's study of Windermere lake sediments (1947). These show that tree birches, requiring a minimum mean summer temperature of 10°C, grew around Lake Windermere during Zone II. Given that mean July temperature tends to be 1.1 - 1.2C°

higher than the mean summer temperature (June - September), the equivalent July mean would have been not less than 11 $^{\circ}$C. By extrapolation from other evidence in central and southern England (which need not be examined here) Manley suggested a January average of —8.3°C.

The Windermere sediment evidence shows that tree birches receded from the area during Zone III when glacier readvance occurred. The estimated summer temperature here is 7.1 $^{\circ}$C at sea-level (July 8.3°) and the January temperature —8.3°C. At this point Manley made use of Ahlmann's curve relating snow accumulation to summer temperature at the snowlines on certain Norwegian glaciers (H.W:son Ahlmann, 1948, p.48). Given that snow accumulation during the last readvance in the central Lake District was 80% of present precipitation (i.e. 70 inches, 1750 mm), a mean summer temperature of 2.5°C at the snowline is suggested. (This assumption is discussed later). Secondly, on the basis of a lapse-rate of 1 $^{\circ}$C per 500 feet (1°C / 150 m), such a temperature would be found about 2500 feet (760 m) above the sea-level temperature of 7.2°C. From parallel calculations he suggested that areas of heavier or lighter precipitation might have snowlines 500 feet (150 m) higher or lower than this 2500 feet (760 m) estimate.

By applying his standard lapse-rate (1 $^{\circ}$C / 500 feet) to the difference between Zone II and Zone III summer temperatures he derived estimates for the Lake District Zone II snowline. As the temperature difference is about 3C$^{\circ}$, the earlier snowline should work out some 1500 feet (455 m) higher than

x$^{\circ}$C refers to an absolute temperature, whereas
yC$^{\circ}$ refers to a temperature range or difference.

the Zone III one. However, for no stated reason, Manley quoted a figure of 1000 feet (p.55, 1951). Furthermore he gave two conflicting estimates of the absolute snowlines during Zones II and III. On p.55 these are 2000 feet (610 m) for Zone III and, by inference, 3000 feet (915 m) for Zone II. Yet on p.60 his figures are 2500 (760 m) and 3500 feet (1065 m) respectively.

In order to estimate contemporaneous Ben Nevis temperatures he assumed, for no apparent reason, that summer temperatures at Ben Nevis (sea-level) were 2.2C° lower than in the Lake District in Zone II, giving a summer mean of 7.8°C at Ben Nevis (p.60, 1951). Yet, in order to assess the Zone II snowline at Ben Nevis, he assumed that the present difference in summer temperature (1.1C° lower than at Windermere) also held during Zone II. This gives a snowline at 2900 feet (880 m) for Ben Nevis, some 600 feet (1.1C° at 1°C / 500 feet) lower than in the Lake District (using the 3500 feet, 1065 m, estimate). For Zone III, once again using the 1.1C° difference in temperature between the two areas, he derived a mean summer value of 6.1°C for Ben Nevis and a snowline at 1900 feet (580 m), some 600 feet (180 m) lower than the 2500 feet (760 m) Lake District snowline (p.60, 1951).

If these approximations are accepted, they have certain implications. The Lake District Zone II snowline at 3500 feet (1065 m) would have lain above the highest peaks, but permanent snowbeds could be expected theoretically as low as 2100 feet (640 m) (In 1949 Manley showed that snowbeds on Ben Nevis, 1884 - 1903, lay as much as c.1400 feet (420 - 450 m)

Figures given here are in Centigrade and normally they refer to sea-level. July temperature figures are reduced by 1.1 - 1.2°C (Manley, 1951, p.54) to obtain average summer temperatures. This facilitates comparison between Manley's various papers, which use a mixture of temperature scales.

below the theoretical snowline). A 2900 feet (885 m) Ben Nevis snowline would be sufficiently low to support numerous high corrie glaciers in at least the areas of heavy accumulation in the Highlands. A lowering in the Ben Nevis area to 1900 feet (580 m) in Zone III would bring widespread glacier advance, accompanied by the reforming of Lake District glaciers with a 2500 feet (760 m) snowline. Whilst this hypothesis conforms approximately to the evidence in the Lake District (Pennington, 1947) and does not differ in its essentials from Manley's later revision (1959), the account of events at Ben Nevis is purely conjectural. Because Manley employed similar reasoning in subsequent discussions of Ben Nevis in the Lateglacial (1959, 1964) and because the question of Zone II glaciers in Scotland is strongly debated. (D.E. Sugden, 1970; J.B.Sissons, 1967a), it is important that the strength or weakness of Manley's argument be appreciated.

The considerable range of organic evidence for a relatively mild Zone II period (for examples see below) in Britain succeeded by colder conditions accords with Manley's idea of a fall in snowline. However his actual figures for Ben Nevis are unsupported. It has been noted that his estimates vary, particularly for snowlines. A second problem, and for the Lateglacial a virtually insoluble one as yet, is the extrapolation of Lake District temperatures, themselves approximate, to the Ben Nevis area. Paterson's comments regarding contemporary glaciology are pertinent here (W.S.B. Paterson, 1969). "Data from distant weather stations are useless for studying local climates" (p.227). Manley assumed that the Ben Nevis area was cooler than the Lake District by the same amount in lateglacial times as it is now. Yet in his 1959 paper one of his principal statements is that " in the Lateglacial the rate of northward decline [of temperature] with latitude was not necessarily the same as we should expect today. Hence some earlier estimates ..... (Manley, 1951) require further revision" (1959, p.189).

Thirdly, his argument is circuitous and estimates tend to be based on approximations. His summer temperature figures are imprecise because they derive from the presence or absence of tree birches. Although unavoidable, the use of approximate snow accumulation figures in conjunction with Ahlmann's Norwegian results is another source of error. Equally unavoidable is the need to assume a standard lapse-rate for temperature (this is discussed below). Therefore Manley's 1951 calculations of temperatures and snowlines for the Lake District and especially for Ben Nevis are subject to several sources of error and should be viewed with reserve.

In 1959, on the basis of detailed snowline calculations using local glacier limit evidence in the Lake District, Manley revised his Zone III figures (but not those for Zone II). He found that the snowline rose from 1600 feet (485 m) in the wettest areas to 2400 feet (730 m) in the driest. A rise of 800 feet (245 m) would correspond to a drop of 1.6C^{o} at his standard lapse-rate. This rise of snowline occurred in localities where the present precipitation decreases from 3250 to 1870 mm (135 - 75 inches). On the assumption that Zone III accumulation was 80% of these totals, the figures would be 2600 and 1500 mm (100 and 60 inches) respectively. In order to test this assumption he used Ahlmann's curve relating accumulation at the snowline to the average summer temperature on present-day Norwegian glaciers (1948, p.48). There 2600 and 1500 mm of accumulation at the firnlines correspond to 3.7^{o} and 2.0^{o}C respectively, a range of 1.7C^{o}.

Since 2600 mm and 1500 mm assumed Zone III accumulation correspond to snowlines of 1600 and 2400 feet (485 - 730 m) respectively, with an assumed temperature difference of 1.6C°, the evidence from modern Norwegian glaciers supports Manley's assumptions. In other words it is reasonable to assume "that in a west coast maritime climate 80% of the annual precipitation at and above the snowline will fall as snow" (1959, p.205), and that Zone III precipitation was approximately the same as at present. The calculations also show that the lapse-rate implied by Ahlmann's Norwegian results equals Manley's assumed lapse-rate and justifies its use. (These three conclusions are relevant to the later discussion of snowlines in western Perthshire).

One further consequence of these snowline calculations is that Zone III summer temperatures in the Lake District are suggested, namely 2.0°C at 2400 feet (730 m), 3.7°C at 1600 feet (485 m), and therefore 6.9°C at sea-level. This summer average is 8C° lower than present. This may be checked by reference to the present theoretical snowline at 5900 feet (1800 m), which is extrapolated from the theoretical Ben Nevis snowline (1951, p.60: 1949). The Zone III average snowline is 3900 feet (1190 m) lower, implying a Zone III temperature 7.8°C lower than present. In comparison with his 1951 paper, the suggested average summer temperature is only 0.2C° lower at 6.9°C. It is thus about 8C° lower than the present summer average. Yet, for the build-up of glaciers to their maxima, Manley suggested an even lower temperature of 5 - 6°C in the summers, that is 9 - 10C° lower than present, with a corresponding lowering of the snowline. Though he did not extend his comments to the Ben Nevis area, use of his 1951 methods would tentatively suggest an average summer temperature of 4 - 5°C initially with the snowline between 300 and 800 feet (90 - 245 m), rising to about 1300 - 1400 feet (295 - 425 m) as the temperature attained 6°C. With a January average at sea-level of —8.3°C, the annual average would have been about —1.9°C. According to R.G. West such an annual average would be low enough for solifluction but not for ice wedges or permafrost (R.G. West, 1968, p.195-6).

By assuming a mean ice thickness of 250 feet (75 m) and an average accumulation of 1500 mm (60 inches) Manley considered that not less than 50 years were required to build up the Lake District glaciers. The Windermere lake sediments (Pennington, 1947) appear to suggest "minor climatic fluctuations of the order of two decades in length", so that the glaciers probably required much more than 50 years to reach their limits. Manley reckoned on 80 - 100 years. Further, if Zone III weather varied at least as much as at the present time, snowlines, temperatures and precipitation could be expected to have fluctuated considerably. Manley's picture of lateglacial weather is worth quoting. "The climate was more unsettled than today ..... precipitation fell more often. The air would be prevailingly damp, with much low cloud at all seasons. Skies from time to time would clear, most probably in winter, with extremely bitter wind" (1959, p.206). Such comments might equally well be applied to the wettest parts of western Perthshire, although the drier more easterly or lowland areas such as the Tay, Earn and Teith valleys would have been less severely affected. A more 'zonal' Atlantic atmospheric circulation (compared with the present tendency to a 'meridional' one) might be expected, with pack-ice "much more prominent ..... in the north-west Atlantic" than is the case today (1964, p.160).

Manley's estimates for Ben Nevis in the Lateglacial may be summarised as follows. In Zone II the average summer temperature may have been about 7.8°C at sea-level, with a 2900 feet (885 m) snowline and small high-level glaciers. January average would have been c.—8.3°, giving an annual average of c.—1.0°C. Initially in Zone III the summer average may have fallen to 4° - 5°C and the snowline to 300 - 800 feet (90 - 245 m) whilst glaciers built up and advanced to their limits. Subsequently the summer average may have risen to about 6°C and the snowline to 1300 - 1400 feet (395 - 425 m). The January average may have remained at about —8.3°C, with the initial annual average at c.—3.0° to c.—2.4°, rising later to c.—1.9°C. It must be emphasised that all of these figures are speculative and that none is based on evidence from the Ben Nevis area.

In J.K. Charlesworth's study of the lateglacial period in the Highlands (1955) the included map of snowlines during the Moraine Glaciation (equated with the Loch Lomond stage) was drawn by Manley from Charlesworth's data. However the basic data are unreliable. In chapter 2 it was shown that Charlesworth's interpretation of the lateglacial sequence is unacceptable. The four bases used for snowline calculations were "the upper limit of the lateral moraines, ... the highest limit of the marginal drainage, ... the cirque or small valley glaciers on the periphery of the ice, ... [and] the arithmetic mean between the glacier snout and the average height of the crest above the firn" (1955, p.897). It is by no means clear from the text that moraines are always lateral (in the accepted usage of the term) or that drainage channels are either marginal or related to the Moraine Glaciation. Further, the methods of estimation are not shown to be compatible. Therefore neither the basic data nor the methods of snowline calculation are acceptable. It may be significant that Manley did not refer to these snowline calculations in his two more recent papers on lateglacial climate (1959, 1964).

Since the publication of Manley's papers much more detailed accounts of Lake District vegetation history have been written (e.g. W. Pennington, 1970, W. Pennington and J.P. Lishman, 1971). These confirm that there was a well-marked Alleröd interstadial (approximately Zone II) during which solifluction virtually ceased. Tree birches were widespread here, though the Lake District lay near the northern and altitudinal limits of continuous birch woodland. Some higher sites seem to have been too cool for local birches. "The organic Alleröd muds of the Lakeland Haweswater show that even the great Mardale corries, where the post-Alleröd Zone III ice was slowest to melt, must have been free from ice during the mild Alleröd period" (Pennington, 1970, p.56). However, this evidence does not necessarily justify her statement that "all ice and permanent snow must have disappeared from the Lake District mountains" in the Alleröd. The great Mardale corries (c. square 4510, sheet 83) are not particularly high. The surface levels of their tarns lie at c.1550 feet (470 m, Blea Water) and c.1450 feet (440 m, Small Water), and the corrie backwalls reach about 2600 and 2000 feet (795 and 610 m) respectively. Manley's estimated snowline of 3500 feet (1065 m) implies that snowbeds could have existed as low as 2100 feet (640 m).

Permanent or semi-permanent snowbeds might easily have existed in gullies in these corrie walls or in higher corries. Very little of the organic content of the Haweswater muds could have been derived from the rocky parts of corries anyway. Consequently the presence or absence of snowbeds from these parts is unlikely to be reflected in the sediments. Therefore Manley's estimates of Alleröd conditions in the Lake District do not require to be modified on this evidence.

Varved clays and silts in Haweswater, mineral sedimentation in lakeland tarns and glacial deposits in some valleys indicate renewed glacial conditions in Zone III. There was periglacial activity in lowland sites and arctic plants (e.g. Salix herbacea and Koenigia islandica) grew near sea-level (quoted from D. Walker, 1966, by Pennington, 1970). Walker and Pennington considered that these facts, particularly plant distributions, support Manley's temperature estimates for Zone III in the Lake District.

A.P. Conolly and E. Dahl (1970) have presented very detailed botanical evidence regarding maximum summer temperatures in lateglacial Britain. Although mean annual maximum temperatures are relevant to the survival of plant species, such temperatures are much more variable than average summer temperatures and so have little relevance to the behaviour of glaciers. Variations of annual maxima need not parallel those of summer averages. Therefore average maxima 4C^{o} less than present for Zone I, 3C^{o} less for Zone II and 1 C^{o} less for Zone III in the Highlands are not useful figures when estimating average climatic conditions (figures from Conolly and Dahl, 1970). The superficial contradiction between these estimates and the accepted botanical evidence that Zone II was the mildest of the three periods may be due in part to the very small amount of evidence available to or used by Conolly and Dahl.

B. Lateglacial and early postglacial vegetation.

Fig. 2.2 shows the distribution of relevant sites in central and northern Scotland with lateglacial organic remains. Pollen diagrams have not so far been published for four sites in Skye and one in Morar (H.J.B. Birks, in the press, 1972), for Gleann Shieldaig (J.J.M. Petrie, unpublished), for Lochs Sionascaig, Clair and Tarff (W. Pennington and J. Lishman, 1971), or for the Callander area (J.J. Lowe, personal communication). Nevertheless the earliest deposits at these localities are useful. Most of the remaining sites have been investigated by either J.J. Donner (1957, 1958, 1962) or Y. and A. Vasari (1968), whose methods have already been reviewed. (It is important to note that the vegetation zonation gives a relative time-scale for each site studied. Without radiocarbon dating, an absolute chronology interrelating the various sites cannot be established with certainty. At best the pollen zones at each may be regarded as "broadly synchronous", which Pennington and Lishman (1970) consider to be the case for Lochs Tarff and Sionascaig when compared with radiocarbon dated zones in the English Lake District.)

The earliest organic deposits amongst these sites belong to Zone Ia (in the Godwin zonation) and refer to the Loch of Park (Vasari and Vasari), Loch Tarff and Loch Sionascaig (Pennington and Lishman). In the latter two the amounts of carbon, iodine and, in Loch Sionascaig, pollen imply that deposition began prior to 12,800 B.P. (This date was suggested by comparison with pollen spectra of the Loch Droma site).

Pollen of pine and birch occur at Loch Sionascaig whilst at Loch of Park the vegetation was generally sparse and poorly developed, though macroscopic remains of local birch trees are present. At each site the basal deposits are barren glacial clay or silt lacking pollen.

In Zone Ib a gradual increase in vegetation is indicated by the change to deposition of clay - gyttja ('organic mud') in the lakes and by the increases of arboreal and non-arboreal pollen amounts. Around Loch of Park there was an open park-tundra landscape with birch tree copses and willow-juniper scrub. Although Pennington and Lishman employ a different scheme of zonation (chronozones and local zones), it appears that zone B marks the beginning of the same mild interstadial as does Zone Ib (the term 'interstadial' is so employed by Pennington and Lishman). By comparing the pollen of Lochs Sionascaig and Droma, Pennington and Lishman concluded that this mild period commenced at about 12,800 B.P. Although the Vasaris detected a slight climatic recession in Zone Ic, when tree pollen and non-tree pollen amounts decreased, Pennington and Lishman found no evidence in pollen or iodine contents for such a recession (which could be correlated with the Bölling oscillation). Despite a possible recession, tree birches continued to grow around Loch of Park. At Loch Kinord there are possible late Zone I deposits of clay-gyttja containing evidence of a birch-willow dominated park-tundra landscape. At Drymen, Donner found insufficient pollen in the lowermost gravel and overlying silt-fine sand deposits. The Vasaris however found only small quantities of pollen whose character indicates a virtually treeless tundra landscape. The absence of local birch trees here suggests that birch pollen at Tynaspirit (Callander) may have been blown in from afar. Pollen of Zone I at Tynaspirit resembles that from Drymen except that juniper was the main shrub at Tynaspirit compared with willow at Drymen (unpublished results for Tynaspirit from J.J. Lowe). Donner found insufficient pollen for analysis in the presumed Zone I clays of Loch Mahaick.

At Drymen, Tynaspirit, Loch Mahaick, Loch Kinord and Loch of Park there is distinct evidence for a climatic improvement during Zone II (the Alleröd, also part of zone B as defined by Pennington and Lishman). The deposition of gyttja in each lake indicates that there was much less bare ground than before. Around Loch of Park and Loch Kinord the park-tundra vegetation was dominated by birch trees with juniper replacing willow as the main shrub. Local pines and local dwarf birches grew at Loch Kinord. At Drymen both the Vasaris and Donner found local dwarf birches, as well as tree birch and pine pollen that may not have originated at the site but in a "birch region ..... not far south" (Donner, 1957, p.253). The vegetation around Loch Mahaick and Drymen seems to have been similar, that is a tundra heathland. At both these upland sites (c.700 feet, 215 m, O.D.) there are lower percentages of birch pollen (15 - 30% and 15 - 20% respectively) than at Tynaspirit in the Teith valley where 30 - 40% birch pollen occurs during Zone II.

There are indications from elsewhere that the glacial conditions of early Zone I had given way to a period of organic deposition. At four sites in Skye (and possibly at a fifth) and in Morar (H.J.B. Birks, 1972) and in Gleann Shieldaig (J.J.M. Petrie) there are organic deposits of Zone II age that lie outside the limits of the last glaciers (Sissons, personal communication; S.B. McCann, 1966).

Marine shells, later incorporated in the terminal moraines at Loch Spelve, Benderloch, Loch Lomond and Lake of Menteith, are evidence of the Zone II interstadial. Organic silts deposited in Loch Tarff and Loch Sionascaig during chronozone B (approximately the Godwin Zones Ib, Ic, II) have been correlated with deposits in Loch Droma by Pennington and Lishman, who consider that the interstadial at each dates back to c.12,800 B.P. Empetrum heath seems to have been dominant. At Loch Droma, the highest and most exposed site (c.900 feet, 275 m), there were snow-patch communities, some soliflucted soils and very few, if any, trees. These three north-westerly sites appear to have been cooler than southern and eastern sites. (Vasaris' pollen analyses of the early Postglacial in Lochs Cuithir and Fada in Skye show the same relative coolness).

Four conclusions may be drawn from the distribution of Zone I - Zone II organic deposits. Firstly the sites so far mentioned became free of glacier ice no later than Zone I, in several cases prior to 12,800 B.P., and were not subsequently re-occupied by glaciers. Secondly the Loch Tarff and Loch Droma deposits show that the succeeding Loch Lomond Readvance of Zone III was much more limited than has sometimes been supposed. (The situation on fig. 2.1 envisaged by Sissons is perhaps more realistic than the other suggestions of much more extensive ice). They also discredit the notion that the last Highland ice sheet could have survived the mild Allerö̈d (Zone II)interstadial (cf. D.E. Sugden, 1970). Fourthly, the presence of tree birches in the lower Dee valley and, by inference, in the Clyde - Forth lowlands indicates that average summer temperatures exceeded 10°C during much of Zone II. Ground above 700 feet

(215 m) in the Clyde - Forth area appears to have been slightly too cool for birch trees.

In the succeeding Zone III period of glacier advance, which began about 10,800 B.P. (Sissons, 1967b; confirmed by Pennington and Lishman by a comparison with English Lake District deposits), there was a reversion to Zone I conditions. "Patches of [bare] mineral ground became more numerous again and the extensive juniper scrub was replaced by willow stands. The copses of tree birches evidently persisted [in the lower Dee valley] , although they decreased in number, but pine is likely to have receded from its habitat at Loch Kinord. There are some indications that the climate of [Zone III] , at least in the beginning, was even more severe than that of" Zone I (Vasari and Vasari, p.74). Thus the botanical evidence agrees with Manley's idea of a greater than average initial lowering of summer temperatures early in Zone III. The Vasaris accept Manley's description of the probable Zone III weather (section A) as applicable to the Highlands. At Drymen they found a distinct decrease in the amounts of juniper and birch pollen, as did Lowe at Tynaspirit, but the Vasaris did not comment on how much poorer the local vegetation may have become. (The Loch Lomond, Menteith and Teith glaciers terminated only a few km from these localities during Zone III).

"In the loch basins the climatic deterioration led to an increase of inorganic sedimentation either as a result of solifluction or of an increase of the [area of] open ground liable to wind transportation" (Vasari and Vasari, p.75) or, it may be added, to erosion by running water. Gyttja deposition ceased. In Loch Droma, on the north-west Highland watershed, meltwater from nearby valley glaciers covered over the organic silt with outwash sands and silts. In eastern Mull, Benderloch, Loch Lomond and Lake of Menteith readvancing glaciers picked up marine shells that grew in Zone II and dumped them in their terminal deposits. In north-eastern Skye pollen from an open tundra was found in Loch Fada whereas the presumed Zone III sediments in Loch Cuithir contain no pollen (Vasari and Vasari).

"It is a curious feature that the first ..... warmth-requiring hydrophytes and heliophytes ..... appear as early as the end of Zone III ..... at the first signs of the impending climatic improvement. The plant cover of the dry ground reacts somewhat more slowly. At the onset of the Postglacial vegetational changes very similar to those characteristic for the Alleröd [Zone II] interstadial recurred" (Vasari and Vasari, p.76 - 7). These comments refer to the Zone III - IV transition zone, included by Donner in Zone IV. The Vasaris described three varieties of vegetation community. At Loch of Park "birches were more abundant than elsewhere", existing as copses in park-tundra. Total pollen, tree pollen and macroscopic remains of local birch trees increased rapidly and deposition of gyttja recommenced, showing that much less bare ground existed locally. Around Loch Kinord and in the upper Forth valley (Drymen, Loch Mahaick) the vegetation was a poorer open park-tundra with much heathland and juniper scrub. Local pine trees reappeared at Loch Kinord.

Deposition of pollen in a lake immediately inside the Teith terminal moraine appears to have begun at this time. The presence of warmth-demanding plants suggests that climatic amelioration had set in and that climate and glacier were out of phase. The plants may or may not imply that the glacier had receded from the vicinity of Callander (J.J. Lowe, personal communication). Again, samples from the Balliemore lake sediments, formed between the Loch Rannoch glacier limit and the Dunalastair rock bar, contain a pollen spectrum similar to that of Drymen, that is of a poor open park-tundra (Dunalastair analysis by Lowe; Drymen analysis by the Vasaris). Two transition periods between the Lateglacial and Postglacial in Loch Sionascaig were noted by Pennington and Lishman and one at Lochs Fada and Cuithir in Skye which was almost completely treeless but had willow-juniper scrub.

In the succeeding period, Zone IV, "the former open type of vegetation was replaced by ..... almost pure birch forests ...." (Vasari and Vasari, p.78) in the Dee valley and in the southern Highlands (Drymen, Gartmore, Loch Mahaick, Loch Creagh, Lochan nan Cat, Tynaspirit and Cambusbeg, the latter pair being near Callander and only 0.5 km apart). "A dense scrub" of juniper and willow "flourished under the upper canopy of birches. The proportion of herbs, typical of the Lateglacial, ... rapidly declined, showing that the vegetation of the field layer changed" (Vasari and Vasari, p.78). Pines grew at Loch Kinord. Gyttja deposition was resumed in Lochs Tarff and Sionascaig and Loch Clair became available for deposition. In Skye, however, the immigration of trees was delayed, although the field layer became richer and gyttja deposition shows that much less bare ground remained locally. (Trees do not appear to have become widespread in Skye until Zone VI, according to the Vasaris).

These sequences of vegetation development seem to follow a common pattern that may be summarised as follows. In Zone Ia the vegetation was still very poor following the decay of the last ice sheet (chapter 14), yet tree birches grew at Loch of Park near Aberdeen. Zone Ib (or zone B according to Pennington and Lishman) saw the beginning of a clear improvement with birch copses in a park-tundra setting in the lower Dee valley. After a possible cooler interruption, Zone Ic, this amelioration was continued in Zone II with trees appearing in the park-tundra along the southern margin of the Highlands. Average summer temperatures here seem to have been slightly less than 10°C, though this figure was probably exceeded not far to the south on low ground and in the lower Dee valley. In the latter the replacement of willow shrubs by juniper, the increasing density of birch and occurrence of pine seem to indicate a temperature higher than the 10°C implied by the birch trees of Zone I. Gyttja (organic mud) deposition in the Drymen, Tynaspirit, Loch Mahaick, Loch Tarff, Loch Droma, Loch Sionascaig and Dee valley sites in Zone II shows that solifluction had ceased at these sites. (In these eight localities there is a sequence of mineral-organic-mineral sedimentation corresponding to Zones I - II - III as first noted by Donner, 1957).

However, during Zone III there was a distinct reversion to colder conditions, with more bare ground and open tundra along the southern Highland edge, though tree birches persisted in the lower Dee valley. This may indicate that the lower Dee valley was much more remote from the main areas of glacier activity than were Drymen, Tynaspirit and Loch Mahaick (three major glaciers reached their termini near the latter three localities). Amelioration began in Zone III - IV, with the tree population along the southern and eastern Highland borders increasing. By Zone IV light birch forests were widespread in the lower Dee, upper Forth (Drymen, Gartmore, Tynaspirit, Cambusbeg, Loch Mahaick) and Tay valley areas

(Loch Creagh, Lochan nan Cat), indicating that average summer temperature easily exceeded 10°C. Vegetation in Skye seems to have been poorer until well into the Postglacial (Zone VI). There is no support in the evidence from the sites shown on fig. 2.2 for the hypothesis that the last ice sheet was maintained throughout Zones I, II and III, with a minor fluctuation during the latter (cf. D.E. Sugden, 1970; see also chapter 14 below).

C. <u>Postglacial conditions.</u>

It is generally considered that there have been only two extended periods of climatic deterioration in Britain during postglacial times, around 2500 years ago with wetter, cooler conditions and the great extension of hill-peat, and more recently in the period c.1500 - c.1900 A.D. (Manley, 1952, chapter 12) "Since the final retreat of the last great glaciation, the greatest advance of the mountain glaciers of the Alps, in Norway and in Iceland has taken place within the past 400 years" (1952, p.291). Historical records reveal that large snowdrifts persisted for many years in high corries on Ben Nevis, Ben Wyvis and in the Cairngorms. Sugden has suggested that "extensive permanent snowbeds or even inactive glacier ice existed as recently as the late seventeenth century" (1971, p.391).

However, in an even more recent paper, Manley disagreed (1971).* By making a detailed study of snow accumulation, temperatures and ablation on Ben Nevis (1884 - 1970) and of the behaviour of the snowbeds, he concluded that there has not

* This is a more sophisticated examination of a theme Manley had taken up in 1949. Both articles present similar conclusions.

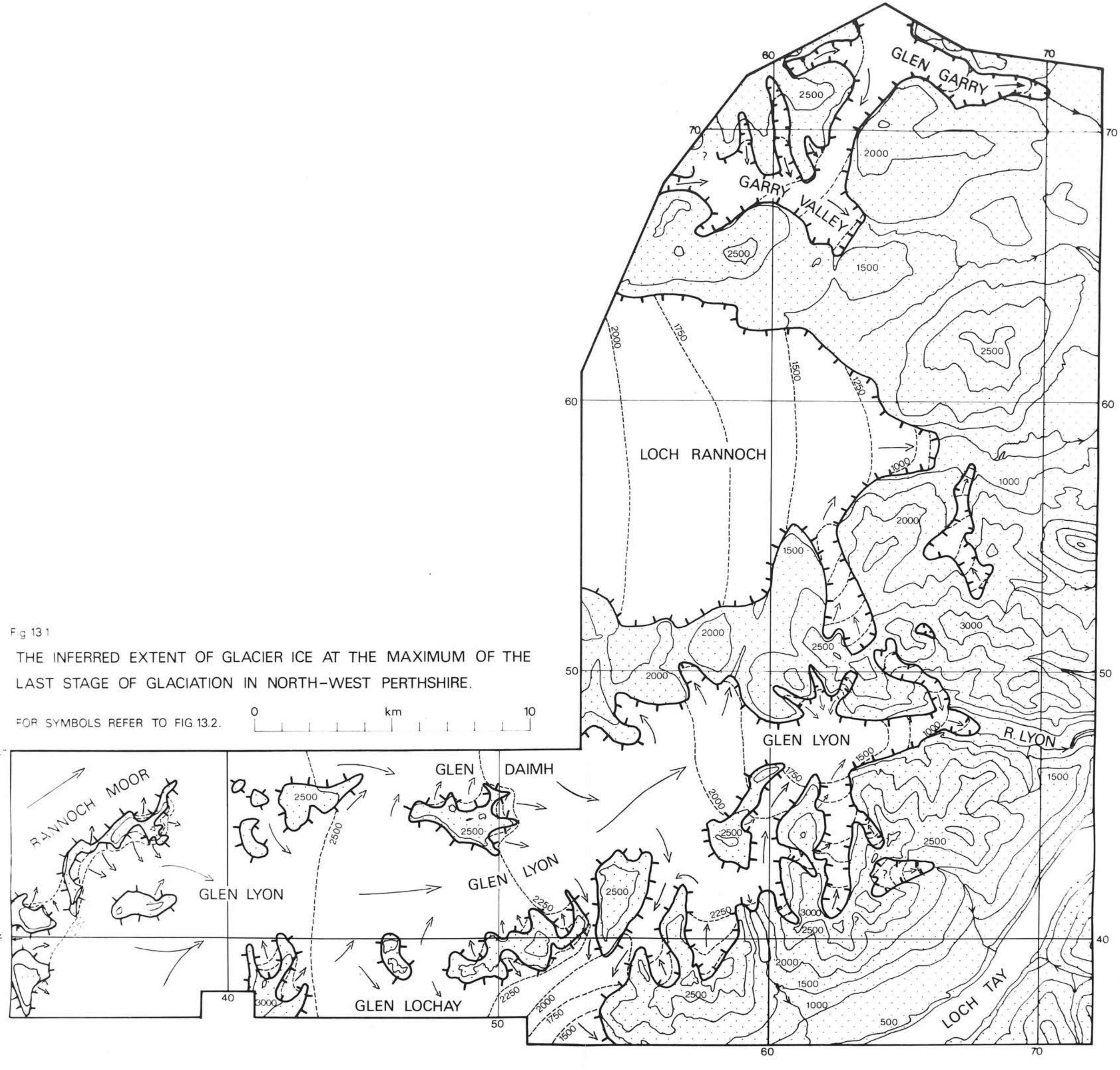


Fig 13.1

THE INFERRED EXTENT OF GLACIER ICE AT THE MAXIMUM OF THE LAST STAGE OF GLACIATION IN NORTH-WEST PERTHSHIRE.

FOR SYMBOLS REFER TO FIG.13.2.

been a sufficiently prolonged "continuous succession ..... of cool summers in historic time" (1690 - present) for the conversion of any snowbed into glacier ice (1971, p.471).

Pollen evidence in the Highlands in general and in the high, east-facing corrie, Lochan nan Cat (2350 feet, 715 m), also implies that glaciers have not recurred during the Postglacial (Donner, 1962). The distribution of major periglacial landforms is also believed to indicate this (Sissons, 1967a, chapter 12). No frost wedges "have yet been found within the limit of the Loch Lomond Readvance. Solifluction has not operated at all on low ground since the glaciers of this stage disappeared, with the consequence that within this limit features such as kames and moraines are extremely sharp and clear" (Sissons, 1967a, p.p.221-2). It is thought that the larger, vegetated periglacial forms are relicts of lateglacial or early postglacial times. For example R.B. King has suggested that major vegetation-covered lobes date from Zone IV (King, in the press). Only minor features such as small lobes and terraces seem to have been actively forming since this time. "O'Brien has dated vegetation layers from a depth of 40 - 70 cm beneath solifluction lobes and these have yielded radio-carbon ages of 4880 $\pm$ 135 and 2680 $\pm$ 120 years B.P." These dates suggest the lobes have moved downslope, perhaps in the period around 2500 B.P. and during the Little Ice Age (sixteenth to early nineteenth centuries A.D.) (Sugden, 1971, p.391). King has similarly concluded that small vegetated stone stripes and polygons "probably date from the Little Ice Age", whilst other small bare stripes and polygons "are active at the present time", generally above about 900 m O.D. (King, 1971, p.375). It is concluded that, since the Loch Lomond Readvance, there has not been a sufficient period of climatic deterioration for either glaciers or major solifluction features to be formed.

D. Snowline calculations.

Following Manley's precedent (1959) an attempt has been made to calculate possible snowlines in the thesis area during the last stage of glaciation. "Primary estimates of the height of the firnline have in general been set half-way between that of the snout and the base of the upper crags. Where allowance should be made for downward narrowing of the valley and diminishing precipitation" he placed his estimate three-fifths of the way up the glacier (1959, p.194). C. Embleton and C.A.M. King however state that "the firnline on a cirque glacier usually occurs about three-fifths of the way [up] between the snout and the upper limit of the ice" (1968, p.198). Calculations using four methods were made for the valley glaciers in the thesis area; namely half-way and three-fifths of the way up to the base of the upper crags, and half-way and three-fifths of the way up to the inferred upper limit of the ice. A number of problems became apparent. Firstly, it has generally been inferred that the upper limit of ice lay near the top of the corrie or valley head that it occupied. It follows that these limits appear to vary with the topography. This seems reasonable but it can be neither proved nor disproved. Secondly, the altitude of the glacier terminus depends to a great extent on the level of the valley into which it flowed. Thus the glacier termini were highest in the north (1200 and 1500 feet, 365 and 455 m, for the Garry) and lowest in the south (250 feet, 75 m, for the Teith). More precisely, glaciers in valley systems most remote from base level (the sea) did not reach levels as low as glaciers terminating nearer the sea. The distance travelled also had an effect, for the small Glen Artney glaciers remained in the upper reaches of this valley system, terminating at 900 - 1000 feet (275 - 305 m).

Thirdly, there is likely to have been only one corrie glacier at the maximum of the last glacial stage (Coire nan Cat, Ben Lawers), and even this is open to doubt. At its maximum all the others were valley glaciers. Therefore Embleton and King's method is not necessarily appropriate. Fourthly, most glaciers belong to valley glacier systems, so that there were several corporate termini, possibly reflecting a range of regime conditions. Fifthly, there are few corries and the bases of their upper crags may not be identifiable. In some cases this break of slope may be irregular; for example that of Coire Liath descends 500 feet (150 m) (6143, sheet 48), that of Coire Chroisg 450 feet (135 m) (6017, sheet 54). In others the base is not identifiable on available contoured maps (e.g. 4745, sheet 47). In still others the area of crags is limited; for example most of the corries around the Glen Lyon - Gleann Daimh confluence (sheet 47), where parts of sidewalls are cliffed but backwalls usually are not. Consequently Manley's method can be applied to only eight corries (Achaladair, 3341, a'Chreachain, 3644, Heasgarnich, 4139, an Lochain, 4845, all on sheet 47; Riadhailt, 5740, nan Cat 6442, both on sheet 48; the two south-facing corries of Ben Vorlich and Stuc a'Chroin, 6116 and 6218, sheet 54). A final problem is that the corries probably largely pre-date the last glacial stage, so that their altitudes need not be related to snowlines at this stage. Nevertheless the floor of each was probably occupied by glaciers at this time, giving a basis for an approximation.

Manley's principle of making an estimate three-fifths of the way up to the base of the upper crags was found to give the most consistent results and to fit the conditions of "downward narrowing of the valley(s) and diminishing precipitation". Estimates half-way and three-fifths of the way up to the upper limit of the ice were on average 180 feet (55 m) and 210 feet (65 m) higher (the ranges were 50 - 500 feet, 15 - 150 m, and 50 - 600 feet, 15 - 185 m, higher respectively). The average value for six of the eight corries, using Manley's method, is 1700 feet (520 m). It has been mentioned that the existence of a Coire nan Cat glacier is open to question, so its result of 2200 feet (670 m) was not used. The other corrie omitted was Coire Riadhailt (5739) because it contributed ice to two or possibly three ice limits (Lochay, Lochan na Lairige, Lyon). (The results for these three termini were 1650 feet (505 m), 2200 feet (670 m), 1750 feet (535 m) respectively).

The estimate accepted as the basis for further calculations was 1700 feet (520 m). Manley's (1959) method of estimating conditions at the snowline was followed. On the assumption that snow accumulation during the last stage of glaciation was 80% of present precipitation, the probable accumulation around each corrie was derived from the Meteorological Office 1:126,720 map sheets. These figures, varying between 1600 mm and 2500 mm (65 - 100 inches), were fitted to Ahlmann's graph relating accumulation to summer temperature at the snowline in Norway (Ahlmann, 1948, p.48). In four cases the results were 3°C, the other two being 3.6°C and 2.3°C, giving an average for the six corries of 3°C. Using Manley's standard lapse-rate of 1°C / 500 feet the appropriate sea-level mean summer temperature is c.6.4°C. By comparison with the present day summer temperature estimate (c.13°C) this represents a fall of 6.6C°.

There are two methods of testing this result. Manley has shown that the present day snowline around Ben Nevis probably lies at about 5300 feet (1615 m) (Manley, 1949). Even though the snowline might be expected to rise eastwards with diminishing precipitation, a drop in the regional snowline from 5300 feet (1615 m) to 1700 feet (520 m) might be expected to result from a 7C° fall in average summer temperature. Secondly, in his 1959 paper Manley implied that average summer temperature (sea-level) in Zone III around Ben Nevis may initially have fallen to 4° - 5°C, subsequently rising to 6°C, or in other words an initial drop of 9 - 10C° followed by a rise of 1 - 2C°. Although these three sets of estimates are not and could hardly be expected to be unanimous, they are in reasonable agreement, implying that the 1700 feet (520 m) snowline estimate is of the right order. Calculations made for a further thirteen corries (mainly between Glen Artney and Loch Earn), where the base of the upper crags rises and falls or is hard to define, ranged from 1300 to 1700 feet (395 - 520 m) with nine of them lying between 1500 and 1650 feet (455 - 505 m). These results seem to be in sufficient agreement with the 1700 feet (520 m) estimate.

The inaccuracies involved in these calculations make it impossible to detect local variations due to differences of aspect, of precipitation, or of the sources of wind-blown snow such as Manley (1959) and Sissons (in the press) have done. However, the general implication is that fairly severe conditions were maintained during the last glacial stage, with average summer temperatures in the 4 - 6°C range. There is thus some agreement with the organic evidence of a drop in summer temperatures well below the 10°C mark to open tundra conditions. The effects of the coolness of summers and the depression of the snowline should be distinguished from the length of time these conditions lasted. Manley has stated that "during the period of advance of the glaciers, the average summer temperature can in many years be presumed to have fallen to values nearly as low as those which prevailed at the maximum of the greater glaciations. This suggests that the main problem for the meteorologist is to explain the varying length of the periods over which low temperatures prevailed, rather than the amount of the fall" (Manley, 1959, p.213). In other words, the duration of the last stage of glaciation was probably a principal cause of its limited extent.

E. <u>Distribution of glaciers.</u>

On the assumption that present precipitation is similar to that of the last glacial stage (this point should not be confused with the relationship of snow accumulation to total precipitation), a comparison can be made of the distributions of precipitation and glaciers. (Manley showed that present and Zone III precipitation in the Lake District were similar). The methods used in drawing the two glacier maps, figs. 13.1 and 13.2, were described in chapter 1. The suggested ice margins are normally the minumum inferred levels when the glaciers were at their maximum extents. Greater confidence can be felt where lateral moraines or the upper margin of hummocky drift coincide with the suggested ice margin. Such localities can readily be identified on the appropriate 1:63,360 sheets.

It appears that the westerly concentration of major glacier sources corresponds to the largest area of high ground and high precipitation in the thesis area. The source areas for the largest trunk glaciers were the western side of Rannoch Moor, with summits of 2500 - 3500 feet (760 - 1065 m)and precipitation of 2540 - 3170 mm (100 - 125 inches), and upper Glen Lyon, with summits in the same height range and precipitation around 2540 mm annually (100 inches). The portion of Glen Lyon between its head and the Gleann Daimh confluence, with 2030 - 2285 mm (80 - 90 inches) precipitation on hills reaching 2500 - 3000 feet (760 - 915 m), also provided several tributaries. The sources of the Teith and Loch Voil glaciers probably lay to the west of the thesis area where 2540 mm (100 inches) or more of precipitation falls on hills reaching 3000 feet (915 m). Sources for the Teith and Voil glaciers within the thesis area lay between hills with over 1780 mm (70 inches) precipitation and summits of 2200 to 2500 feet (670 - 760 m). Thus the principal sources were in areas of 2540 mm (100 inches) or more precipitation with summits of 2500 - 3500 feet (760 - 1065 m).

The flow of glaciers in the thesis area was generally eastwards away from these centres of high ground and high precipitation. In this direction the area of high ground, the amount of precipitation and the sizes of the glaciers tend to decrease. Five areas nourishing their own glaciers lie well to the east of the major western sources. The Garry glacier flowed from an area with 1780 - 2030 mm (70 - 80 inches) precipitation and hilltops of 2500 - 3000 feet (760 - 915 m). In the Carn Mairg area (lower Glen Lyon) the precipitation is similar on summits around 3000 feet (915 m) high. Nearby were glaciers mostly flowing north from the Ben

Lawers group of hills, which generally reach 3000 - 3500 feet (915 - 1065 m) and again have 1780 - 2030 mm (70 - 80 inches) precipitation. The area of glaciers with the lowest summits (2500 - 2750 feet, 760 - 840 m) and lowest precipitation (over 70 inches, 1780 mm) was the most easterly, Glen Almond. The separate southerly centre of glacier build-up, Ben Vorlich - Stuc a'Chroin (Glens Artney, Vorlich and Ample), today receives 2030 - 2540 mm (80 - 100 inches) precipitation on summits reaching 2500 - 3000 feet (760 - 915 m), or 1750 - 2000 feet (535 - 610 m) in two cases. In the latter, the Allt Ollach valley and Coire a'Choire, the considerable precipitation may have been sufficient to compensate for the apparent lack of altitude. With these exceptions, it is apparent that areas nourishing glaciers have summits exceeding 2500 feet (760 m) and present precipitation exceeding 1780 mm (70 inches). By comparison, Manley concluded for the Lake District that "glaciers did not develop on uplands having less than 70 inches annual precipitation today" (1959, p.211).

A corollary is that areas that apparently failed to nourish glaciers during the last glacial stage lie mostly below 2500 feet (760 m) or receive less than 1780 mm (70 inches) precipitation or both. The broad upland below about 2000 feet (610 m), lying between Loch Earn, Glen Almond, the Dochart-Tay valley and Glen Ogle (sheets 48 - 54), has over 1780 mm (70 inches) precipitation, but the valleys here seem to have been too low and therefore insufficiently cold for glaciers to form. On the other hand the broad ridge between Loch Tummel and the River Tay reaches 2500 feet (760 m) in places but, with only 1020 - 1520 mm (40 - 60 inches) precipitation, glaciers apparently were unable to form at the last glacial stage. There are two anomalous cases of areas with summits well over 2500 feet (760 m) and precipitation exceeding 1780 mm (70 inches) where there is no known evidence for glaciers having existed during the last glacial stage. The western half of the Carn Mairg hill group nourished glaciers tributary to the Loch Rannoch and Lyon valleys, yet there is no sign of glaciers having formed in the eastern part of these hills where the valleys face east or north-east. The southern side of Glen Quaich is analagous, for tributaries of the Almond glacier flowed from the southern side of this hill mass, yet none appears to have formed on the equally high and wet northern side. Both hill areas lie at the eastern margin of the part of western Perthshire occupied by the last glaciers.

The absence of glaciers from parts of each area may be explained to some extent by the eastward rise of the snowline. It has been shown by Manley (1959) and by Ahlmann (1948) that a rise in the snowline is produced by a decrease in precipitation. For example, in the Lake District Manley correlated a rise of the snowline from 1400 feet (425 m) to 2200 feet (670 m) with a decrease in present annual precipitation from 3300 mm (130 inches) to 1780 mm (70 inches). In the present thesis area the eastward decline in the sizes of glaciers and their absence from the eastern parts of the area match the eastward decrease of precipitation and the expected eastward rise of the snowline. Presumably the portions of the Carn Mairg and Glen Quaich hills under discussion either were only just unable to nourish glaciers or supported glaciers that were insufficiently active to leave recognisable traces of their existence.

Snowbeds were probably common in localities not occupied by glaciers. Manley (1949) has calculated that the lowest permanent snowbeds in mountain areas with a "cloudy maritime climate" may lie as much as 450 m (c.1480 feet) below the snowline and at an altitude with an average summer temperature of 5^{o} - 6^{o}C. Snowline calculations have suggested that sea-level summer temperature in the thesis area may have been around 6.4^{o}C. Accordingly it may be expected that permanent snowbeds may have occupied sheltered hollows to low levels in the hills in the parts of the thesis area not occupied by glaciers.

F. Aspects of the form and activity of the glaciers.

As a result of the expected considerable annual accumulation of snow in the thesis area and of the presumably considerable ablation caused by mild Atlantic winds, the glaciers in the area should have had a relatively high rate of flow. The larger glaciers, such as the Rannoch Moor - Loch Rannoch glacier and the Lyon glacier, presumably had a greater rate of flow than glaciers with a much slower rate of accumulation, such as the Almond, other things being equal. The higher rate of activity of these larger glaciers would also have been in part a result of their greater thickness (thickness will be discussed below). Although the smaller glaciers would have tended to be less active by virtue of a smaller total budget (accumulation plus ablation) and lesser thickness, their greater surface slopes would have tended to compensate for this.

It will be apparent from figs. 13.1 and 13.2 that in most glaciers there was a "rapid increase in ice thickness back from the ice limits" (Sissons, 1967a, p.143). This suggests that advancing valley glaciers "were suddenly checked" and thereafter were in retreat (Sissons, 1967a, p.143).

"The effect ..... of a small reduction in mass balance ..... is large near the terminus ..... [where it] causes a substantial retreat" (W.S.B. Paterson, 1969, p.205). This idea of most glaciers not having attained a state of equilibrium at their maximum extents need not conflict with the existence of the Teith terminal moraine at Callander. Whereas all the glaciers except the Teith terminated as narrow tongues within Highland valleys, the Teith spread out laterally as it passed from its narrow Highland course into its broad unrestricted Lowland course. At a distance of 1 km back from the ice margin this piedmont tongue appears to have been only about 200 feet (c.60 m) thick, whereas most other glaciers appear to have been 250 - 400 feet (75 - 120 m) thick at this distance. Thus it follows that the forward motion of the Teith glacier is likely to have been dissipated by lateral spreading. The thinning thereby achieved and the increased ablation of an enlarged surface area could have brought the tongue into equilibrium and thus permitted the build-up of a terminal moraine.

Certain aspects of the surface gradients of the glaciers are evident from figs. 13.1 and 13.2. Those of the major trunk glaciers tend to be similar to those of minor glaciers in relatively gently sloping valleys. For example, the Lyon (150 feet per km, 45 m / km) and the Dochart (180 feet per km, 55 m / km) compare with the Glen Artney glaciers (Gleann a'Chroin 120 feet per km, 35 m / km, or Gleann an Dubh Choirein 200 feet per km, 60 m / km). (These figures refer to the average gradient over the terminal 5 km of each glacier. A longer distance would include the steeper gradients at the sources of the smaller glaciers). Secondly, in most cases the gradient seems to double in the terminal 1 km of each glacier by comparison with the slope of the terminal 5 km.

For example, the Lyon steepens from 150 to 300 feet per km (45 - 90 m / km), the Lochay from 200 to 400 feet per km (60 - 120 m / km), Gleann an Dubh Choirein from 200 to 350 feet per km (60 - 105 m / km), and the Almond from 140 to 250 feet per km (40 - 75 m / km) in its northern branch terminating above Loch Tay. By contrast, on small glaciers in steeply sloping valleys, the surface gradients in the last 1 km seem to have been no steeper than in the preceding 4 km. For example, the Invergeldie sloped at about 320 feet per km (95 m / km), the Turret and the Ample at 300 feet per km (90 m / km), and the Allt Ollach at 300 - 400 feet per km (90 - 120 m / km). The Dochart alone amongst major glaciers seems not to have steepened in its last 1 km (180 feet per km, 55 m / km), for here it began to descend from the gently sloping Dochart valley floor into the head of the Loch Tay trough.

The gradients mentioned here and in earlier chapters compare with measured gradients on some present day glaciers. Amongst outlets from the Vatnajökull ice cap the Heinabergsjökull slopes at 200 feet per km (60 m / km) near the snout, diminishing headwards to 100 feet per km (30 m / km) (S. Thorarinsson, 1938), whilst nearby the Breidamerkurjökull surface gradient varies between 165 feet per km (50 m / km) down the axis of the snout and 330 feet per km (100 m / km) along the margins, in each case over the terminal 6 km of the glacier (R.J. Price, 1969). In Spitsbergen the Nordenskiöldbreen descends at a rate of about 150 feet per km (45 m / km) for over 20 km (G.S. Boulton, 1970, p.238) and the Fourteenth of July glacier declines at a rate of 160 feet per km (50 m / km) over 17 km (Ahlmann, 1948, p.9). On some Austrian mountain glaciers, J.A.T. Young has measured gradients as low as 3° - 5° (175 - 290 feet per km, 55 - 90 m / km) for distances of

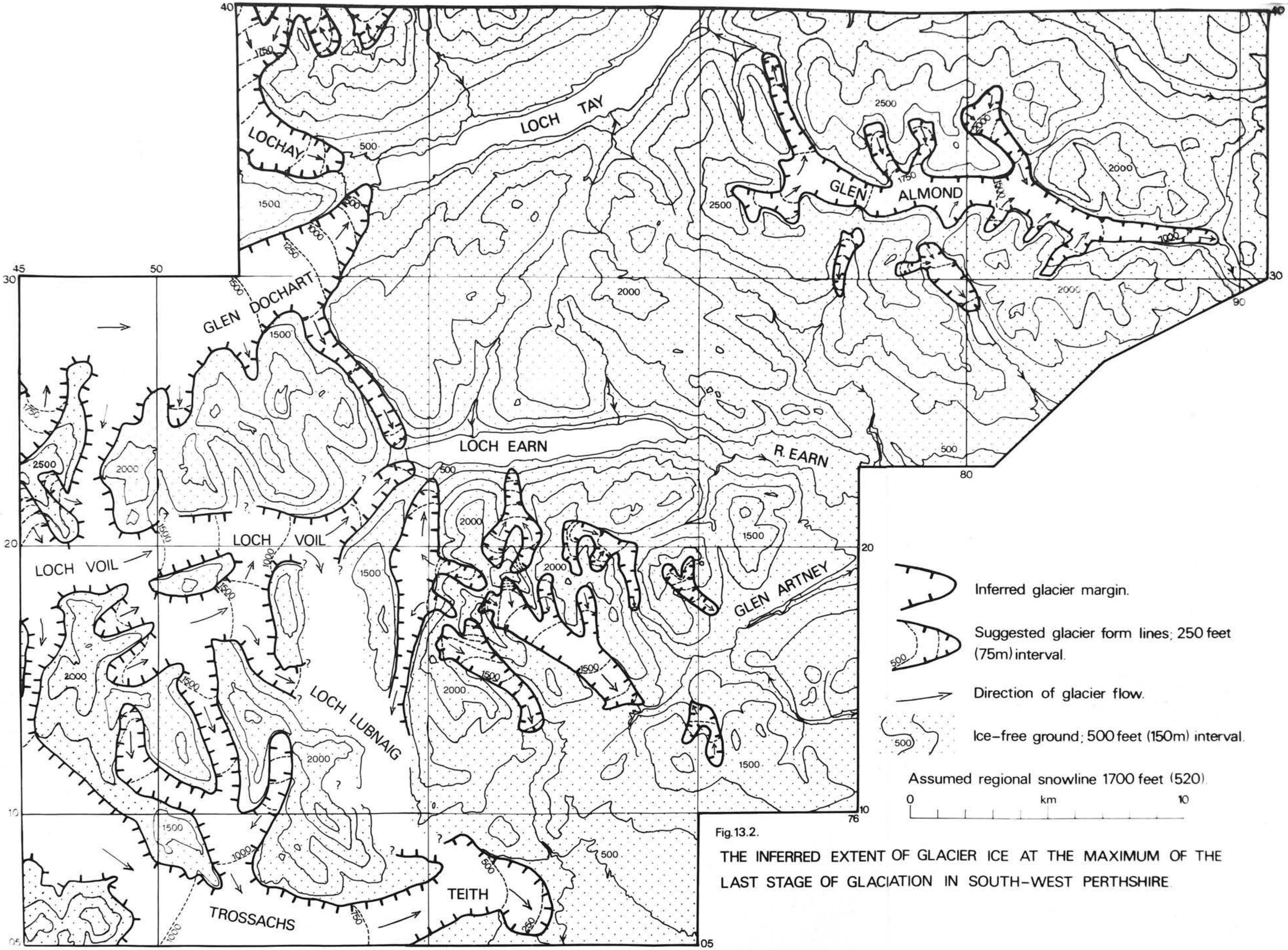


Fig. 13.2.

THE INFERRED EXTENT OF GLACIER ICE AT THE MAXIMUM OF THE LAST STAGE OF GLACIATION IN SOUTH-WEST PERTHSHIRE up to 2 km. Young found that there was a close correspondence between the slopes of the ice surface and the underlying valley floor (Young, personal communication). Accordingly it is reasonable to expect that glaciers flowing along gently declining valleys in the thesis area had quite low surface gradients. Gradients less than 100 feet per km (30 m / km) have been suggested for parts of the Lyon and Loch Rannoch glaciers. The figure of 30 feet per km (9 m / km) for the upper reaches of the Lyon is a minimum estimate, for the ice surface may have been even higher than is suggested on fig. 13.1. A gradient of 40 feet per km (12 m / km) is indicated by prominent lateral moraines for part of the Loch Rannoch ice margin where this glacier was traversing a gently sloping valley bench. These figures compare with Sissons' suggestions for the lowermost 13 km of the Menteith glacier and 20 km of the Loch Lomond glacier. His map shows that they descended at about 50 feet per km (15 m / km) over these distances (Sissons, 1967a, p.99). In Sweden C.M: son Mannerfelt calculated from marginal (or sub-marginal) meltwater channels that the margin of the decaying ice sheet sloped at 30 - 65 feet per km (10 - 20 m / km) (Mannerfelt, 1949). Thus there are adequate parallels from past and present glaciers for the surface gradients that have been deduced for the last glaciers of western Perthshire.

G. Deglaciation.

It was shown in chapter 3 (C) that much of the hummocky drift in the thesis area may consist of kames for, underneath the ubiquitous cover of angular 'morainic drift', bedded water-worn fluvioglacial deposits have been found in most of the major valley systems. In chapter 3 (D) it was concluded that identifiable eskers were deposited under stagnant ice in conditions of impeded drainage (on the Loch Rannoch valley benches) or under the stagnating termini of valley glaciers (Teith and Glen Artney - Srath a'Ghlinne). In the preceding section of this chapter (13.F) it was pointed out that the rapid increase in ice thickness back from the ice limits implies that the advancing valley glaciers were suddenly checked and thereafter were in retreat. With the exception of the Teith glacier terminus, which attained stillstand in consequence of lateral spreading, there are no end moraines, though this need not imply that terminal moraines could not have been created and then destroyed or obscured. A recessional moraine appears to have been built up by one of the Glen Artney glaciers (chapter 10) and three stages of recession are recorded in Glen Almond (chapter 9). The arcuate group of mounds, including kames, that crosses upper Glen Lyon at Lubreoch (chapter 3.C) may mark a stage in the retreat of the Lyon glacier. With these exceptions recessional moraines are absent, as are terminal moraines. In other words, at their limits and during retreat, most glaciers failed to attain a state of equilibrium for long enough to build up terminal features and, after reaching their limits, most retreated more or less continuously.

It seems from the published accounts of present and former glacier activity that deglaciation may follow one of three courses. Firstly it may be by recession of an active glacier in which flow is maintained right up to the snout and the snowline lies below the highest sources. A series of recessional features, particularly moraines with outwash graded from them, would be expected to form at various stages of retreat. Even if the moraines were destroyed by later erosion, complex scattered terrace fragments would probably remain. However, the spreads of hummocky drift and absence of outwash terraces from all but three of the glacier limits in the thesis area do not accord with this suggested method of deglaciation.

The second possible course appears to occur when the snowline rises above the highest sources so that the glacier becomes climatically dead and subsequently gradually becomes immobile. It is generally thought that the last Scottish ice sheet stagnated in situ, thus causing numerous meltwater channels and kame terraces to be formed along its margins and eskers and channels underneath it. These features indicate that meltwater drainage systems were well developed when the ice was immobile throughout its mass. If the last valley glaciers in the thesis area had become entirely immobile once deglaciation began, it would be reasonable to expect that subglacial esker systems and possibly kame terraces would be well developed, even if meltwater channels were absent from the fairly steep valley sides. However, with the special exceptions of some glacier limits and the Loch Rannoch valley bench (these are discussed at the end of this chapter), eskers and kame terraces have not been identified amongst the widespread, chaotic moundy drift.

By a process of elimination it is suggested that a third method of deglaciation is more likely, namely retreat combined with stagnation of the terminal zones of the glaciers. Deglaciation in the cool temperate maritime climate of Highland Scotland was presumably brought about by a rise in average summer temperatures, which would lengthen the ablation season, bring milder winds and rain rather than snow. The change to a negative budget would have brought a relatively quick response in such rapidly flowing glaciers. As has already been noted, "the effect ..... of [even] a small reduction in mass balance ..... is large near the terminus ..... [where it] causes a substantial retreat" (Paterson, 1969, p.205). The terminal 1 km or so of most valley glaciers was an area of rapidly decreasing thickness (section F). The effect of local ablation here in addition to that of reduced mass balance implies that the glaciers began to recede and that their terminal zones thinned rapidly once deglaciation began. Eventually the terminal zone of a given glacier must have thinned so much that it became dynamically dead, even though the thicker proximal parts of the glacier may have remained dynamically active. Once immobile, the ice mass may have become detached from the remainder of the glacier and the process would have been repeated on the shortened glacier.

Meltwaters in the stagnant ice may have picked up material on, in and under the ice. Crevasses and marginal depressions were probably enlarged by both glacial meltwater and streams draining from ice-free hillsides. "Debris was accumulated in subglacial tunnels, crevasses were filled in, and blocks of ice were surrounded by or buried beneath the stream deposits" (Sissons, 1967a, p.108). A lot of unstable material may have slipped or fallen on to the glacier from the valley sides. Most would have accumulated in the terminal zones of the glaciers, partly by sliding down the surface of the glacier towards the snout and partly because of the relatively rapid rate of flow bringing forward the detritus when the glaciers were still active. Washing and sliding of the material on the irregular ice surface would have filled in hollows and crevasses (cf.V.Okko, 1955). Finer particles would most easily have been removed by meltwater.

"When the ice finally melted, the crevasse and tunnel fillings were left as upstanding ridges and mounds ..... while the sites of ice blocks were marked by depressions. Lying discordantly amidst [or on] the deposits ..... boulders may occur. Such boulders fell into or on to the deposits from the ice above, the incorporated ones probably having been released from the roofs of subglacial tunnels as the meltwater rivers were forced against them by the accumulation of their own deposits" (Sissons, 1967a, p.108-9). "The boulders are usually mixed with an assortment of stones of all sizes, as well as with finer material" (Sissons, 1967a, p.95). This is the 'morainic drift' that is so commonly exposed on the surfaces of the mounds. It is interpreted as ablation till (chapter 3.C). The partial rounding of stones often noted in this deposit may have been produced by washing about on the surface of the ice (cf. Okko, 1955).

Temporary ice-marginal lakes in which kame terraces accumulated were probably common. Preserved terraces are uncommon however, being observed only near the limits of the Loch Rannoch, Lyon, Almond and Teith glaciers. In every other locality any kame terraces must have been destroyed or rendered unrecognisable by melting out of contiguous ice, thus producing kame and kettle topography. (cf. G.D. McKenzie, 1969, for example, who noted the progressive kettling and deformation of a kame terrace lying on dead ice). Since identifiable meltwater channels are comparatively uncommon, almost all occurring in drift on the Loch Rannoch valley benches, it must be presumed that the bulk of eroding meltwaters escaped from the ice via the courses of the present rivers. Other meltwater routes in the ice were presumably obscured by shifting debris.

Although it does not seem possible to deduce from the available evidence whether stagnation rapidly became widespread or was limited to the thinner terminal portions of the glaciers, it is likely that deglaciation would have proceeded more quickly if tributary and trunk glaciers became separated (cf. Ahlmann, 1948, p.66).

It is noticeable that the landforms produced during glacier melting in the last glacial stage within the thesis area seem to be less massive than those formed during decay of the last or previous ice sheets in Scotland. It is commonly accepted that massive fluvioglacial accumulations and many meltwater channels record ice sheet deglaciation. For example meltwater channels crossing spurs may be continued by eskers or kame terraces (e.g. Sissons, 1967a, chapter 6). Sugden (1970) in the Cairngorms, R.J. Price (1963) in the Southern Uplands and C.M. Clapperton (1969) in the Cheviots, for example, have noted that "fluvioglacial landforms bearing only a minimal relationship to the underlying relief owe their position and orientation to a major ice mass" that submerged the valleys and uplands (Sugden, 1970, p.205). In other words they are ice-directed landforms largely "discordant with the older relief" (Sugden). Englacial and subglacial drainage are influenced by glacier structures, by the direction of movement of the ice, that is by the direction in which hydrostatic pressure diminishes, and by the underlying topography (J. Gjessing, 1960). The conflict between glacial and topographic controls presumably impeded drainage and led to erosion or deposition on a much larger scale than might have been the case had the two controls coincided. The greater volume of ice and meltwater in large ice masses must have been another important factor.

On the other hand, the last glaciers in at least western Perthshire were confined to the valleys. Meltwater in or under them presumably flowed down-glacier, that is down-valley, so that there can have been only minor subglacial barriers to drainage. There is only one known instance of a major barrier. This is in Glen Lyon (5647, sheet 48) where four meltwater channels cross a spur. It was inferred from depositional evidence that this spur was submerged by the Lyon glacier as it spilled northwards into Coire Odhar (5548 - 5948). Thus the channels may record the impeding of meltwater draining englacially in the direction of ice movement.

The other features interpreted as the consequence of restricted drainage are the Loch Rannoch valley bench eskers (chapter 3.D) (sheet 48, hundred km squares 55, 56, 66). Those on the southern side of the loch run along exceedingly gentle ground slopes, as do some to the north, whilst the remainder run transverse to the present drainage lines. In the latter case the drainage is towards the south whereas the glacier flowed eastwards. In the cases of these eskers and the Glen Lyon meltwater channels ice-directed drainage was in conflict with the topographic influence. It is suggested that these exceptional landforms (in the context of the thesis area) are the consequence of this exceptional circumstance. (Rock basins must also have suffered impeded drainage but any landforms in them are submerged by lochs). Thus there may be at least a partial explanation for the contrast between the hummocky drift characteristic of the last valley glaciers and the massive, well-developed and apparently more complex fluvioglacial landforms produced by melting of the last ice sheet in Scotland. These ice sheet deposits frequently include landforms produced beside, in or under the ice in conditions of drainage that was impeded as a consequence of the frequent discordance of glacial and topographic controls. On the other hand, in the case of the last valley glaciers, the comparative rarity of landforms reasonably correlated with impeded drainage seems to be a consequence of the relative ease of drainage in and under these glaciers. The much smaller volumes of ice and meltwater of the last glacial stage were presumably another important factor.

Chapter 14. The last stage of glaciation.

In the interpretation of the evidence in the thesis area the basic assumption has been that the last stage of glaciation was accomplished by the readvance of valley glaciers. This assumption contains three parts, namely that there was a readvance, that it was by valley glaciers, and that this last stage of glaciation in each valley system took place during the same period. Although it seems to the author that this is the simplest, most obvious and most reasonable manner in which to interpret the evidence, the approach does require justification, especially in view of the different accounts of lateglacial history that have been given for various parts of Scotland (cf. J.K. Charlesworth, 1955; D.E. Sugden, 1970). The argument will be presented in terms of three hypothesis: firstly, that the fresh hummocky drift in each valley is the result of one stage of glaciation; secondly, that this was the last stage of glaciation in Scotland, occurring not later than and probably during pollen Zone III; and thirdly, that this stage of glaciation was distinct from and later than the preceding stage of ice sheet glaciation, that is the last stage was a readvance rather than the reactivation of the last ice sheet. It will be demonstrated that each hypothesis is supported by the evidence in the thesis area and that this interpretation of the lateglacial sequence accords with evidence elsewhere in Scotland.

There are several reasons for proposing the first hypothesis, that the fresh hummocky drift in each valley is the product of one stage of glaciation. Firstly, there are clear down-valley limits to this drift in all the major valley systems and in no instance is there more than one limit. In Glens Garry, Lochay, Dochart and Almond, in parts of Glen Artney, and around the head of Loch Earn the valley-floor spreads of hummocky drift terminate abruptly. In Glen Lyon the fading out of moundy drift coincides with the abrupt beginning of a series of outwash terraces. At the eastern end of Loch Rannoch the valley floor is covered with outwash laid down when a glacier occupied the loch immediately to the west, while the slopes north and south of the loch support innumerable drift mounds that do not recur east of the loch (within the confines of the thesis area). Near Callander, in the Teith valley, a large terminal moraine and series of kame terraces, together with proglacial outwash terraces, indicate the former terminus of a large glacier that appears also to have deposited moundy drift in much of the Trossachs and Loch Voil valley systems. (In Glen Almond the three postulated stages of retreat seem to accord with the identification of a single limit of glacier advance).

The hummocky drift within each down-valley limit is remarkably consistent in character. Despite variations in thickness of deposits, the mounds are numerous, apparently chaotically arranged, normally gravelly with boulders littering their surfaces, and remarkably fresh-looking. The consistency of these qualities suggests that the mounds in the various valleys were formed in similar ways and that they have subsequently been subjected to the processes of weathering throughout more or less the same period. Their freshness in particular suggests that they have not had to endure a prolonged period of solifluction which would probably have smoothed off and subdued their clear outlines.

The third reason for interpreting the hummocky drift as the product of one stage of glaciation is that, by and large, this drift passes from one major valley system into the next without a break, or with only a slight break at an intervening watershed. Thus the widespread hummocky drift on Rannoch Moor is connected to that in Glen Lyon, which in turn passes without a break into that in Glen Lochay and Glen Dochart (more precisely upper Glen Dochart, called Strath Fillan). Only a slight break in three passes separates the mounds of lower Glen Lyon from the lateral moraines above Loch Rannoch. While to the north of Loch Rannoch there is only a very low watershed between the mounds marking the margins of the Loch Rannoch and Garry glaciers. Evidence recorded by the Geological Survey (chapters 5 and 6) and reconnaissance studies by the author indicate that the widespread hummocky drift of Rannoch Moor was left by the last glacier which moved eastwards across the Moor and used the Loch Rannoch valley as a major exit. This outflowing glacier has been named the Loch Rannoch glacier in this thesis.

The numerous mounds in Glen Dochart join those in the Loch Voil - Loch Earn valleys by two routes, the Monachyle Glen and Glen Ogle, while the Invernenty valley is a similar link between the Loch Voil and Trossachs valleys. In the appropriate chapters (11, 12) reasons have already been given for regarding the terminal moraine at Callander as marking the limit of the glaciers in the Trossachs and Loch Lubnaig valleys, which are recorded by the moundy deposits that pass into these valleys from the Loch Voil valley system. To the east the evidence of glaciers radiating from the Ben Vorlich - Stuc a'Chroin hill group is only slightly separated from that of glaciers in the Loch Lubnaig - Loch Earn areas. Near Lochearnhead the tongues of the Glen Ample, Strathyre and Glen Ogle glaciers appear to have been only slightly separated. In only one case, Glen Almond, is there a substantial break in the continuity of deposits between the valley systems. Here, the interpretation of the lateglacial sequence is based on the character and extent of the moundy deposits in the glen compared with the rather different nature of the landforms outside it (chapter 9).

The evidence of the former extent of glaciers has been employed to attempt a reconstruction of the pattern of ice sources, glacier surfaces and termini (figs. 13.1, 13.2). This has been done in each valley system largely on the basis of the evidence within that system, though taking note of closely related evidence in neighbouring valley systems. The conclusions reached have been justified chapter by chapter so that each chapter represents an independent case.

Accordingly the unanimity of the conclusions reached in all these cases supports the argument that the last stage of glaciation in each major valley system occurred during the one period. The inferred pattern of valley glaciers seems an inherently logical one, matching as it does the distributions of likely sources of great accumulation and of high ground. The reasonableness of this pattern, the similarity and continuity of the deposits throughout the area, and the presence of a single clear limit in each valley system seem to justify the proposition that the fresh hummocky drift in each valley system is the product of one stage of glaciation.

Support for the second hypothesis, that the last stage of glaciation in the thesis area occurred not later than and probably during pollen Zone III, is found to a considerable extent in the conclusions reached by other workers in the field of Scottish lateglacial history. Most of this material has already been reviewed in the discussions of previous literature (chapters 2, 8, 12) and of climate (13) and need only be outlined here.

Investigations of pollen and sediments in sites above the upper Forth valley and near Callander led J.J. Donner (1957, 1958) to conclude that the Loch Lomond and Menteith terminal moraine complexes were formed during pollen Zone III. They also showed that Loch Mahaick, 7 km east of Callander, has not been covered by glacier ice since pollen Zone I, and therefore that the last stage of glaciation in the Callander area was later. Similar studies at Drymen, in the lower Dee valley and in Skye led the Vasaris (1968) to agree with Donner.

In the vicinity of Callander J.J. Lowe has found a continuous sequence of deposits dating back to Zone I at Tynaspirit 2 km outside the Callander terminal moraine. However, in the Mollands lake immediately inside the moraine the earliest pollen-bearing deposit appears to date from a period between glacial Zone III and postglacial Zone IV when the Teith glacier had begun to retreat from the vicinity of Callander (chapter 12; appendix 1). On account of the sequence of deposits at Tynaspirit (glacial gravel - Zone I clay - Zone II peat - Zone III clay - postglacial peat) and of the dating of the earliest deposits at Mollands it is concluded that the Callander moraine was formed during pollen Zone III.

Furthermore it was argued in chapter 12 (Teith valley) that there is good morphological evidence for ascribing a Zone III age to the Callander ice limit. Firstly, the moraine lies at the mouth of the Trossachs valley, whose two neighbours southwestwards are the Loch Ard and Loch Lomond valleys. The Menteith and Loch Lomond terminal moraine complexes lie at the mouths of these valleys in positions closely comparable to that of the Callander moraine. It was suggested (chapter 12) that much of the ice flowing along the Trossachs valley to Callander was derived by diffluence from the Loch Lomond glacier, which may well have supplied much of the ice that terminated at Lake of Menteith. The dating of each terminal moraine as Zone III by stratigraphic studies (Donner, Lowe) and of the Loch Lomond and Menteith moraines by radiocarbon analyses (Sissons, 1967b) provides independent agreement with this argument.

A second morphological argument was put forward in chapter 12 in respect of the Callander ice limit. It was shown that the set of proglacial outwash terraces that runs down the Teith valley from the Callander moraine is closely related to a large gravel fan between Blairdrummond and Stirling. This fan, now buried by postglacial estuarine deposits (D.D. Kemp, 1971), appears to have been formed of river Teith gravels mainly during a lateglacial period of low sea-level. The high buried beach in the Forth valley, mapped by Sissons (1966) and Kemp (1971) and shown to have been forming whilst glacier ice stood at the Menteith moraine during Zone III, is higher than much of the fan but absent from it. Kemp considered that deposition of this beach on the fan was prevented because Teith outwash gravels were being deposited on the fan at this time. He further considered that slight dissection of the apex of the fan and redeposition farther down the fan occurred whilst the Teith outwash was being dissected into terraces. These terraces commence at the Callander terminal moraine. Thus there are several lines of evidence supporting the hypothesis that the Callander moraine was formed during pollen Zone III.

It has been shown that the glacier that terminated at Callander flowed from the Trossachs and to some extent from the Loch Voil valley systems, thus implying that the abundant moundy deposits in these valleys were formed during this period. Since the evidence given in this thesis shows that the fresh hummocky drift in the various valley systems, including these two above, is the product of one stage of glaciation, it follows from the Callander evidence that this was the Zone III stage. Likewise the evidence from Lochan nan Cat (Donner, 1962) clearly shows that no glacier ice has occupied this high-level corrie since Zone III (at the latest). Further evidence, from the Dunalastair (Balliemore) lake site just outside the Loch Rannoch ice limit (J.J. Lowe, personal communication), seems to confirm that the Loch Rannoch glacier reached its limit at the end of the lateglacial period, that is in Zone III. Pollen evidence in general (e.g. S.E. Durno, 1956) certainly indicates that none of the glacier limits described in this thesis could belong to any period later than Zone III.

At Lake of Menteith and Loch Lomond, as has been mentioned, and at Benderloch and on Mull marine shells that grew during Zone II were covered by or incorporated in glacial deposits during Zone III (Sissons, 1967b; J.D. Peacock, 1971; G.M. Gray and C.L. Brooks, 1972). These shells are proof of the readvance and of its date. On morphological evidence

S.B. McCann (1966) had earlier concluded that the ice limits at Benderloch, Loch Leven, Loch Linnhe, Loch Shiel and Loch Morar represented the Loch Lomond Readvance. J.G.C. Anderson's work (1949) on the Gare Loch ice limit (near Loch Lomond) carries the same implication. It seems entirely logical to expect that the limits in the Highland part of western Perthshire that do not happen to have been independently dated by pollen studies should have been formed in the same period as those that have been dated.

Thus the morphological evidence in the thesis area, the studies of organic and mineral sediments by Donner and Lowe, the evidence of other glacier limits to the south-west and west of the thesis area, and the radiocarbon dates obtained for shells from some of the latter, all point towards the conclusion that each limit was formed during the last stage of glaciation which occurred in pollen Zone III. This stage is called the Loch Lomond Readvance (after J.B. Simpson, 1933), but the term 'readvance' has been avoided above. The subject of 'readvance' is discussed later in this chapter.

Further support for the second hypothesis, that glacier limits in the thesis area belong to the last stage of glaciation, is contained in Sissons' studies in other parts of the Highlands. Working with A.J.H. Grant in the Lochnagar area, he found that major solifluction features exist as low as 1650 - 2300 feet (500 - 700 m) immediately outside the limits of the last glaciers in the area but nowhere inside these limits, even at much higher altitudes. Furthermore, the hummocky deposits of the last glaciers "are sharp and fresh-looking" even at the altitudes of the major solifluction forms outside the limits.

It was shown in chapter 3.F that periglacial forms are poorly developed on ground thought to have been covered by ice in the last glacial stage. Stone-banked features, blockfields, tors and solifluction sheets have developed on ground that lay above or outside the extent of the last glaciers, and some solifluction sheets occupy valley sides overrun by the last glaciers. However, no periglacial features have been identified in corries or valley heads that acted as ice sources at this time, even though these lie well above the lower limit of periglacial landforms (approximately 2200 feet, 670 m). Where hummocky drift (of the last glaciers) occupies an ice source above this altitude, it does not seem to have been modified by solifluction. It was concluded in chapter 3 that these major features (stone-banked forms, blockfields and solifluction sheets) were last active during deglaciation when much ground had been vacated but while the ablating glaciers still occupied their sources (cf. R.W. Galloway, 1961). "Since the last period of severe cold occurred in Zone III, the simplest explanation is that the [major solifluction features in the south-eastern Highlands and, by inference, in western Perthshire] were formed or further developed at this time, thus in turn implying that the glaciers are of Zone III age" (Sissons and Grant, 1972).

The third hypothesis is that the last stage of glaciation was distinct from and later than the preceding stage of ice sheet glaciation, that is the last stage was a readvance rather than the reactivation of the last ice sheet. Although in this thesis the evidence seems naturally to be most easily explained in terms of valley glaciers, a different view of lateglacial ice activity has been taken by D.E. Sugden working in the western Cairngorms (1965, 1970). Sugden maintains that during Zone III the Cairngorms were submerged by an ice sheet whose surface level exceeded 3000 feet (915 m) or even 4300 feet (1310 m) (p.215). Since such thick ice could not have been built up in this area during the short Zone III period following a Zone II period with little or no glacier ice, his hypothesis requires the persistence of an ice sheet through Zones I - II - III (p.216). Thus he arrived at "the concept of an ice sheet downwasting <u>in situ</u> with only a minor fluctuation [during Zone III] to interrupt its overall decline" (p.213).

Apart from presenting detailed morphological evidence, Sugden employs three main lines of supporting argument. Firstly he quotes the general opinion "that the distinctiveness of the hummocky moraine [such as is found in the Cairngorms] reflects a valley glacier advance following the disappearance of the last ice sheet" (p.213). Accepting that "in the Cairngorms the hummocky moraine consists of fluvioglacial landforms (eskers) associated with widespread stagnant ice" (p.213), it does not necessarily follow that "in a mountainous area stagnation on such a scale is more likely to reflect the downwasting of an ice sheet ..... than more regular glacier withdrawal characteristic of diminishing valley glaciers" (p.213). For example, Sissons has described the dead-ice deposits in the Menteith terminal moraine complex and the immense quantity of fluvioglacial deposits of presumed Zone III age that indicate widespread glacier stagnation in Glen Roy and Glen Spean (1967a, p.p.119 - 122). Furthermore, Sugden's equation of the Cairngorm 'esker' - like hummocky moraine with the hummocky moraine found in other parts of the Highlands is not necessarily justified, for the characteristics he describes are not those found in, for example, the present writer's thesis area. ("The mounds form a distinctive linear pattern of ridges ..... [which] in any one group show a tendency to originate at approximately the same altitude on a valley side" (p.207). Often the ridges run downslope from the lower ends of subglacial chutes or from the level of the highest kame terrace (p.208 - 9). He concluded that the hummocky moraines are eskers formed in association with an englacial water table). Therefore the Cairngorm hummocky moraine need be equated neither with hummocky moraine found elsewhere nor with ice sheet melting.

Sugden's second argument for an ice sheet during Zone III follows from his finding that only eight of the "high and impressive (Cairngorm) corries have supported no more than minor glaciers" since the downwasting of the Spey ice sheet (p.214). If these are equated with a major Loch Lomond Readvance elsewhere, why do a further twenty-two corries not show similar evidence? This implies that evidence of a Zone III readvance cannot be found other than in corries. However, in two papers on the adjacent Lochnagar - Mount Keen area, Sissons is able to show "that small corrie glaciers and large valley glaciers existed contemporaneously", thus implying an alternative interpretation for a Zone III readvance in the Cairngorms. He also specifies evidence in some Cairngorm valleys that supports the notion of a Loch Lomond valley glacier readvance.

Sugden's third line of reasoning is based on his acceptance of the proof of a limited Zone III readvance in western Scotland (cf. Kirk and Godwin, 1963) which, he asserts, "is not incompatible with ..... the view of a widespread cover of ice in the Cairngorm area during Zone III times. There are analogies in Scandinavia where ice caps persisted in the east after western areas had been deglaciated" (p.215). Thus an ice cap in the east could survive during Zone II whilst there was deglaciation in the west. Sissons has countered this argument as follows. "Analogies with Scandinavia are not appropriate since the climate of much of Scandinavia is (and presumably was) quite different from that of Scotland, the mountains are much higher, and the Scandinavian ice sheet was very much larger than the British ice sheet and hence took longer to decay. It is more logical to make analogies with western Scotland and to argue that, since a Zone III readvance of valley glaciers occurred there, it should have occurred in the east also" (Sissons and Grant, 1972).

Support for Sissons' rebuttal of Sugden's hypothesis is provided by the analysis of lake sediments in Loch Tarff near the south-western end of Loch Ness (Pennington and Lishman, 1971). By a comparison with the radiocarbon date from Loch Droma (Kirk and Godwin, 1963), they showed that this site in the middle of the Great Glen was probably deglaciated prior to 13,000 B.P., at least 2000 years before Zone III. In numerous sites in north-western Scotland organic remains dating back to Zone II have been found outside the Loch Lomond Readvance limits, but so far only postglacial deposits have been discovered inside (fig. 2.2; chapter 13).

Sugden's concept of a thick Cairngorm ice sheet in Zone III is directly incompatible with the present writer's evidence of the extent and thickness of ice during this last period of glaciation. Sugden considers that the Cairngorm ice sheet was "derived from the west and south-west" and that it may have had a surface gradient of 1:100 (following C.M:son Mannerfelt, 1949). The implication of Rannoch granite erratic evidence (L.W. Hinxman et al., 1923) is that much of this ice came from the Rannoch Moor area. A direct extrapolation along the 80 km distance between an ice level of over 4300 feet (1310 m) in the Cairngorms (p.215) and the Rannoch Moor area (via Loch Ericht) would indicate an ice surface level of 6900 feet (2105 m) over the latter. This is irreconcilable with the very clear evidence that a main outlet glacier from Rannoch in the last stage of glaciation terminated at 700 feet (215 m) at the eastern end of Loch Rannoch.

Apart from the criticisms made above, that there are reasons for disputing the hypothesis of a Cairngorm ice sheet existing in Zone III, there are excellent grounds for proposing that this stage involved a readvance of valley glaciers in this thesis area. In chapter 2 and earlier in this chapter it has been mentioned that the organic remains, radiocarbon dated to the last interstadial (Zone II) by Kirk and Godwin (1963), Sissons (1967b), Peacock (1971) and Gray and Brooks (1972), are proof of a readvance in Scotland during Zone III. The pollen evidence of Donner (1957, 1958), the Vasaris (1968) and Lowe (personal communication) supports this conclusion for the thesis area. There is also a great deal of morphological evidence in the thesis area that points to a valley glacier readvance. In each chapter it has been shown in some detail that the evidence of fresh hummocky drift may be accounted for in terms of valley glaciers. They appear to have flowed from high valley heads and corries along the valleys to clear termini. For example, the well developed lateral moraines of the Loch Rannoch glacier clearly delimit a valley glacier, whose terminus is equally clearly marked; the thickness and extent of this glacier are obviously much less than those of the preceding ice sheet. The calculated ice surface gradients, especially for the terminal zones of every glacier in the thesis area, are relatively steep (e.g. a fall of 450 feet in the final 3 km of the Garry, 550 feet in 3 km on the Loch Rannoch, 900 feet in 5 km on the Dochart, 400 feet in 1 km on the Ample). Such gradients are characteristic of valley glaciers and they contrast sharply with the gentle surface gradients calculated for the last ice sheet as it decayed away (chapter 13).

It has already been stated (chapters 2, 5, 6) that the Rannoch granite erratic evidence indicates a westward and eastward movement of glacier ice outwards from Rannoch Moor during the last ice sheet period. Yet the Glen Coe volcanic erratics and Rannoch granite erratics prove that the last stage of glaciation saw a through-flow from west to east across the Moor (Hinxman et al., 1923) and out of it into the Loch Rannoch valley. Comparison with the recorded striations on the hillslopes not covered by ice of the last stage confirms that the predominant directions of movement of the last ice sheet were not repeated during the later valley readvance stage when the ice in the area was much thinner.

Further evidence of the readvance is afforded by the absence of fresh hummocky drift from the valleys outside the ice limits (but within the thesis area). This contrast has been remarked on elsewhere, for example in the Lochnagar and Mount Keen areas (Sissons, in the press) and in the North-west (Sissons, 1967a). In some places there are virtually no moundy deposits for many km down-valley from the limit of the last glacier. For example, in the Earn valley there are almost no mounds for over 20 km eastwards from the three ice limits at Lochearnhead. In others there are scattered areas of very subdued mounds well to the east of and much higher than the clear hummocky drift limit, as for example on the Tummel - Lyon watershed by the Keltneyburn east of the Loch Rannoch limit. In only one case are there numerous clear mounds adjacent to and outside an ice limit, for at Callander the kames of the last ice sheet lie immediately outside the Zone III terminal moraine. This points to another contrast that, whereas obviously fluvioglacial deposits are uncommon inside the limits, they may be well developed outside, as in the Teith valley, or in the river Tay valley (J. Rose and A.G. McLellan, 1966). Sissons has reached the same conclusion in the Lochnagar - Mount Keen area.

It has been shown in this chapter that the evidence in the thesis area and in neighbouring areas of glacial deposits and their associated limits and of pollen deposits points towards one conclusion, that the Zone III period was a time of valley glacier readvance. The author's principal conclusion is that the evidence here presented shows that the limits to the fresh hummocky drift in western Perthshire represent the extent of the last valley glaciers that are correctly correlated with the Loch Lomond Readvance of pollen Zone III.

Appendix 1. Stratigraphical investigations.

A. Introduction.

It was noted in chapter 2 (C) that J.J. Donner found that lateglacial chronology can be elucidated from studying the sequence of mineral and organic layers in present or former lake sites (1957, 1958, 1962). He found that mineral matter poor in pollen was deposited during the cold periods, Zones I and III, and that a much greater concentration of organic material was deposited during the milder Zone II, Zone IV and later periods. Later work by Vasari and Vasari (1968), including detailed vegetation studies, has amply confirmed Donner's conclusion. Accordingly Donner's method was applied to this thesis area in an attempt to provide independent dating of the lateglacial sequence.

Most of the sites investigated are raised peat bogs and most lie outside the limits of the last glaciers in the thesis area. During the preparation of this thesis no facilities were available for investigating existing lakes, although it is hoped to do so in future (cf. W. Pennington and J.P. Lishman, 1971). A strengthened Hiller peat sampler with a 30 cm chamber was used for boring into the sediments and their character was assessed in the field. None of the samples was subjected to laboratory examination by the author, for Mr J.J. Lowe undertook the pollen analysis of several sites. Samples for pollen analysis were collected by means of a Hiller peat borer with a 50 cm chamber and a larger bore than the instrument used for sediment investigations. Several exploratory boreholes were made at each site in order to assess variations in the stratigraphy and to find the deepest, oldest deposits. In the following account, unless otherwise stated, the record is of the deepest known part of the site. However, because the borer is unable to penetrate more than a few cm into gravel, only soft sediments can be sampled. Consequently the thickness of a gravel layer and the nature of any underlying material could not be ascertained.

Investigations of stratigraphy were made in the vicinity of Callander, near Amulree (Glen Almond district), and in the Loch Rannoch - Loch Garry area, and five of the sites were chosen for pollen analysis by Mr Lowe. Although parallel to the writer's study, Lowe's work forms the subject of a Ph.D. thesis which will not be completed for a considerable period after submission of the present thesis. However, Mr Lowe has kindly allowed the writer to quote preliminary results in the preceding chapters. For convenience, summaries of his conclusions are presented below together with the stratigraphy of the sites.

B. Callander.

Four localities were probed in the vicinity of Callander (sheet 60). A large kettlehole at 633071 in the kettled kame terrace E was found to be less than 2 m deep and is filled with floating aquatic vegetation. This was clearly of little interest, so a neighbouring peaty valley at Mollands was explored (6206, G). This site lies within the Callander terminal moraine (X - Y - Z) and it was thought that it may have become a lake during the retreat of the Teith glacier. The lowest deposits sampled were clay, which is interpreted as lacustrine because the local till is stony, the outwash gravels of the adjacent terraces are coarse and the streams at present draining into the site deposit sand and fine gravel. Lowe interprets pollen from this clay as belonging to a period between glacial Zone III and postglacial Zone IV. Instrumental levelling of this site by the writer was related to an Ordnance Survey bench mark, itself tied to the Liverpool datum (appendix 2).

Mollands stratigraphy.

Ground level c.244 feet (74.4 m).

0.00 - 3.17 m	sphagnum peat
3.17 - 3.85 m	coarse sand, peat and grit mixture.
3.85 - 4.38 m	peat
4.38 - 4.47 m	coarse sand and grit.
4.47 - 5.18 m	peat
5.18 - 5.25 m	layers of grit or sand or peat.
5.25 - 7.32 m	peat
7.32 - 8.11 m	soft, light grey clay.
8.11 - 8.54 m	light grey clay, becoming stiffer and yellow-brown downwards.

216 feet (65.8 m): too stiff for farther penetration.

Samples for pollen analysis were subsequently taken from the lowermost 1.4 m, using the smaller Hiller borer (30 cm chamber) because of the stiffness of the deposits. The sand and grit layers are interpreted as stream deposits, the peat as normal subaerial peat, and the clay as lacustrine.

Cambusbeg.

The Cambusbeg site is a deep, peat-filled kettlehole in the kame and kettle belt formed in the deglaciation of the last ice sheet. The site lies about 1.5 km outside the

Teith glacier terminal moraine (658051, sheet 60). The kettlehole is about 300 m x 100 m in the part represented by marsh symbols on this map. At present a small stream drains through it to the Teith, and the centre of the bog is exceedingly wet, soft and unstable. A series of bores from the edge to the centre of the bog showed that the gravelly bottom of the kettlehole drops steeply away from the edge. Samples for pollen analysis were taken in the deepest central part of the bog. Provisional results of the analyses suggest that the base of the postglacial deposits lies at about 10.94 m with lateglacial material below this depth.

Cambusbeg stratigraphy.

Ground level approximately 200 feet (60 m).

0.00 - 9.00 m	wet peat.
9.00 - 9.50 m	grey-black organic-rich layer X.
9.50 - 10.00 m	X, with yellow powdery sand layers, which are thickest c. 9.57 - 8 m, c. 9.64 m, c.9.91 m.
10.00 - 10.22 m	X, with abundant small shell fragments.
10.22 - 10.25 m	yellowish-brown silty clay.
10.25 - 10.30 m	X
10.30 - 10.35 m	greyish organic silty clay.
10.35 - 10.94 m	X, with some possible shell fragments.
10.94 - 10.99 m	dark greenish-brown organic clay.
10.99 - 11.35 m	very dark grey organic-rich layer, similar to X.
11.35 - 11.42 m	light grey silty clay.

too stiff for farther penetration.

Tynaspirit.

Tynaspirit, 0.5 km south-east of Cambusbeg, is also a kettlehole largely infilled with peat (662048; fig. 12.15 shows the site). Very closely spaced trial bores showed that the gravel bottom of the kettle is very irregular. Nevertheless each bore in the centre of the bog revealed the same sequence of gravel - clay - peat - clay - peat. Pollen analysis has dated this succession as glacial gravel - Zone I clay - Zone II peat - Zone III clay - postglacial peat. The coincidence between stratigraphic and zonal boundaries is not exact but is as close as in the sites analysed by Donner (1957, 1962) and the Vasaris (1968). The clays were presumably brought in by the small stream that drains from the clayey till area immediately upstream from the kettle (cf. B.M. Shipley, 1967, and fig. 12.11). The predominance of clay deposition during the cold periods (Zones I and III) implies that there was much bare ground and probably solifluction of the till. The clays are less likely to have come from the adjacent kames for gravel and cobblestones predominate in them locally and they include a lower percentage of clay. The smaller Hiller borer was employed for the initial stratigraphic probes and the larger Hiller for obtaining samples for analysis.

Tynaspirit stratigraphy.

Ground level approximately 200 feet (60 m).

0.00 - 3.90 m	peat
3.90 - 4.18 m	peat with wood fragments
4.18 - 4.90 m	peat
4.90 - 6.06 m	sphagnum peat
6.06 - 6.37 m	grey clay
6.37 - 6.83 m	peaty gyttja

6.83 - 6.93 m	transition downwards, becoming more clayey.
6.93 - 7.00 m	grey clay.

impenetrable gravel.

Stratigraphy encountered when taking samples for pollen analysis.

0.00 - 5.68 m	peat layers.
5.68 - 6.00 m	light grey clay.
6.00 - 6.20 m	peaty gyttja.
6.20 - 6.50 m	grey clay.
6.50 - 6.70 m	gravel.

impenetrable gravel.

C. Amulree.

The site is a raised bog surrounded by occasional kames on the col between Glen Almond and Strath Braan (894336, sheet 48). The presumed limit of the last Glen Almond glacier lies 2 km to the south immediately east of Newton Bridge (8831). Around the site and to the north in the vicinity of Amulree are fluvioglacial deposits thought to date from deglaciation of the last ice sheet. Numerous probes made across the bog revealed that the base of the site is very irregular and that the lowest, earliest deposits are not present everywhere. The clay deposits are interpreted as lacustrine, for the drainage outlet to the north is impeded by kames and the gradient is slight.

Provisional results of pollen analyses (stratigraphy B) suggest that the peat is postglacial and the underlying sediments lateglacial (below 8.23 m in B). The initial stratigraphic probe was done with the smaller Hiller borer, whereas collection of samples was by the larger borer.

Amulree stratigraphy.

A. Ground level slightly less than 1000 feet (305 m).

0.00 - 5.70 m	sphagnum peat with wood fragments.
5.70 - 7.15 m	soft light grey silty clay.
7.15 - 7.35 m	stiff light grey clay.
7.35 - 7.41 m	grey silty clay with pink mottling.
7.41 - 7.67 m	stiff grey silty clay.
7.67 - 7.81 m	grey silty clay with pink mottling.
7.81 - 8.02 m	light grey silty clay.
8.02 - 8.21 m	stiff grey clay.
8.21 - 8.27 m	medium-grey clay-silt.
8.27 - 8.32 m	stiff grey clay.
8.32 - 8.70 m	medium-grey clay-silt.
8.70 - 8.84 m	grey-pink clay-silt.
8.84 - 9.30 m	pinkish-grey clay becoming pinker downwards.
9.30 - 9.40 m	pink clay.
9.40 - 9.47 m	grey clay with pink mottling.

impenetrable gravel.

The pink clay at 9.30 - 9.40 m is a dull pink, whereas any other layers with pink have pink mottling of predominantly grey clay.

B. Stratigraphy encountered when taking samples for pollen analysis.

0.00 - 8.23 m	peat.
8.23 - 9.00 m	fine light grey clay, coarsening below 8.80 m.
9.00 - 10.19 m	fine grey clay.
10.19 - 10.26 m	pinkish-grey clay.

10.26 - 10.64 m	grey clay with pink mottling.
10.64 - 10.82 m	fine grey clay.
10.82 - 11.03 m	pinkish-grey clay.
11.03 - 11.34 m	fine grey clay.
11.34 - 11.50 m	greyish-pink clay with pink mottling.
11.50 - 11.70 m	pinkish-grey clay.
11.70 - 12.00 m	grey clay; pink mottling increasing and becoming coarser downwards.

too stiff for farther penetration, gritty.

In addition to this site several others were tested in the kettles west of Amulree (8836 - 8736) and in Highland Glen Almond (sheet 48) but only very shallow peats were found, none of which was thought likely to contain lateglacial material.

D. <u>Loch Rannoch district.</u>

Three areas were explored here. The first was the small valley of Balliemore near Dunalastair to the east of Loch Rannoch (7059). It will be evident from figs. 5.1 and 5.7 that a number of boreholes were put down in a north-south line along this valley, thereby revealing a bed of silty fine sand. This appears to have been deposited in a quiet corner of a lake whilst in the main part of the lake (6858 - 7058) meltwater from the Loch Rannoch glacier was depositing coarser material. Samples for analysis were taken from the lacustrine silty sand where the deposit is thickest. The top of each borehole was instrumentally levelled, using the known water-level in Dunalastair reservoir as datum, this being tied to Newlyn datum (appendix 2).

Dunalastair stratigraphy.

Ground level 662 feet (201.8 m) O.D.

0 - 0.2 m	peat.
0.2 - 1.96 m	light grey silt.
1.96 - 2.57 m	yellowish-brown silty fine sand.

bedrock.

A sample from 0.90 m analysed by Lowe yielded a pollen spectrum provisionally dated to a period between lateglacial Zone III and postglacial Zone IV.

Lochan an Daimh.

The southern margin of this small lochan was tested at several points. The lochan had been infilled by deposits prior to c.1900 A.D. (second edition O.S. 1:10,560 sheet 37) but has subsequently been partially flooded by damming. Boring revealed that a thin layer of recent peat lies on sands and silts of the fan that has infilled the lochan. Boring below 3 m was prevented by the stiffness of the deposits. No analyses were made.

Garry - Errochty pass.

A large raised bog on the watershed between Loch Garry and Loch Errochty (6366) proved equally unproductive. Numerous bores revealed that 2 - 3 m of soft peat cover an extensive spread of sand, presumably laid down as fans from the neighbouring hillsides. Fan formation can be seen along the margins of the bog at the present day. No analyses were made here.

Appendix 2. Survey methods and interpretation of results.

A. The Teith valley.

The terraces and associated features in the Teith valley were mapped at the scale of 1:10,560 on Ordnance Survey map sheets and subsequently levelled from bench marks (Liverpool datum). During the intervening period the distal parts of kame terraces K and J became the sites of gravel extraction, so that they could not be levelled. Terraces at three localities on the left bank of the river Teith had been previously excavated and so could not be studied in this thesis (south of Cambusmore c.652052, near Torrie c.658047 and c.662044, and south-east of Drumvaich c.6703; sheet 60). The 564 spot heights obtained were plotted on 1:10,560 maps (figs. 12.2, 12.3) and further used in the construction of a series of cross-valley profiles (figs. 12.5 - 7) and a down-valley height-distance diagram (fig. 12.4) at the 1:10,560 scale. The characteristics of the height-distance method of representation have been lucidly stated by R.P. Kirby (1969), whose procedure has been followed here. It should be emphasised that the geomorphological interpretation was based on field observation and on study of the morphological maps containing the spot heights (figs. 12.2 - 3), not on the profile diagrams alone (figs. 12.4 - 7).

Heights were measured along the long axis of each proglacial terrace. This avoided occasional abandoned channels, which tend to occur along the inner edges of terraces, or backswamp depressions, as well as inner edges blurred by colluvial infill. It also avoided the degraded outer edges and levées of some. The kettled outer edges of some kame terraces were also avoided. Positions chosen for height determination were at regular intervals for ease of plotting on the maps. The scatter of spot heights on the kame terraces appears less regular than on the proglacial terraces, principally because the kame terraces slope much less regularly and are kettled. A few heights for the level of the river Teith were obtained, to place the terraces in context. In each case the water level was known to be fairly normal.

Excepting the points measured in meltwater channels, every spot height on the eskers, kame terraces and proglacial terraces was incorporated in the long-profile (fig. 12.4). No attempt was made to compute a line of best fit. The effect of using all the points is to reveal the depth of kettling, giving a profile more complicated but closer to reality than would otherwise be the case. For the sake of consistency the proglacial terrace profiles also incorporate every spot height. A simpler picture was obtained by using only the highest points along each terrace to construct fig. 12.12.

Ideally the vertical base plane for projection, which is represented by a line on the map, should follow the curving course of the river that formed each terrace. However the great majority of the kame and proglacial terraces tend to be markedly elongated, enabling a straight line to be drawn parallel with the long axis of each terrace fragment, or a curving series of short straight lines to be drawn approximating to the axis of a curvilinear terrace. The angle of bearing (relative to the National Grid) of each line was calculated and the figures placed in three groups relating to different parts of the valley: the valley downstream from the Teith - Keltie confluence; the Teith valley upstream from the confluence; and the Keltie (fig. 12.4). For each group the median and arithmetic mean values were calculated. In the group of terraces downstream from the confluence the median was 120°, the mean 119.8°. 120° was accepted as the base line, since in addition it corresponds to the overall alignment of the valley. For the Keltie terraces the median was 154°, the mean 168°. For the Teith above the confluence the median was 163.5°, the mean 159°, whilst for the latter two groups the median of all the values was 163°, and the mean 160.5°. A compromise value of 161.5° was adopted as the bearing of the base line for the Teith and Keltie above their confluence. This bearing corresponds to the general alignments of both valleys, of their terraces and of the present river courses. Spot heights were projected at 90° on to the base lines to create the long-profile diagram (fig. 12.4), and at 90° on to the appropriate member of a series of cross-profile lines, themselves drawn at 90° to the base line (figs. 12.5 - 7). Whilst it is true that as the long axis of a feature deviates from the base line, so "the apparent slope of the terrace will be steeper than the measured slope" (Kirby, 1969, p.5), this small error is acceptable because the relationships between the kame terraces and adjacent proglacial terraces are best illustrated with a single base line. The profiles could not be presented on one graph if a separate base line was used for each terrace.

B. Kinloch Rannoch - Dunalastair.

The first period of levelling of the outwash and associated features near Kinloch Rannoch provided a much wider and in places denser coverage of spot heights than fig. 5.1 suggests. Unfortunately no bench mark lists were available at this time and only one bench mark (near letter N, fig. 5.1) of reliably known height was discovered. The remaining bench marks on the second edition 1:10,560 map sheets had either been destroyed, moved or lost to view. Partly in consequence of this it was not realised until the end of this period that there was a substantial error in the instrument that could not be corrected in the field. Subsequently another series of points (most are shown on fig. 5.1 and are marked with a cross) was levelled using an instrument of proven accuracy. (The altitude of the bench mark previously used is recorded as 0.46 foot (0.14 m) lower with respect to Newlyn datum than it was to the earlier Liverpool datum.) This series stretched from areas N to Q, so as to include most of the long-profile and a number of bench marks previously observed but either considered to be of doubtful altitude or of unknown altitude. Bench mark lists had become available by this time. Thus it was possible to check on the heights previously ascribed to features in the vicinity of this series and on the heights of several temporary bench marks. The levels of the water in Loch Rannoch and in Dunalastair reservoir for the earlier period were obtained from the North of Scotland Hydro-Electric Board as a check on the surveyed heights of adjacent areas.

It was confirmed thereby that all the points measured east of Kinloch Rannoch on the north bank were seriously in error (in excess of 1 foot, 0.3 m) but that the later series of levelled points corresponded very closely to the earlier in the area west of Dunalastair reservoir. (Numerous temporary bench marks provided an additional check in the area). Although most points probably have a small error (less than 1 foot, 0.3 m), this is no greater than the errors inherent in the roughness of the ground due to coarse gravel, thick vegetation, deep ploughing, and soft peat (in channel B). Accordingly the spot heights west of Dunalastair reservoir have been accepted, although each is represented as a value covering a small area, not a specific point; this avoids crediting the heights with too great an accuracy.

The long-profiles on fig. 5.2 follow the curve of each feature shown, the two of the outwash surface matching the adjacent valley side and the third running the length of channel B. Consequently these represent as nearly as is possible the maximum gradient of the features without exaggeration. Although this means that the profiles cannot be compared with respect to the same base line, the purpose of the diagram is to illustrate more clearly certain relationships known from the map (fig. 5.1). No interpretation has been made that does not derive from this map. The reservations attached to the interpretation of the long-profile diagram (fig. 5.2) do not apply to the cross-profiles (figs. 5.3 - 5.7) for each is based on one straight base line.

The lake site at Balliemore was separately studied (fig. 5.7). The tops of boreholes were levelled from the datum of Dunalastair reservoir water level, this level being known to within 0.02 m.

The total number of spot heights regarded as sufficiently accurate is 155.

C. <u>Loch Tulla.</u>

After mapping the Loch Tulla area every terrace-like feature was marked out with surveyor's poles and levelled with respect to bench marks (Newlyn datum). The points chosen were along the long axis of each feature to avoid the degraded front edge or aggraded rear edge. Contemporary mass movement and stream erosion is everywhere evident on all but the 815 feet (248 m) Parallel Road north of Loch Tulla. On fig. 6.3 the spot heights on the southern side of the valley have been located with respect to a series of pylons lying below the terraces. On the northern side the relationships between the Roads and prominent stream courses, rock outcrops and breaks of slope were used to position the series of spot heights. Inevitably the points could not be identified with absolute precision but, as they refer to horizontal or nearly horizontal features, this is no practical disadvantage.

At the scale used in fig. 6.3 the width of the features is so small that it is sufficient to represent them by a line joining the measured heights. Where a feature was observed to be continuous it is joined by a continuous line. Where one fragment was obviously partnered by another a short distance away at the same height they are joined by a dotted line. Where only an altitude appears on the map, the feature it represents is no longer than and probably shorter than the area of ground represented by the numbers. A total of 140 spot heights was obtained for the Parallel Roads of Loch Tulla.

Agassiz, L. 1840 On the evidence of the former existence of glaciers in Scotland, Ireland and England. Proc. geol. Soc., Lond., 3, 327-332.

Ahlmann, H.W:son. 1948 Glaciological research on the North Atlantic coasts. R. geogr. Soc. Res. Ser., 1, 83 pp.

Anderson, J.G.C. 1949 The Gare Loch Readvance moraine. Geol. Mag., 86, 239-244.

Bailey, E.B. et al. 1916 The Geology of Ben Nevis and Glen Coe. Mem. geol. Surv. Gt. Br.

Boulton, G.S. 1970 On the deposition of subglacial and melt-out tills at the margins of certain Svalbard glaciers. J. Glaciol., 9, 231-245.

Brown, Rev. T. 1870 On the old river terraces of the Earn and Teith, viewed in connection with certain proofs of the antiquity of Man. Trans. R. Soc. Edinb., XXVI, 149-176.

Buckland, W. 1840 On the former existence of glaciers in Scotland. Edinb. New phil. J., 30, 194-198.

Buckland, W. 1842 Memoir on the evidences of glaciers in Scotland and the North of England. Proc. geol. Soc., 111, 332.

Chambers, R. 1848 Ancient Sea Margins.

Chambers, R. 1853 On glacial phenomena in Scotland and parts of England. Edinb. New phil. J., 54, 229-281.

Charlesworth, J.K. 1955 Late-glacial history of the Highlands and Islands of Scotland. Trans. R. Soc. Edinb., 62, 769-928.

Clapperton, C.M. 1969 Channels formed by the superimposition of glacial meltwater streams, with special reference to the East Cheviot Hills, Northeast England. Geogr. Annlr., A,50, 207-220.

Clark, R.P.K. 1969 Kettle holes. J. Glaciol., 8, 485-6.

Conolly, A.P. and Dahl, E. 1970 Maximum summer temperature in relation to the modern and Quaternary distributions of certain arctic-montane species in the British Isles. in Walker, D. and West, R.G. Studies in the vegetation history of the British Isles. Cambridge.

Donner, J. J. 1957 The geology and vegetation of Late-glacial retreat stages in Scotland. Trans. R. Soc. Edinb., LXIII, 221-264.

Donner, J. J. 1958 Loch Mahaick, a Late-glacial site in Perthshire. New Phytol., 57, 183-186.

Donner, J. J. 1962 On the post-glacial history of the Grampian Highlands of Scotland. Soc. sci. Fenn., Comm. biol., 24, 29 pp.

Durno, S. E. 1956 Pollen analysis of peat deposits in Scotland. Scott. geogr. Mag., 72, 177-187.

Embleton, C. and King, C. A. M. 1968 Glacial and Periglacial Geomorphology.

Forbes, J. D. 1845 Notes on the topography and geology of the Cuchullin Hills in Skye, and on the traces of ancient glaciers which they present. Edinb. New phil. J., 40, 76-99.

Francis, E. H. et al. 1970 Memoir on the geology of the Stirling district. Mem. geol. Surv. Gt. Br.

Galloway, R. W. 1961 Solifluction in Scotland. Scott. geogr. Mag., 77, - 75-87.

Geikie, A. 1863 On the phenomena of the glacial drift of Scotland. Trans. geol. Soc. Glasg., 1, 1-190.

Geikie, A. 1901 The scenery of Scotland viewed in connection with its Physical Geology. (3rd. ed.)

Geikie, J. 1894 The Great Ice Age. Third edition.

Gilbert, G. K. 1914 The transportation of debris by running water. U.S. geol. Surv. Prof. Pap., 86.

Gjessing, J. 1960 Isavsmeltningstidens drenering, dens forlop og formdannende verkning i Nordre Atnedalen. The drainage of the deglaciation period, its trends and morphogenetic activity in northern Atnedalen (east-central southern Norway). Ad Novas, 3; 441-485 (English summary).

Godwin, H. 1956 The History of the British Flora.

Godwin, H. 1961 Radio-carbon dating and Quaternary history in Britain. Proc. R. Soc. Lond., B, <u>153</u>, 287-320.

Godwin, H. and Willis, E.H. 1961 Cambridge University natural radiocarbon measurements. Radiocarbon, <u>3</u>, 60-76.

Gray, J.M. and Brooks, C.L. 1972 The Loch Lomond Readvance moraines of Mull and Menteith. Scott. J. Geol., in the press.

Gregory, J.C. 1926 The Parallel Roads of Loch Tulla. Trans. geol. Soc. Glasg., <u>XVII</u>, 91-104.

Gregory, J.W. 1926 The Scottish kames and their evidence on the glaciation of Scotland. Trans. R. Soc. Edinb., <u>LIV</u>, 395-432.

Groom, G.E. 1959 Niche glaciers in Bünsow land, Vestspitsbergen. J. Glaciol, <u>3</u>, 368-376.

Hinxman, L.W. <u>et al.</u> 1905 The geology of the country round Blair Atholl, Pitlochry and Aberfeldy. Mem. geol. Surv. Gt. Br.

Hinxman, L.W. <u>et al.</u> 1923 The geology of Corrour and the Moor of Rannoch. Mem. geol. Surv. Gt.Br.

Holder, C-G. 1957 Deglaciations förloppet i Torneträsk - området efter senaste nedisningsperioder med vissa tillbaklickar och regionala jamförelser. Geol. För. Stockh. Förh., 79, 291-528.

Jack, R.L. 1876 Notes on a till or boulder clay with broken shells, in the lower valley of the river Endrick, near Loch Lomond, and its relation to certain other glacial deposits. Trans. geol. Soc. Glasg., <u>5</u>, 5-25.

Jamieson, T.F. 1862 On the ice-worn rocks of Scotland. Quart. J. geol. Soc., <u>18</u>, 164-184.

★ Kemp, D.D. ★ 1971 The stratigraphy and sub-carse morphology of an area on the northern side of the river Forth between the Lake of Menteith and Kincardine-on-Forth. Ph.D. thesis, Edinburgh.

King, R.B. 1971 Boulder polygons and stripes in the Cairngorm mountains, Scotland. J. Glaciol., <u>10</u>, 375-386.

King, R.B. Lobes in the Cairngorm Mountains, Scotland. Biul. Peryglac., <u>21</u>, in the press.

Kirby, R.P. 1969 Morphometric analysis of glaciofluvial terraces in the Esk basin, Midlothian. Trans. Inst. brit. Geogr., 48, 1-18.

Kirk, W. and Godwin, H. 1963 A late-glacial site at Loch Droma, Ross and Cromarty. Trans. R. Soc. Edinb., 65, 225-249.

Kuenen, Ph.H. 1953 Significant features of graded bedding. Bull. Am. Ass. Petrol. Geol., 37, 1044-1066.

Linton, D.L. 1940 Some aspects of the evolution of the rivers Earn and Tay, part 2. Scott. geogr. Mag., 56, 69-79.

Linton, D.L. 1949 Watershed breaching by ice in Scotland. Trans. Inst. brit. Geogr., 15, 1-15.

Linton, D.L. 1957 Radiating valleys in glaciated lands. Tijdschr. K ned. aardrijksk. Genoot, 74, 297-312.

Linton, D.L. 1959 Morphological contrasts between eastern and western Scotland. In Geographical Essays in Memory of Alan G. Ogilvie, edited by R. Miller and J.W. Watson, Edinburgh, 16-45.

Linton, D.L. 1962 Glacial Erosion on soft-rock outcrops in Central Scotland. Biul. Peryglac., 11, 247-257.

Linton, D.L. 1963 The forms of glacial erosion. Trans. Inst. brit. Geogr., 33, 1-28.

Linton, D.L. and Moisley, H.A. 1960 The origin of Loch Lomond. Scott. geogr. Mag., 76, 26-37.

Manley, G. 1949 The snowline in Britain. Geogr. Annlr., 31, 179-193.

Manley, G. 1951 The range and variation of the British Climate. Geogr. J., 117, 43-68.

Manley, G. 1952 Climate and the British Scene. Glasgow.

Manley, G. 1959 The lateglacial climate of N.W.England. Lpool. Manchr. geol. J., 2, 188-215.

Manley, G. 1964 The evolution of the climatic environment. In the British Isles: a systematic geography, edited by J.W. Watson and J.B. Sissons, 152-170, Edinburgh.

Manley, G. 1971 Scotland's semi-permanent snows. Weather, 26, (11), 458-471.

Mannerfelt, C.M:son 1949 Marginal drainage channels as indicators of the gradients of Quaternary ice caps. Geogr. Annlr., 31, 194-9.

Mathieson, J. and Bailey, E.B. 1925 The glacial strandlines of Loch Tulla. Trans. Edinb. geol. Soc., 11, 193-9.

Milne-Home, D. 1847 On the Parallel Roads of Lochaber, with remarks on the change of relative levels of sea and land in Scotland. Edinb. New phil. J., 43, 339-364.

Milne-Home, D. (alias Milne, D.) 1849 On the Parallel Roads of Lochaber, with remarks on the change of relative levels of sea and land in Scotland, and on the detrital deposits in that country. Trans. R. Soc. Edinb., 16, 395-418.

Milne-Home, D. 1871 The Estuary of the Forth.

Mitchell, G.F. 1952 Lateglacial deposits of Garscadden Mains, near Glasgow. New Phytol., 50, 277-286.

Movius, H.L. 1942 The Irish Stone Age. Cambridge.

Murray, Sir J. and Pullar, L. 1910 Bathymetrical survey of the Scottish freshwater lochs. 6 volumes. Edinburgh.

McCann, S.B. 1966 The limits of the late-glacial highland, or Loch Lomond, readvance along the west Highland seaboard from Oban to Mallaig. Scott. J. Geol., 2, 84-95.

McKenzie, G.D. 1969 Observations on a collapsing kame terrace in Glacier Bay, south-eastern Alaska. J. Glaciol., 8, 413-425.

Maclaren, C. 1849 On grooved and striated rocks in the middle region of Scotland. Edinb. New. phil. J., 47, 161-182.

Macnair, P. 1908 The geology and scenery of the Grampians and the valley of Strathmore. 2 vols., Glasgow.

North of Scotland Hydro-Electric Board Borings and geophysical surveys part III, 44/01/5 (late 1940's).

Nye, J.F. 1952 The mechanics of glacier flow. J. Glaciol., 2, 82-93.

Okko, V. 1955 Glacial drift in Iceland. Bull. Commn. géol. Finl.

Paterson, W.S.B. 1969 The physics of glaciers. Oxford.

Peach, B.N. and Horne, J. 1910 The Scottish lakes in relation to the geological features of the country. in Murray, Sir J. and Pullar, L. Bathymetrical survey of the Scottish freshwater lochs, 1, 439-513.

Peacock, J.D. 1967 West Highland morainic features aligned in the direction of ice flow. Scott. J. Geol. 3 372-373.

Peacock, J.D. 1971 Marine shell radiocarbon dates and the chronology of deglaciation in western Scotland. Nature, Physical Science, 230, 43-45.

Pennington, W. 1947 Lake sediments of Windermere. Phil. Trans. R. Soc., B, 233, 137-175.

Pennington, W. 1970 Vegetation history in the north-west of England: a regional synopsis. in Walker, D. and West, R.G. (eds.). Studies in the vegetation history of the British Isles. Cambridge.

Pennington, W. and Lishman, J.P. 1971 Iodine in lake sediments in Northern England and Scotland. Biol. Rev., 46, 279-313.

Penny, L.F. 1964 A review of the last glaciation in Great Britain. Proc. Yorks. geol. Soc., 34, 387-411.

Pettijohn, F.J. 1957 Sedimentary Rocks. New York.

Price, R.J. 1963 A glacial meltwater drainage system in Peeblesshire, Scotland. Scott. geogr. Mag., 79, 133-141.

Price, R.J. 1969 Moraines, sandar, kames and eskers near Breiðamerkurjökull, Iceland. Trans. Inst. brit. Geogr., 46, 17-43.

Ramsay, A.C. 1862 On the glacial origin of certain lakes in Switzerland, the Black Forest, Great Britain, Sweden, North America and elsewhere. Quart. J. geol. Soc., 18, 185-204.

Rose, J. and McLellan, A.G. 1966 Landforms of eastern Perthshire. Scottish Field Studies Ass., 14-29.

Shipley, B.M. 1967 The soils of Cambusmore estate, Callander, Perthshire. Unpublished report, Macaulay Institute for Soil Research.

Simpson, J.B. 1933 The late-glacial readvance moraines of the Highland border west of the River Tay. Trans. R. Soc. Edinb., 57, 633-645.

Sissons, J.B. 1966 Relative sea-level changes between 10,300 and 8,300 B.P. in part of the Carse of Stirling. Trans. Inst. brit. Geogr., 39, 19-29.

Sissons, J.B. 1967a The Evolution of Scotland's Scenery. Edinburgh.

Sissons, J.B. 1967b Glacial stages and radiocarbon dates in Scotland. Scott. J. Geol., 3, 375-381.

Sissons, J.B. The last glaciers in part of the south-east Grampians. Scott. geogr. Mag., in the press.

Sissons, J.B., Cullingford, R.A.C. and Smith, D.E. 1966 Late-glacial and post-glacial shorelines in south-east Scotland. Trans. Inst. brit. Geogr., 39, 9-18.

Sissons, J.B. and Grant, A.J.H. 1972 The last glaciers in the Lochnagar area. Scott. J. Geol. in the press.

Smith, D.E. 1965 Late and postglacial changes of shoreline on the north side of the Forth valley and estuary. Ph.D. thesis, Edinburgh.

Sugden, D.E. 1965 Aspects of the glaciation of the Cairngorm Mountains. D. Phil. thesis, Oxford.

Sugden, D.E. 1970 Landforms of deglaciation in the Cairngorm Mountains, Scotland. Trans. Inst. brit. Geogr., 51, 201-219.

Sugden, D.E. 1971 The significance of periglacial activity on some Scottish mountains. Geogr. J., 137, 388-392.

Thorarinsson, S. 1938 The ice-dammed lakes of Iceland with particular reference to their values as indicators of glacier oscillations. Geogr. Annlr., 21, 216-42.

Vasari, Y. and Vasari, A. 1968 Late - and postglacial macrophytic vegetation in the lochs of Northern Scotland. Acta Botanica Fennica, 80, 120 pp.

Walker, D. 1966 The late Quaternary history of the Cumberland Lowland. Phil. Trans. R. Soc. B, 251, 1-210.

Walker, F. 1961 Tayside Geology. Dundee.

Wilson, J.S.G. 1888 A bathymetrical survey of the chief Perthshire lochs and their relation to the glaciation of that district. Scott. geogr. Mag., IV, 251-258.

Wright, W.B. 1914; 1937 The Quaternary Ice Age. London.

*Jamieson, T.F. 1863 On the Parallel Roads of Glen Roy, and their place in the history of the glacial period. Quart. J. geol. Soc., 19, 235-259.