THE GLACIATION AND DEGLACIATION OF UPPER NITHSDALE AND ANNANDALE

BY

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TO MY MUM AND DAD, FOR EVERYTHING

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SUMMARY

TITLE. "The Glaciation and Deglaciation of Upper Nithsdale and Annandale".

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Introduction.

The purpose of this thesis is to examine the glacial geomorphology of an area in the central Southern Uplands. By detailed examination of glacially and fluvioglacially eroded landforms and glacial and fluvioglacial depositional forms, the sequence of events and processes at work during the last major period of glaciation and deglaciation can be reconstructed.

Recent research work, Price (1961), Clapperton (1967), McLelland (1967) and Holden (1977), in adjacent areas has virtually encircled Upper Nithsdale and Annandale. As a result, implications regarding the glacial history of the area had been made from a variety of sources. However, little detailed study of the glacial and fluvioglacial landforms and deposits to be found here had been carried out. Consequently, the purpose of the thesis was two-fold,

a) to ascertain the glacial history of an area only previously examined in a perfunctory fashion, mainly during the early decades of the twentieth century.
b) to attempt to bring together previous research and provide a unified theory for the build-up outward movement and dissipation of the laste ice sheet to cover a large part of Southern Scotland.

Procedure.

A wide variety of literature was examined during the course of the study period. Accounts making direct reference to Upper Nithsdale and Annandale are scarce. Consequently, a strong emphasis was placed on the examination of literature pertainging to glacial and/...

and fluvioglacial conditions and processes in adjacent areas and similar upland regions elsewhere, both in Britian and abroad. Reference was also made to methodology used in a variety of glacial geomorphological studies.

Large - scale maps (1 : 10,560) displaying the glacial geomorphology of the thesis area were compiled after consultation of borehole records, air photographic coverage, and detailed fieldwork examination of both the landforms and deposits to be found in Upper Nithsdale and Annandale. The total amount of fieldwork exceeded 8 months and was carried out mainly during the summers of 1977 and 1978. In both fieldwork seasons till fabric analysis were completed and samples brought back to the laboratory for further analysis. Also during 1977, 3 weeks was spent in south-east Iceland examining comtemporary upland glaciers.

Conclusions

1) All of the evidence in Upper Nithsdale and Annandale indicates that the last major ice sheet to submerge the entire area built up during the Late-Devension, approximately 25,000 years B.P.
2) Between 25,000 years B.P. and approximately 18,000 years B.P. ice originating from local dispersal centres in the Tweedsmuir and Lowther Hills, and beyond the western boundary of the thesis area in the uplands surrounding Carinsmore of Carsphairn, became confluent over Upper Nithsdale and Annandale and completely covered the landscape.
3) At the ice sheet stage, the dominant direction of ice movement was south/south-eastwards across the thesis area.

4) The period of deglaciation and dissipation of the ice sheet was dominated by the varying regional importance of ice from each of the 3 main centres.
5) During the deglaciation period the development of extensive fluvioglacial landform assemblages depended strongly upon the interaction of glaciological with underlying relief conditions.
6) From 18,000 years B.P. to approximately 10,000 years B.P. the deglaciation of the area was completed.
7) After the main period of deglaciation there was a return to colder conditions over the higher parts of the thesis area, between approximately 11,000 years B.P. and 10,000 years B.P., and small glaciers were established/re-established in the Lowther and Tweedsmuir Hills.

John A. May, B.Sc.
January, 1981.

DECLARATION

I declare that the following research entitled, "The Glaciation and Deglaciation of Upper Nithsdale and Annandale is the product of my own work and has not been accepted for a higher degree at any other university.

John A May

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

The aim of this thesis is a comprehensive study of the glacial geomorphology of a limited area in the Southern Uplands of Scotland. The term "glacial geomorphology", embraces both the processes and the results of erosion and deposition arising from the presence of an ice mass on the landscape.

The former existence of such an ice mass is clearly shown by the abundant evidence of both glacial and associated fluvioglacial landforms and deposits. By the accurate mapping of these features, as found today in northern Dumfries and Galloway and southern Strathclyde, comparisons of form and distribution can be made with known areas of contemporary glaciation. As a result, a greater knowledge and more accurate understanding of the condition and extent of the last ice mass over the central Southern Uplands will be obtained for a variety of stages in its build up and dissipation.

It is only by adopting an all encompassing approach and including both the periods of glaciation and deglaciation, that a full understanding of the various processes at work during the several thousand years that ice directly influenced the thesis area, resulting in the fossilised glacial landscape of Upper Nithsdale and Annandale at the present day, can be obtained.

1.2 BACKGROUND TO THE STUDY

"In keeping with the rest of South Scotland, Dumfriesshire is practically virgin territory for the glacial geomorphologist." (Stone, 1957, P53). Since this date, a number of detailed studies concerning evidence of former glaciation have been carried out in the Southern Uplands and their associated lowlands.

Price (1961) studied an area in Peebleshire, Clapperton (1967) an area in Roxburgh and Selkirk, while McLellan (1967) and Holden (1977) worked in Central Lanarkshire and Central Ayrshire respectively. Despite this insurgence of modern geomorphological ideas into Southern Scotland in the last two decades, much of Dumfriesshire has remained apparently shunned by the glacial geomorphologist. Indeed, recent research work has virtually encircled Upper Nithsdale and Annandale, with the result that implications regarding directions of ice movement and ice activity generally within this area have been made from a variety of sources, but until now little detailed study of the glacial landforms and deposits to be found here has been carried out. Consequently, this research was undertaken in an attempt to bring together previous research and hopefully provide a unified theory for the build up, outward movement and wastage of the last ice sheet to cover a large part of Southern Scotland.

The thesis area was systematically mapped in detail and the results analysed in the light of the most recent glacial geomorphological/...

geomorphological concepts and techniques, obtained by research in areas both presently undergoing and having formerly undergone modification by glacial ice. Developments in both areas have shown the benefits that can be gained by the use of modern techniques such as aerial and satellite photography, drift analyses, radiometric dating, pollen analyses, etc., when examining the sequence of events that characterise the glaciation and deglaciation of any particular region. (APPENDIX I, II, III).

1.3 UPPER NITHSDALE AND ANNANDALE - LOCATION AND EXTENT

Scotland falls very simply into a threefold division on the basis of morphological and geological considerations; the Highlands, the Central Lowlands and the Southern Uplands. On both sides, the Central Lowlands are bounded by a series of discontinuous faults which run diagonally from south-west to north-east across the country and separate this region from the uplands to the north and south. These faults are known collectively as the Highland Boundary fault in the north and Southern Uplands fault in the south. As the thesis area lies almost completely to the south of this latter demarcation on the landscape, it is contained within the hilly land of Southern Scotland, and indeed occupies 725 km^2 of the Central Southern Uplands in the vicinity of the Lowther Hills (Fig. 1.1).

The boundary lines delimiting the thesis area are complex. (Fig. 1.2). The eastern boundary is represented by the Borders/Dumfries and Galloway Regional boundary, until its/...

its junction with the north-south grid line NT 20, at grid reference NT 200 083, whereafter the regional boundary is replaced by this linear demarcation. (Fig. 1.2).

The northern boundary to the thesis area can be divided into three portions. The eastern portion is again represented by the Borders/Dumfries and Galloway Regional boundary until it reaches NT 047 140, where it is replaced by the east-west grid line NS/NT 14 for 25 km, depicting the central portion of the northern boundary. The western portion of the boundary follows the course of the Crawick Water for a short distance, linking grid line NS 14 to NS 17, the latter continuing westwards to its junction with the Strathclyde/ Dumfries and Galloway Regional boundary. (Fig. 1.2).

Similarly, the western boundary can also be divided into three portions. The northern portion is represented by the aforementioned Strathclyde Regional boundary, the central portion links several local hill crests to grid reference NS 800 050, whereafter the north-south grid line NS 80 depicts the southern portion of the limit. (Fig. 1.2).

The southern delimitation of the thesis area is principally represented by the east-west grid line NS/NT 00. However, along the central portion of this limit the boundary locally juts further south for a short distance following a course which links several hill crests, but returns northwards to the grid line along the north-west boundary to the Forest of Ae (Fig. 1.2). The main settlements contained within this area are Kirkconnel, Sanquhar, Mennock, Wanlockhead, Enterkinfoot,/...

Enterkinfoot, Durisdeer, Moffat and Beattock. National grid lines were used to demarcate parts of the thesis area in order to keep the scope of the study within manageable proportions. However, the shortage of natural physical boundaries in no way detracts from the significance of this area in the context of the Southern Uplands as a whole.

The central Southern Uplands (in effect the thesis area) are believed by Ogilvie (1952), to represent a separate physical entity between the contrasting landscapes to the south-west and north-east. To the south-west is found the highly dissected, rugged topography associated with the harsh grandeur of the granite intrusions of Galloway. The highest peak in Southern Scotland, Merrick (842 m.o.d.), is found here and several other peaks exceed 700 m.o.d.

To the north-east is the more open and smoothly rounded landscape of Tweedale, often regarded as characteristic of the Southern Uplands as a whole. In this area the highest hills lie near the headwaters of the Tweed and Annan, where Broad Law, White Coomb, Hart Fell and other summits all exceed 700 m.o.d. in altitude. The thesis area thus incorporates part of both of these very different landscapes and as such is distinctive within the Southern Uplands as a whole.

1.4 UPPER NITHSDALE AND ANNANDALE - GEOLOGY AND RELIEF

"The Southern Uplands are remarkable for an extraordinary complexity of geological structure. But this complexity is/...

is so uniform in its character, and so widespread in its distribution that it produces results on the topography such as might be expected only from a much simpler arrangement of the rocks " (A. Geikie, 1901, P 310). It would appear that Geikie was referring to the previously mentioned smooth, rounded landscape which is dominant in the thesis area. Two-thirds of a century later, the explanation for this "smooth and rounded topography" remained basically the same. Sissons (1976) stated,"..... the typical Southern Uplands scenery of rounded hills and smooth slopes..... relate largely to the rapid lithological variations and often steep dip that cause individual beds to have narrow outcrops that have not favoured the production of large structurally-controlled features. Weathering of these rocks rarely results in the production of boulders, but instead produces mainly small flattish stones and lesser debris that contribute further to the rounded appearance " (P 8). Clearly therefore, a detailed account of the underlying geology is inherent in any description of landscape in the thesis area.

It can be seen from figure 1.3 that the greater part of the area is underlain by strata of Lower Palaeozoic age. These Ordovician and Silurian sediments, whose complex stratigraphy was first studied on the basis of graptolite successions (Lapworth, 1878, P240 - 346) are believed to consist of alternating steeply dipping and horizontal beds which together suggest,"...... a series of monoclines (or grossly asymmetrical anticlines)" (Craig, 1965, P 220). In addition, the beds have been extensively faulted. Together, the folding and faulting, both/....

both of which occurred during the Caledonian orogenic period, imparted a strong south-west to north-east trend upon the structures of the thesis area.

The older Ordovician rocks outcrop mainly in the western part of the thesis area, in the uplands flanking Nithsdale. These consist mainly of greywackes, grits, shales and siltstones of Llandeilo and Caradoc age. However, there was also limited contemporary volcanic activity, Bail Hill in the Lowther foothills to the north-east of Kirkconnel consisting of vent agglomerates also of Caradoc age (Fig. 1.3). The Ordovician strata are succeeded stratigraphically by the Silurian, which underlie more than half the thesis area (Fig. 1.3). Indeed, the definition of the Ordovician/Silurian boundary within the British Isles was moved from,".....Llandovery in Wales to Dobb's Linn, near Moffat, because of the fact that there is no hint of unconformity here and a complete sequence representing all of the Upper Ordovician and Lower Silurian graptolite zones is exposed" (Cocks, Holland, Rickards and Strachan, 1971, P 104). The Silurian strata, having accumulated in the same type of deep-water environment as the Ordovician, are basically similar in character and again consist for the most part of greywackes, grits, black shales, mudstones and siltstones. The Silurian succession, like the Ordovician, is also divided on the basis of graptolite zones, rocks of Llandovery and Wenlock age dominating in the thesis area. Only the older series of the Silurian succession are present as a result of uplift and associated erosion of the Lower Palaeozoic rocks in Late Silurian - Early

Devonian/...

Devonian times. These final spasms of the Caledonian orogeny resulted in the initiation of two major north-east to south-west trending fault-lines in the thesis area, in addition to reinforcing the characteristic "grain" of the topography previously referred to.

A section of the Southern Uplands Fault, which extends from Dunbar to 30 km south of Girvan, is found in the extreme north-west of the thesis area (Fig. 1.3). However, only a very small part of the area studied lies on the north-western, downthrown side of this normal fault, which may have been re-activated as recently as the Pleistocene (Lumsden and Davies, 1965). The second major tectonic feature initiated at this time is found further east and extends for 20 km down the length of Moffatdale. However, this fault has involved strike-slip and not normal displacement.

The uniform lithology of the Lower Palaeozoic strata generally, while lending a homogeneous character to the upland terrain, has helped little in the determination of former directions of ice movement by the study of distinctive erratics in the glacial deposits.

Both extrusive and intrusive igneous rocks of Devonian age are found in the thesis area, but are of limited extent (Fig. 1.3). Andesites,basalts and lava conglomerate are found solely on the downthrown side of the Southern Uplands Fault, while a sill of granodiorite outcrops in the centre of the area along a ridge crest in the Lowther Hills, Similar granodioritic intrusions are found outside of the thesis/...

thesis area at Loch Doon, Cairnsmore of Fleet, Cairnsmore of Carsphairn, Crifell and Spango. However, unlike the more extensive Lower Palaeozoic rocks, these limited Devonian outcrops are important as sources of distinctive erratics by which ice movement into and across the thesis area and over much of the Southern Uplands generally can be determined, (Charlesworth, 1926a; Simpson and Richey 1936; Eyles et al, 1949; Sissons, 1967a).

Carboniferous deposits are restricted to two outliers in the Nith Valley, at Sanquhar and Thornhill, (Fig. 1.3). "Throughout Britain, a three-fold classification of the sequence of rocks which constitute the Carboniferous system, based mainly on lithology has been adopted. The Carboniferous Limestone series at the bottom is succeeded by the Millstone Grit Series which, in turn, passes up into the Coal Measures" (Greig, 1971, P 61).

The deposits of the Nith Valley are predominantly of Upper Carboniferous age and several suggestions have been put forward to explain their occurence. Trueman (1947), suggested that during Coal Measure times even the Southern Uplands, which formed a barrier between the two main depositional areas (Midland Valley and Northumbrian trough) in the Lower Carboniferous, finally became submerged, as evidenced by the full Coal Measures development at Sanquhar and Thornhill. However, Davies (1970) believed that during Lower Carboniferous times access to the Nith Valley from the depositional trough of the Midland Valley was restricted and postulated that movements along the Southern Uplands Fault (George, 1960), were/...

were the controlling factors that influenced deposition in this area. Whatever the exact reason, Coal Measure deposits are over 600m thick in Sanquhar, but thin in the direction of Thornhill, where only 150m are present. The deposits in both areas however, take the form of cyclic developments of sandstones, siltstones, mudstones, coals and seatclays and are extensively faulted. In parts of the Upper Coal Measure deposits at Sanquhar, secondary reddening by oxidation has taken place, but at Thornhill the effects of oxidation were more severe, removing coals which may have been present in the cyclic sequence originally, as well as giving rise to secondary reddening of the associated strata.

In addition to sedimentary deposition,there is also limited evidence of igneous activity in the thesis area during the Carboniferous period. In particular, it is now believed that "Permian" basaltic lavas (Simpson and Richey, 1936), associated with the Sanquhar and Thornhill basins are in fact of Carboniferous age (Mykura, 1965).

Towards the end of the Carboniferous and before the deposition of the earliest New Red Sandstone strata, there was a period of non-deposition, while the rocks of Southern Scotland were folded and faulted by the earth movements of the Armorican orogeny. These earth movements were responsible for the oxidation of the Coal Measure deposits. Another result of the orogenic activity is that the New Red Sandstone lies unconformably on deposits of Carboniferous and earlier age throughout its distribution in the thesis area.

The New Red Sandstone deposits are mainly Permian in age and/...

and are found in the two main river valleys of the thesis area, outcropping along the floor and lower slope, throughout almost the entire length of Annandale, but only in the Thornhill basin in Nithsdale (Fig. 1.3). The rocks are all continental red beds and occur either as sandstones or breccias. The sandstones are predominantly aeolian in origin, while the breccias consist of greywacke and other associated Lower Palaeozoic rocks eroded from surrounding uplands.

The New Red Sandstone outliers in Nithsdale and Annandale occupy structural basins aligned in a north-south direction. Concerning the origin of these "basins", it was suggested by Bott and Masson-Smith (1960) after carrying out gravity surveys of the area, that the deposits were neither the remnants of New Red Sandstone age valleys draining into the Carlisle Basin, as postulated by White (1949), nor the isolated "... relics of a large massof sandstones and breccias which at one time covered a great portion of the South of Scotland " (Harkness, 1856, P 265). In contrast, they postulated that the New Red Sandstone outcrops represent the deposits of "... contemporaneously sinking basins" (Bott and Masson-Smith, 1960, P326), and suggested further, that downwarp may have taken place locally as a direct consequence of the uplift of neighbouring regions of relatively negative gravity anomalies towards isostatic equilibrium.

No sedimentary rocks representative of the time between the Triassic and Pleistocene periods are found in the thesis area, or/...

or indeed anywhere in Southern Scotland. However, Greig (1971) believed that,".... early Jurassic sediments were deposited in the region, at least as extensively as the Permian and Triassic rocks which now remain and that in the Upper Cretaceous the chalk was laid down over most of the region" (P 96). Although such a possibility cannot be completely dismissed, in the light of recent research work in the North Sea (Zeigler (1974); Halstead (1977 pers.comm.)), it is now generally believed that a chalk cover was not present over Southern Scotland in Cretaceous times.

The only rocks of the Triassic-Pleistocene interval now present are basic Tertiary dykes which cross the thesis area in a north-west to south-east direction (Fig. 1.3). The majority of these dykes are fairly narrow and generally less than one kilometre in length, but one form, the Eskdalemuir dyke which runs south of Moffat, is over 55m in width and continuous throughout the thesis area.

Strong geological control over relief conditions in Upper Nithsdale and Annandale is therefore readily apparent. The comparatively resistant Lower Palaeozoic strata are responsible for the dominantly upland character of the thesis area; both the Tweedsmuir and Lowther Hills contain extensive areas of terrain lying above 550 m.o.d. and are characterised by relative relief values which generally exceed 170 m.o.d.. Similarly, it is only in the vicinity of the two main valleys, where the younger and generally less resistant strata outcrop, that there is noticeable diversification/...

diversification from the repetitive rolling upland topography.

It was suggested by several authors that the uplands of the thesis area and the South of Scotland in general, have been incised by one or more erosive processes to produce distinctive planation surfaces at certain altitudes. Hollingworth (1938), working in south-west Scotland suggested the presence of surfaces at 790-820, 325, 220-245, 170 and 120 m.o.d; George (1955), in a study of the west-central Southern Uplands identified horizontal planation surfaces at 810, 700, 510, 325 and 180 m.o.d. In the same area, Jardine (1959, 1966), identified surfaces at 790-850, 580-610, 520-550, 410-425, 300-335, 230-260, 180-215, 135-150 and 60 m.o.d. Halstead (1954), in his hypsographic survey of the Southern Uplands as a whole, recognised surfaces at 300, 700 and 800 m.o.d.

Two main theories were invoked to explain the formation of these planation surfaces or "tablelands". The first favoured a marine origin and the exponents of this theory generally gave a limited vertical range or no range at all for specific surfaces. Hollingworth (1938), George (1955) and Jardine (1959, 1966), were all adherents to this belief, formation of the horizontal marine surfaces occurring when relative stillstands interrupted a period of emergence. However, only surfaces at 800 m.o.d., which represent the altitude of the summits in the area, and at 300 m.o.d., were recognised by all three authors.

The second theory suggested a subaerial origin for the planation/...

planation surfaces and assigned a greater altitudinal range to individual surfaces. This, in many respects, was a more realistic view when the variability of geological structure and rock resistance to erosion is taken into consideration. However, there was much disagreement as to the exact method of subaerial denudation, although one of the strongest advocates of the theory, Linton (1951, 1959),postulated formation by slope retreat under sub-tropical climatic conditions.

Sissons (1960c),attempted to link both the marine and subaerial hypotheses,"The formation of an extensive subaerial planation surface implies the contemporaneous development of a marine planation surface in suitable locations. With subsequent uplift, the valley slopes and marine cliffs bounding such features may be envisaged as continuing to retreat, while a new surface of subaerial and marine origin is developed at a lower level" (P 25).

Halstead (1974 pers. comm.), also accepted the possibility that the planation surfaces may have been created by combined subaerial and marine erosion, but in more specific terms believed that altiplanation was, and still is, a major factor influencing formation. Halstead also postulated differential isostatic readjustment as an explanation for the tilting of benches and the occurrence at varying altitudes of surfaces formed contemporaneously in Southern Scotland.

Although in theory, the identification of planation surfaces in the thesis area should be made easier by the generally uniform/...

uniform lithology of the underlying bedrock, even here their recognition over an extended area is far from simple. In this respect, Upper Nithsdale and Annandale may support the differential affects of isostatic readjustment within a small area, as suggested above by Halstead (1974). One of the few facts concerning the surfaces that can be stated with any certainty is their age; they were produced after the intrusion of the Tertiary dykes, 50-55 million years ago. Consequently, the author is forced to arrive at a similar conclusion to that of Sissons (1976),"... while there is no doubt that planation surfaces exist in many parts of Scotland, it is far from established how individual remnants relate to each other". (P 25). Therefore, the importance of planation surfaces in the relief of the thesis area cannot be accurately assessed, but it can be assumed that they played a significant role in the evolution of drainage networks, both fluvial and glacial.

1.5 UPPER NITHSDALE AND ANNANDALE - EVOLUTION OF PRESENT DRAINAGE SYSTEM

The origin of the fluvial drainage system of Southern Scotland has given rise to almost as much speculation and controversy as the formation of the planation surfaces. Early writers, A.Geikie (1865), Mackinder (1902), Peach and Horne (1910 and 1930) and Mort (1918), put forward the concept of south-east flowing streams initially dominating the Scottish landscape. Indeed, Mort (1918) suggested that the present River Nith was all that remained of a larger river which rose in the Western Highlands and flowed across the Central Lowlands to its destination in the Solway Firth. However, such a situation/...

situation seems highly improbable.

A second theory, postulating initial eastward flowing drainage, was suggested by Ramsay (1878), Cadell (1886) and Bremner (1942). However, Linton (1951) is probably the best-known contributor to this group. Linton developed Bremner's ideas and invoked the superimposition of the present drainage of most of Scotland from a Cretaceous chalk cover tilted eastwards. As previously mentioned, however, recent research in the North Sea has rendered Linton's theory unlikely also.

A third interpretation was introduced by Hollingworth (1938) and applied by George (1955, 1965, 1966). It is known that Scotland suffered severe erosion during early Tertiary times, (e.g. George 1955, 1965, 1966; Sissons 1967a, 1976; Halstead 1977, pers. comm.) and George suggested that with a subsequent rise in sea-level the whole country was at one time submerged. During later pulsed uplift marine surfaces were produced on which the present drainage system was initiated. However, there is no direct evidence for the submergence of Scotland at this time (Sissons 1967a, 1976).

Sissons (1976),by combining the above hypotheses put forward a fourth theory in which he too, like Linton, invoked the origination of the drainage network on a Mesozoic, (perhaps Cretaceous), surface. He further suggested that severe erosion during early Tertiary times and uplift and volcanic activity associated with the separation of the Greenland and Scotland tectonic plates in the later Tertiary, accentuated the major watershed of the country, (thought to have been approximately/...

approximately north-south trending, as at the present day). These processes were also believed to be responsible for the initiation of minor watersheds in Southern Scotland. Marine erosion associated with the late tertiary uplift was an additional factor to be considered and Sissons stated,"..with each period of uplift streams would be extended seawards over the emerging marine benches" (Sissons, 1976, P 36). In effect, Sissons identified the major geological events that have taken place in the last 225 million years and developed his theory around these.

Lastly, Halstead (1977 pers. comm.) postulated that the main drainage network originated in the early Tertiary and that since this time many of the main rivers have been able to keep pace with isostatic uplift, thus imparting an antecedent character on the drainage. By this explanation, Halstead can account for the epigenetic character of many of the rivers in Southern Scotland.

As with the examination of the closely associated planation surfaces in the previous section, it is impossible to state conclusively which, if any of the theories on drainage initiation is completely accurate. Such information can only be utilised to supply a suitable background from which a more detailed study of the present drainage network in the thesis area can be extended.

As the title given to the thesis implies, the rivers Nith and Annan and their associated tributaries, all of which tend to flow in a southerly direction, are dominant within the area studied (Fig. 1.4). However, rivers following northerly courses/...

courses, mainly representative of tributaries of the Upper Clyde are also of major significance (Fig. 1.4). This fundamental distinction between northward flowing and southward flowing drainage is taken to be the most suitable method of subdividing the river network within the thesis area. Lebon (1935), also separated the rivers draining north and south from the principal watershed of the Lowther Hills. However, he stressed the fact that this watershed is "markedly asymmetrical" and as such "... must be unstable.... The northern flowing Upper Clyde is a perfect example of stream maturity, while the southward flowing streams are vigorously youthful" (Lebon, 1935, P 7).

Looking first at the "more active" southward flowing drainage and the Nith in particular, the river which dominates the west-central Southern Uplands rises outside the thesis area on the western slopes of Cairnsmore of Carsphairn, entering the area along its north-west margin, mid-way between New Cumnock and Kirkconnel. At this point, the Nith flows in an east to south-east direction, adopting its more southerly course further downstream in the vicinity of Enterkinfoot. It is generally believed (e.g. George, 1956; Linton, 1933) that the Nith is a composite river, "... embodying both consequent and subsequent elements in its present course" (Linton, 1933, P 171). However, the exact delimitation of such stretches along the course of the river is extremely difficult.

Borehole evidence (Lumsden and Davies, 1965), indicates that the Nith possesses a buried channel which stretches across the/...

the Southern Uplands Fault from four miles west of New Cumnock, eastwards to Sanquhar. Lumsden and Davies believe that the buried channel represents a pre-glacial course of the Nith itself, whose present subterranean form relates to movement along the Southern Uplands Fault and subsequent infilling by drift during the Quaternary.

The River Annan similarly dominates the east-central Southern Uplands but unlike the Nith, has its source within the thesis area. The Annan rises in the vicinity of the Devil's Beef Tub and follows a southward course throughout the thesis area. It is joined just south of Moffat by its two major tributaries, the Evan Water from the north-west and the Moffat Water, a fault-line subsequent, from the north-east.

The Annan and Nith Valleys have a great deal in common, in particular the fact that both are extensively floored by younger and less resistant deposits of Carboniferous and New Red Sandstone age (Fig. 1.3). In each dale, the excavation of the younger sediments proved much more facile than valley cutting in the surrounding Lower Palaeozoic strata. Consequently, this favoured location enabled rapid headward regression of the youthful Nith and Annan in comparison to the more mature and northward flowing Clyde and Tweed. The watershed in this part of the Southern Uplands is thus being pushed northward, with the inevitable inference, that drainage basins on the southern side (Nith and Annan) must be growing, while those on the northern side must be contracting. In such circumstances, as suggested previously/...

previously, piracy is unavoidable and the evolution of the drainage pattern within the thesis area is marked by repeated encroachment on the Clyde, and to a lesser extent Tweed, river systems. Indeed, "... some 50ml^2 (128 km^2) of the Clyde and Tweed basins" (Lebon, 1935, P 13), are believed to have been annexed by the northward offensive of the Nith and Annan. Several spectacular cases of piracy have resulted from this but these will be examined in later chapters.

Other significant rivers which trend in a broad southerly direction within the thesis area include the Wamphray and Garpol, tributaries to the Annan, and Carron, Mennock and Crawick, tributaries to the Nith (Fig. 1.4).

The Upper Clyde and its tributaries are the principal northward flowing streams, and these are found wholly to the north of the Lowther Hills watershed. Within the thesis area the Clyde itself is of little significance and it is the upper part of its tributaries, the Daer and Potrail, which exert the greatest influence on the landscape. However, as mentioned, such streams are substantially modified in their pattern by encroachments and beheading from the south-east and south-west, such that the significance of the Clyde Basin as a whole in the Central Southern Uplands is continually being reduced. Other important streams which follow a generally northward course are the Euchan and Kello, tributaries to the Nith, which anomalously lie to the south of the main watershed, but these will also be examined in greater detail in later chapters.

In/...

In conclusion, it can be seen that the Nith and Annan drainage basins are growing at the expense of the Clyde (and to a lesser extent the Tweed). Although the Clyde is by far the longest of the three rivers in Central and Southern Scotland, it has a much gentler gradient than the southward draining Nith, Annan and their tributaries. When taken into consideration with the relative susceptibility to erosion of the Upper Palaeozoic rocks of Nithsdale and Annandale, these factors together help explain the development of the present drainage network in the Central Southern Uplands.

1.6 ORGANISATION OF THE THESIS

The thesis consists of six chapters. The first chapter details the nature of the study and introduces the area in terms of geology, relief and drainage. The second chapter summarises the published literature on the glaciation of Southern Scotland as a whole, but with particular reference to Upper Nithsdale and Annandale, and briefly reviews the development of Quaternary studies to the present day. Chapters 3, 4 and 5 describe and analyse the affects of glaciation on the landscape of Upper Nithsdale and Annandale. For the sake of convenience, the thesis area has been arbitrarily divided into three sub-areas (Fig. 1.5), although an attempt was made to relate each of these to one of the main drainage systems, i.e. the Annan, Clyde and Nith. Area I is discussed in chapter 3, Area II in chapter 4 and Area III in chapter 5. In each of these chapters, the location, extent, relief, drainage and geological conditions of the area concerned are outlined prior to a detailed description and analysis of the features and deposits related/...

related to glaciation. In respect of the highly varied affects of glaciation, the account for each area is subdivided under the headings of glacial erosion, glacial deposition, fluvioglacial erosion and fluvioglacial deposition. Under each heading the form and distribution of the characteristic landforms and/or deposits is detailed, often depicted at an enlarged scale, and accompanied by the results of particle-size, till fabric and erratic count analyses where appropriate. At the end of each of these chapters this diversified information is gathered together and the main ice sources, directions of movement and nature of ice wastage for the sub-area ascertained. A tentative glacial chronology is also suggested in the conclusions for chapters 3, 4 and 5. Chapter 6 is the overall conclusion. In this chapter the inter-relationship of points arising in the foregoing conclusions for each of the three areas are assessed and an overall model for the glaciation and deglaciation of Upper Nithsdale and Annandale put forward. A more detailed glacial chronology on the basis of pollen analyses and radiometric dates from this and adjacent areas is also suggested. Finally, the findings of research in surrounding areas are re-examined in conjunction with the conclusions for Upper Nithsdale and Annandale, and the main sources and general pattern of ice movement over a large part of southern and west-central Scotland during the last major glaciation depicted.

CHAPTER 2

LITERATURE REVIEW

Any appraisal of the literature concerning the glacial geomorphology of a selected part of Scotland must examine, at least superficially, the origins of the glacial theory itself and its progression to the present day. Consequently, in this section of the thesis it is intended to briefly summarise the evolution of the glacial theory and examine the way in which developments in Quaternary studies generally have influenced the literature written on the thesis area.

Today, it is accepted that the Scottish landscape owes much of its grandeur and mantle of superficial deposits to the actions of glacial ice. However, at the beginning of the nineteenth century, few geologists anywhere in Europe regarded glaciers, or land ice in general, as anything more than a phenomenon peculiar to high altitudes and high latitudes, with no major role in geological processes. At this time, ".... only the unorthodox thought of trying to explain the structure and history of the earth outside the framework which the Mosaic account provided" (North, 1943, P. 2). Consequently, the Reliquiae Diluvanae (Great Submergence, Buckland 1823) or Noachian Flood was seen as being responsible for the origin of the landforms and superficial deposits in Scotland. There was an awareness by the 1820's of the concept of glacier movement, the ability of glaciers to transport debris and the former greater extent of Alpine glaciers. (Scheuchzer 1723; Martel 1744; Hutton 1795; Playfair 1802, 1822; Eskmark 1827) However, such ideas received little credence from the more emminent scientists of the period and consequently did not gain widespread/...

widespread recognition and acceptability. A more pressing problem was the explanation of anomalies in the nature of the superficial deposits within the framework of the existing methodology, in particular their generally unstratified nature, the angularity of clasts, and the widespread occurrence among the clasts of rock types exotic to a specific area. Visits to areas of contemporary glaciation by Lyell (1833) led to the introduction of floating ice into the theory of submergence and Lyell used "iceberg deposition" to account for the depositional irregularities described above. It is argued that this single modification prevented the rapid acceptance of the glacial theory and "... delayed for decades its achieving dominance" (Hansen, 1970, P 137).

In 1840, Louis Agassiz became the first "recognised scientist" to support the glacial theory, when he presented "his" paper on glaciation to the Societe Helvetique des Sciences Naturelles at Neuchatel. This theory was basically similar to earlier statements invoking the former greater extent of glaciers, with the possible exception that Agassiz realised its application to areas such as Britain, where although no glaciers existed in the nineteenth century, their former presence was certainly implied from descriptions of the landscape. However, because of the prominent position that Agassiz held in the scientific world at that time, the origins of the glacial theory are often attributed to him.

Agassiz visited Britain in 1840, travelled widely and found abundant evidence for the former existence of glacier ice. This visit generated local interest in the glacial theory and led to its acceptance by certain prominent geologists of the period, including/...

including Buckland, Lyell and Darwin, all formerly advocates of the Great Submergence. Nevertheless, overall acceptance was not forthcoming, mainly as a result of the influential Murchison, who supported the floating-ice hypothesis. The glacial theory was not disproved, but argued out of importance. Murchison persuaded Buckland to back down from his glacial stance in 1841 and ".... by his eloquence and influence delimited the general outlook of British geology for at least two decades" (Hansen, 1970, P. 140).

Although the acceptability of the glacial theory waned over the period 1840 - 1860, research by individual workers continued and for the first time, some of this research had direct relevance to the thesis area. Chambers (1853) stated, "... I have found a large lateral moraine near Maxwellton House in Kirkcudbrightshire and seen fine smoothings with striations on the surface of Corncockle Muir in Dumfriesshire" (P. 244). In this article, the author also speculated upon a general glaciation of Scotland, followed by a more restricted glaciation which he termed a "...sub-aerial valley glaciation" (P. 244). In a later paper, Chambers (1855) elaborated upon moraines in general and stated that they occur, ".... in the more elevated class of mountains, being usually placed in front of these (glaciers) as a fender is placed before a fire. On lately visiting for the first time the well-known Loch Skene in Dumfriesshire, I found it to be formed by a moraine of this order ....In a south-looking recess, backed by a lofty wall of bare rock, and on a platform which cannot be less than 1,200 feet (366 m.o.d.) above sea level lies the celebrated/...

celebrated lake, hemmed in towards the south by a bewildering number of hillocks and ridges of grey coarse drift, the manifest spoils of the ice which once filled the recess. In front of a similar sinus to the westward, we have the same lines and humps of detritus, but the water has there made a passage for itself and escaped" (PP 99 - 100). From these statements, Chambers implies that the Loch Skene moraines are common knowledge among glacial theorists of the time, but no mention of these well-preserved features can be found prior to this date. However, Chambers' paper generated wider interest, and after visiting the site with A.Geikie in the early 1860's, Young (1864) wrote a classic paper on the moraines of the Loch Skene area. In his paper, Young remarked upon the extent of country lying above 762 m.o.d. in this vicinity and stated, "This wide plateau and these long slopes would, under other climatical conditions, form an extensive snow-field whence glaciers might descend to the valleys beneath" (P. 453). Young postulated the former directions of movement of individual glaciers and classified these as "... social or solitary..." (P. 453), depending on whether, in his opinion, they became confluent downslope. He also differentiated between lateral and frontal moraines and identified more than twelve of the latter in the Loch Skene area. In conclusion, Young suggested that the 1,000 feet (305 m.o.d.) contour marked the lower limit of glaciation for the district and stated ".... nor is it probable that the glaciers ever extended much lower beyond the moraines ... which illustrate the last stages of decay" (P. 462). The detail of Young's work is admirable (Fig. 2.1) and it will be later seen that many of his findings/...

findings still withstand rigorous scrutiny today.

Young's publication on Loch Skene represented the first paper specifically written on the thesis area after the revival of the glacial theory in the early 1860's, the revival itself brought about mainly as a result of studies by Jamieson (1862) and Ramsay (1862). Both men were firmly convinced that Scotland had formerly been completely covered by ice. More importantly however, their work convinced Archibald Geikie, the first of a family combination that was to have a greater influence on the development of the glacial theory in Britain than any other two men in the evolution of the subject, of the significance of a former ice cover in Scotland. With his book "The Scenery of Scotland", first published in 1865, A.Geikie effectively disposed of the "Deluge" and "Ice-berg" theories by detailed analysis of striae and ice moulding, the results of which clearly showed that terrestial and not floating ice could have been the sole agent of formation. "After long years of doubt and discussion, geologists are at length led to believe that during a comparatively recent geological period, the whole of the northern half of Great Britain was cased in ice, as North Greenland is today" (A Geikie, 1865, P. 78).

A.Geikie was also a significant figure in the Geological Survey of Scotland and contributed a great deal to early geological "Memoirs" or "Explanations" in the second half of the nineteenth century; those of particular interest with regard to the thesis area being the Explanations for sheet 9, Kirkcudbright (north-east part) and Dumfriesshire (south-west part), 1877 and sheet 15, Dumfriesshire/...

Dumfriesshire (north-west part), Lanarkshire (southern part), Ayrshire (south-east part), 1871. Based upon evidence derived from the study of striations, roches moutonees and erratics, A.Geikie et al suggested the directions of former movement and origins of the last ice mass to occupy these areas. The summary for sheet 15 stated, "It appears that the high grounds ranging from the sources of the Afton north-eastwards through the Lowther and Leadhills to the Clyde, have served as a central axis of dispersion for the ice of the glacial period. This is shown by the fact that the striae on the rocks diverge from this axial line to the low grounds on the north and south" (Geikie et al, 1871, P. 38).

For the more westerly area encompassed by sheet 9, Geikie et al postulated a generally eastward movement of ice from dispersion centres in the vicinity of Cairnsmore of Carsphairn, into the thesis area. However, on reaching the Nith Valley it was believed that the course of this eastward moving ice was."... deflected towards the south" (P.37). In the third edition of "The Scenery of Scotland", A.Geikie (1901) summarised the literature which had appeared in several disjointed Explanations of the Geological Survey, to speculate upon the build up, dispersion and wastage of glacier ice over Southern Scotland as a whole. "... It is evident that the Southern Uplands formed another centre of dispersion, for the southern part of the Scottish ice-sheet. (To speak more accurately there were several distinct centres of movement of the ice that lay on these uplands. But the southern ice-field may be regarded as one vast sheet that moved outwards and downwards into the low ground on all sides)". (P. 341 - 342). A.Geikie further stated,"...

that/...

that valley-glaciers continued in the "coombs" and "hopes" of the Southern Uplands as they did in the corries and glens of the Highlands, after the ice-sheet had crept back from the lower grounds, is admirably revealed by many a group of moraines" (P. 344 - 345). Both Loch Skene and parts of the Lowther Hills are cited as areas exhibiting such features. Archibald Geikie was therefore the first person to provide a unified theory for the glaciation of Scotland, drawing on information from all parts of the country and who, with particular reference to the thesis area, stressed the importance of the Southern Uplands as an independent source of glacier ice.

James Geikie, Archibald's brother, fulfilled a similar role in the development of the glacial theory with the publication in 1873 of his book, "The Great Ice Age". This volume not only dealt with Scottish landforms and deposits, but extended its boundaries to include the origin and stratigraphy of deposits in England, Ireland, Scandinavia, Switzerland and North America. J.Geikie reiterated the main points that his brother had made regarding ice action in the Southern Uplands, but in addition stressed more forcefully the significance of high altitude moraines in indicating that there was either a prolonged halt during, or subsequent re-introduction of small glaciers after, the general decay of the last ice sheet. Using Loch Skene as a typical example, he stated, "The mounds and concentric ridges of the Highlands and Southern Uplands can only be terminal moraines and point to a time when snow covered the higher districts of the country ..... That these glaciers really belong to the closing period of the Great Ice Age, is proved by the fact that in the Southern Uplands/...

Uplands they have sometimes scooped out the moraine of earlier times from the bottom of the valley, but have left it untouched at heights on the hill-slopes which the later glaciers were unable to reach. Yet not a few of these latest glaciers were of considerable importance, as one may judge from the size and position of the moraines. Even the most extensive however, were but pigmies when compared to those of earlier cold periods" (J.Geikie, 1873, P. 269).

Despite Scotland's position at the forefront of major developments in Quaternary studies, as a result of the Geikie brothers, in the first 25 years of the twentieth century the most significant advances occurred outside the country in areas of contemporary glaciation, particularly Alaska. (Tarr and Martin 1906; Tarr 1909; Tarr and Butler 1909; Von Engeln 1912; Tarr and Martin 1914; Muir 1915). Another event of particular significance during this period took place in England, with the publication in 1902 of Kendall's famous paper concerning, "A system of Glacier-lakes in the Cleveland Hills". Kendall postulated that ice was watertight and could act as a dam to permit the development of large lakes in valleys not otherwise occupied by ice. As will be seen later, the general acceptance of this theory of ice-dammed lakes and associated overflow channels, retarded the development of alternative ideas in fluvioglacial studies until the 1950's.

The major contributor to glacial research in Southern Scotland over the period 1920 - 50 was J.K.Charlesworth, his most notable papers both published in 1926:-

(a) Glacial Geology of the Southern Uplands, west of Annandale and Upper Clydesdale.

(b)/...

(b) The Re-advance marginal kame-moraine of the south of Scotland and some later stages of retreat.

Only the first paper dealt specifically with landforms and deposits found in the thesis area. By extremely detailed fieldwork based on the identification of striae and erratic boulders, Charlesworth postulated upon the build up and outward movement of ice from the Western Southern Uplands. He concluded, "The Southern Uplands west of Annandale and Upper Clydesdale were glaciated (in the main) by local ice centred in the hills extending from the Merrick, Corserine (in the Rhinns of Kells),Cairnsmore of Carsphairn and Lowther Hills" (Charlesworth, 1926 a , P. 23). Having established the main source areas, Charlesworth then turned his attention to the identification of retreat stages in the decay of the Southern Uplands ice sheet from its maximum extent. The retreat stages were delimited by moraines or outwash fans, "... due to the general absence of meltwater channels in the area" (p. 8). On this basis, Charlesworth ascertained that with the onset of deglaciation, the regional ice sheet backwasted into a series of independent glaciers which occupied the major valleys of south-west Scotland. Further decay was then indicated by the moraines, formed during temporary stillstands or readvances within the valleys themselves; the last stage marked by corrie moraines (Fig. 2.2). By attempting to delimit stages in the build up and decay of the last ice sheet, Charlesworth was adopting an approach similar to that used by Young (1864) for the Loch Skene area. However, Young was dealing with definite morainic forms over a limited area, whereas Charlesworth was attempting to correlate stages/...

stages in glacier retreat over many miles by the use of "moraines" whose origins as such were by no means certain, as will be shown later.

In the second paper, Charlesworth (1926 b) postulated a major re-advance of Highland ice,marked by his "Lammermuir-Stranraer Moraine" which stretched along the northern flanks of the Southern Uplands, but did not extend into the thesis area itself. This outermost "moraine" and a series of "retreat moraines" which Charlesworth also identified, "... present the appearance of a rolling belt of country in which countless hillocks and hollows, ridges and troughs succeed each other rapidly and tumultuously. They exhibit the bold, billowy relief of the swell and sag topography, with rapidly shifting curves and choppy surface, or a more subdued relief and gently undulating scenery" (PP. 25 - 26).

Also at this time, Gregory (1926, 1927) after extensive fieldwork similar to that of Charlesworth, published his results, again in two articles :-

(a) The Scottish Kames and their evidence on the glaciation of Scotland (1926).

(b) The moraines, boulder clay and glacial sequence of south-west Scotland (1927).

The first paper was a county by county Scottish study of the distribution of ridges of sand and gravel. Reference in this was made to several such features in the central Southern Uplands but none of these lay within the thesis area itself.

In the second paper however, Gregory refers to "... small moraines... on the main slopes of the Lowther Hills at levels of over 1,000 feet (305 m.o.d.) and... in the hills around Loch Skene, on the Moffat Water/...

Water down to 1,000 feet (305 m.o.d.) and on the Moffat Water down to 500 feet (152 m.o.d.)" (1927, P. 36). The studies carried out by Gregory and Charlesworth give a good indication of the state of knowledge regarding the nature of ice build-up and decay, and the emphasis on specific glacial landform identification prevalent in the 1920's.

In 1927, Eckford and Manson again made reference to "Glacial Phenomena around Loch Skene" (PP. 508 - 510), but this paper merely repeated what had previously been observed and published by Chambers (1855) and Young (1864).

In the 1930's and 40's only the officers of the Geological Survey of Scotland were actively involved in adding to the literature on the glacial geomorphology of Upper Nithsdale and Annandale. The Summary of Progress for 1930, postulated upon the directions of both ice advance and retreat across part of the thesis area. From a study of Spango granite and Crawfordjohn essexite erratics in the vicinity of Crawfordjohn, a north-east movement of ice across the north-west part of the thesis area was invoked. In addition, "... west of Kirkconnel and south of the river Nith... a number of overflow channels were mapped. The channels in every case slope down towards the east and supply further evidence of a westerly retreat of ice" (Simpson, Richey et al, 1930, P. 26).

Of greater significance however, was the revision of the geology in the Upper Nith Valley, which led to the publication of "The Geology of the Sanquhar Coalfield" (Simpson and Richey, 1936). The glacial landforms were mapped (Fig. 2.3) and the glacial history of the area summarised on the basis of local evidence:

." 1./...

" 1. An advance of a regional ice sheet down the Nith Valley from west to east, which resulted in the formation of a boulder clay now covering and largely masking the solid rocks; 2. A subsequent retreat in the reverse direction during which extensive spreads of morainic gravels were deposited on top of the boulder clay and many well-defined marginal drainage channels were formed by the glacial meltwaters...... After the waning of the general ice-sheet, local centres of dispersal remained or re-established themselves on the higher parts of the Southern Uplands" (Simpson and Richey, 1936, PP. 91 - 92). However, there is no evidence in the Nith Valley itself ".... that a later boulder clay of local origin overlies that deposited by the eastwards moving ice..." due to the fact that, "... the ice sheet situated to the west was still large enough to nourish and maintain a powerful glacier in a main river valley like the Nith as far as or further east than Sanquhar, at a time when the high ground in that neighbourhood was partly ice-free and sustained only a small ice-cap. From this, ice moved westwards from the higher ground in times of re-advance but was prevented from depositing material in the already ice-filled Nith Valley" (P. 92). In the context of this latter statement, Simpson and Richey made no mention of lower limits regarding this re-advance in the Upland areas,but merely implied that at its maximum extent the re-advance ice was confluent with ice already present in the main river valley. A postulated date for this secondary glacial phase was also omitted, although it may have been correlated with Charlesworth's (1926 b)

Lammermuir/...

Lammermuir - Stranraer Re-advance. Whatever the date however, the re-advance suggested by Simpson and Richey was much more extensive than those previously suggested on the basis of high altitude moraines by J.Geikie (1873), Young (1864) and Gregory (1927).

The Memoir for the Sanquhar Coalfield indicated the progress that the Geological Survey had made in the seventy years since their first publications had appeared. No longer were points of glacial interest divided into separate categories such as erratics, striae etc, but the varied landforms and deposits were brought together in an attempt to gain a more accurate overall conception of the advance and retreat of the last ice-sheet to affect the area. It is also significant that in this Memoir, there was a tendency towards greater emphasis on glacial drainage channels.

Throughout the period 1940 - 1960, the importance of meltwater in the overall glacial process became more apparent, mainly as a result of fluvioglacial studies in areas of contemporary glaciation. Scandinavian workers made the biggest impact in such studies, with Mannerfelt (1945, 1949) leading the field. Accompanying the increasing awareness of the importance of fluvioglacial activity, there was increasing acceptance of glacial retreat by downwastage, widespread stagnation and decay in situ, as opposed to backwastage. This latter idea was first developed by Flint (1929) and later expanded upon by the Scandinavians (Mannerfelt 1945, 1949; Hoppe 1950; Gillberg 1956; Holdar 1957; Gjessing 1960). "Hollingworth (1952) was the first British worker to apply the conclusions of the Scandinavian workers in/...

in Britain, but it was Sissons (1958 a , 1958 b , 1958 c , 1960 a , 1960 b , 1961 a , 1961 b , 1961 c) who really followed the Scandinavians methodology and applied their concepts of downwastage and subglacial and englacial drainage with great success" (Price, 1973, P. 10).
Sissons (1958 b , 1960 b , 1961 a utilised the new information on fluvioglacial erosion initially to disprove Kendall's (1902) statements on the supposed common occurrence of ice-dammed lakes during deglaciation. He recommended that evidence other than the existence of "overflow channels" had to be sought before the former presence of ice-dammed lakes could be invoked and that most of Kendall's "overflow channels" were in fact meltwater channels produced by supraglacial, englacial or subglacial streams during downwastage. By detailed analysis of meltwater channel patterns and fluvioglacial deposits, Sissons also ascertained the minimum altitude of the former ice surface, the probable slope of this surface and the mode of ice dissipation in various parts of southern Scotland (1958 a , 1961 b 1961 c).
The new concept of downwastage and ice stagnation and the increased significance of fluvioglacial landforms and deposits, meant a re-appraisal of existing descriptions of glacial and fluvioglacial features in Upper Nithsdale and Annandale. Stone (1957, 1959) applied these concepts to part of Mid-Nithsdale, just south of the thesis area (Fig. 2.4). As a result, Stone questioned several of the conclusions that Charlesworth (1926 a) arrived at concerning glacial retreat in the Nith Valley.
"Although J.K.Charlesworth states that ice-marginal channels are not/...

not widely found in Nithsdale, they are in fact well-developed features in the area examined", and ".... detailed mapping of the kame and kettle topography makes it readily apparent that there are no clearly defined crescentic trends as described by J.K.Charlesworth" (Stone 1959 PP. 164 - 166). In contrast to the findings of Charlesworth, (1926 a), Stone concluded,"The picture envisaged of downwastage in Nithsdale is therefore one of a jerky, yet fairly continuous recession.... On downwasting down to the height of 150 - 200 feet (46-61 m.o.d.) the dwindling glacier seems to have been no longer active but to have become shattered by great fissures and crevasses into blocks of "dead" ice which wasted away in situ" (Stone, 1957, P. 64). Sissons also questioned some of Charlesworth's conclusions, in particular the existance of his Lammermuir - Stranraer moraine (Sissons 1961 c). Sissons stated that the central and eastern parts of this moraine ".... are composed almost everywhere of fluvioglacial deposits found in association with dead ice" (1961 c , P. 391). However, having concluded that the Lammermuir - Stranraer morainic belt was not representative of a major re-advance of ice Sissons himself (1963 a , 1964) propounded a re-advance based upon an original hypothesis by Simpson (1933), the Perth Re-advance. The evidence for this was based mainly on morphology and stratigraphy in scattered localities. In the context of the thesis area, at the maximum of the supposed Perth Re-advance ice from the Southern Uplands completely."... occupied the region south of a line from Maybole to New Cumnock" (Sissons 1964 P. 31),(Fig. 2.5). In 1967, Sissons brought together the wealth of information that

'had/...

had accumulated on Quaternary studies in Scotland since the mid-nineteenth century, with the publication of his book, "The Evolution of Scotland's Scenery". In this, Sissons postulated two other major re-advances postdating the maximum of the last glaciation, in addition to the Perth Readvance; an older Aberdeen-Lammermuir Readvance, and the most recent Loch Lomond Readvance (Fig. 2.5). Both re-advances have since been disproved, the Aberdeen-Lammermuir by Clapperton and Sugden (1972) and the Perth by Paterson (1974). Consequently, it is now generally agreed that conclusive evidence exists for only one major re-advance,the Loch Lomond Re-advance.

Detailed regional studies in areas adjacent to Upper Nithsdale and Annandale were carried out by Price (1960), McLellan (1967) and Holden (1977). The research by Price and Holden is of particular interest in that the areas studied, Peeblesshire and Central Ayrshire respectively, immediately adjoin the north-east and north-west boundaries of the thesis area. The principal conclusions arrived at by Price (1960) were as follows :-

1. At the glacial maximum, Peeblesshire was completely overriden by ice originating in the Southern Uplands.
2. One of the centres of dispersal of this ice-sheet lay to the south-west or Peeblesshire, there being a generally northward movement of ice across the area studied.

3./...

3. During downwastage, hills, ridges and spurs emerged as nunataks and ice remained longest in the valleys. The meltwater drainage system that became established on and in the ice-sheet ignored the underlying relief. Parts of this drainage system were superimposed onto the underlying relief.

4. After the final wastage of the ice sheet there was a local re-advance in the Tweedsmuir Hills. A series of end moraines indicate that these valley glaciers descended to about 1,100 feet (335 m.o.d.).

Holden (1977), in his summary similarly emphasised several points of particular reference to Upper Nithsdale and Annandale :-

1. Central Ayrshire was crossed by two ice masses, from the West Highlands and Southern Uplands, which merged over the area.

2. Southern Uplands ice from the high ground at the head of the Afton Valley and Loch Doon occupied the southern part of Central Ayrshire. In the east, the Southern Uplands ice was deflected by Highland ice to flow in a generally east to north-east direction into Dumfriesshire. Part of this ice stream also moved east to south-east down the Nith Valley.

3. A local re-advance of ice in the uplands of southern Central Ayrshire was suggested by the presence of moraines similar to those detailed by Price (1960) in/...

in the Tweedsmuir Hills. By their altitude and situation, Holden attributed the formation of these moraines to the Loch Lomond Re-advance.

4. The Nith Valley was a major routeway for eastward trending meltwater throughout the period of deglaciation.

McLellan (1967), suggested that Central Lanarkshire, like Central Ayrshire (Holden 1977), was also affected by two confluent ice masses, one from the Southern Uplands, which moved from a generally west to south-west direction and the other of Highland origin, which moved from a west to north-west direction.
An abridged but updated version of "The Evolution of Scotland's Scenery" was produced by Sissons in 1976, entitled "The Geomorphology of the British Isles - Scotland".
The publication is heavily slanted towards recent research in glacial geomorphology but generally in the national context, with only passing reference made to the thesis area.
The only other recent publications of interest to Quaternary studies in the thesis area have centred upon the assessment of sand and gravel resources in southern Scotland. McLellan (1967, 1969) initiated this research, it was continued by Goodlet (1970). and most recently by the Institute of Geological Sciences, with the publication of "Sands and Gravels of the Dumfries and Galloway Region of Scotland" (Cameron 1977). Such literature on sand and gravel resources could have proved beneficial to Quaternary research, with the increasing emphasis placed on fluvioglacial processes since 1945. However, it has generally been the case that, with the exception of McLellan's work (1967, 1969), the sand and gravel reports for southern Scotland do/...

do not represent a re-appraisal of the field evidence in the light of recent research, but merely a re-appraisal of the existing literature on the areas concerned. As a result, such reports have added little to the existing knowledge on the distribution of,and processes responsible for, fluvioglacial landforms in the thesis area.

Much of the chronological reconstruction of the last major glaciation to affect Scotland, mentioned above, has since the 1950's been confirmed, or more commonly disproved, by the use of relative and/or absolute methods of dating. Determinations of relative age are mostly based on stratigraphical relations, mainly by the use of pollen analysis, a result of the widespread occurrence of pollen in Quaternary sediments. The pollen assemblages,mainly obtained from lake sediments and peat bogs, indicate successive changes in vegetation, and by correlation climate, that have taken place since the final stages of deglaciation. The pollen succession is divided into eight main zones of which the first three are grouped together as Lateglacial and the last five as Postglacial. The ages of the zoned boundaries were approximately determined by absolute radiocarbon dating (Godwin 1961).

Radiocarbon dating is the most commonly utilised means of absolute dating and is based upon the measurement of the radiocarbon activity (^{14}C) of biogenic material such as wood, peat and shells. The radiocarbon is incorporated into the biosphere by the intake of carbon dioxide, carbonates and bicarbonates which, upon the death of the organism, decay at

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a calculated rate. By measuring the radioactivity of fossil biogenic material containing carbon, the date at which death took place can be determined.

Pollen analysis and radiocarbon dating have been little utilised in previous studies of the thesis area, the only known references being to pollen sites at Loch Skene (Lewis 1906, Erdtman 1928) and Sanquhar (Bishop and Coope, in Lowe and Gray, 1977). However, when considered in association with research in adjacent parts of southern Scotland (Donner 1957, 1970; Moar 1963, 1969; Bishop 1963; Bishop and Coope 1977) and in the country as a whole (summarised in Sissons 1967a, 1976; Lowe and Gray 1977), it is possible to suggest an accurate chronology for the last major glaciation to affect Upper Nithsdale and Annandale :-

1. Most if not all of Upper Nithsdale and Annandale was ice free 26,000 - 27,000 years ago.
2. The last major glaciation in Scotland, the Devensian, started approximately 25,000 years ago and attained its maximum extent, covering the whole of the country, some 17,000 - 18,000 years ago.
3. Downwastage and retreat of the ice sheet was rapid and much if not all of the thesis area was ice-free by 12,500 years B.P.
4. There was a return to cold conditions and advance or re-advance of ice from the higher parts of the country between approximately 11,000 - 10,000 years B.P. in Pollen Zone III or Younger Dryas times. This cold period is known in Scotland as the Loch Lomond/...

Lomond (Re) advance.

5. There is no evidence to suggest the re-establishment of glaciers after approximately 10,000 years B.P.

CHAPTER 3

AREA I

3.1 : INTRODUCTION : LOCATION AND EXTENT

The boundary lines by which Area I is delimited (Fig. 3.1), represent a combination of physical and cartographic considerations. As with many other studies of this size and scope, it was deemed necessary in terms of manageability to introduce grid lines as boundary markers in certain localities. Consequently, to the east, the area is delimited by the Borders Regional boundary until its junction with the north-south grid line NT 20, whereafter the grid line is adopted. To the north, the boundary separating the Borders Region from the Dumfries and Galloway Region again represents the limit of the area until the junction with the Strathclyde Regional boundary at grid reference NT 047140. The western demarcation is initially represented by the Strathclyde Regional boundary until its junction with the north-south grid line NT 00, after which the grid line continues southward. The southern boundary is again a grid line, in this case NT 00 which runs east-west.

Within the area enclosed by these boundaries a wide selection of glacial and fluvioglacial landforms and deposits occur.

3.2 : RELIEF AND DRAINAGE

Area I contains the upper segments of 3 major river systems, the Evan Water, the Moffat Water and the River Annan (Fig. 3.2). These 3 river valleys form a trident configuration and as such are an obvious means by which to further subdivide the area.

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A fundamental distinction in terms of relief can be made between the areas to the west and east of the river Annan, the central axis of the trident.

To the west, the terrain rises gradually to a maximum altitude of 567 m.o.d. in the Lowther foothills. Only in the extreme north-west are there rapid increases in altitude, and this is essentially a gently undulating area, mainly below 305 m.o.d. and of low relative relief values, which slopes eastwards to the Annan and Evan Water. Such descriptions could not be applied to the area east of the river Annan. Here, in the Tweedsmuir and Eskdalemuir Hills, the maximum altitude is 820 m.o.d., and large parts of the area lie above 457 m.o.d.. Much of this extensive upland plateau has been greatly affected by glacial processes, lending it a deeply dissected, sometimes rugged character, with high relative relief values. Deep, steep-sided valleys separated by smooth, rounded ridges and hill tops are therefore typical, and well-illustrated by those forms occupied by the Dryfe Water, Wamphray Water, Carrifran Burn and Blackhope Burn (Fig. 3.2).

The River Annan, which rises in the Devil's Beef Tub, a deep steep-sided semi-circular depression, follows a fairly constricted course in its upper reaches to the north of the town of Moffat. Just south of Moffat however, the floodplain almost doubles in width to over 800m and has been artificially straightened and constrained by levées. Here, the two major tributaries, the Evan Water and the Moffat Water, become confluent with the main stream. The Annan continues southwards out of the thesis area, following a gently meandering course across a floodplain 700-800m in width/...

width.

The Evan Water, which joins the Annan from the north-west follows a gently sinuous course, its floodplain seldom exceeding 400m in width and continually bounded by steeply-inclined slopes, except near the confluence with the Annan. Indeed, the valley could almost be termed "gorge-like" in places. The Evan Water has 2 significant tributaries, the Cloffin Burn and the Garpol Water, both of which rise in the Lowther foothills and join the river from the west. The width restrictions emplaced upon the Evan Water floodplain are the result of narrow, rocky valley sides, in great contrast to the glacial and fluvioglacial deposits which flank the Annan.

The Moffat Water valley is similarly characterised by steep, bedrock walls along its upper course, although fluvioglacial deposits extend across the lower valley sides near the junction with the Annan. The valley, which joins Annandale from the north-east, is remarkably straight, having been incised along the line of a major fault and shatter belt. The faulting severely weakened the surrounding rocks and left them highly susceptible to erosional processes, particularly those associated with glaciation. As a result, a wider, deeper valley than might otherwise be expected has been produced, such that although Moffatdale follows a direct route to its junction with Annandale, the Moffat Water itself follows a very sinuous course across a comparatively wide floodplain, (500-600m maximum width).

As would be expected of any river flowing between 2 upland masses which exceed 610 m.o.d., the Moffat Water has a large number of tributaries. Throughout its upper course, these

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are generally small and join the river from the north, principally the Carrifran and Blackhope but also the Tail Burn which leads down from Loch Skene. Further downstream, nearer the junction with the Annan, the tributaries are mainly derived from the hills to the south, the largest of these being the Selcoth and Cornal Burns.

It can be seen, therefore, that the valleys of the Evan Water, Annan and Moffat Water direct the drainage of their surrounding uplands in a generally southward direction at the present day.

3.3 : GEOLOGY

The geology of Area I (Fig. 3.3), is dominated by rocks of Silurian age, approximately 90% of the area being underlain by greywackes, grits, dark grey shales or black siltstones which are highly folded and faulted around a north-east to south-west axis. The uniform lithology of Area I may have aided the formation of extensive upland surfaces, but has certainly not been of assistance in the identification of former directions of ice movement by examination of the erratic content of the glacial deposits.

Small outcrops of slightly older Ordovician rocks, again mainly greywackes and shales can be seen at scattered localities throughout Area I (Fig. 3.3), but are best-revealed by faulting in a narrow belt south and east of the Moffat Water. As both Silurian and Ordovician rock types are essentially similar, there is no superficial expression of the change from one to the other. Only the New Red Sandstone outcrops, of Upper Palaeozoic age, break the monotony of the Lower Palaeozoic rocks to any real degree (Fig. 3.3). These red sandstones and breccias, which rest unconformably on the underlying Silurian rocks, form a narrow/...

narrow north-south trending belt which extends down the Annan valley from the Devil's Beef Tub. The comparative susceptibility of the New Red Sandstone rocks to erosive processes has played a major role in the formation of the broad, gently sloping valley sides which typify much of Annandale, and indeed in the establishment of any fairly extensive lowlying region within Area I as a whole.

The youngest solid rocks in the geological sequence to be found in Area I, and the only igneous rocks, are the Tertiary dykes (Fig. 3.3). There are 9 of these features scattered across the area, all indicating various degrees of discontinuity. The dykes are of basic composition and follow a generally west-north-west to east-south-east trend, cutting across all 3 major valley systems, but with little surface expression.

3.4 : GLACIAL EROSION

"In areas of considerable local relief, the results of glacial erosion are easily recognised" (Price, 1973, P.52). This statement is of particular relevance to Area I, for as illustrated in figures 3.4 and 3.5, there are numerous major and minor landforms of glacial erosion to be found here. The landforms vary in dimension from small-scale grooves and striations produced by clasts at the base of moving ice, to large-scale and often spectacular glacial troughs, where a variety of glacial processes were concentrated.

GLACIAL TROUGHS. "In some localities, as at the head of Annandale, in Talla Water, round Loch Skene, and in several of the glens that open into the Vale of the Moffat Water, the smooth contour of the hillside is varied/...

varied by the occurrence of abrupt craggy scars and precipices which present scenes suggestive rather of parts of the northern Highlands than of the soft pastoral air of the Southern Uplands" (A. Geikie, 1863, P. 160). It is fairly evident from the above description, that Geikie is referring to the main glacial troughs of the Tweedsmuir Hills (Fig. 3.5).

Principal among the troughs of Area I is the steep-sided trench occupied by the Moffat Water, orientated in a north-east to south-west direction (Plate 3.A). It can be seen from figure 3.6 that this valley possesses the characteristic U-shaped or more correctly parabolic (Svennson 1959; Graf 1970; Sugden and John 1976), cross-profile associated with glacial troughs. The form of Moffatdale is not solely attributable to glacial erosion however, for as mentioned the valley also follows a major fault and shatter belt (Fig. 3.3). The importance of this line of former tectonic action cannot be underestimated, "... a crucial part of glacial erosion involves any process which loosens or weakens blocks of rock beneath a glacier" (Sugden and John, 1976, P. 157). Consequently, it was the interaction of tectonic and glacial processes which resulted in the linear, steep-sided form of Moffatdale at the present day.

The cross-sections taken at various localities within Moffatdale (Fig. 3.6), indicate that the trough widens and deepens in the south-west direction. When considered in conjunction with the alignment of striations and roches moutonnees along the valley sides (Fig. 3.5), this strongly suggests that a major ice mass moved south-west down the Moffat Water valley.

The Carrifran and Blackhope valleys, which join Moffatdale from/...

from the north-east, are very similar in character both to each other and to the main valley (Plates 3B, 3C). Both these tributary valleys again possess the parabolic cross-sectional form associated with glacial troughs and have steep, often scree-covered slopes leading down from craggy tops (Fig. 3.6).

Both valleys descend abruptly from the upland surface at the valley heads and at their mouths curve round to present a smooth, ungraded junction with Moffatdale. Similarly, both valleys contain evidence in the form of moraines for a more recent glaciation which post-dates trough formation.
At the head of the Carrifran trough, local terrain rises 400m, mainly over smoothed, polished bedrock, in just over one kilometre (Fig. 3.6). A similar steep rise, in this case of 370m over the same horizontal distance, is found at the head of the Blackhope trough, both trough heads tending to be convex upwards (Fig. 3.6). There is no indication of cirque development in the vicinity of either trough head, and no obvious local source for glacial ice.
Similarities regarding morphology can be drawn between the Carrifran and Blackhope troughs and troughs in the Cairngorm mountains described by Sugden (1968) as, "... ending abruptly in trough heads whose cliffs rise more than 300m to the plateau behind" (P. 85). Sugden suggested that the trough forms owe their origin to the former existence of an ice cap over the Cairngorm plateau at the glacial maximum, their form and location representative of the major routes taken by ice flowing off the plateau. He termed such troughs "Icelandic", after Linton's (1963) classification of glacial troughs; "... here (with the Icelandic type) the areas of/...

of ice accumulation have been plateau surfaces only exceptionally dominated by higher ground and discharge has been by steep ice falls into the ends of valleys, dissecting the plateau" (Linton, 1963, P. 9). By implication, the Carrifran and Blackhope Valleys were similarly carved by descending tongues of ice fed by an ice cap over the Tweedsmuir Hills, these particular troughs representative of the main southern routeways of ice discharge during the last major glaciation to affect the area.

By examining the interrelationship of the glacial troughs in the vicinity of Moffatdale, some indication as to the sequence of events leading to the build up of ice over this area can be gained. Embleton and King (1975a) stated that, "In order to erode effectively... there must .... be a free outlet for the ice to lower ground" (P. 271). Such conditions have obviously prevailed for the ice masses descending the Carrifran and Blackhope troughs and the resultant combined ice mass moving south-west down Moffatdale. The ice masses descending the Tail and Polmoody valleys did not have such ready access to lower ground however, because of the larger ice mass occupying Moffatdale itself (Fig. 3.5). As a result, these valleys were left "hanging", 152m above the main valley floor in the case of the Polmoody and 173m in the case of the Tail. Postglacial fluvial activity created waterfalls at both these localities, the more spectacular of the two, the "Grey Mare's Tail", found where the Tail Burn joins Moffatdale (Plate 3D). The Tail and Polmoody valleys are classic examples of "hanging valleys" produced by the deepening and widening of the main valley, (along the fault line and shatter belt), by glacial erosion, at a rate more rapid than that at which the tributary valleys were cut. Figure 3.7 illustrates the/...

the sequence of events relating to the build up of ice which resulted in the creation of similarly orientated hanging valleys, Tail and Polmoody, and glacial troughs, Carrifran and Blackhope, within 2 - 3 km of each other.

Similar trough forms, though not as well-developed as those previously mentioned, lead down from the western Tweedsmuir Hills towards Annandale (Figs. 3.4, 3.5). The Auchencat, Lochan and Tweedhope valleys all fall into this category, their ice-modified form the result of supply via cols at the valley heads. All 3 troughs terminate well-above the floor of Annandale which, on the basis of striae and roche moutonnee evidence (Fig. 3.5), fulfilled a similar function to that of Moffatdale and acted as a major routeway for southward flowing ice. The fact that the cross-sectional profile of the Annan valley (Fig. 3.6). does not suggest extensive modification by glacial ice, and that the junctions between the tributary valleys and the main valley are not characterised by spectacular waterfalls, as in Upper Moffatdale, is strongly related to the comparative ease with which the New Red Sandstone rocks which occupy the lower flanks and floor of Annandale were eroded.

The steep-sided Evan Water valley also acted as a major ice routeway, bringing external ice from the north-west into Area I (Fig. 3.5; Plate 3E). With regard to the more sinuous nature of this trough, Sugden and John (1976) stated, "... a sinuous trough represents the exploitation of a pre-existing river valley by a glacier. Troughs of this type seem to occur most frequently when they lie approximately parallel to the direction of ice movement" (P.185). Linton (1963) also postulated a south-east movement of/...

of ice in this vicinity, "... Beattock Summit (at the head of the Evan Water valley) heads a trough that carried Clyde ice into Annandale" (P. 10).

The troughs to the east and south-east of Moffatdale form a radiating pattern outward from the vicinity of Ettrick Head (Fig. 3.5), the principal trough following the course of the Wamphray Water south-west, in a direction parallel to Moffatdale itself. All of the troughs have glacially-breached cols at their heads, such that although some locally derived ice may have contributed to the moulding of this eastern landscape, the major source apparently lay further to the north-west, in the vicinity of Moffatdale itself. During the build up of ice on the southern side of the Tweedsmuir Hills, the ice masses descending the Carrifran, Blackhope and Moffat Water troughs coalesced in Central Moffatdale, a logical progression from Stage 1, figure 3.7. As a result, overspillage of ice into the Ettrick Water valley via the series of cols along the eastern flank of Moffatdale took place (Stage 2, Fig. 3.7). On entering the Ettrick catchment area, some of this Tweedsmuir ice moved north-east down the Ettrick Valley itself, but of greater significance to Area I, was the build up of ice in the vicinity of Ettrick Head and resultant outward movement from here, predominantly in a southerly direction.

GLACIALLY-BREACHED COLS. "When a glacier fills a valley above the height of the notches in its watershed, it flows over these notches, if it is not hindered by ice masses on the other side of the pass. By overflowing it exercises on the pass a conspicious erosive action/...

action by which the pass is lowered and widened" (A. Penck, 1905, P.11). There are over 60 examples of such "overflowing" or glacial breaching in Area I (Fig. 3.5). The glacially-breached cols are typically flat-floored, often possess concave sides and are markedly catenary in cross-profile. The altitude of the cols ranges from 243 - 732 m.o.d.. When taken in conjunction with the fact that most of the summits in the area exhibit some degree of ice moulding, this strongly suggests that Area I was entirely covered by ice at the maximum of the last major glaciation. With this in mind, Embleton and King (1975a) differentiated between two types of glacially-breached col produced at different stages in the glaciation of an area, the diffluence col and the transfluence col, (P. 264 -269). Diffluence cols are produced in a manner similar to that described by Penck above, and by definition are therefore associated with the early stages of ice accumulation over an area. Transfluence cols by contrast refer to those forms produced when, "... all available cols are used by a series of diffluent ice streams" (Embleton and King, 1975a, P. 174), suggesting ice cap or ice sheet conditions, at or near the glacial maximum. It should be stressed however, that in practise it is often very difficult with individual forms to differentiate between the two stages of formation. The orientation and altitude of all the cols in Area I is indicated on figure 3.8. While there must be some doubt as to the relative importance of glacial as opposed to preglacial processes influencing the alignment of any particular col, and as such the suitability of cols in general as indicators of former directions of ice movement, the clusters produced on figure 3.8 sufficiently confirm with other indicators/...

indicators of ice movement in Area I (ie troughs, striae, roches moutonnees etc indicated on figure 3.5), as to suggest that for the most part the cols of Area I are an integral part of the landscape of glacial erosion. On the basis of the information depicted on figures 3.5 and 3.8 , the cols of Area I can be separated regionally into 3 main groups.

(1) In the far west of Area I, there is a concentration of cols between 366 - 533 m.o.d., orientated in a generally east-west direction. These cols reflect the eastward movement of diffluent ice across the watershed which marks the western boundary to the area.

(2) South of Moffatdale, a much more diffuse pattern for the cols is indicated, but with two main concentrations. Firstly, there is a concentration of forms between 396 - 488 m.o.d., aligned in a generally north-north-east to south-south-west direction. These cols reflect the overall south-west movement of ice across this area, as indicated by the alignment of the two main troughs found here, Moffatdale and the Wamphray valley. Secondly, a slightly higher cluster of cols occurs between 427 - 564 m.o.d., orientated in a generally east-west direction. This latter concentration reflects the overflow of ice from the two principal troughs mentioned above, in particular the eastward flow of ice into the vicinity of Ettrick Head. Most of the breaching in this south-east area has taken place as a result of glacial diffluence. A particularly good example of diffluent ice flow is represented by the col which separates Big Hill (NT 127 036) and Yadburgh Hill/...

Hill (NT 136 033). This col is one of the largest in Area I; it is over 700m in length and incised more than 300m below the surrounding upland surface (Fig. 3.9).

(3) To the north of Moffatdale, the pattern of regional ice movement is again well-indicated, with a distinct concentration of cols in the north-north-east to south-south-west direction between 329 - 518 m.o.d.. A second, very diffuse pattern is also evident above 610 m.o.d.. The lower group of cols owe their origin to diffluent ice flow, but the altitude and alignment of the higher group has puzzled previous workers in the Tweedsmuir Hills. Price (1961), viewing these higher cols from the region to the north of Area I stated, "The occurrence of these through cols in the southern and eastern sides of the Upper Tweed Basin is puzzling when it is realised that the best evidence of glacial erosion, in the form of cirques .... indicates a movement of ice to the south and east ..... The location and alignment of the through cols suggest that they are related to the stage in the glaciation of the area when the whole surface was covered by ice with the centre of the ice sheet being outside the Upper Tweed Basin, possibly to the west or south-west" (P. 60 - 62). Like Price, the author believes that the cols were incised when the entire upland surface was covered by ice, but not necessarily all at the same time, or for that matter by ice from the same source.

There seems little doubt that the easterly cols referred to by Price, located along the northern margin of Area I, were/...

were incised by ice centred locally over the Tweedsmuir Hills themselves. However, regarding the more southerly forms, which lie to the north-west of Area I, there are two possible explanations. These may have been incised by ice from an external source following a north-east course into the Upper Tweed Basin. Alternatively, the ice-breached cols were incised at a stage when an axis of dispersion, as opposed to a centre of dispersion, lay across a sizeable part of the Tweedsmuir Hills, aligned in a broadly east-west direction.

CIRQUES. "A cirque is a hollow, open downstream but bounded upstream by the crest of a steep slope (headwall), which is arcuate in plan around a more gently sloping floor. It is "glacial" if the floor has been affected by glacial erosion while part of the headwall has developed subaerially, and a drainage divide was located sufficiently close to the top of the headwall for little or none of the ice that fashioned the cirque to have flowed in from outside" (Evans and Cox, 1974, P.151). On the basis of this definition, 8 landforms were identified as cirques in Area 1 (Fig. 3.5). All of these features were found in the upland north-east corner of Area I, bounded by the river Annan to the west and Moffat Water to the south.

The cirque forms which best-illustrate the above characteristics are those incised into the flanks of White Coombe (cirques F, G, H, Fig. 3.5), and Lochraig Head (cirque J, Fig. 3.5). The latter is by far the most spectacular cirque in Area I, its steep, scree-covered headwall rising over 240m above the cirque floor, which is/...

is presently occupied by the moraine-dammed Loch Skene.
Other cirque forms perched along the upper flanks of the Carrifran and Blackhope troughs (cirques B, C, D, E, Fig. 3.5), are not as clearly-developed (Plate 3F). Although possessing the arcuate plan form and steep headwall, the gently sloping floor is poorly-developed in these cirques. This variation in cirque morphology is a direct result of their location along the flanks of two major troughs. As Linton (1963) stated, "... corries (cirques) have been reduced to trifling dimensions by the paving away of the lateral spurs by trough glaciers" (P. 24). Excavation by trough glaciers has removed all traces of the existence of cirques from the north-east side of the Blackhope valley. However, their former presence in this locality is strongly implied by the steep-sided, narrow arête ridge which separates the Carrifran and Blackhope valleys (Fig. 3.5), its form resulting from cirque headwall erosion on both its north-east and south-west flanks.
Figure 3.10 indicates the altitude and orientation of all cirque forms within Area I. Sissons (1967a, P. 61 - 63) and Flint (1971, P. 136), both noted that cirque floors tend to lie at or slightly above the snowline at the time of their formation. By making the assumption that all of the cirques within Area I relate

to one, and the same, period of glaciation, it can be stated that during the period of their formation, the regional firn-line over the Tweedsmuir Hills was at an altitude of approximately 420 m.o.d..
With regard to the orientation of the cirques (Fig. 3.10), the majority are found between north-east and east-south-east,

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a similar alignment to cirque forms in other parts of Scotland (Sissons 1967 a . P. 56 - 63; 1976 P.51 - 54; Sugden 1969). Such orientations reflect the interaction of a number of factors contributing to cirque formation, but in particular the nature and orientation of the preglacial relief with regard to climatic conditions during the onset of the glacial period. Although there are too few cirques within Area I to draw any major conclusions regarding former climatic conditions, the dominant east-north-east alignment does suggest that during the period of their formation, the main snow-bearing winds were from the south and west. Embleton and King (1975a) stated, "... hollows most favourable for snow accumulation and therefore cirque glacier growth were those facing in the opposite direction, (from the snow-bearing winds), where drifting snow could most effectively collect" (P. 222).

It was suggested by Eckford (1958), that the steep-sided, semi-circular hollow at the head of Annandale, known locally as the "Devil's Beef Tub" (Fig. 3.4), was also representative of cirque formation. However, although this feature is arcuate in plan, orientated in a south-east direction, and shows evidence of modification by glacial erosion, its low altitude (the foot of the"headwall" is at 274 m.o.d.), effectively dissociates this form from the other cirques in Area I. It is more likely that the Devil's Beef Tub owes its origin to the concentration of glacial processes, associated with southward flowing ice, in a narrow zone of comparatively less resistant geological strata, marked by the former greater extent of the adjacent New Red Sandstone rocks (Plate 3G).

STRIATIONS/...

STRIATIONS, ROCHES MOUTONNEES AND ICE-MOULDED BEDROCK. Several localities where glacial striations are to be found in Area I are indicated on the Geological Survey 1-inch and 6-inch maps which cover the area. Some of these striations, although by no means all, were located in the field, but others not indicated on the maps were also identified. All of the above-mentioned forms are indicated on figure 3.5.

In general however, striations are not particularly abundant or readily identifiable in Area I, as A. Geikie (1863) stated, "The decomposing nature of the Silurian strata, which compose so large a proportion of the southern counties of Scotland, tends to obliterate the finer traces of the general abrasion .... I have geologized over several 100 ml^2 of the Silurian district of the south of Scotland, and yet the instances of striations which I have met with might be reckoned on the fingers" (P.28). Although their usefulness as indicators of former directions of ice movement has been questioned on many occasions (e.g. Embleton and King, 1975a, P. 182 - 187), and it is continually stressed that striations only indicate basal ice movements at a particular locality and need not be in accord with long-term regional ice movements (e.g. Flint, 1971, P. 90 - 95), it is interesting to note that the striations in Area I generally parallel the three main river valleys, the Moffat Water in the east, and the Annan and Evan Water further west.

Roches moutonnees are, "... the universal earmark of the invasion of an area by glacier ice" (Fluckiger, 1934, P. 23), their smooth, streamlined stoss and shattered and plucked lee sides being characteristic of the unique erosional capabilities of ice/...

ice masses. However, not only do roches moutonnees indicate the former presence of an ice mass over an area, but also by their shape, the direction of movement that the ice mass followed. As Flint (1971) stated, "Because of their pronounced asymmetry, stoss-and-lee hills (roches moutonnees) are more reliable guides to the direction of glacier motion (at least within 10 - 15° of are) than are most striations and also withstand postglacial erosion through a larger time" (P. 98 - 99).

Roches moutonnees are well-represented in Area I, (Fig. 3.5), varying in size from small mounds 2m high and 10 - 15m in length, to ridge crests which rise 50 - 60m above the surrounding terrain and are several 100m in length. Their location is as varied as their size, and roches moutonnees occur along the floors and walls of glacially-breached cols, cirques and glacial troughs, at hill top locations and indeed anywhere in Area I where conditions were favourable for their formation and preservation. The orientation of the roches moutonnees within the area again indicate that the principal directions of ice movement paralleled the 3 major valleys, in a broadly southward direction. There are slight deviations from this general pattern in the extreme eastern and western parts of the area (Fig. 3.5), where a more easterly direction for ice movement is indicated.

At a similar scale to the roches moutonnees are a series of streamlined mounds, hillocks and hills consisting entirely of bedrock, which were collectively termed "ice-moulded forms" (Fig. 3.5). Such features characteristically possess steep stoss slopes facing the direction of ice advance, with streamlined, tapering lee slopes. The ice-moulded forms also suggest a generally southward/...

southward movement of ice across Area I.

SUMMARY. The large and small-scale landforms of glacial erosion combine to indicate the principal directions of movement followed by the last major ice mass to cross Area I, as depicted on figure 3.11. From this, it would appear that there were two major centres of ice dispersal, one at least partly within the area itself, the other wholly external.

The principal centre was the ice cap over the upland surfaces of the Tweedsmuir Hills. Ice from here followed a broadly southerly course, eventually covering much of the central and eastern parts of Area I. Initial directions of outward ice movement were strongly controlled by the pre-existing relief. Consequently, processes associated with subglacial erosion were also concentrated in such localities, and in parts of the area this remained the case throughout the glacial period. The fossil pattern of large-scale landforms in the Tweedsmuir Hills indicate that many, if not all, of the circues and glacial troughs were principally incised shortly after the onset of glacial conditions. Not all of the erosional landforms can be attributed to this early stage however, and with particular reference to the ice-breached cols, it is extremely difficult to accurately ascertain when these were produced. Nevertheless, from their altitude and alignment, the higher cols at least suggest formation at or near the glacial maximum when the axis of dispersion in the enlarged ice mass over the Central Southern Uplands still ran through this local centre of dispersion, approximately along the northern boundary of Area I itself.

The western part of Area I was crossed by ice whose source lay outside the area, to the west or north-west. The exact location of this secondary/...

secondary centre of dispersal will be examined in greater detail in Chapter 4. Ice from the two sources, both following broadly parallel courses, coalesced over Area I and continued southwards down Annandale (Fig. 3.11).

3.5 : GLACIAL DEPOSITION

"In the Highland and upland districts superficial deposits appear to be for the most part restricted to valleys ... the rounded swellings of the south of Scotland showing but little trace of them at the higher elevations" (J. Geikie, 1877, P. 4 - 5). This situation is well-illustrated in Area I (Fig. 3.4), where deposits of both glacial and fluvioglacial origin cover the valley floors and lower valley slopes. At higher altitudes only peat and solid rock are present at the surface.

The dominance of glacial erosion, (previous section) obviously restricted deposition in Area I, but nevertheless extensive parts of the area are masked by accumulations of glacial till (Fig. 3.4). The greatest till deposition has taken place across lower valley flanks below 275 m.o.d.. Although till does occur above this altitude, it is only as a sporadic, discontinuous veneer, which extends into upland valleys to an altitude of approximately 400 m.o.d.. It is difficult to give an exact figure for the vertical extent of till in Area I as a result of varying local topography, but a further complication is that in an area of such uniform lithology it also becomes increasingly difficult to differentiate between till and other superficial material produced by mass wastage with increasing altitude. This problem is particularly acute in the well-developed glacial troughs in the north-east of Area I. Both types of valley-fill deposit descend from the valley sides towards/...

towards the present stream in the form of sloping benches and it is often only possible to discriminate between the two by analyses of the orientations of individual clasts within the matrix. If the material is the product of mass wastage, the clasts will be aligned at right angles to the valley axis and if glacially derived in situ, parallel to the axis. Consequently, above 400 - 450 m.o.d., the true character of a deposit, whether it be till or slope material, the latter possibly derived from the former by solifluction, could not always be stated conclusively from the poor exposures often found here. The delimitation of the till deposits at higher altitudes in Area I, as depicted in figure 3.4, is therefore by definition tentative. The largest section in Area I reveals 18m of till. It should be stressed, however, that it is only in the vicinity of valley floors that the till thickness exceeds 3m and that away from here thicknesses are generally less than 2m. It may well be that the thickness of till revealed by the largest section is exceeded at depth, below the sand and gravel deposits on the floor of the Annan and/or Moffat Water valleys. However, without supporting evidence from borehole records, and there are no records of drift thickness from the few borings made in this vicinity, (Institute of Geological Sciences, Edinburgh) only speculative estimates as to the maximum till thickness can be made at present. The tills of Area I generally consist of angular, sub-angular and sub-rounded clasts of Lower Palaeozoic greywackes, grits, shales and siltstones in a coarse gritty, clayey matrix. The only exceptions are the tills occupying southern Annandale, where fragments of Permo-Triassic sandstones and breccias dominate the/...

the deposit and the matrix itself is less compact, containing a much higher percentage of sand. The occurrence of this sandier till in an area where sand and gravel deposits are abundant, led to problems of till identification at certain localities.

The colour of the till is indicative of the geological source areas, but not necessarily indicative of the bedrock on which the deposit rests. However, once again the uniform lithology in Area I prevented any great variety of till colour, although minor variations do occur. Dark brown tills are dominant, but along the floor of the Annan valley the colour changes to a reddish-brown, while in Moffatdale the tills are generally darker, reflecting the enhanced development of black shales along the line of the valley (Greig, 1971, P. 34 - 49).

Only one till unit is found overlying bedrock in Area I, although in some localities the till itself is overlain by fluvioglacial deposits. This till, although differing in colour locally is of a generally compact nature throughout. Together, these factors strongly suggest that it is lodgement till (Goldthwait, 1971, P. 3 - 26), which is widespread in Area I.

More detailed examination of the best-exposed till sections in Area I, (Exposures 3L - 3R, Fig. 3.4), was carried out in an attempt to aid description and identify any local variations in character which were not initially apparent. At each of the 6 sites, preferred-stone orientation analysis particle size analysis and erratic counts were carried out, the results of which are depicted in table 3.1, table 3.2 and figure 3.12.

Exposure/...

Exposure 3L′ is in the valley of the Lochan Burn, close to its confluence with the Kinnel Water (Fig. 3.4; Table 3.1).
From a preferred-stone orientation analysis, a mean orientation of stones contained in the till of 162° was calculated (AppendixII Table 3.2; Fig. 3.12). A chi-square value of 32.1 was also calculated for the mean orientation (Appendix III ; Table 3.2). When tabulated with 8 degrees of freedom this value, known as the orientation strength, is statistically significant at the 99.9% confidence level. The larger the orientation strength, the greater the concentration of pebbles around a specific orientation, there being a fairly strong concentration in this case. A dip-strength value of 2 was also calculated. (Appendix III ; Table 3.2), which when tabulated with one degree of freedom is not statistically significant at the 95% confidence level. There is therefore no evidence in this case to suggest an uneven distribution in the angle of dip of the clasts.
The importance of results such as these has been recognised for many years. As early as 1884, Miller stated, "... the longer axis of the stone is often directed in the line of glaciation" (P. 167). Such initial research into till fabrics and stone orientations was elaborated upon by a number of workers, (e.g. Richter 1932, 1936; Holmes 1941; Harrison 1957; Harris 1968; Andrews 1971). Nevertheless, the original postulation, that the majority of clasts tend to have their long axes aligned parallel to the former direction of ice movement, is still generally accepted. There is a major division in opinion however, as to the direction in which such stones should dip. Many of the earlier workers, (Richter 1932, 1936; Holmes 1941; and Harrison 1957), were/...

were of the opinion that the stones have a tendency to have their long axes dipping down from the horizontal in an up-glacier direction. Harris (1968, 1969), held the opposite viewpoint and suggested that the stones have a tendency to dip in a down-glacier direction. Therefore, from the alignment of the long axes of clasts in till, it can be stated that the depositing ice moved in one of two directions parallel to the long axes orientation, the two directions separated by 180°. However, it cannot be stated conclusively which of the two directions is correct on the basis of pebble orientation alone.

In this manner, the mean orientation at Site 3L (Table 3.1; Fig. 3.12), of 162° is indicative of a depositing ice medium moving from either the north-north-west or south-south-east. Examination of other characteristics of the till itself and the alignment of adjacent indicators of the direction of ice movement, e.g. striations, roches moutonnees etc., may clarify the situation. Directions of ice movement are also interpreted from the positive identification of indicator rocks or erratics, from well-mapped sources (e.g. Holmes 1952; Dreimanis 1956; Sissons 1967a ; Goldthwait 1971). However, once again the uniform lithology of Area I renders this method largely unsuitable at exposure 3L and the other 5 sites in the area. Nevertheless, an erratic count of 50 pebbles was made at each site.

With regard to exposure 3L, all of the erratics are of Lower Palaeozoic origin. If ice movement was from the south-south-east direction it might have been expected to find New Red Sandstone clasts in the matrix (Fig. 3.3). However, their total/...

total absence supports the suggestion of movement from the dominant area of Lower Polaeozoic rocks, to the north and west of exposure 3L.

Similar analyses were carried out at each of the other 5 sites examined in detail in Area I (Exposures 3M - 3R, Fig. 3.4); the results are depicted in tables 3.1, 3.2 and figure 3.12. The combined information relating to the till exposures in Area I indicate the principal directions of ice movement responsible for deposition at each of the 6 sites and suggest the broad pattern of movement over the area as a whole. The 6 exposures can be broken down into 3 closely linked groups of two : in Moffatdale, exposures 3P and 3Q; at the head of Annandale, exposures 3M and 3N; and downstream on the flanks of Annandale, exposures 3L and 3R. The rose diagrams for stone orientations at each of these sites (Fig. 3.12). indicate a south-south-west or north-north-east movement of ice in Moffatdale at the head of Annandale, but a north-north-west or south-south-east movement further down the Annan valley. Locally, at the head of Annandale, the erratic content of the tills can for once be utilised to clarify the direction of movement of the depositing ice mass, as a result of local geological conditions. The till at exposure 3M (Stotfield Gill), rests upon red sandstone bedrock, while that of exposure 3N (Auchencat Burn), is found only 100 - 200m from the distinctive red outcrops, although resting on greywacke. New Red Sandstone rocks occupy the lower flanks and floor of Annandale and extend down the valley for 30 kms (Fig. 3.3). Nevertheless, New Red Sandstone erratics are totally absent from/...

from both of these exposures (Table 3.2), which strongly suggests that the depositing ice mass moved down Annandale from a broad northerly direction.

With regard to the other sites, the rose diagrams in Moffatdale (Exposures 3P, 3Q, Fig. 3.12). indicate an ice movement parallel to the alignment of the valley itself. It was previously suggested, on the evidence from landforms of glacial erosion (Fig. 3.5), that Moffatdale was occupied by south-west flowing ice during the last major glaciation and the alignment of clasts at both exposures 3P and 3Q would therefore tend to support this. Lower down the Annan valley the stone orientations at exposures 3L and 3R relate to a generally south to south-east movement of ice, again on the basis of adjacent landforms of glacial erosion (Fig. 3.5). Clasts of New Red Sandstone origin might have been expected to occur in the erratic count at exposure 3R (Beldcraig Wood), and thus substantiate the claim of a north-westerly source (Table 3.2), but their absence can be accounted for in terms of local ice movements. This lower eastern part of Annandale was glaciated by ice descending Moffatdale which was re-directed along a more southerly course at its junction with the Annan valley (Fig. 3.5).

The particle-size information relating to all 6 exposures (Table 3.2), indicate little variation in the character of the tills throughout Area I. This is only to be expected when the uniform lithology of the area and the similarity in the erratic counts at each of the 6 sites (Table 3.2), is taken into consideration. Two slight anomalies indicated in table 3.2 need/...

need explanation however. The high concentration of cobbles and boulders at exposure 3Q (Grey Mare's Tail), may reflect the proximity of the ice source to this till site and subsequent lack of comminution that occurred during the short distance of transport (Plate 3H). In a similar fashion, although no sizeable erratics of New Red Sandstone rocks were recovered from exposure 3M (Stotfield Gill), the high concentration of sand-sized particles in the deposit is thought to reflect the at least limited presence of the underlying sandstone, and by contrast with the previous site, its susceptibility to comminution.

DRUMLINS. Although the morphological expression of glacial deposition was mainly restricted to a masking of the underlying bedrock by a comparatively thin veneer of till, in places the till deposits and indeed bedrock also, were moulded into drumlinoid forms. These external morphological expressions of glacial deposition (and erosion) were also useful in ascertaining former directions of ice movement, but only over a limited part of Area I. Drumlins are restricted to selected parts of the floor and lower flanks of the Annan valley (Figs. 3.4, 3.13). Table 3.3 (Fig. 3.13), also indicates the dimensions of the principal drumlin forms and their postulated constituents. The scarcity of borehole evidence severely restricted accurate determinations of the internal constituents however, and consequently, the descriptions in table 3.3 are based solely upon limited surface exposures (Plate 3I).

Drumlins which apparently consist mainly or wholly of till

are/...

are restricted to the floor of the Annan valley, below 110 m.o.d. The higher forms, found along the eastern flank of the valley up to an altitude of approximately 240 m.o.d. consist either partly or wholly of bedrock (Fig. 3.13). Occasionally, the larger or "Megadrumlin" forms have smaller drumlinoid forms superimposed upon their flanks or crest, e.g. drumlins A and E, figure 3.13 (After Rose and Letzer, 1977). The existence of more than one size population of drumlins in an area is indicative of,"... variations in available energy and sediment supply at the ice debris interface ....", and suggests that, "... the two populations are related to a diminishing energy regime" (Rose and Letzer, 1977, P. 477). Such statements imply that drumlin formation occurred at a late stage in the period of glaciation, but the exact method of formation is still the subject of great debate, (Smalley and Unwin 1968; Boulton 1975; Aario 1977; Gillberg 1977).

It is generally agreed, however, that drumlins trend approximately parallel to the direction of ice movement, the stoss-end usually pointing upstream, in the direction from which the ice has moved, (Gravenor 1953; Flint 1971; Embleton and King 1975a). All of the drumlins in Area I (Fig. 3.13), with the possible exception of drumlin B, have their stoss-end facing north and thus also suggest a southerly movement of ice across this part of the study area.

MORAINES. Moranic landforms and deposits are restricted to the extreme north-east part of Area I, (Fig. 3.4), in the upland valleys of/...

of the Carrifran, Blackhope and Tail Burns, the principal south-east trending outlets from the Tweedsmuir Hills and tributaries to the Moffat Water. By far the best morainic forms are found in the Upper Tail Burn, in the vicinity of Loch Skene. These moraines have previously been mentioned by Chambers (1855) and A. Geikie (1863), and described in greater detail by Young (1864) and Eckford and Manson (1927). More recently, the moraines in the vicinity of Loch Skene and similar morainic landforms in the upper parts of the adjacent northward trending Talla, Megget, Gameshope and Fruid valleys were described by Price (1961) and Sissons (1967 b , 1976).

Air photographs, at a scale of approximately 1:10,000, of those valleys containing moraines, were examined stereoscopically and then taken into the field where the initial landform pattern was checked by detailed field mapping. As a result, it was possible in many cases to accurately locate individual mounds (Fig. 3.14).

a) Loch Skene Moraines. "Mounds of detritus lie below the smoothed but nowhere striated declivity at its (Loch Skene) head, and skirt the loch on either side, while beneath the water, whose depth is unknown, appear the ruins of heaps which near the outflow project their tops above the surface. The stream cuts through a series of mounds arranged in concentric curves pointing down in the axis of the lower half of the loch". (Young, 1864, P. 457). From the description by Young and by reference to figure 3.14, it can be seen that the Loch Skene moraines encircle the steep-sided cirques at the head of the loch itself and the immediately/...

immediately adjacent Midlaw Burn (Plate 3J). The morainic landforms consist of a series of mounds and ridges which vary in height between 2 - 16m. In terms of length, there is a marked contrast between ridge forms, such as "the Causey" (Fig. 3.15), which runs discontinuously along the eastern side of Loch Skene for almost a kilometre, (the steep, western face to the ridge is 11m in height, but when viewed from an easterly direction the ridge crest rises only 2 - 3m above the surrounding terrain), and areas of short, badly-slumped hummocky mounds only 2 - 3m in length (Plate 3K). The true dimensions and indeed total areal extent of the moraines are difficult to assess accurately in certain parts, because of extensive peat development which has filled or partially-filled every depression found in association with the depositional forms. 5 - 6m of peat have accumulated in places, the greatest peat thicknesses occurring to the east of Loch Skene, at the head of the Winterhope valley. Nevertheless, it can be stated with a reasonable degree of confidence that all the mound and ridge forms in the vicinity of Loch Skene lie between 457 - 610 m.o.d.

The extensive peat development has also limited the availability of exposures illustrating the internal constituents of the moraines, but several good sections have been incised through ridge forms by the Tail Burn (Plate 3L). These exposures typically reveal a grey-brown, gravelly matrix containing a large number of angular and sub-angular clasts of local origin; the clasts are generally less than 4cm in diameter, although larger blocks up to 50cm also occur. Boulders up to 6m in diameter are found scattered across/...

across the surface of the mounds and ridges. There is no evidence of sorting or stratification in any of the exposures examined and no indication of the compact dark brown till found at lower altitudes in other parts of the Tweedsmuir Hills.
The constant alignment of successive mound and ridge forms at the furthermost extent of the morainic deposits and again in the vicinity of the cirque heads suggests that in these localities at least, the moraines relate to the ice margin of a retreating but active ice tongue and as such are probably end moraines.
Between the two areas where end moraines can be identified, there is a more chaotic landscape with no apparent preferential alignment to the mound or ridge forms. This "chaotic landscape" is termed hummocky moraine. The end moraines and associated areas of hummocky moraine in the vicinity of Loch Skene are indicated on figure 3.15.
A multiple end moraine sequence extends down the Tail Burn from the southern shore of Loch Skene in association with the well-developed ridge form, "the Causey" (Fig. 3.15; Plate 3M).
These ridges have steeper sides and are higher than any other forms in the vicinity of Loch Skene, exceeding 15 - 16m in places.
The width of ridge crests varies between forms. Along most of its length, the crest of "the Causey" is only 3 - 6m wide, but one of the end moraine ridges flanking the southern shore of Loch Skene has a crest width of 50 - 60m (Fig. 3.15). Several of the wider ridge forms in this multiple sequence have kettle hole depressions along their crest, suggesting that in part the ridges were originally ice-cored. The best example of such a depression is Hogg's Well (Fig. 3.15), a kettle hole approximately 30m in diameter which still retains a sizeable volume of water (Plate 3N)./...

(Plate 3N). In profile, all of the moraine ridges along the southern shore of Loch Skene have convex sides facing downstream in a southerly direction and concave flanks facing upstream, their method of formation suggested by Chambers (1855), "... being usually placed in front of these (glaciers) as a fender is placed before a fire" (P. 99). The moraine ridges which extend down the course of the Tail Burn are believed to represent the maximal limits and initial stages of subsequent intermittent retreat of a small ice mass in the vicinity of Loch Skene. Clearly identifiable discontinuous ridge forms, again taken to represent end moraines, are also found in the Midlaw and Loch Skene cirque heads. Referring to the area near the head of the Midlaw Burn, A. Geikie (1863) stated, "... the bottom of the corrie (cirque) for about $\frac{1}{4}$ mile (360m) is a flat plain .... from which the hills rise with single abruptness. This plain has all the appearance of having been at one time occupied by a lake. It's lower end is barred across by a great convex rampart of earth and stones about 40ft (12.5m) high, pointing down the valley, and sloping away up on the north-eastern side into a well-defined ridge of the same materials, which runs along the hill which bounds the valley to the north-east. This transverse mound is a true terminal moraine; and the ridge on the hill-side above is in like manner, a lateral moraine" (P. 162; Fig. 3.15). At the head of Loch Skene, a similar sequence of end moraines to that of the Midlaw cirque is found along the north-east lower cirque wall. The discontinuous pattern of postulated frontal and lateral end moraines which occupy the Midlaw and Loch Skene cirques most-likely represent several late-stages in the retreat of/...

of the ice mass previously referred to. The former existence of a small lake, whose waters were retained by a morainic dam at the head of the Midlaw cirque in a similar fashion to Loch Skene at the present day, could be neither verified or disproved. A boring revealed one metre of peat overlying coarse angular debris, with no evidence of lake clays. However, as the "morainic dam" is breached at two localities, it is possible that the short-lived nature of the lake limited the development of such deposits (Plates 3O, 3P, 3Q).

Young (1864) described the area between the postulated morainic dam in the Upper Midlaw valley and Loch Skene as "... a sea of mounds showing no trace of order, their surface strewn with large blocks" (P. 456). Such a statement typifies the difficulties of describing the chaotic landscape generally associated with areas of hummocky moraine. There are two main areas of hummocky moraine in the vicinity of Loch Skene: at the head of the Winterhope valley, to the north of "the Causey" end moraine; and on the regional slope leading down from the Upper Midlaw Burn to the Tail Burn. In both areas there is a complete intermixture of mound and minor ridge forms aligned in a variety of directions, whose dimensions apparently vary at will. Some of the forms are flat-topped and exceed 100m in width, often with kettle holes interspersed across their surfaces, others are narrow ridges only 1 - 2m in width. The kettle holes, small meltwater channels, and irregular peat accumulation, further add to the disordered appearance. Generally however, relative relief values in the areas of hummocky moraine are between 4 - 10m (Plate 3R)./...

(Plate 3R).

A third area of hummocky moraine may be found beneath the waters of Loch Skene itself, the only indication of this being the small morainic islands, representative of the crests of mounds and ridges, which project above the loch surface. The limited nature of the bathymetric survey work which has been carried out at Loch Skene (Fig. 3.16), makes it impossible to substantiate such a claim at the present time.

b) <u>Moraines in the Carrifran & Blackhope Valleys.</u> Similar morainic landforms, but less abundant and certainly less well-developed than those in the vicinity of Loch Skene, are found on the floors of the steep-sided Carrifran and Blackhope troughs (Figs. 3.17, 3.18). The moraines in both valleys are represented by a series of boulder-strewn mounds whose dimensions vary up to 10m in height and 50 - 70m in length. However, such a statement regarding dimensions is slightly misleading as the majority of the forms are indistinct and possess only low-angle sides, occasionally blending imperceptibly into the valley flanks. No readily identifiable end moraines are visible. Indeed, it is difficult to identify any pattern to the scattered mound forms in either the Carrifran or Blackhope valleys, but if anything they appear to be aligned downvalley, at a low angle to the regional contour pattern.

Slope processes on the steep valley sides, for which there is abundant evidence particularly in the Upper Carrifran (Fig. 3.18), may have masked the full extent of the morainic accumulations and at least partially contributed to their ill-defined appearance at the/...

the present day. All evidence relating to the occurrence of morainic landforms in the Carrifran and Blackhope valleys is found between 243 - 366 m.o.d., within approx. 60m of the valley floors. Therefore, although there is little doubt that moraines are found in the Carrifran and Blackhope valleys, their numbers, dimensions and morphology are far inferior to the similar forms in the vicinity of Loch Skene.

c) Formation of Morainic Mounds in Area I. "There can be little doubt but that the mountainous area around Loch Skene was an independent centre of dispersal during the Great Ice Age and there is evidence that towards the close of the period a recurrence of colder conditions gave rise to valley glaciers" (Eckford and Manson, 1927, P. 508 - 509). The morainic mounds in the vicinity of Loch Skene, and in the Carrifran and Blackhope valleys. other similar high-altitude forms in the Southern Uplands, and more extensive and dateable forms in the Highlands, are believed to have formed during the "recurrence of colder conditions" associated with the Loch Lomond, Zone III or Younger Dryas readvance or advance of ice, either during or after the main period of deglaciation associated with the last ice sheet (Sissons, 1967b, 1976, 1979a; Gray and Lowe 1977).

A tentative reconstruction of the last glaciers to be present in Area I, based principally upon the extent of the morainic landforms, is illustrated in figure 3.19. In the vicinity of Loch Skene, the ice masses spawned in the cirques at the head of Loch Skene and the Midlaw Burn coalesced, and tongues of ice extended down the Winterhope and Tail valleys. The maximum extent of these ice lobes/...

lobes and their initial stages of retreat are well-marked by end moraine mounds and ridges. During the later stages of decay it appears that this enlarged Loch Skene ice mass again became dissociated into two separate cirque glaciers, the final stages in dissipation of these also being well-marked by end moraines. The location, morphology and extent of the morainic accumulations in the Carrifran and Blackhope valleys suggest formation in association with two narrow, low-lying glaciers occupying mainly the valley floors. The extensive evidence of mass movement down the steep flanks of both valleys, in close association with the moraines, may relate to enhanced periglacial activity when the glaciers were present.

3.6 : FLUVIOGLACIAL EROSION

The erosive capacity of meltwater is well-exhibited in Area I. Most of the channel forms were identified in the field by the anomalous positions of their in-takes and outlets in relation to the present-day drainage pattern. Other forms were identified only with difficulty, being occupied along at least part of their course by stream activity. The vast majority of channel forms are incised across the slopes of the major valley systems into bedrock, although a few forms are cut wholly into drift material in the valley floors. Postglacial modification of channel form was particularly significant in relation to channel development in the upland areas, where infilling by mass wastage and the formation of peat often masked true channel dimensions.

Several hundred channels were identified in Area I (Figs. 3.4, 3.20), but the uneven distribution of these makes it desirable to sub-divide/...

divide the area and examine the main concentrations individually. As suggested above, channel concentrations are found in association with the major valley systems, and on this basis a three fold division of Area I was adopted (3.20).

CHANNEL SYSTEMS IN MOFFATDALE. Geikie wrote the following lines referring to the Silurian district of southern Scotland, "... there occur, numerous ravines and narrow valleys, either with one or both ends cut off running along the sides of the hills, especially where these border a principal valley. Such depressions are cut through the solid rock; they have frequently steep sides and have every resemblance to water courses, but they are either quite dry or are traversed merely by the drainage of small springs issuing from the hillside" (A.Geikie, 1863, P. 28). Such statements may well have been written about Moffatdale, for as illustrated on figures 3.4, 3.20, there is a dense if discontinuous record of meltwater activity across the flanks of the valley, running generally parallel or at a low angle to the contour pattern. A greater understanding of glacial conditions at the time of this meltwater activity may be gained by detailed examinations of individual channel systems and their relationship to surrounding glacial and fluvioglacial deposits. Channel systems C and D (Figs. 3.20, 3.21), consist of a series of two-sided channels and one-sided bench forms which were incised into the north-west flank of Moffatdale, on the slopes of Carrifran Gans. The highest channels in these systems (D1 and D2, Fig. 3.21), have their in-takes at altitudes between 701 - 732 m.o.d., and plunge directly downslope towards the Carrifran Burn, to terminate at altitudes/...

altitudes between 487 - 533 m.o.d.. However, these channels are unrepresentative of the main part of the system (D3 - D12, Fig. 3.21), which runs across the slope, generally parallel to the contour pattern and to the alignment of the Moffat Water valley itself. Channel D3 (Fig. 3.21), takes the form of a one-sided bench, 18m wide, incised wholly into bedrock throughout its length. The in-take is found at 686 m.o.d., but the nature of the bench is such that where it terminates, having run across the slope in a south-westerly direction for 220m, it is only a few metres lower in altitude. Another bench of similar dimensions is found 5 - 6m below D3, but this form D4 (Fig. 3.21), although again principally following a course across the regional slope, also possesses a segment which trends more directly downslope from the bench for 3 - 4m before terminating abruptly. D5 is yet another bench, and the most continuous form in the system. The bench, which is 14m wide at its in-take, begins at approximately 640 m.o.d. and although breached by postglacial stream activity a short distance along its course, continues across the slope for 660m. Throughout its length the bench closely follows the contours of the hillslope, falling only 15 - 20m in altitude, although it gradually narrows to 4m in width at its outlet. The gradient of D5 is approximately 1:40.

Channel forms D10 and D11, (Fig. 3.21), are found between 442 - 479 m.o.d.. In both cases it is not an individual channel form which is represented, but a series of closely spaced narrow benches, separated by only 1 - 2m in altitude, all of which run parallel or at a low angle to the contour pattern. The benches represented by D10 are replaced over the last 100m of their 400m/...

400m length by a single channel form, 8m deep and with a flat floor 22m wide, which is incised into the northern flank of the rock knoll, Dun Knowe. Similarly, the lower bench forms of D11 are replaced 170m along their course by a channel form (D12, Fig. 3.21), 5m deep and with a flat floor 3m wide, which trends more obliquely downslope for 275m towards Dun Knowe. In the vicinity of the rock knoll, the course of this latter channel changes dramatically to plunge directly downslope for 180m at right angles to the contour pattern, finally terminating at 243 m.o.d..

Channel system C (Fig. 3.21), is found 300 - 400m to the north-east of system D, the channel forms occurring at broadly similar altitudes. However, there are several significant differences between the two systems. Firstly, the channel forms of system C are all incised across a poorly-developed spur descending eastwards from Carrifran Gans, and not on the south-west to north-east trending main valley slope, as was the case with system D. Secondly, the orientation of the higher channels, particularly those above 580 m.o.d., indicate formation by meltwater derived from a more northerly source than that which formed system D. However, the alignment of the channels strongly suggests that on joining the main valley, the meltwater which incised system C has followed a more south-westerly course and may also have incised system D downvalley. Thirdly, whereas with system D, all the channel floors sloped down in a south-west direction from their point of in-take, several of the long-profiles for channels in system C suggest formation by meltwater which flowed uphill along at least part of its course. Channel C5 (Fig. 3.21), illustrates this situation well. The channel has twin in-takes

at/...

at 472 m.o.d. which merge upslope to form a wide, flat-floored form which is incised across the crest of the spur. Where best-developed the floor of the channel is 85m wide and 5m deep. On the southern flank of the spur crest, the channel form narrows, but is clearly continuous, finally terminating at an altitude of approximately 335 m.o.d.. It is difficult to be certain as to the exact limit of meltwater erosion on this southern flank of the spur, as part of channel C5 has been subsequently utilised by postglacial stream activity.

On the southern side of the Moffat Water valley a similar discontinuous channel pattern to that found on the flanks of Carrifran Gans is represented by systems N and O (Figs. 3.20, 3.22), which are incised across spurs projecting into Moffatdale from Croft Head. The highest channel form is N1 (Fig. 3.22), a bench 30 - 35m wide, which runs across the crest of the spur for 175m at an altitude of 540 m.o.d.. The bench stops abruptly at the southern edge of the spur crest, but there is evidence in the form of a small channel, (2m deep with a flat floor one metre wide), to suggest that at some time a small flow of meltwater continued downslope on the lee side of the spur, albeit only for 60 - 70m. The other channel forms of system N are of similar dimensions to N1 and occur at successively lower altitudes across the spur, the lowest at 427 m.o.d.. In all cases the forms are incised across the crest of the spur, and trend parallel to the alignment of the Moffat Water valley itself. The highest channels of system O (Fig. 3.22), run directly downslope on the southern flank of the spur between 503 - 457 m.o.d.. These five channels represented by O1, O2 and O3 (Fig. 3.22), all possess similar/...

similar dimensions. They are 3 - 6m deep, with flat floors 3 - 4m in width. Channel 03 is of particular interest in that it has a semi-circular in-take to its downslope course. There is no evidence of meltwater erosion across the crest of the spur in the vicinity of these channels. Lower down the spur, channels are incised directly across the crest at a variety of angles, but broadly parallel to the alignment of the main valley. One of the largest forms is channel 06 (Fig. 3.22), found at 381 m.o.d.. The channel is 150 - 160 m.o.d. in length, has a flat floor 9m in width, and is incised 5m into bedrock. When viewed in long-profile, the channel can be seen to be humped, with the high point of the channel floor coinciding approximately with the crest of the spur. Several other discontinuous channel systems are incised into both the northern and southern flanks of the valley further down Moffatdale near its junction with Annandale (systems I, J, K,L, P, Q, R, S, Figs. 3.4, 3.20). The channel forms are again most commonly found incised into the spurs which extend into Moffatdale itself.

The meltwater channel pattern within Moffatdale as a whole can therefore be seen to be aligned essentially in a north-east to south-west direction, parallel to the main valley and generally parallel to the regional contour pattern also. The only deviations from this are found at the junction of Moffatdale with Annandale, where meltwater has followed a route more directly southwards, and at those parts within the valley itself where locally there was a tendency for meltwater to trend more directly downslope (Figs. 3.4, 3.20).

CHANNEL/...

CHANNEL SYSTEMS IN UPPER ANNANDALE

a) Area to the North of Moffat. The meltwater drainage pattern in this area differs greatly from that incised in the vicinity of Moffatdale, for although there is evidence of meltwater entering this part of Area I from the north and north-west up to altitudes exceeding 615 m.o.d. (Figs. 3.4, 3.20), the vast majority of channel forms are found below 243 m.o.d.. Furthermore, as also indicated on figures 3.4, 3.20 the channel forms found here generally trend directly downslope at a high angle to the local contour pattern and that only in isolated cases do they run parallel to the contour pattern in the manner typical of Moffatdale. This fact is well-illustrated by channel systems BB, CC, EE, FF, GG, II (Fig. 3.20, 3.23, 3.24).

Channel system II (Fig. 3.23), is located on the lower western flank of Annandale and consists of a series of channel forms which are aligned directly downslope, at right angles to the contour pattern. The highest in-take of the system is that of II 1(Fig. 3.23), at approximately 250 m.o.d., on the western side of the B719 road. At the road itself, the channel is incised 5m into bedrock and possesses a flat floor 2m wide. An indistinct bench form continues for just over one hundred metres to the north-west of the main point of in-take. Moving downslope from here across the road, channel dimensions gradually increase, and the principal meltwater flow down channel II 1 was augmented by two smaller tributaries from the south. The lower part of the channel, slightly disconnected from the upper segments and here termed II2 (Fig. 3.23), is presently occupied by the Holehouse Linn Burn. Over this part of the channel length meltwater has cut/...

cut a deeply-entrenched feature into bedrock, 15 - 16m in depth, with a narrow floor 1 - 2m wide. Channel II 1 - II 2 terminates abruptly at its junction with the Annan floodplain at 146 m.o.d.. Channel II 4 (Fig. 3.23), has two semi-circular plunge-pool in-takes, a northern form and a western form, the latter partly hidden by the road; both are at approximately 227 m.o.d. and laterally within 100m of each other. Along the first 300 - 350m of II 4 meltwater flowed at a fairly low angle to the contour pattern, across the slope, in a channel 8m deep and 15m wide. The course of the channel then changes abruptly at 213 m.o.d., and plunges more directly downslope, becoming deeply-incised. Along this part of the course, the channel is 10m deep but the floor only 1 - 2m in width. The channel finally bifurcates to give twin outlets, both of which grade into the Annan floodplain at 146 m.o.d.. Of the two outlets, the southern form is the more deeply-incised, but of limited length, as it becomes a tributary to channel II 5 (Fig. 3.23). Channel II 5 also starts its course abruptly, again with a semi-circular plunge pool in-take, but at the slightly lower altitude of 213 m.o.d.. The channel runs directly downslope throughout its 500m length. At the point of in-take it has a flat floor 4 - 5m wide and is incised 8m into bedrock. Moving downslope the channel narrows but deepens, such that after the junction with channel II 4, floor width is only 2m but the channel is incised to a depth of 12m. The smaller channel forms, II 6, 8 and 9 (Fig. 3.23), all start abruptly also, but run downslope for only a short distance before terminating equally abruptly, their courses extending from 179 - 170 m.o.d., 167 - 149 m.o.d., and 197 - 167 m.o.d. respectively.

Part/...

Part of the course of channel II 7 (Fig. 3.23), has also been occupied by postglacial fluvial activity, in this case by the Gardenholm Linn Burn.

On the eastern flank of Annandale between the Granton and Lochan Burns there is another detailed channel pattern, and once again the largest and best-developed examples of fluvioglacial erosion are occupied by present day streams, in this case the lower courses of the misfit Lochan, Auchencat and Granton Burns, in association with which channel systems CC, EE, FF and GG are found.

Channel system CC is dominated by the channel presently occupied by the Lochan Burn (CC 1, Fig. 3.24). This feature has a flat floor, 45m in width and is incised to a depth of 10m through drift material into the underlying bedrock. The wide, deeply-incised nature of the Lochan Burn is first evident at approximately 228 m.o.d. and the channel form continues downstream to 197 m.o.d., where it blends into the Annan floodplain. There is only one small channel, CC 2 (Fig. 3.24), leading into the main channel. In a similar fashion, the channel occupied by the Auchencat Burn dominates channel system EE (Fig. 3.24). Enlargement of the fluvial form by meltwater erosion first becomes apparent again at approximately 228 m.o.d., where the Auchencat Burn plunges down a steep-sided gorge which opens out to become a wide, flat-floored channel, deeply-incised through drift deposits into the underlying bedrock. The floor of the channel varies between 30 - 40m in width, the channel sides rising 10 - 13m above this. The Auchencat channel (EE 1, Fig. 3.24), joins the Annan floodplain at approximately 167 m.o.d.. The only large feeder for this channel is the "Herring Loup", channel EE 2 (Fig. 3.24), which follows a short course, starting abruptly at 205 m.o.d.

where/...

where meltwater has incised through sand and gravel deposits into bedrock to a depth of 12m. This channel runs for only 200m before smoothly joining the Auchencat channel at 195 m.o.d.. There is another small feeder to the Auchencat channel, channel EE 3 (Fig. 3.24), which joins the main channel from the north and is incised entirely into drift deposits (Plate 3S).

All of the channels of system FF (Fig. 3.24), found between the Auchencat and Granton Burns are cut entirely into drift deposits and run downslope at a high angle to the contour pattern. These forms are not as deeply-incised or sharply-defined as the forms incised through to bedrock, and as such are often difficult to identify, being only a few metres wide and 1 - 2m in depth. The points of in-take for these channels vary slightly in altitude, as do the outlets, one form (FF 1, Fig. 3.24), leading across the slope to debouch into the Granton channel, while the two others (FF 2, FF3, Fig. 3.24), trend more directly downslope to the Annan floodplains (Plate 3T).

The Granton channel is the major meltwater routeway of system GG (Fig. 3.24). The channel has two major points of in-take; at 221 m.o.d., where the course of the Mere Beck Burn swings through 90 degrees coming down from the uplands (GG 1, Fig. 3.24), and at 197 m.o.d., along the lower course of the Granton Burn itself (GG2, Fig. 3.24). Where best-developed, the Granton channel is 20 - 30m wide and incised 18 - 20m through drift deposits into bedrock. This major channel narrows at its outlet to grade smoothly into the Annan floodplain at 162 m.o.d.. In addition to the channel forms which lead into the Granton channel from the north, there are also smaller features, again incised entirely into drift deposits, which run obliquely across the regional slope to join the main channel from its southern side (Channels GG5, GG6, GG7, Fig. 3.24).

Channel/...

Channel GG 8 (Fig. 3.24), "Hind Gill", which is aligned approximately north-south and has its in-take to the south of channels GG 1 - GG 7, at 235 m.o.d., is believed to have formed in intricate association with the other channels in systems EE, FF and GG. Hind Gill (GG 8), has an up-down long profile, is incised to a depth of 7 - 9m into bedrock and has a flat floor 15 - 20m wide (Plate 3U).

In order to fully understand the mode of formation of channel systems CC, EE, FF and GG, brief mention must be made at this point of the close association of the channel forms with evidence of fluvioglacial deposition in this vicinity (Fig. 3.24). The points of in-take of all the channel forms of systems CC, EE, FF and GG, with the exception of those presently occupied by the Lochan, Auchencat and Granton Burns themselves, are found in close association with, and often commence at, fairly narrow, level, terrace-like spreads of sand and gravel found along this eastern flank of the valley. From exposures, the narrow gravel spreads can be seen to consist of 3 - 4m of poorly-bedded, sub-rounded and sub-angular pebbles, mainly less than 2cm in diameter, in a clayey-gritty matrix and by their constituency, morphology and location are tentatively termed marginal lake deposits (Fig. 3.24).

Fluvioglacial deposits continue downslope of the marginal lake deposits, but as a series of irregular mounds and short ridges, generally aligned at a high angle to the contour pattern and dissected by the meltwater activity associated with systems CC, EE, FF and GG (Plate 3V).

b) <u>Area to the South of Moffat.</u> As indicated on figures 3.4, 3.20 all of the channels in this area are incised entirely

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into drift deposits, mainly sand and gravel. As a result, channel form is often indistinct and channel dimensions vary greatly. All points of in-take and outlet are found below 122 m.o.d..

CHANNEL SYSTEMS IN THE VICINITY OF THE EVAN WATER VALLEY.

The channel systems in the vicinity of the Evan Water (Figs. 3.4, 3.20), have similarities in distribution with both the contrasting patterns which are dominant in Moffatdale and Annandale respectively, described above. Although channel forms are not well-developed on the steep sides of the Evan Water valley itself, to the west of the Evan Water both benches and channels are found incised across the crests and flanks of west-east aligned spurs and ridges. Much of the meltwater activity in this western area has been masked by the work of the Forestry Commission in recent years and as a result was mapped by the examination of air photographs. Despite this limitation on fieldwork however, clear correlation of the higher channel pattern of the area with the channels incised across the spurs of Moffatdale is readily apparent. The forms incised across spurs in the vicinity of the Evan Water trend in a south to south-east direction and dominate the regional pattern, Locally however, within the Garpol Water valley (System TT, Fig. 3.20), channels trend directly downslope and have developed in close association with fluvioglacial deposits, as in Upper Annandale. Channel system RR (Fig. 3.25), is incised across the crest of Tarnis Head and the two spurs which descend in a south-easterly direction from here on either side of the Tarnis Burn. All the individual channel forms slope down in a broadly southward direction, although/...

although slight local variations are readily apparent from figure 3.25.

The forms incised across Tarnis Head itself, at approximately 396 m.o.d., typify the channels in this vicinity, in that they have been heavily infilled with peat, which masks their true dimensions. Despite infilling however, the best-developed of these higher forms, RR 13, RR 14 (Fig. 3.25), are incised 16 - 18m into bedrock and have flat floors 20 - 60m in width. Channels RR 13 - 17 (Fig. 3.25), are not in fact incised across the entire ridge crest, but principally developed on the south-eastern flank. Indeed, dominant development on the southern side of the spur crests is characteristic of the vast majority of the channels in the area of Tarnis Head and is particularly well-illustrated by the anastomosing patterns of channels RR 9 and RR 10. With both channels, the dimensions of the complex forms are similar, with incision into bedrock to a depth of 5 - 8m and flat peat-filled floors 10 - 20m in width.

In contrast to those forms incised mainly or solely into the southern side of the spur crest, are the channels developed across both the northern and southern sides of the crests and which possess a humped or up-down profile, e.g. channels RR 6, 12, 25, 26, 29, 30 (Fig. 3.25). Such forms characteristically have a short northerly uphill section, less than 100m in length, but as before are best-developed down the southern flank of the spur crests.

Regardless of the exact form and location of any particular channel, two general conclusions can be drawn from the pattern depicted/...

depicted on figure 3.25 : 1) the channels occur at successively lower altitudes when followed eastwards down the spurs;
2) it seems highly probable, by their altitude and alignment, that the meltwater which incised the higher channels of system RR (RR 9 - 15, Fig. 3.25), was also responsible for the incision of at least some of the forms RR 18 - 32 (Fig. 3.25), although it is impossible to match the two groups of channels accurately. Channel system RR therefore mirrors the larger pattern for the area in the vicinity of the Evan Water as a whole (Fig. 3.20), with channel forms aligned in a south to south-east direction concentrated across west-east trending spurs and ridges.
Channel system TT (Fig. 3.26), found in the Garpol Water valley, is fundamentally different from the higher channel systems in this area. The channels of system TT do not cut across the grain of the local topography, but are incised downslope at a high angle to the contour pattern, towards the Garpol Water, and occur in close association with fluvioglacial landforms and deposits. Channel in-takes are concentrated between 213 - 243 m.o.d., the forms generally terminating at the valley floor (approximately 182 m.o.d.). The Garpol Glen, which links the Garpol Water with the Evan Water, and is incised 16 - 18m through drift deposits into bedrock, with a flat floor 25 - 30m wide, acted as a major routeway for meltwater leaving the valley. Channel forms on the adjacent Beattock Hill, (e.g. at "Hell's Hole"), indicate meltwater flow in a south to south-east direction at altitudes over approximately 243 m.o.d..
Summarising meltwater conditions in this western part of Area I,
channel/...

channel forms at higher altitudes, generally above 243 m.o.d., are incised in a south to south-east direction across the underlying topography, while those below this level tend to run downslope at some high angle to the local contour pattern.

CONDITIONS LEADING TO THE FORMATION OF THE MELTWATER CHANNEL PATTERN IN AREA I.

The complex and highly varied meltwater channel pattern in Area I, is indicative of formation by meltwater encountering the equally varied underlying relief in several different glacial environments. Taking an overall view of meltwater movements across the area (Fig. 3.20), it can be seen that there was no single source responsible for this pattern. In the west of Area I, those channels which do not plunge downslope at right-angles to the local contour pattern, slope generally south to south-east. Over Annandale a dominant southerly flow of meltwater is indicated, while in the vicinity of Moffatdale the principal direction of meltwater flow was south-west. Price (1973) suggested that, "The general direction of meltwater movement also gives a general indication of the surface slope of the ice mass and therefore general direction of ice movement" (P. 128). As the above southward trending pattern of meltwater channels is found at all but the lowest altitudes, the surface slope of the ice mass during downwastage is also believed to have declined in this direction across Area I.

The densest concentration of channels, as previously mentioned, is found in Moffatdale. The discontinuous nature of the channel forms found here and their occurrence either parallel to

or/...

or at a low angle to the regional contour pattern, is generally associated with formation in a marginal or sub-marginal environment (Von Engeln 1908; Mannerfelt 1949; Sissons 1961a; Price 1961). Both one-sided bench and two-sided gulley forms are found together and while bench forms were formerly considered to represent formation along an ice margin, with ice forming one wall of the channel and rock slope the other, the development of bench or channel is now considered to be dependent upon the length of time that a rock slope was exposed to meltwater erosion and as such, bench forms can also be produced in a submarginal position (Sissons, 1961a, P. 15 - 16). In all probability the vast majority of the channel forms across the flanks of Moffatdale were incised in a submarginal position (Tarr 1909; Von Engeln 1912). Formation in an entirely marginal position is impossible to prove with any certainty, but a distinction between these two end members of what is virtually a continuum of forms based upon the gradient of the channels was suggested by Sugden and John (1976, P. 312). On such a basis, the more continuous channels, such as D5 (Fig. 3.21), with gradients of approximately 1:40, are the only forms which may possibly have been incised in a wholly marginal position. It is further suggested that a submarginal origin is more probable for the forms which trend obliquely downslope at some intermediate angle between approximately parallel, and at right-angles, to the contour pattern, in the manner well-illustrated by channels throughout Moffatdale.

The vast majority of the channel forms flanking Moffatdale are short features, seldom extending across a slope for more than/...

than 300 - 400m and generally not incised more than 3 - 4m, except where found running downslope at right-angles to the contour pattern. In addition, there is little interlinkage of channel forms, it being more common to find a series of minor channels which have developed individually across a spur or hillslope (e.g. systems F, M, N, O Figs. 3.4, 3.20). Such a pattern of channel development was principally determined by the underlying relief conditions in the vicinity of Moffatdale during downwastage of the last ice sheet (Figs. 3.6, 3.20). By comparing the cross-sectional form of Moffatdale with figures 3.4, 3.20 illustrating channel distribution, it becomes readily apparent that there was no marginal (this term referring to all channel forms produced in the lateral zone of a downwasting ice mass, generally occurring at a low angle to the local contour pattern) channel development along the steeply sloping south-east flank of Moffatdale upvalley of Bodesbeck (NT 015097, Fig. 3.4), or on the steeper lower slopes below 305 m.o.d. throughout the valley. Marginal channel development was concentrated above 305 m.o.d., where the rise to higher ground is achieved more gradually, the longest and most continuous channel forms occurring on the more gently-inclined slopes. On this basis, it is suggested that where the confining hill-slopes to a downwasting ice mass are steeply-inclined, marginal meltwater flow is more likely to cut into the ice than the rock slope (Fig. 3.27), and consequently the evidence of the meltwater drainage pattern must necessarily be of a fragmented nature. Such a situation is illustrated even on individual spurs, the large channel 06 (Fig. 3.22), occurring where locally the steepness of the spur slope is reduced. This channel/...

channel attains much larger dimensions than any of the other forms incised into the steeper parts of the slope in this vicinity.

As indicated on figure 3.20 the channel forms are found both along the valley flanks and across the spurs which join the main valley from the north-west, in Upper Moffatdale and south-east, down-valley near the junction with Annandale. There is no discernible pattern to channel development, other than the relationship to steepness of slope, in either location. However, there does appear to be a greater concentration of channel forms on the spurs, although their exact location on these varies enormously. Some channels merely run across the crest of the spur, or part of the crest, the floor of the channel generally sloping down in a south-west direction, (e.g. N 1, N 2 and N 3, (Fig. 3.22); others have a short up-hill section from their in-take, but fade away over the ridge crest itself, (e.g. C 1, C 2, M 2 Figs. 3.21, 3.22); others still run uphill from their in-take to the crest of the spur and then continue for a short distance down the lee slope of the spur, to produce an up-down or humped profile, (e.g. O 6, O 7, Fig. 3.22); while some channel forms have developed solely on the lee side of ridge crests, (e.g. O 1, O 2, O 3, Fig. 3.22). Shreve (1972), related the frequent occurrence of channels on bedrock convexities and their location upon a particular prominence to variations in the pressure gradient responsible for subglacial meltwater flow at the base of active ice (Fig. 3.28). Where there is no forward movement of the ice (A, Fig. 3.28), there is a downstream increase in transporting capacity which causes the

erosion/...

erosion of a rock channel across the divide, and an up-down or humped channel is produced. With ice movement across the divide (B, Fig. 3.28 , the zone of erosion is shifted towards the lee side, and it is in this vicinity that meltwater incision is concentrated.

Sugden and John (1976) used the part of Shreve's theory invoking subglacial meltwater flow beneath great thicknesses of ice, to account for the discontinuous nature of meltwater channels across bedrock convexities. Such channels were formerly attributed to the superimposition of englacial meltwater routes onto the underlying topography as the ice thinned during downwastage, the depth of meltwater incision being controlled by a descending zone of meltwater penetration (Price 1961, 1973; Derbyshire 1961; Embleton 1961; Sissons 1963; Clapperton 1968).

It is tempting to adopt Shreve's theory in its entirety to explain the channel pattern over Moffatdale and indeed Area I as a whole. In this manner, the high percentage of channel forms best-developed on the lee sides of spurs and other convexities would be attributed to formation during forward movement of the ice mass, and the up-down channels produced during periods of stillstand.

However, the close areal association of these two channel types in Area I, often both upon the same spur, or the presence of different forms at similar altitudes on adjacent spurs, would suggest on the basis of Shreve's theory very fitful ice movement over short distances. In addition, the theory does not explain the forms which are best-developed on the stoss sides of spurs.

Consequently/...

Consequently, it is believed that <u>both</u> subglacial meltwater flow beneath active ice <u>and</u> superimposition of englacial (and supraglacial) streams during downwastage, have played their part in the establishment of the channel pattern across bedrock convexities in Area I, although it is impossible to isolate channels formed by the two processes. Locally, over Moffatdale, the superimposition hypothesis is preferred because of the high frequency of poorly-developed channel and bench forms, the low gradients exhibited by the more continuous channels, and the improbability of wholly subglacial meltwater flow descending and re-ascending through altitudes up to 500m over horizontal distances as small as one kilometre. A dense network of englacial streams, derived both supraglacially and extraglacially from ice-free uplands and occupying lateral positions in relation to the valley slopes, are therefore believed to have impinged upon the steeply-sloping topography of Moffatdale for short periods during downwastage.

The channel pattern in Moffatdale does not solely relate to formation by south-westward flowing meltwater occupying a marginal position however, for in places channels plunge directly downslope in the manner associated with subglacial chutes (Mannerfelt 1945). Most of the chute forms are found on the north-west flank of Moffatdale (Fig. 3.4), often at the junction of steeply-incised valley and upland plateau, suggesting that during downwastage gaps in the decaying ice mass developed in such localities, allowing supraglacial or englacial streams to flow more directly downslope. Elsewhere in the area however, subglacial chutes are found in association with the marginal drainage/...

drainage pattern, indicating the re-direction of meltwater from a course sub-parallel to the regional contour pattern, to a course directly downslope at right-angles to the contour pattern (Fig. 3.4). The re-direction of meltwater flow was the result of changing relief and/or glaciological conditions during downwastage. Consequently, meltwater has become increasingly focused downslope into the ice mass itself during the period of deglaciation, as evidenced by the total absence of marginal channel forms below the level of many chute in-takes in Moffatdale (Fig. 3.4). Such a theory, implying the concentration of meltwater in mid-valley at the deepest point, has been suggested by several authors (Shreve 1972; Weertman 1972; Sugden and John 1976). Therefore, at a late-stage in the downwastage of the ice mass over Moffatdale, the local channel pattern suggests that subglacial and englacial drainage formed a three-dimensional dendritic tunnel pattern within the ice, leading down to a subglacial master tunnel which ran along much of the length of Moffatdale. Consequently, although the steep-sided form of the fault-line valley is mainly attributed to the actions of glacial erosion, it is believed that Moffatdale itself represents the largest meltwater channel in the area and that the valley floor was further deepened by concentrated fluvioglacial erosion by meltwater following a south-westerly course.

In complete contrast to the situation in Moffatdale, the majority of the channels in Annandale occur at low altitudes and trend downslope at a high angle to the contour pattern, indicative of a subglacial origin as stated above. The scarcity of channels at higher altitudes in Annandale can be attributed to the interaction of two factors : 1) It was previously stated that the ice gradient over Annandale sloped from north to south, ice being/...

being derived both locally from the Tweedsmuir Hills and from an external source to the north-west of Area I. During downwastage however, although the principal direction of meltwater drainage over Annandale was in a southerly direction, it is believed that much of the drainage from the Tweedsmuir Hills followed the major ice routes, that is the Auchencat and Lochan Valleys, swinging southwards only at the junction with Annandale itself. Sugden and John (1976) stated, "Where pre-existing valleys run in the direction of ice movement, there may be no recognizable channels since the meltwater tends to follow the valley" (P. 316). In this way, the absence of channels from spurs in this vicinity can be explained.

2) This also involves consideration of underlying relief conditions in that there are no major convexities aligned at right-angles to the direction of ice movement in Annandale, unlike Moffatdale. Consequently, at higher altitudes the southward trending meltwater drainage over Annandale remained confined almost wholly within the ice mass itself, coming into contact with the underlying relief and thus supplying evidence to its existence, only rarely.

The above situation changed dramatically at approximately 243 m.o.d.. It is at this altitude that the points of in-take of channel system II (Fig. 3.23), are found, the system itself being supplied by meltwater from the north-west. The plunge pool in-takes of several of these channel forms indicates that they were fed by streams descending through the ice and encountering the subglacial rock with considerable force (Price, 1973, P. 119; Fig. 3.29). The frequency of similar channel forms in this vicinity all trending downslope at right angles to the contour pattern/...

pattern, suggests that there was some fundamental change in glaciological conditions within the downwasting ice mass at approximately 243 m.o.d.. As a result, meltwater which formerly followed a south to south-east course, leaving little trace of its presence, was forced to plunge down through the ice in the form of subglacial chutes onto the western flank of the Annan valley. In a similar fashion, all of the channel forms across the lower slopes of eastern Annandale also have their in-takes below 243 m.o.d. and as mentioned were formed in association with several narrow marginal lakes which developed between the valley side and the downwasting ice mass over the valley floor (Figs. 3.24, 3.30A). The major source of meltwater for the Auchencat marginal lake was the Auchencat valley itself, although the Lochan valley may possibly have augmented this. The source of meltwater for the Granton lake is not so readily apparent, with only one small sinuous channel, GG 4 (Fig. 3.24), leading into this area. However, it is possible that the main channel GG 1 (Fig. 3.24), was itself initially depositional in nature before cutting down through the lacustrine deposits at a later stage. Possible supply from supraglacial and englacial streams must also be taken into consideration. Channel GG 8, "Hind Gill", (Fig. 3.24), with its intake at 235 m.o.d. at the southern end of the Granton lake, acted as a major overflow channel, although it is possible that there may have been a submarginal channel in this vicinity prior to the formation of the lake itself.

The similar altitude of the terrace-like lacustrine forms and the concentration of channels and fluvioglacial deposits below this level suggests that both the Granton and Auchencat marginal lakes were/...

were controlled by an englacial water-table, found between 213 - 243 m.o.d.. It was the collapse of this water-table and subsequent drainage of the lakes that produced the subglacial channel forms found in this vicinity. Channel CC 1 the Lochan Burn valley Channel EE 3 and channels FF 1, FF 2, FF 3 (Fig. 3.24), all acted as subglacial drainage outlets from the Auchencat lake. From the altitudes of their in-takes, it would appear that channels FF 1, FF 2, FF 3 and EE 3 were utilised in succession, but from their degree of incision, little meltwater evidently followed these courses. Indeed, the main subglacial drainage outlet, (Gillberg 1956), was the Auchencat valley itself, with meltwater also joining this via the Herring Loup (EE 2, Fig. 3.24). Similarly with the Granton lake, prior to the collapse of the water-table meltwater escaped from here via channel GG 8 (Hind Gill), but with collapse several outlets aligned downslope were again utilised. Channel GG 5 (Fig. 3.24), acted as a minor outlet for the lake, but of far greater significance were the deep subglacial courses incised by channels GG 1 and GG 2. Support for the postulation that the Granton valley functioned as a major meltwater routeway is supplied by the fact that channels FF 1 and GG 5, GG 6 and GG 7 (Fig. 3.24), all lead down to, but are left hanging above, the wide, flat channel floor (Fig. 3.30B).

The deeply-incised nature of the lower Granton, Auchencat and Lochan valleys is not solely attributable to the actions of meltwater and postglacial stream activity however. It should also be noted in this context, that there is a fundamental change in bedrock lithology along the eastern flank of Upper Annandale between/...

between 198 - 243 m.o.d. (Fig. 3.3). At these altitudes, the Silurian greywackes and grits are replaced downslope by comparatively less resistant breccias and sandstones of New Red Sandstone age. Therefore, it was the combination of concentrated subglacial meltwater erosion in an area of comparatively less resistant bedrock, that resulted in the enhanced dimensions of the channel forms to be found along the lower eastern flank of Annandale.

The collapse of the englacial water-table within the decaying ice mass over Annandale at approximately 213 - 243 m.o.d., perhaps as a result of complete stagnation, was also responsible for the sudden downward movement of meltwater at a similar altitude on the western valley side which resulted in the incision of the subglacial chute forms of channel system II. Also associated with the collapse, and the final wastage of ice in Annandale, are the fluvioglacial deposits along the valley floor and lower slopes, particularly on the eastern valley side. Fluvioglacial deposits are best-developed to the south of the town of Moffat, the channels found here being incised between and among the mounds and depressions which typify dead-ice topography (Fig. 3.4). These channels are representative of subglacial and proglacial drainage during the final stages of ice decay.

The similarities in occurrence of channel forms in the vicinity of the Evan Water valley with those in Moffatdale and Annandale, as previously described, suggest similarities in their methods of formation. The presence of discontinuous channel systems at higher altitudes over this western area which are incised across bedrock convexities (e.g. systems OO, PP, QQ, RR, SS, XX, (Fig. 3.20), reintroduces the subglacial/superimposition debate. It/...

It could be argued that there is greater justification for attributing a higher percentage of these channels to formation by subglacial meltwater flow associated with active ice, on the greater restriction of channel forms to spur crests, and the less extreme relief conditions to be found in this western area than in Moffatdale. With this in mind, the fact that the best-developed channel forms of system RR (Fig. 3.25), are all found on the lee sides of divides and the anastomosing patterns of RR 9 and RR 10 (Fig. 3.25), only found in such a locality, is readily explained (Fig. 3.28). However, elsewhere in this area and with particular reference to system XX (Figs. 3.20, 3.31), the close association of the channels with landforms of fluvioglacial deposition, strongly suggests that locally both fluvioglacial erosion and deposition were carried out by the superimposition of englacial streams during downwastage. (Channel system XX and the fluvioglacial deposits associated with this are discussed in greater detail in the section devoted to fluvioglacial deposition).

Again therefore, it is impossible to state with absolute certainty that a particular group of channels incised across a bedrock convexity were formed by wholly subglacial or superimposed englacial meltwater flow. Instead, it would appear that both types of meltwater stream may have been in existence and that the greater importance of one over the other in a particular area was dependent upon local glaciological and/or underlying relief conditions.

The channels at lower altitudes over the Evan Water district, generally below 243 m.o.d., e.g. system TT (Fig. 3.26), trend downslope/...

downslope at a high angle to the conour pattern, in a similar manner to the forms in Upper Annandale. Such channels were also formed at a late-stage in downwastage when glaciological conditions facilitated themovement of large amounts of meltwater down through the ice onto the underlying terrain. The close association of system TT with fluvioglacial deposits suggests that a residual tongue of ice stagnated and wasted away in the Garpol Water valley. However, the similarity in altitude of the in-takes for the subglacial chute forms in the Garpol Water valley with the altitude at which downslope meltwater activity began in Annandale, suggests that meltwater erosion over a large part of Area I was controlled by the same englacial water-table, even at such a late-stage in ice wastage.

<u>SUMMARY</u>. The overall pattern of meltwater activity in Area I, although complex, may therefore be summarised as follows:

1) Within Area I, the highest channel forms occur at altitudes exceeding 700 m.o.d., which suggests that during the last major glaciation, ice covered the area to at least this altitude. The orientation and form of channels above 243 m.o.d. indicates that the surface slope of this ice mass declined in a broadly southward direction.

2) During downwastage ice lingered longest in Moffatdale and Annandale on the periphery of the Tweedsmuir Hills and further west in the vicinity of the Evan Water valley.

3) The nature and distribution of channels incised in association with these decaying ice masses was strongly controlled by the underlying relief conditions, channel forms at higher altitudes being best-developed on bedrock convexities aligned at/...

at right angles to the direction of meltwater flow.

4) The majority of the higher channel forms were cut by a series of englacial meltwater streams, their depth of incision controlled by an englacial water-table. With downwastage and the lowering of this water-table, the englacial streams became superimposed onto the underlying relief. Over Moffatdale such streams were concentrated in a marginal position. In some localities where conditions were favourable, channels produced by the superimposition of the englacial drainage network are found alongside channels incised by subglacial flow controlled by pressures within the ice mass. It is difficult to differentiate between such forms.

5) The collapse of the englacial water-table, perhaps as a result of complete stagnation, occurred at an altitude between 213 - 243 m.o.d., and led to the rapid downslope movement of the englacial drainage in the manner of subglacial chutes. Over the eastern flank of Annandale, subglacial meltwater flow of this type took place in association with the drainage of several small and short-lived marginal lakes.

6) Other subglacial chute forms were incised at higher altitudes where the steepness of terrain facilitated the creation of gaps between the ice mass and the rock slope.

7) Final decay of the ice sheet in Area I took place in the valley floors and resulted in the incision of channels between and through landforms of fluvioglacial deposition.

3.7 : FLUVIOGLACIAL DEPOSITION

The extensive evidence of meltwater erosion in Area I is paralleled by the similarly extensive occurrence of landforms and deposits associated with fluvioglacial deposition. Sand

and/...

and gravel deposits are found in all three major valleys and discontinuously throughout the area as a whole between 366 - 391 m.o.d.. To facilitate a more detailed examination of the varied character and morphology of these deposits, a similar tripartite division of Area I to that used in the previous section is adopted. The three sub-divisions are therefore Moffatdale, Upper Annandale and the region in the vicinity of the Evan Water valley.

MOFFATDALE. The narrow, steep-sided character of Upper Moffatdale has limited fluvioglacial deposition to a series of discontinuous, badly slumped terrace forms (Fig. 3.4). It is only in the lower part of the valley, where valley sides are less steep and a comparatively more open valley form is found, that there is evidence of an uninterrupted sequence of depositional landforms along the lower valley slopes. A series of terraces between 99 - 167 m.o.d. are found in close association with areas characterised by an irregular assemblage of mounds, ridges and hollows (Fig. 3.4). A 10m exposure in the side of one of the terraces (Exposure 3S, Fig. 3.4), illustrates the character of the fluvioglacial deposits. A sequence of intermixed sand and gravel beds, which lie almost horizontally or dip slightly in a south-west direction, are overlain by a more compact, clayey deposit. The nature of the sand and gravel beds varies considerably, with layers of fine sand-clay found together with beds of coarse gravel or cobbles. All of the clasts within the gravel layers exhibit some degree of rounding and although the vast majority are less than one centimetre in diameter/...

diameter, cobbles up to 50 - 70 cms in diameter are also found. Geologically, all of the pebbles are of local origin, with a predominance of greywackes.

The thinner, more discontinuous deposit overlying the sands and gravels is of a more compact, clayey nature and as a result slightly overhangs these beds. A large number of clasts are contained within this light-brown clayey matrix; the clasts varying in size from 1 - 40cm in diameter, and in shape, from angular to rounded. This exposure is of particular interest in that the clayey deposit not only overlies the sand and gravel beds, but extends down through these in a wedge form 3m in length. The formation of the wedge seems to have been responsible for the folding of the sand and gravel beds and for the small-scale faulting that is also apparent around the wedge form. Within the upper part of the wedge itself, the incorporated clasts exhibit no common orientation, but when traced vertically down the form, the clasts take on a vertical alignment. Furthermore, formerly bedded gravels have slumped against the northern side of the wedge and in doing so have lost much of their stratified character. On the basis of the above descriptions, it is apparent that the wedge-shaped clayey deposit is an ice-wedge cast (Johnsson 1959; French 1976), the cast itself representative of secondary infilling as a former ice-wedge slowly melted (Plate 3W and 3X).

Morphologically, the terrace form in which this exposure is revealed has a fairly level surface 120 - 140m in width, with a steep north-west face, 17 - 18m in height. The morphology, internal sedimentary characteristics and location of this feature, perched onto the lower valley slopes, indicate that/...

that it is a kame terrace, "... deposited by meltwater flowing along the edge of an ice mass between the ice and the valley wall". (Embleton and King, 1975, P. 485). As indicated on figure 3.32,this particular kame terrace, (Kame terrace A), is one of several such features which extend for 2½kms down both flanks of lower Moffatdale. The altitudes of the kame terraces decrease downvalley; the highest form, terrace A, found to the north-east and the lowest, terraces C and D, to the south-west (Fig. 3.32; Plate 3Y).

Despite the density of channel forms at higher levels in Moffatdale, there is little indication of the meltwater streams responsible for the accumulation of the kame terrace forms. However, esker 1 (Fig. 3.32), which terminates 500m to the north-east of terrace A at an altitude of 130 m.o.d., may represent the former course of one such feeder stream. The occurrence of the esker at an altitude below that of the terrace itself does not rule out such a possibility. The ridge form may have accumulated in a supraglacial or englacial environment and was subsequently let down onto the sub-ice surface with continued ice-wastage in the manner described by Price (1973, P. 131 - 178). In general however, the paucity of erosional or depositional channel forms across the lower slopes of Moffatdale suggests that truly marginal or submarginal drainage contributed little to the formation of the kame terraces and that these "marginal" landforms in fact accumulated by deposition in association with supraglacial and/or englacial streams occupying a mid-valley position. Similarly, with particular reference to terrace A, as there is also no indication as to how the small marginal/...

marginal lake in which the terrace accumulated has drained, it must be assumed that drainage took place through extensively decayed and crevassed ice occupying the valley floor.

Terraces B and E (Fig. 3.32), despite their location on opposite valley sides are believed, by their similar altitudes, to have formed contemporaneously (Sissons, 1967a, P. 113 - 117). Both kame terraces are highest at their north-east extremities, (122 - 130 m.o.d.), and slope very gradually downvalley to terminate at approximately 114 m.o.d.. Once again there is little indication of feeder channels for the terrace forms. In contrast however, the drainage of these small marginal lakes has taken place, at least partly, along channels 2 and 3 (Fig. 3.32), which run directly downslope from terraces B and E, indicating a sudden subglacial escape of water beneath the retaining ice walls.

The lowest, but most extensive terrace forms, terraces C and D (Fig. 3.32), at the mouth of Moffatdale are also believed to have formed contemporaneously. Terrace D is heavily wooded and as such difficult to identify in parts but generally both terraces are fairly level and best-developed around 106 m.o.d.. There is also the suggestion of lower, narrower terrace forms 2 - 3m below the altitude of terraces C and D, adjacent to the river itself (Fig. 3.32). However, it is difficult to be certain that these lower terrace forms relate wholly to depositional processes and were not produced by meltwater incision into the higher terraces at the constricted valley mouth.

The absence of channel forms at the upper limits of terraces C and D again suggests that aggradation occurred from supraglacial and/or englacial streams, and with particular reference to terrace C,/...

C, drainage took place in a similar fashion, through the decaying ice. By contrast, drainage of the marginal water-body in which terrace D accumulated was by a subglacial route, via the large channel on the south-west flank of the kame terrace (Channel 4, Fig. 3.32). The well-developed, north-south trending asker found in close association with both terrace D and channel 4 (Esker 2, Fig. 3.32), acted neither as feeder nor outlet for the kame terrace. This esker formed at a later stage in downwastage, in association with the meltwater drainage pattern of the decaying ice mass in Upper Annandale.

The series of kame terraces, decreasing in altitude downvalley, and closely related kettle holes, kames and eskers also depicted in figure 3.32, are indicative of formation in association with a stagnant ice mass in Moffatdale, which with continued downwastage retreated downvalley in a south-west direction. Within this decaying ice mass, the presence of an englacial water-table for at least part of the time during the final stages of deglaciation controlled the altitude of fluvioglacial deposition in small marginal lakes along both valley sides. Continued downwastage resulted in the lowering of this water-table, as reflected by the decreasing altitude of the kame terraces. The extensive nature of terraces C and D strongly suggests formation in the proglacial rather than the marginal environment. Extraglacial meltwater moving down Moffatdale was dammed by the final vestiges of the Moffatdale ice mass blocking the valley mouth. A more irregular sequence of fluvioglacial mounds and associated kettle holes are found in those parts of Moffatdale where, as a result of glaciological and/or geological conditions during deglaciation, the accumulation of deposits/...

deposits in short-lived marginal lakes was not possible.

Despite the abundance of marginal and sub-marginal channels at higher altitudes in Moffatdale, most of the meltwater flow near the valley floor took place in a supraglacial, englacial or even subglacial mid-valley environment. Figure 3.33 indicates postulated stages in the formation of the kame terraces and other accompanying fluvioglacial landforms in lower Moffatdale.

UPPER ANNANDALE. The fluvioglacial deposits of Upper Annandale can be sub-divided on the basis of their morphology, altitude and areal distribution into two groups; a group to the south-east of Moffat and a group to the north-west of the town (Fig. 3.34).

a) Fluvioglacial deposits to the south-east of Moffat. Topographically, this is essentially a low-lying area where the river Annan is joined by its major tributaries, the Evan Water, Birnock Water and Moffat Water and where as a result, the Annan floodplain attains its greatest dimensions. The floodplain is flanked on all sides by steeply rising uplands and it is on and against the lower flanks of these uplands that the fluvioglacial deposits have accumulated.

All of the sand and gravel deposits are found below 220 m.o.d. and over much of the area occur below 120 m.o.d.. Delimitation of the deposits depended primarily upon their distinctive morphology, but with the concentration of fluvial activity in this area, there are also many more exposures visible than in Moffatdale.

A particularly good, although "man-made", section is revealed at Rogermoor Farm (NTOO, 095050), where 3 - 4m of coarse gravel consisting mainly of sub-rounded clasts in a gritty matrix is revealed/...

revealed (Exposure 3T, Fig. 3.4). The vast majority of the clasts are greywackes and less than 4cm in diameter, although cobbles up to 30cm in diameter are also present. There is little evidence of sorting or stratification, although an occasional small lense of sand or fine gravel is revealed in the face. The sands and gravels rest upon an uneven surface of red sandstone breccia. This exposure is found on the western side of a large gravel mound which has become detached from surrounding deposits as a result of fluvioglacial and/or fluvial erosion. Elsewhere in this vicinity, up to 6m of sand and gravel can be seen, or be inferred, to overlie bedrock.

In addition to isolated exposures revealed by fluvial and/or human incision, excavation involved in the laying of a gas pipeline across the area also provided useful information and a more continuous record regarding the thickness of fluvioglacial deposits and their relationship with other drift deposits in the area. Although much of the pipeline course had been excavated and re-filled prior to the commencement of this research project, test sections, generally 100 - 150m in length, remained unfilled and the information gained from these is depicted on figure 3.35.

The nature of the sand and gravel deposits remained basically similar at all 5 test sections. Numerous sub-rounded and sub-angular clasts, mainly the former, were found in a grey-brown coarse sandy-fine gravelly matrix. The clasts were generally less than 4cm in diameter although cobbles up to 50cm in diameter were also present. There was little evidence of sorting or stratification at any of the exposures examined. Although the pipeline cuttings indicate a minimum thickness of 3 - 4m for the fluvioglacial deposits in this vicinity, it seems highly probable that/...

that accumulations in the central part of the Upper Annan valley would far exceed this figure.

As indicated on figure 3.4, the morphological expressions of fluvioglacial deposition in this area are complex, with several varied forms found in close association. Such variation is well-illustrated in the vicinity of Dyke Farm (NT00, 086036). (Fig. 3.36). Here, a heavily fragmented terrace form, 4 - 6m above the Annan floodplain at 95 - 106 m.o.d., extends for 1½km to the north of the Evan Water. The surface of this terrace, although still fairly level in parts, is more commonly heavily pitted as a result of numerous kettle hole formation. The kettle holes vary greatly in their dimensions, but commonly possess a circular plan-shape, the diameter at the lip of the hollow generally exceeding 30m. Steeply-dipping sides to an often marshy floor, 2 - 5m below the general surface level, also characterise these depressions. A similar form to the kettle holes is the steep-sided indentation along the eastern flank of the terrace (A, Fig. 3.36). This semi-circular depression has a diameter exceeding 200m and is 7 - 8m in depth, viewed from its western flank. Such large depressions that are not quite enclosed are termed "dead ice hollows" (Clapperton 1968). The surface of the terrace is also disrupted by several kame mounds which stand above its general level, and by esker 1 (Fig. 3.36). This short, discontinuous ridge, the total length of which is less than 300m, is aligned in a north-south direction and is approximately 4m in height. On the surface of the terrace itself the ridge bifurcates (Fig. 3.36), the two segments separated by a kettle hole 4m deep. However, neither segment continues for any great distance and as they are followed southwards, there is a gradual decrease in the steepness of the ridge flanks, and corresponding increase/...

increase in the width of the ridge crests, until both segments blend smoothly into the terrace surface (Plate 3Z).

It is strongly suggested that the Dyke Farm terrace and its associated landforms are continued on the southern side of the Evan Water to the vicinity of Tassies Height (Fig. 3.4, 3.37). In this area also, the horizontality of a terrace-like surface at approximately 100 m.o.d., is disrupted by kettle holes and kame mounds, but not to the same degree as is found further north. In addition, the southern terrace form is not as fragmented, although a large meltwater channel (channel 1, Fig. 3.37), does lead off in a southerly direction from its southern flank. This channel, cut entirely into drift, runs around Tassies Height to join the Annan floodplain. It is over 1700m in length and has a wide, flat marshy floor, 140m in width. Channel sides rise 8 - 10m above the floor, but as they are cut into drift they are not particularly well-developed. In the vicinity of the channel there appears to be a greater concentration of kame mounds, kettle holes and generally hummocky topography, than on the surface of the terrace itself to the north of the channel in-take.

The morphological and sedimentological characteristics of the fluvioglacial landforms described above, on both the northern and southern flanks of the Evan Water, are indicative of formation in association with a mass of stagnant ice. The extensive terrace developments, with locally adjacent eskers, kames and kettle holes, are representative of kame terraces which accumulated as a result of ponding along the western margin of the decaying ice mass which formerly occupied the Annan valley floor. The horizontality of the kame terrace remnants indicates that deposition in the marginal environment/...

environment was controlled by an englacial water-table at an altitude of approximately 100 m.o.d.. However, the density of kettle holes in the northern part of the terrace at Dyke Farm suggests that in this vicinity at least, part of the terrace deposition took place in an englacial-marginal and not wholly extraglacial-marginal environment (Fig. 3.38). Sissons (1967a) described a similar situation in the Eddleston Valley, "... the ice wasted back from the hillslope ..... to allow a small lake to develop in which rapid sedimentation took place. Such a lake could not be held up by the rotten ice of the marginal zone but was impounded by the firm ice further back from the margin" (P. 18), (Fig. 3.38). As in Moffatdale, there is little evidence of the meltwater streams that supplied this marginal lake, with the exception of esker 1 (Fig. 3.36), but this is merely representative of one small feeder for the northern part of the kame terrace. Consequently, it must again be assumed that much of the meltwater was supplied by supraglacial and/or englacial streams following a generally southerly course within the decaying ice mass, or by extraglacial flow along the Evan Water valley itself (Fig. 3.38). The level of the marginal lake was controlled not only by the englacial water-table but also by channel 1 (Fig. 3.37, 3.38), which acted as a subglacial outlet from the lake in a southerly direction.

With continued dissipation of the dead ice mass occupying the Annan valley floor, the englacial water-table collapsed and drainage of the Evan Water marginal lake took place. Along the southern margin of the kame terrace, drainage of the lake resulted in the development of kame and kettle topography across the lower slopes/...

slopes of the upstanding till hillocks which comprise Tassies Height. On the northern flank of the terrace, the post-depositional concentration of fluvioglacial and fluvial erosion in the immediate vicinity of the Annan and Evan Water floodplains has resulted in the present fragmented appearance of the depositional landforms.

b) Fluvioglacial deposits to the north-west of Moffat. The area to the north-west of Moffat extends up Annandale to the Devil's Beef Tub and in effect represents the head of the Annan river valley. This is an area of high relative relief values such that, although fed by several substantial south-west draining tributaries, this part of the Annan valley is characterised by a generally narrow floodplain, only 300 - 450m in width. The western margin to the floodplain is represented by steeply-rising terrain, particularly between 152 - 274 m.o.d., leading upslope locally to Ericstane Hill (427 m.o.d.). The gently-inclined lower slopes of the Tweedsmuir Hills constitute the eastern margin to the floodplain, but above 218 - 305 m.o.d. the terrain here also rises steeply, in this case to altitudes exceeding 762 m.o.d..

Almost all of the evidence relating to fluvioglacial deposition is restricted to a narrow band along the eastern flank of the valley betwen 122 - 260 m.o.d. (Fig. 3.34). Within the southern part of this band, between Moffat and the Granton Burn (Fig. 3.24), the fluvioglacial deposits are distinguished primarily by their distinctive hummocky morphology, with only limited support from a few, small exposures. Such exposures reveal less than one metre of unsorted and unstratified gravels in a dark brown, coarse sandy matrix. The included clasts are sub-rounded and sub-angular

in/...

in shape and generally 1 - 3cms in diameter, although larger clasts 15 - 30cms in diameter are also present.

Morphologically the deposits are represented by a series of kame mounds and minor ridge forms, both of which are aligned either directly downslope towards the valley floor, or downvalley at a high angle to the local contour pattern. These mound and ridge forms vary greatly in their dimensions, but are generally less than 100m in length, and between 3 - 6m in height. In places, one or both sides of a mound have been washed by small-scale meltwater action.

Nearer the head of Annandale, the fluvioglacial deposits at the mouth and to the north of the Granton Burn are again in places characterised by kame mounds aligned downvalley, at a high angle to the contour pattern (Figs. 3.4, 3.24). However, in association with these areas of irregular mound topography are found a series of fairly narrow, terrace-like forms which from exposures can also be seen to consist of sands and gravels. Exposures are most abundant at the head of the valley, reflecting the greater concentration of fluvial activity from the Tweedsmuir Hills.

One such exposure at Herring Loup (Exposure 3U, Fig. 3.4), in the side of one of the narrow terrace-like forms, reveals 4m of sand and gravel overlying red sandstone. The lower 1 - $1\frac{1}{2}$m of drift is poorly-bedded fine gravel, consisting of sub-rounded and sub-angular clasts, less than 3cm in diameter, in a dark brown sandy-clayey matrix. This is overlain by $2\frac{1}{2}$ - 3m of coarse, unsorted and unstratified gravel. The higher gravel layer consists of numerous sub-rounded and sub-angular clasts and cobbles in a fine gritty matrix; the majority are less than 3cm in diameter/...

diameter, but a large number are 2 - 5cm in diameter, and some exceed 25cm.

Another section is revealed in the face of an old quarry excavated into the northern side of White Hill (Exposure 3V, Fig. 3.4). At this site, only the upper 2m of the level terrace-like surface of White Hill is clearly exposed, the remainder of the 6m section being obscured by slumping. The top 50cm of the exposure is characterised by unsorted and unstratified clasts in a sandy matrix. The clasts are again generally less than 3cm in diameter, although forms up to 30cm in diameter are also present. Below the coarse gravels, a layer of amber coloured sand, containing only scattered sub-rounded pebbles less than 2cm in diameter, extends a further 1½m down the exposure, the remainder being obscured by slumped material.

Other smaller exposures in this area illustrate a similar intermixture of stratified and non-stratified deposits, although where only the upper part of a section can be seen, it generally consists of unstratified and unsorted gravels. Throughout the area to the north of the Granton Burn, 1 - 5m of sand and gravel overlies bedrock.

The mode of origin of some of the fluvioglacial deposits has been previously mentioned in connection with the meltwater channel pattern (Fig. 3.24). The narrow, level, terrace-like spreads of sand and gravel are taken to represent accumulation in several narrow, short-lived marginal lakes which formed between the eastern valley side and the downwasting ice mass over the valley floor. The meltwater which supplied these lakes /...

lakes was primarily derived extraglacially, along the valleys which drained the adjacent Tweedsmuir Hills, the principal direction of meltwater drainage in the ice mass itself being southwards. Initial ponding of meltwater from the Tweedsmuir Hills occurred at 250 - 260m.o.d. in the Tweedhope valley (Fig. 3.4), but evidence of more extensive ponding, apparently controlled by an englacial water-table is found at lower altitudes. The similarity in altitude of the marginal lake accumulations, (Fig. 3.24), and the concentration of subglacial channels downslope from these, indicate that deposition within and at the margins of the decaying ice mass occupying Upper Annandale was controlled by such a water-table at approximately 243 m.o.d.. The altitude of the water-table was determined by the large meltwater channel Hind Gill (Channel GG8, Figs. 3.4, 3.24, 3.30), which leads southwards around Gallow Hill to the Birnock Water valley. The water-table and marginal lakes ceased to exist when continued ice-decay allowed meltwater to drain to the valley floor. Associated with the collapse of the water-table was the deposition of a chaotic assemblage of kame mounds at and below the western margins of the lacustrine deposits. The number and size of these kame mounds indicate that the decaying ice mass had a high debris content.

The concentration of fluvioglacial deposits along the eastern slopes of Upper Annandale and the almost total absence of such deposits along the western slopes is the direct result of differential insolation and local sources of sediment supply. Flint (1971), attributed the more extensive development of kame terraces on eastern as opposed to western slopes in north-south/...

south orientated valleys to differential insolation, "....
the eastern parts of the former glacier lobes having received solar radiation during the afternoon, when the western parts lay in the shadow of the western sides of the valley" (P. 210). Complementing this was the fact that although during the early stages of ice downwastage over Upper Annandale the principal direction of meltwater movement was southwards, as downwastage continued the main valleys draining the Tweedsmuir Hills in a westerly direction became ice-free and carried an increasing amount of meltwater. The sediment load from these extraglacial meltwater streams accumulated upon, against and within the eastern margins of the decaying ice mass. When combined, the two factors of differential insolation and source of sediment supply thus account for the asymmetrical pattern of fluvioglacial deposition.

The distribution and character of the fluvioglacial landforms and deposits in Upper Annandale, both to the south-east and north-west of Moffat are therefore indicative of formation in association with a stagnant, downwasting ice mass over the area as a whole.

The extensive development of kame terraces and other landforms characteristic of accumulation in short-lived marginal lakes at approximately 243m.o.d. and 100m.o.d. in Annandale, and their close association with meltwater channels where present, strongly indicates that fluvioglacial deposition at these altitudes was at least partly controlled by an englacial water-table. Re-establishment of the water-table at the lower altitude/...

altitude of 100 m.o.d. may be the direct result of the concentration of large amounts of southward flowing extraglacial meltwater and its associated sediment load from the upper parts of the Annan, Evan Water and Moffat Water valleys, against, upon and within the stagnant ice mass which occupied Annandale at the confluence of all three valleys. Between 100 - 243m.o.d., the landscape of fluvioglacial deposition is more irregular and characterised by an often chaotic intermixture of kames, eskers and kettle holes. With the final disappearance of ice from Upper Annandale, the similar concentration of postglacial fluvial activity in the vicinity of the tripartite river confluence, destroyed or fragmented many of the fluvioglacial landforms and removed many of the deposits.

FLUVIOGLACIAL DEPOSITS IN THE VICINITY OF THE EVAN WATER VALLEY.

As in Upper Moffatdale, the steep-sided character of the Evan Water valley limited fluvioglacial deposition to isolated terraces perched on the lower valley slopes. Consequently, the main concentrations of deposits are found further west in the eastward draining Lochan, Garpol and Cloffin valleys (Fig. 3.39). Greatest deposition occurred in the Garpol Water and Lochan valleys and these will be examined in greater detail.

a) Garpol Water Valley. The evidence of fluvioglacial erosion in the Garpol Water valley has been previously detailed (P. 92). The same meltwater streams that incised the channels also deposited sands and gravels, the morphological expressions of which are a series of kame mounds and esker ridges (Fig. 3.26). Traces of fluvioglacial deposits are found/...

found between 177 - 238 m.o.d. in the Garpol Water valley, the greatest thickness occurring near the valley floor.

The nature of the fluvioglacial deposits is revealed at exposure 3W (Fig. 3.26), where esker 1 has been truncated by the river. The esker is 8m high at this point, but only the lowest 4m of drift immediately above the river itself, are well-exposed. Numerous rounded and sub-rounded clasts, generally less than 3cm in diameter, are revealed in a dark brown sandy matrix. Larger boulders 50 - 70cm in diameter are also present, but even these exhibit some degree of rounding. The clasts are sorted into indistinct beds which present an anticlinal appearance, being generally horizontal in the central core of the ridge but curving round to parallel the ridge sides towards the flanks.

Esker 1, in which the exposure occurs, is 850m in length and first emerges, from a fairly flat-topped kame mound, at approximately 210 m.o.d. (Fig. 3.26). The esker emerges 2m below the surface of the kame and at this point is itself 2m in height. The height of the ridge crest gradually increases as the sinuous course of the esker is followed downslope in a northerly direction. At 190 m.o.d. the ridge, now 3½m high and with a crest width of 5 - 7m, swings north-west across the regional slope for 200m, before returning to a more direct northerly course towards the valley floor (Fig. 3.26). Throughout the latter part of its length, the height and width of the ridge crest both continue to increase downslope, before terminating at the river (Fig. 3.26). Along the lower part of its course, kame mounds are found in close association with esker 1, particularly along its south-east flank (Plate 3AA).

The/...

The series of mounds and minor ridges, 2, 3, 4, 5, 6 and 7 (Fig. 3.26), which vary in height from 2 - 8m and in length from 80 - 150m are believed to represent the discontinuous remains of a second esker form. The west-east orientation of this esker and its location just above the floodplain, have resulted in its "beaded" appearance at the present day. There are no large exposures in any of the mounds or ridges, but several small sections reveal numerous rounded and sub-rounded pebbles in a fine, gravelly matrix.

It would appear from their alignment, and the alingment of adjacent fluvioglacial landforms that esker 1 and esker 2 - 7 were not deposited by the same meltwater stream, but relate to two separate directions of meltwater flow. The presence of the two eskers at right angles appears at first glance to strongly contradict the belief that, eskers show a close correspondence with the most recent direction of regional ice movement, in this instance generally southwards, as suggested by several authors, (Embleton 1964; Sissons 1967a; Price 1973; Sugden and John 1976). However, when taken into consideration with other fluvioglacial landforms in the vicinity, both depositional and erosional (Fig. 3.26), it is believed that the landforms in the Garpol Water valley were produced at a stage in ice downwastage when local movement of ice and meltwater were of greater significance than regional. All of the fluvioglacial landforms and deposits in the Garpol Water valley indicate formation in association with a stagnant or dead ice mass which downwasted in situ.

Regional/...

Regional movement of meltwater to the west of the Evan Water was in a south-east direction. As a result, with downwastage meltwater flow across the southern rim of the Garpol Water valley was controlled by the deeply-incised channel, "Hells's Hole", the floor of which is at 241 m.o.d. (Fig. 3.26). When the altitude of meltwater incision fell below this level, ice-directed meltwater flow in a south-east direction collapsed and free, downslope movement of meltwater was established. The features of fluvioglacial erosion and deposition within the Garpol Water valley relate to this latter stage in ice down-wastage. Movement of meltwater was downslope towards the valley floor and hence to the Evan Water valley via the deeply-entrenched Garpol Glen. The variable width of the ridge crest of esker 1 is a clear indication of ponding along the course of the stream which formed the esker, and is further testimony to the fact that the ice mass which occupied the Garpol Water had become extensively decayed and crevassed at this time and was in effect "dead" (Price, 1973, P. 26; Fig. 3.40).

b) <u>Lochan Valley.</u> The Lochan valley, like that of the Garpol Water has a fairly open form, with gently-inclined valley sides throughout most of its length. It is only in the vicinity of the valley head, at the edge of the Lowther Hills, that the valley sides steepen significantly. The fluvioglacial deposits extend down both flanks of the Lochan valley in a narrow band between 213 - 335 m.o.d., but are thickest along the northern valley side (Fig. 3.4). Also included with the "Lochan valley" for the purpose of this study are the limited fluvioglacial deposits of/...

of the adjacent Upper Kinnel Water valley (Fig. 3.4). As indicated on both figures 3.4 and 3.31, the sand and gravel deposits of this area are again found in close association with evidence of fluvioglacial erosion and characterised morphologically by kame mounds and esker ridges.

Exposure 3X (Fig. 3.31), is in the Kinnel Water valley where esker 2 is breached by the Threepen Burn. At this point the esker is 10 - 11m in height, but because of slumping only part of the exposure is visible. Numerous sub-rounded and sub-angular clasts, mainly the latter, are revealed in a coarse, dark brown, gritty matrix. The clasts are generally less than 3cm in diameter, although small boulders up to 50cm are also present. The deposit is poorly-bedded.

Similar erosive action by the Lochan Burn reveals numerous sub-rounded and sub-angular clasts in another badly-slumped section, where esker 1 is incised (Exposure 3Y, Fig. 3.31). Here also the pebbles are generally less than 3cm in diameter, although larger boulders up to one metre in diameter are present near the top of the 20m exposure. A large sand lense found parallel to the steep northern flank of the ridge indicates that some degree of sorting has taken place, although this has subsequently been modified by slumping (Plate 3BB).

There are three well-developed esker ridges within the area encompassed by the Lochan valley (Fig. 3.31), eskers 1 and 3 on the southern side of Peat Hill and esker 2 to the north. Esker 1 is altitudinally the highest of the three forms, emerging from the hillside below the col separating Peat Hill from Harestanes Heights

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at approximately 355 m.o.d. (Fig. 3.31). The ridge follows a steep, sinuous course downslope, generally at right angles to the contour pattern, finally terminating on the southern side of the Lochan Burn at 315 m.o.d.. Although initially only 1 - 2m in height and morphologically indistinct, ridge dimensions increase downslope, such that at its southern extremity the esker is 18 - 20m in height, with steep symmetrical sides. Similarly, the width of the ridge crest increases from 2 - 3m at the northern end of the esker to over 40m where the ridge is incised by the Lochan Burn. Upslope from the north end of the ridge in the floor of the col, are found 3 small, indistinct meltwater channels which trend in a southerly direction (Channels 1, 2, 3, part of system XX, Fig. 3.31).

Esker 2 is similar to esker 1 in that it too is aligned in a north-south direction, commences on the slopes of Peat Hill and follows a course at right angles to the contour pattern down to the valley floor; in this case however, it is the Kinnel Water valley. Regarding morphology and altitudinal extent however, the two ridge forms are fundamentally different. Esker 2 is found between 280 - 311 m.o.d. and follows a generally straight course, particularly on the valley floor itself.

At its upslope limit, esker 2 emerges from the surface of a terrace. This terrace, perched on the northern slope of Peat Hill at 305 m.o.d., is over 100m in width and has steep, marginal slopes leading down in both east and west directions. The highest point on the terrace is found where the esker emerges from the otherwise level surface to begin its downslope course. It is worth noting at this point that 50m upslope from the terrace, the in-take of a well-developed up-

down/...

down channel form incised 15 - 20m into bedrock is found (Channel XX5, Fig. 3.31). This northern in-take is at an altitude of 320 m.o.d., the high point of the channel at 330 m.o.d. and the outlet, on the southern flank of Peat Hill at 300 m.o.d.. The varying dimensions of esker 2 along its course are indicated on figure 3.41 (Plate 3CC).

Esker 3, located between the Lochan Burn and the southern slopes of Peat Hill (Fig. 3.31), is aligned in a north-east to south-west direction and is of more limited altitudinal extent than the previous two forms. The ridge is found between 289 - 298 m.o.d., being best-developed along the north-east part of its course where it emerges gradually from surrounding peat to attain a height of 12m. In this vicinity the ridge crest is 5 - 6m in width. As it is followed south-west, the ridge bifurcates at a pond which occupies the floor of a large kettle hole. The main portion of the esker continues in a southerly direction, but a minor tributary ridge, 2 - 3m in height, leads westwards. The main ridge is only 6m in height where breached by the Hoarlaw Burn and continues to decrease in height south-westwards, finally terminating against the eastern flank of a flat-topped kame mound, 2m below the surface of this feature. The mound is approximately 50 - 60m in width but varies in height from 8 - 12m, being generally higher and steeper along its southern and eastern flanks. The discontinuous tributary of the main ridge also terminates at this mound form (Fig. 3.31). It is difficult to be certain as to the continuation of the esker system beyond the flat-topped kame, but the presence of an isolated mound of sand and gravel 80 - 90m further east at Lochanhead, suggests that the system originally continued in this direction.

Esker/...

Esker 3 also developed in close association with evidence of fluvioglacial erosion. Approximately 100m beyond the north-eastern origin of the ridge, a short but deeply-incised channel, (incised 10 - 12m into bedrock), parallels the esker course (Channel XX6 , Fig. 3.31). The floor of this channel, although heavily peat-infilled, clearly slopes upwards in a south-west direction. There is no obvious continuation of Channel XX6 to the north-east, but by its alignment it appears to be intricately associated with the channel forms cut across the eastern slopes of Peat Hill, in particular channel XX7 (Fig. 3.31; Plate 3DD).

The above descriptions clearly indicate that the morphology, location and orientation of eskers 1, 2 and 3 (Fig. 3.31), are all closely linked with the network of meltwater channels incised across the crest and slopes of Peat Hill. As previously mentioned, these channels and others in the regional pattern indicate formation by a series of southward flowing englacial streams which become, "... superimposed onto the underlying land surface when the zone of meltwater penetration descends downwards as the ice surface downwastes" (Price, 1973, P. 119). Similarly, Clapperton (1968) showed the tendency for such englacial drainage to become concentrated over/in cols in the underlying relief as a result of lateral migration of meltwater within the ice itself. Although there is only slight evidence of fluvioglacial erosion in the floor of the col between Peat Hill and Harestanes Heights, at 381 m.o.d., (Fig. 3.31), 2km to the south the floor of the col between Lamb Hill and Lonnachie Rig, at 366 m.o.d. and lying just outside the thesis area, has been deeply-incised by southward flowing meltwater. Assuming that meltwater flow was concentrated along the line of these low/...

low points in the underlying terrain, the pattern of fluvioglacial erosion suggests that the gradient of the meltwater stream(s) following this course was similar to that depicted in figure 3.42 the meltwater being wholly contained within the ice mass at the Peat Hill col, but subglacial at the Lamb Hill col.

With continued downwastage of the ice surface, the zone of meltwater penetration fell below the level of the Lamb Hill col. As a result, the through-flow of meltwater was restricted, meltwater velocity decreased, and deposition occurred within the englacial tunnel(s) over the area between the two cols. The sinuous depositional course of one such englacial stream was let down onto the sub-ice surface as esker 1, adjacent mounds and minor ridges produced in a similar fashion (Fig. 3.42).

Eventually, the zone of meltwater penetration dropped below the level of the Peat Hill col and alternative lower courses were found for continued englacial flow in a southerly direction. The distribution of channels in the vicinity of Peat Hill indicates that meltwater flow below 366m.o.d. was re-directed around the eastern side of the hill. The best-developed channel along this eastern slope is channel XX5 (Fig. 3.31). This deeply-incised form with its distinctive up-down profile, is also attributed to the superimposition of englacial drainage, in the manner described by Price (1973). "The major part of the channel was cut as the superimposition of the englacial stream proceeded and continued until the meltwaters flowing in the ice-tunnel were able to cut down faster than the meltwaters flowing in the channel cut through the spur. The meltwater stream then had to flow up-hill under hydrostatic pressure, if it was to continue along its course through the spur" (P. 122), (Fig. 3.43). When the zone of meltwater penetration dropped

to/...

to such a level that the head of water necessary for up-hill flow under hydrostatic pressure could no longer be maintained, this meltwater developed a depositional role and esker 2 was formed. The decrease in water velocity initially resulted in englacial ponding, as indicated by the kame terrace form at the in-take of esker 2, but with the continued supply of meltwater to this point, a subglacial route down to the valley floor was created. At the junction with the valley floor, increased deposition occurred as a result of the reduction in meltwater velocity, but generally the esker follows a straight course and as such typifies the "subglacially engorged or slope eskers", referred to in the literature (Mannerfelt 1945; Sugden 1970; Embleton and King 1975a; Sugden and John 1976; Fig. 3.43).

Although locally meltwater forced a route down to the valley floor, the regional pattern remained unchanged, as indicated by the sequence of channel and bench forms below channel XX5 on the eastern flank of Peat Hill (Fig. 3.31). Several of these minor forms coalesce at the circular, plunge-pool in-take of channel XX7 (Fig. 3.31), which flows downhill in a southerly direction to terminate at approximately 275 m.o.d.. A short distance to the south-west of the outlet of channel XX7, channel XX6 (Fig. 3.31), has its in-take and it appears likely that the two forms were incised by the same meltwater stream. The uphill gradient of the floor of channel XX6 can again be explained by meltwater flow under hydrostatic pressure. With the reduction of meltwater velocity in the south-westerly direction, deposition of esker 3 in a subglacial, or possibly englacial, environment near the base of the ice took place. The sinuous, bifurcating nature of this ridge is a reflection of the meandering nature of the meltwater course/...

course itself.

Fluvioglacial landforms in the Lochan valley therefore relate to formation during three different stages in the downwastage of ice over this area. Each esker ridge and its associated channel forms reflect local adjustments to the pattern of meltwater drainage, necessitated by the altitudinal descent of the zone of meltwater penetration, and its interaction with underlying relief conditions (Fig. 3.44). The more sinuous south-westerly course followed by esker 3, strongly suggests that at the time of its formation, regional control over meltwater drainage was waning and that the ice mass occupying the Lochan valley was in a semi-stagnant condition. General movement of glacier ice and its associated meltwater across the area in the vicinity of the Evan Water valley was in a southerly direction. With the dominant alignment of the underlying topography at right-angles to this, continued downwastage resulted in the detachment of stagnant ice masses which wasted away in situ, in each of the major east-west trending valleys. As a result, the landforms of fluvioglacial deposition found in these transverse valleys, with the exception of certain forms at higher altitudes, owe their distinctive characteristics to the control exerted by local topography over meltwater conditions within extensively decayed or stagnant ice masses and not to widespread regional dictates.

<ins>SUMMARY</ins> . The deposits of fluvioglacial origin are found in close association with the three major valley systems of Area I, and when considered in conjunction with the landforms of fluvioglacial erosion, indicate stages in the decay and disappearance of the last ice sheet over this area.

In/...

In the vicinity of the Evan Water valley, the earliest phases of deglaciation are represented by ice-directed meltwater channels and associated eskers. However, with downwastage, ice occupying the east-west orientated valleys of this area became cut off from its source of supply and stagnated in situ, providing ideal situations for the concentration of meltwater and formation of fluvioglacial landforms (Sugden 1970).

The Annan and Moffat Water valleys run parallel to the regional direction of ice movement, but still possess extensive fluvioglacial deposits across their lower slopes. These deposits decrease in altitude in a southerly direction, their morphology and internal constituents strongly suggesting that almost all deposition took place in an ice-contact environment.

It therefore appears that over this central and eastern area also, ice remained longest in the valley floors. Similar conditions of ice wastage were described by Hoppe (1950); G Holmsen (1963) and Sugden (1970). Holmsen's (1963) description would appear to equate most accurately with prevailing conditions during the later stages of deglaciation in Annandale and Moffatdale: "Glaciofluvial deposits in adjacent valleys suggest that "dead" plateau glaciers existed while ice bodies occupied valleys. Meltwater from ice on the plateaux carried sand and gravel to the valleys, deposited the material along or upon remnant ice bodies" (P. 887). The general absence of sand and gravel deposits below an altitude of 91 m.o.d., suggests that final meltwater drainage occurred very rapidly, perhaps as a result of the establishment of a subglacial escape route through the "remnant ice body" occupying the Upper Annan valley.

3.8 : CONCLUSIONS

From the evidence relating to the landforms and deposits produced by glacial and fluvioglacial processes in Area I, it is possible to suggest the sources, directions of movement, and mode of decay of the last major ice sheet to affect the area:-

1) The glacial landforms and deposits in Area I indicate that the region was crossed by ice from two distinct source areas, one at least partially internal, the other wholly external. Over the western part of the area an external source to the west-north-west is indicated, but over the central and eastern parts of Area I most glacial features radiate southwards from the high ground of the Tweedsmuir Hills.

2) The Tweedsmuir Hills acted as a primary centre of ice dispersal during the last major glaciation to affect Scotland, as tentatively suggested by previous authors. (A Geikie 1863; Young 1864; J Geikie 1873; Eckford and Manson 1927; Eckford 1955; Charlesworth 1957; Price 1961; Greig 1971; Sissons 1979c). The upland surfaces of this area supported an ice cap or ice dome (after Manley 1951, 1955, 1959), from which outlet glaciers flowed radially, presumably guided, at least initially, by the upper reaches of the principal valleys. It was the divergent outward flow of ice from here in the south and south-west directions that eventually covered much of Area I.

3) A second, external source, in the general vicinity of the Lowther Hills, supplied ice which entered the western part of Area I from a west-north-west direction.

4) These two ice masses became confluent in Area I and together flowed southwards down Annandale.

5) The presence of meltwater channels and glacial breaches at the highest altitudes in Area I, and the streamlined form of many hill and ridge crests, indicates that the area was probably completely covered by ice at the maximum of the last glaciation.

6) Throughout Area I meltwater channels are best-developed across spurs and bedrock convexities aligned transversely to the regional directions of ice movement. The vast majority of these channel forms were incised by the superimposition of ice-directed supraglacial and englacial streams onto the underlying topography as the ice surface downwasted, the depth of meltwater incision controlled by a descending zone of meltwater penetration. Other channel forms may have been produced by subglacial meltwater flow at the base of the ice.

7) Meltwater channels which plunge directly in the manner of subglacial chutes, and fluvioglacial deposits, are concentrated below 243 m.o.d. over a large part of Area I. These landforms and deposits strongly suggest formation in association with stagnant ice. Relict patches of stagnant ice, isolated from their source of supply, downwasted in situ/...

situ in the Annan, Moffat Water, Garpol and Cloffin valleys.

8) Meltwater from ice-free uplands carried deposits into, onto and against the stagnant ice masses, with deposition at certain altitudes controlled by the presence of an englacial water-table.

9) The general absence of fluvioglacial deposits below 91 m.o.d. suggests that final meltwater drainage from Area I was very rapid, through or between decaying ice masses.

10) Either during or after the general dissipation of the last ice sheet, there was a return to colder conditions in pollen Zone III times, approximately 11,000 - 10,000 years B.P., when glaciers were (re-)established in the Blackhope, Carrifran and Tail valleys of the Tweedsmuir Hills. The limits of these glaciers, and stages in their retreat in the case of the ice mass occupying the Tail valley, are indicated by moraine mounds and ridges. Periglacial slope processes were also important during Zone III.

CHAPTER 4

AREA II

4.1 INTRODUCTION : LOCATION AND EXTENT

Area II is the central, upland part of the thesis area and extends over approximately 230 sq. km. (Fig. 4.1). In order to deal with an entirely upland area and also to later examine the Upper Nith Valley as one unit, (Area III), part of the western and southern boundaries of Area II were drawn parallel to the Nith itself, along the upland edge of the Lowther Hills.

The northern boundary of Area II is the simplest of the delimitations, represented by the east-west grid line NS 14, from its eastern junction with the Strathclyde Regional boundary at NT 047 140 to the Crawick Water Valley, NS 785140. The western boundary parallels the upland edge and is represented by a line linking the crests of Knockenhair (404 m.o.d.), Auchensow (420 m.o.d.), Black Hill (531 m.o.d.) and East Morton (328 m.o.d.). The southern limit to Area II also follows the upland edge linking East Morton (328 m.o.d.) to the north-western edge of the Forest of Ae, through the peak of Nether Dod (351 m.o.d.). The boundary to the forested region also represents the southern part of the eastern boundary to Area II, but is replaced by the north-south grid line NT 00 at their junction, at NT 000998. The grid line in turn is replaced by the Strathclyde Regional boundary, which represents the eastern boundary of Area II to the north of NT 000 047.

Area II contains evidence of glacial erosion, glacial deposition, fluvioglacial/...

fluvioglacial erosion and fluvioglacial deposition. The upland character of the area restricted the processes of deposition, both glacial and fluvioglacial and as a result landforms of erosion dominate. Detailed analysis of all these landforms and deposits will enable the major ice sources, and directions of ice movement across the area, to be hypothesised.

4.2 RELIEF AND DRAINAGE

The boundary line by which Area II is delimited effectively encompasses the central part of the Lowther Hills, and as such gives the area a homogeneous upland character (Fig. 4.2). Relative relief values generally exceed 175m and summit values rise to over 650 m.o.d., for example, Queensberry (697 m.o.d.), Gana Hill (668 m.o.d.), Ballencleuch Law (691 m.o.d.), Rodger Law (688 m.o.d.), Lowther Hill (725 m.o.d.), Green Lowther (732 m.o.d.), Dungrain Law (667 m.o.d.). Locally, valley sides are steepest and the terrain most rugged in the valleys radiating from the Lowther Hill - Green Lowther - Dungrain Law ridge, in particular the Glen Franka, Peden, Riccart, Lang, Potrenick, Carron and Enterkin valleys (Fig. 4.2). In the east and south-east parts of Area II, relative relief values are slightly lower and although the terrain is still deeply-incised, valley slopes are generally less steep and hill and ridge crests smoother and more rounded in character.

The Lowther Hills also represent the principal watershed within the thesis area and a major divide for north and south flowing streams in Southern Scotland as a whole. The northward flowing streams which rise in Area II form an extensive dendritic pattern, but/...

but are all tributary to one of two major rivers, the Potrail Water and the Daer Water. The valleys of both the Daer and Potrail contain glacial drift, now mostly redistributed by the meandering streams to form floodplains 300 - 500m in width. The course of the larger Daer Water is disrupted by the construction of a reservoir along its length. Both the Potrail and Daer merge along the northern boundary of Area II to form the Upper Clyde. The southward flowing streams are all tributary to the Nith or Annan rivers, mainly the former. Principal among these are the Carron Water and Mennock Water, both of which occupy steep-sided, gorge-like valleys, the valley sides rising 250 - 300m from narrow floodplains, throughout their course in Area II. Both rivers are incised entirely into bedrock and it is extremely unlikely that the present Carron or Mennock carved these valleys. There is little indication of glacial drift along the flanks of either valley. The other southward flowing streams generally follow a short, often steep course in Area II, but as with the Mennock and Carron, frequently occupy large valleys which far surpass their present erosive capabilities.

As mentioned in Chapter I, capture of the headwaters of northward flowing streams in the Lowther Hills was carried out by tributaries of the river Nith. The Carron Water illustrates one example of this. It is suggested (George 1956) that the Dinabid Linn and its associates formerly flowed into the Potrail Water, and that the Dalveen Lane is a "... secondarily adjusted reversed obsequent stream " (George, 1956, P. 14). Capture took place as a result of local geological conditions which are described below.

4:3/...

4.3 GEOLOGY

As was the case in Area I, the geology of Area II is dominated by rocks of Lower Palaeozoic age (Fig. 4.3). Over 95% of Area II is underlain by Ordovician or Silurian greywackes, grits, shales or siltstones, highly folded and faulted in a north-east to south-west direction. The older Ordovician rocks are again in the minority, although they occur over a sizeable area in the north-west of Area II (Fig. 4.3). Rocks representative of accumulation in a geosynclinal environment are typical, but in addition there are two small anomalous outcrops of igneous rock, also of Ordovician age. In the extreme north-west corner of the area, two limited outcrops of extrusive ash and spilitic lava occur. The more extensive deposits of Silurian age rest conformably on the Ordovician. The boundary separating the two groups of rock is irregular (Fig. 4.3), but parallels the regional trend, being orientated in a north-east to south-west direction. With the similarity in rock types of the Ordovician and Silurian deposits, there is no superficial expression of the change from one to the other.

The rocks of Devonian age in Area II are represented as igneous intrusions (Fig. 4.3). In the west-central part of the area a granodiorite sill caps the ridge which connects Ballencleuch Law with Rodger Law, while further north-west, two small dykes of acid-porphyrite composition occur.

Three small disconnected outcrops along the western boundary and just beyond the upland edge, represent the extent of Carboniferous rocks in Area II (Fig. 4.3). The most northerly of the three is revealed by/...

by faulting and comprises sandstones, shales, coal seams, seat earths, mudstones and limestones of the Coal Measure and Carboniferous Limestone Series. The southerly outcrops consist of sandstones, shales, mudstones and coal seams of the Coal Measure Series, which in places are overlain by olivine-basalt lavas. The latter outcrops are found in association with younger deposits of New Red Sandstone age, in a north-south orientated basin which extends down Nithsdale in a similar fashion to the New Red Sandstone basin in Annandale (Figs. 3.3 and 4.3). Only marginal parts of the basin lie within Area II however.

The New Red Sandstone rocks, which rest unconformably on the Carboniferous, are represented by red desert sandstones and breccias. The younger deposits of this basin, however, are generally more susceptible to erosion than the surrounding Lower Palaeozoic rocks. As a result, incision by the Carron Water along the line of the basin took place at a much greater rate than similar incision by the Potrail Water to the north. This is suggested as the reason behind the "capture" of the headwaters of the Potrail Water by the Carron mentioned above (George 1956).

Once again the youngest solid rocks in the geological sequence are the igneous intrusions of Tertiary age. In Area II however, only one major dyke is present. This feature follows a north-west to south-east trend and is continuous across Area II, but has little or no surface expression on the landscape.

4.4 GLACIAL EROSION

Landforms produced by glacial erosion in upland areas are well-exhibited in Area II (Figs. 4.4, 4.5).

GLACIAL/...

GLACIAL TROUGHS. There are two major types of glacial trough found within Area II. Firstly, there are the trough forms which originate in the higher parts of Area II leading down from upland surfaces and often with cirques at their head or along their flanks. Such troughs are most common in the north-west part of Area II (Fig. 4.5), and generally follow the valley systems which descend from the vicinity of Green Hill and more significantly the Dungrain Law - Lowther Hill ridge. The more deeply-incised of these troughs follow a broadly southward course, and are presently occupied by the Glendyne, Mennock, Enterkin, Lang, Riccart and Peden streams. (Figs. 4.4, 4.5).

The second type of glacial trough has a more scattered distribution and is found incised across the regional watershed, with no readily apparent source areas (Figs. 4.4, 4.5). The troughs are generally open at both ends and often have glacially-breached cols at their heads. The "watershed troughs" are shorter in length than the forms which originate in the higher parts of Area II, and are occupied by only the headwaters of the Carron, Kirk, Glenleith, Capel, Lochan, Kinnel and Cloffin streams (Fig. 4.4). The alignment of these troughs was strongly controlled by the location of the watershed itself, and consequently they form a divergent pattern between 50^{o} east and west of the southern compass direction.

As indicated on figure 4.6, the troughs which originate in the higher parts of Area II are generally larger and more deeply-incised than the forms found across the watershed. There are two major exceptions to this rule however, the "watershed troughs"/...

troughs" occupied by the Kirk Burn and the Carron Water (Figs. 4.5, 4.6). The Kirk trough, like many of the more southerly watershed forms is characterised by a fairly narrow, steeply sloping floor. However, in this case the floor flattens and widens as it is followed southwards across the watershed, such that near the trough mouth the floor exceeds 140m in width. The trough is incised more than 300m into bedrock, but is surpassed in this respect by the neighbouring Carron trough, the steep sides of which descend over 360m below the surrounding upland surface. This latter trough, also known locally as the Dalveen Pass, has a wide, flat, drift-filled floor, approximately 300m in width (Plate 4A). The larger dimensions of the Kirk and Carron troughs in comparison with the other forms which are incised across the watershed, (Fig. 4.6), is attributable to the comparative susceptibility to erosion, both fluvial and glacial, of the New Red Sandstone rocks which outcrop at the mouth of both forms (Fig. 4.3).

Within the group of troughs incised across the watershed, it is possible to make a general distinction between those trending in a north-south and those trending in a west-east direction. The north-south aligned troughs (Fig. 4.5), although shorter than the forms in the north-west part of Area II, all generally exceed $1\frac{1}{2}$ km in length and possess the previously mentioned steeply sloping floors. The forms aligned west-east across the watershed (Fig. 4.5), are all less than one kilometre in length and have gently sloping floor gradients by comparison. The differences in trough dimensions are attributable to differences in the pre-glacial valley forms. Rapid headward regression by the southward flowing/...

flowing streams (Lebon, 1935, P.8; George, 1956, P.13), produced steep gradients in the uplands which were accentuated by glacial erosion. In contrast, the eastward flowing streams are characterised by gentle gradients in their upper reaches, and as a result are not as spectacularly enlarged.

The dendritic pattern of troughs descending from the higher parts of Area II concentrated glacial action in the Mennock and Potrenick valleys (Fig. 4.5). This is well-reflected in trough dimensions (Fig. 4.6). The Mennock however (Plate 4B), is only one of three major troughs, the Glendyne and Enterkin being the other two, which drain the north-west part of Area II in a south-south-west direction. In all three cases the trough form disappears at the upland edge, where ice descending these troughs joined the Nith Valley.

The tributary troughs which join the Potrenick also originated locally. The Loch and Riccart troughs descend steeply from the upland surface around Green Lowther, while the Lang trough has a well-developed cirque at its head. All three troughs merge smoothly at their junction with the Potrenick, there being no evidence of hanging valleys in this vicinity (Plate 4C). The close proximity of the troughs however, imposes a rugged character onto this part of the Lowther Hills which contrasts markedly with the smoothed topography of these uplands generally.

The Potrenick trough, its tributaries, and the Peden trough further north, all indicate an east-south-east movement of ice from this upland core of the Lowther Hills. The Lang, Riccart and Peden troughs also contain evidence in the form of moraines for

a/...

a more recent glaciation which post-dates trough formation, and in this respect are similar to the major troughs which descend from the Tweedsmuir Hills in Area I.

The two main types of glacial trough distinguished within Area II can, on the basis of their form and location, be related to different stages in the build-up and movement of ice across the area. The troughs in the north-west part of Area II are similar to the "Alpine" or "Icelandic" forms described by Linton (1963), and indicative of formation from local source areas of ice accumulation, either cirque or plateau glaciers. In contrast, the forms incised across the watershed in the southern and eastern parts of Area II represent "open" or "through" troughs (Sugden and John, 1976, P.151 - 209), which "... have been eroded beneath ice sheets" (P. 179). Therefore, it is suggested that local centres of ice accumulation were established at an early stage in the glacial period over the uplands in the north-west part of Area II and that ice descending from these centres was responsible for the pattern of glacial troughs found here. At a much later stage, when most, if not all, of Area II was covered by ice, the open troughs were incised across the watershed by an almost radial outward movement of ice from a north-west source.

GLACIALLY-BREACHED COLS. Glacially-breached cols are numerous in Area II, with over 60 examples identified (Figs. 4.4, 4.5). The cols are generally flat-floored and cut abruptly into the surface of the uplands. All of the cols possess an open, catenary cross-section. However, where large amounts of ice were concentrated, as in the col linking the Enterkin/...

Enterkin trough with the Carron trough, col sides are steeper and the floor restricted in width, giving the form more of a V-shape (Plate 4D). Altitudinally, glacial breaching occurred between 305 - 636 m.o.d. but as many of the summits in this area exhibit some degree of ice moulding, it is strongly suggested that like Area I, Area II was entirely covered by ice at the maximum of the last glaciation.

The orientation and altitude of the glacially-breached cols in Area II were examined in an attempt to gain a greater insight into the former directions of ice movement across the area (Fig. 4.7). On the basis of the information depicted on figure 4.7, the cols can be separated regionally into two groups, a southern and eastern group, and a north-western group. The two groups are separated by a line which follows the Potrail and Carron Waters, linking the two rivers across the watershed at Dalveen Lane (Fig. 4.5).

To the south and east of the Potrail-Carron line three main concentrations of cols can be identified (Fig. 4.7). The first group, found between 315 - 483 m.o.d. in altitude and aligned in a broadly east-west direction are dominant along the eastern boundary of Area II, and were previously described in relation to Area I, (Pages 53-57). The majority of these cols were incised across the watershed by generally eastward moving diffluent ice. In places, as at the head of the Lochan and Cloffin Valleys (Fig. 4.5), such breaches lead into open troughs of the type mentioned above. By their location, the breaches at the head of the open troughs strongly suggest that although initially produced by diffluent ice, they also acted as major through routes for ice at or near the/...

the glacial maximum.

A second, higher group of cols can be identified between 381 - 602 m.o.d., aligned in a north-east to south-west direction (Fig. 4.7). These cols are similar to the first group in that they reflect movement across the watershed, but in this case across the higher, southern portion of this divide. The largest and best-developed breaches are found at the head of the Kirk and Capel troughs (Fig. 4.5). The Kirk breach is incised more than 152m below the upland surface and has craggy, scree-covered slopes, bounding a flat-floor 80 - 100m in width (Plate 4E). Again therefore, although many of the cols were produced by southward trending diffluent ice, there is evidence to suggest that certain forms were established, or more likely enlarged, by ice following a similar course, but under conditions of ice transfluence.

The first two groups of cols can be taken together as representative of the build-up and overspillage of ice from the Upper Potrail and Daer Valleys across the Lowther Hills watershed, in broadly easterly and southerly directions. Directions of ice movement appear to have remained basically similar at a later stage in the glacial period, with several of the breaches acting as feeders for open troughs incised beneath a more extensive ice cover.

The third group of cols extend between 305 - 640 m.o.d., in altitude, but are concentrated below 483 m.o.d. These cols are aligned in a north-west to south-east direction and occur throughout the area to the south and east of the Potrail-Carron line. With the exception of two forms along the northern boundary (Fig. 4.5), these breaches are taken to represent a generally south-east movement of ice across much of Area II, (on the basis of/...

of roche moutonees,striations etc.). Although developed across the watershed where local relief conditions encouraged breaching in this direction, this third group of cols are most obvious in the uplands flanking the higher north-west part of Area II, and to the south of the regional watershed, along the upland edge (Fig. 4.5). The cols along the northern boundary, were produced by ice following the opposite north-north-west course into the Upper Clyde Valley, on the basis of other landforms of glacial erosion in this vicinity. Consequently, the pattern of cols found across the area to the south and east of the Potrail-Carron line suggests an almost radial outward movement of ice in north, east, south-east and southerly directions.

To the north-west of the Potrail-Carron line there are no such readily identifiable concentrations of glacially-breached cols (Fig. 4.7). The cols are found at generally higher altitudes than those to the south and east, but form a very diffuse pattern, particularly above 580 m.o.d. There is evidence of diffluent ice breaching in a south-west direction from the Potrenick, Lang and Riccart troughs, but two kilometres further north, diffluent ice from the Peden trough incised a large breach in a north-west direction (Fig. 4.5). The altitude of the glacially-breached cols in the area where the large scale affects of glacial erosion are most evident and their generally diffuse pattern, are taken to be attributable to formation in close association with the local centres of ice accumulation which were established in this vicinity. Some of the lower altitude cols were incised by diffluent ice during the outward movement of glaciers at early stages in the glacial period. However, most of the higher cols formed beneath the ice cap/ice dome which/...

which existed over this core region of the Lowther Hills during the later stages of glaciation, when directions of ice movement were controlled more by regional than local considerations. The pattern of glacially-breached cols in Area II as a whole, suggests that much of the ice that covered the area originated in the north-west upland core of the Lowther Hills, and that outward movement from here was in broadly easterly and southerly directions. The location and alignment of the higher cols and open troughs also suggests, that when the whole surface was covered by ice, the centre of the ice sheet lay over the central part of Area II itself.

CIRQUES. Twelve cirques were identified in Area II. (Figs. 4.4, 4.5). Nine of these features are concentrated in the higher north-west part of the area, the other three cirques found in the uplands flanking the headwaters of the river Daer. The best-developed cirque forms are deeply-incised into the eastern flank of the ridge linking Lowther Hill with Dungrain Law, at the head of the Lang and Peden troughs (cirques H and I respectively, fig. 4.5; Plate 4C). Both cirques possess an arcuate plan form and have steep headwalls, 160 - 170m in height. However, there is no development of a gently sloping floor in either cirque, with the result that beyond the foot of the headwall the cirque form blends imperceptibly with the upper part of the trough in both cases. Cirques A and B, (Fig. 4.5), occupy similar locations to cirques H and I at the head of the Glendyne and Glenclach troughs. Referring to cirques in the Alps, Penck (1909) stated, "The true corries (cirques) with basins in their bottoms are therefore mostly the/...

the beds of isolated hanging glaciers which did not descend far below the snow limit .... But if on the slopes we have glaciers which feed the valley glaciers then we have usually to deal only with an increase of their cross-sections and their bottoms descend without interruption" (p. 16). Penck referred to the latter forms, similar to cirques A, B, H, and I in Area II, as "open corries" (cirques).

Cirques E and F, (Fig. 4.5), perched along the western flank of the Enterkin trough, have a more directly eastern orientation than cirques H and I, but again are characterised by the arcuate plan form and steep headwall, although here the headwall is only 100 - 110m in altitude. As before however, there is little development of cirque floors. Cirques E and F, and the similar forms C and D on the flanks of the adjacent Mennock trough, are identical to the cirques along the upper flanks of the Carrifran and Blackhope troughs, described in the previous chapter (cirques B, C, D, E; Fig. 3.4). The similarity in location and morphology is attributable to a similarity in the mode of formation, the cirques of the Enterkin and Mennock troughs reduced in size and left hanging along the upper flanks by the more vigorous erosive action of the trough glaciers; as in the Carrifran and Blackhope troughs.

Cirques J, K and L, (Fig. 4.5), to the south-east of the main group, all possess east or north-east orientations and are located on the lee side of fairly extensive upland surfaces. None of these cirques are as well-developed as the forms in the main group, their headwalls being generally less than 50m high.

Figure 4.8 indicates the orientation and altitude of all cirque forms within Area II. The majority of the cirques are orientated in an

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east-south-east direction, a slightly more southerly aspect than the forms in Area I (Fig. 3.10). It is interesting to note in this context that all the cirques in Area II, with the exception of cirques C and D, occupy positions on the lee side of upland surfaces. This reinforces the previously stated belief that wind-blown drifting snow was an important factor in cirque formation (Embleton and King, 1975, P.222), and suggests a west or west-north-west source for the main snow-bearing winds during the glacial period.

With regard to cirque altitudes, (Fig. 4.8), assuming contemporaneous formation for all of the forms in Area II, a regional firn-line at approximately 380 m.o.d. is indicated for the Lowther Hills during the period of cirque genesis. This altitude is only 40m below that suggested for the Tweedsmuir Hills further east.

The morphology, altitude and orientation of the cirques give a further indication to the manner in which glacial conditions became established over Area II. The first glaciers were the cirque forms in the higher north-west part of Area II. At this early stage in the glacial period, Dort (1957) stated, " Ice is formed faster than it flows from the cirque. As a result the upper surface of the ice attains elevations higher than the top of the headwall and the summit area into whioh the cirque is being eroded...... This upland ice will of course flow off the summit area toward all points of the compass" (P. 540). The establishment of such ice caps or ice domes over the higher upland surfaces in the north-west part of Area II is also supported by the postulated altitude of the regional firn-line (Manley 1949, 1955). The presence of local centres of ice accumulation and dispersal explain the pattern of troughs radiating from this area and the closely associated open cirques, the latter produced/...

produced by the concentration of ice from ice caps, down pre-glacial valleys via the cirque heads. In this respect, it is interesting to note that Evans (1969) stated, "..... open cirques are more common well above the snowline, in major glacial source areas of high relief" (P.371). Open cirques are only found in the north-west part of Area II.

STRIATIONS AND ROCHES MOUTONNEES. Striations are not common in Area II (Fig. 4.5). Several localities where striations are to be found however, are indicated on the geological maps which cover the area, but not all of these were located in the field. By combining the information from the geological maps and the writer's own fieldwork, a total of only 15 striations were identified in Area II. The 15 forms can be readily broken down into two widely separated groups (Fig. 4.5); a north-west group and a south-east group.

The north-west group consists of only two striations, both aligned in a north-east to south-west direction, broadly parallel to the troughs which are found in this vicinity. The south-east group are found in close association with the regional watershed and consequently can be sub-divided into those found along the eastern part of the watershed and those found along the southern part. The striations along the eastern margin of Area II indicate the movement of ice in a broadly eastward direction across the watershed. Similarly the more southerly forms indicate a southward movement of ice, again crossing the watershed.

Two further striations were identified to the south of the Daer Reservoir, both aligned in a north-south direction, with locally a northward movement of ice suggested as being responsible for the formation/...

formation of one of the forms by the Geological Survey (Fig. 4.5). This latter striation is the only form which does not suggest a broadly southward or eastward movement of ice across the south-east part of Area II.

Roches moutonnees are more abundant than striations in Area II and are more accurate indicators of former ice movements (Fig. 4.5). The roches moutonnees are also most common along the watershed region, often found as small mounds and ridges generally less than 30m in length and 3m in height, on the floors of glacial breaches or open troughs. Once again, movement of ice across the watershed in a direction between east and south along the southern and eastern margins of Area II is strongly indicated. Further west, the affinity of roches moutonnees for breaches in the watershed is emphasised at the head of the Carron trough, where three forms indicate a west-south-west movement of ice broadly parallel to the alignment of the trough itself (Fig. 4.5). In the vicinity of the Daer Reservoir, near the centre of Area II, several moutoneed forms indicate an east-south-east movement of ice (Fig. 4.5). Two other roches moutonnees are worthy of note. The first is found along the western upland edge between the Mennock and Enterkin troughs (Fig. 4.5), and indicates a south-east movement of ice parallel to the Nith Valley, but at right-angles to the alignment of the troughs themselves. This form was produced at or near the glacial maximum by ice following the course of the Nith Valley, but also exerting its influence along the upland edge. The second roche moutonnee is found along the northern boundary of Area II, (Fig. 4.5), and indicates a northward movement of ice.

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The small-scale features of glacial erosion are therefore in agreement with the larger forms in suggesting an almost radial pattern of ice movement outward from the higher parts of Area II.

SUMMARY. The landforms of glacial erosion indicate the principal directions of movement followed by the last major ice mass to cross Area II and strongly suggest that much of this ice originated within the area itself (Fig. 4.9). A local centre (or centres) of ice accumulation existed over the upland surfaces linking Green Hill with Dungrain Law in the north-west part of Area II, from which glaciers descended principally westwards, southwards and eastwards. The courses followed by these glaciers were initially strongly controlled by the upper reaches of the existing valley systems and in the case of some southward and westward trending forms, this remained the situation throughout their length in Area II. However, with particular reference to the eastward flow of ice, on escaping the upland constraints continued movement away from the core area of the Lowther Hills was fan-like.

Ice from the Lowther Hills moved northwards into the Upper Clyde valley, (Charlesworth, 1926b, P.7), but more significantly southwards and eastwards to accumulate against, overspill across, and eventually be incised through the restraining pre-glacial watershed. Although an almost radial outward movement of ice from the Lowther Hills is strongly suggested for the area as a whole, most of the ice which crossed the extensive central and eastern part of Area II followed a course between east and south.

Along the upland edge which parallels the west and south-west boundaries/...

boundaries of Area II a south-east movement of external ice down the Nith Valley is indicated. Ice following this course overspilled onto the lower flanks of the Lowther Hills at the glacial maximum.

4.5 GLACIAL DEPOSITION

Glacial deposits are not widespread in Area II and indeed are restricted to the floors and lower flanks of certain valleys, in all cases thinning out rapidly with increasing altitude. The surface of this upland area is dominated by the presence of peat, solid rock or debris derived from mass wastage, with the result that glacial till is severely limited in its distribution. The continuous upland character and uniform lithology make it even more difficult to readily identify till deposits and delimit their extent than was the case in Area I. Lodgement till, soliflucted till and superficial material produced by mass wastage are all similar in character in Area II and difficult to differentiate from the often limited exposures which are available. All three types of valley-fill descend from the valley sides towards the present streams in the form of sloping benches and can only be distinguished by stone orientation analyses. Consequently, no attempt was made to delimit the full extent of glacial till within Area II (Fig. 4.4), although tentative limits are indicated in peripheral areas where the true character of the deposit can be ascertained with greater certainty. In these peripheral parts, glacial till can be identified up to an altitude of 366 m.o.d., but it is speculated that in scattered pockets in the central part of the Lowther Hills, "till" may extend upslope in places to 411 m.o.d.

As/...

As was the case in Area I, good natural exposures revealing deposits which are taken to represent glacial till are rare, but where found generally occur in the vicinity of valley floors, the result of fluvial incision. The largest section indicates a till thickness of 12m overlying a layer of disintegrated bedrock. In many cases, however, the true thickness of the deposit cannot be ascertained as the lower part of the exposure is obscured by slumped material.

Areas I and II are also similar geologically, the dominance of Lower Palaeozoic rocks over much of Area II again resulting in the formation of a coarse, gritty till containing mainly greywackes, grits and siltstones. It is only along the west and south-west margins of the area that the character of the till changes slightly, with the presence of sandstones, shales, lavas and tuffs of Carboniferous and New Red Sandstone age in the deposit. The matrix of the tills in these marginal areas appears to be slightly more compact than that derived from wholly Lower Palaeozoic outcrops. Throughout Area II however, the shape of the included clasts remains generally constant, angular and sub-angular clasts dominating, although sub-rounded forms are also occasionally present. The colour of the tills also remains constant, despite the slight difference in geological source areas, with dark brown tills dominant. Along the south-west margin of the area however, the dark brown colour of the till is tinged with red, reflecting the influence, although slight, of underlying red sandstone. All of the exposures of till in Area II indicate a single unit overlying bedrock with the exception of Site 4F (Fig. 4.4) in the Lower Capel Valley, but this exposure will be examined in greater detail later. At no exposure was sand and gravel revealed overlying till/...

till, but on several occasions the number of angular clasts contained within the deposit increased towards the top of the section, suggesting that the till in fact merged vertically with superficial material produced by mass wastage.

In Area II, more so than any other area, detailed examinations of till characteristics were completed at various sites where the deposit was best-exposed. There were two main aims behind this:-

(a) to verify that the deposit examined was in fact glacial till,

(b) to indicate the origin and former direction of movement of the ice by which the till was deposited.

In total, 9 exposures of till were examined (Fig. 4.4, Sites 4A - 4J), the nature of the deposit and dimensions of its included clasts described, and preferred-stone orientation analyses, particle-size analyses and erratic counts carried out. The results obtained from each of the sites are summarised on figures 4.10, 4.11 and tables 4.1, 4.2, 4.3. Several points are readily apparent from these figures and tables.

The rose diagrams for stone orientations within Area II (Fig. 4.10) and table 4.2, suggest a complex pattern of movement by the ice mass responsible for till deposition. The alignment of the long axes of clasts contained within the tills indicate that deposition in most of Area II was carried out either by an ice mass flowing radially outwards from this area or by an ice mass (or masses) moving into the Lowther Hills from all compass directions. Along the west and south-west margins of Area II, a more consistent north-

west/...

west or south-east movement of ice is indicated by the preferred-stone orientation results. Throughout Area II however, the suggested directions of ice movement imply that local relief conditions exerted a strong control over the pattern of ice flow. The identification of erratics within the tills helped to clarify the pattern of ice movement slightly, but once again the uniform lithology over much of Area II greatly restricted the widescale adoption of this method (Figs. 4.3, 4.11 and Table 4.3). The Lowther Hills consist almost entirely of greywackes and grits of Lower Palaeozoic age and this is strongly reflected in the constituents of the tills found over most of Area II. Only along parts of the west and south-west margin are outcrops of younger rocks of Carboniferous and New Red Sandstone age found. Sandstones and extrusive igneous rocks dominate these fairly small peripheral outcrops, although more extensive outcrops of a similar lithology are present in other parts of the Nith Valley (Figs. 4.3, 4.12). As Carboniferous and New Red Sandstone rocks are only found in the Nith Valley, the presence of these characteristic "Nithsdale erratics" for example at sites 4A, 4F (Figs. 4.11, 4.12), is taken to indicate ice movement into Area II from a generally west or north-west direction. Consequently, the erratic content of glacial tills in Area II, (Fig. 4.11; Table 4.3), strongly suggests that during the last major glaciation, ice from a generally west or north-west source was restricted to the west and south-west margins of the area. The remainder of Area II was covered by an ice mass which deposited a till sheet containing only Lower Palaeozoic/...

Palaeozoic rocks of the type which are found locally in the Lowther Hills.

The particle-size data on till constituents, (Table 4.3), indicates relative homogeneity in the composition of the tills of Area II. The gritty tills characteristic of derivation from Lower Palaeozoic rocks in Area I are similarly dominant in Area II, with again the concentration of clasts in the coarser particle-size range. The exposures along the west and south-west margin of Area II which contain Nithsdale erratics (Sites 4A, 4F, Fig. 4.4), do not have the concentration of larger clasts found elsewhere, and as a result tend to have more compact and tenacious matrices. The high percentage of sand in the lower Capel Burn till, (Site 4F, Fig. 4.4; Table 4.3), reflects the red sandstone on which the deposit rests, although no sizeable erratics of red sandstone were identified in the till itself. The slight differences in particle-size distributions between those tills consisting wholly of Lower Palaeozoic rocks and those containing Carboniferous and New Red Sandstone erratics, is a reflection of the relative resistance to erosion of the erratics during transport by the ice mass. Flint (1971) stated, ".....non-durable rocks such as sandstones.... broke up or wore out in transit to a greater extent than did their durable neighbours" (P. 81). The comparatively greater resistance to erosion of the greywackes and grits explains the predominance of the coarser fraction in the tills consisting wholly of Lower Palaeozoic erratics.

By combining the information obtained from stone orientation analyses,/....

analyses, erratic counts and particle-size analyses with evidence of the direction of ice movement derived from the examination of the landforms of glacial erosion (Fig. 4.9), the pattern of ice movement responsible for glacial deposition in Area II can be more closely established. Once again it is strongly indicated that a local centre of ice dispersal was present over the higher parts of the Lowther Hills during the last major glaciation to affect the area. Ice followed an almost radial pattern outward from the local centre, as indicated by the divergent alignments of the mean stone orientations for the tills at exposures 4B, 4D, 4G, and 4H (Fig. 4.10). The full extent of Lowther ice cannot be delimited, but the erratic content of the tills suggests that local ice extended across most of Area II. Along the foothill zone which marks the west and south-west margin of the area however, there is evidence to suggest that local ice became confluent with an ice mass moving down the Nith Valley. The dominant direction of movement of the Nithsdale ice mass was south-east, but it appears, again from erratic evidence, to have overspilled into Area II at only scattered localities (e.g. Sites 4A, 4F, Fig. 4.11), probably at the glacial maximum. This south-east movement of ice is strongly reflected in the rose diagram for Site 4E, Garroch Water (Fig. 4.10), although Nithsdale erratics are totally absent from the till itself (Fig. 4.12; Table 4.3). This indicates that ice following a southerly course from the Lowther Hills was forced eastwards on becoming confluent with the more powerful Nithsdale ice mass.

The varying influence of Lowther and Nithsdale ice over the zone of confluence along the south-west margin of Area II is reinforced by the complex nature of the glacial deposits at Site 4F in the Lower Capel Valley (Fig. 4.10; Plate 4F). Two till units are found here, a lower till 9m in thickness overlying red sandstone, and an upper till 1.5 - 2m in thickness which rests conformably on the lower unit. Preferred-stone orientations, particle-size analyses and erratic counts were carried out on both till units (Figs. 4.10, 4.11; Tables 4.1, 4.2, 4.3). The mean stone orientation for clasts in the lower till is 250° but for the upper till the alignment is 138.4° (Fig. 4.10; Table 4.2). This would suggest that the two tills were deposited by two ice masses following fundamentally different courses, the lower unit by ice which moved from a north-east or south-west direction, and the upper unit by ice following a south-east or north-west course. The chi-square values for the two tills (Table 4.2), indicate that there is a much stronger concentration of clasts around a specific orientation in the lower till than in the upper till. Similarly, regarding the dip-strengths (Table 4.2), the alignment of clasts in the lower till unit indicate a strong concentration of dips in a south-west direction, whereas the clasts in the upper unit have no apparent preferential dip direction. The particle-size data (Table 4.3), indicate that the lower till unit contains a higher percentage of fines, although the high concentration of sand was previously explained. The lower unit is the more compact of the two, the upper till being/...

being of generally coarser character with more clasts present in the matrix. Examination of the erratic content of the two tills however (Fig. 4.11;Table 4.3), reveals no great difference between the two deposits. Greywackes and other Lower Palaeozoic rocks dominate the two units, but erratics of Nithsdale origin are also present in both tills.

The Nithsdale and Lowther ice masses were confluent along the southern margin of Area II at the glacial maximum. On the basis of the above evidence, the lower and more dominant till unit was deposited at a time when Lowther ice, following a generally southward course down the Capel Valley, exerted the greater influence over regional ice movement in this vicinity, only a fairly small percentage of Nithsdale erratics being incorporated into the deposit. It appears however, that at a later period, deposition in association with the same ice mass, as indicated by the similar erratic content, was controlled more by the regional influence of Nithsdale ice. As a result, the clasts in the coarser and thinner upper till unit, which may represent an ablation or flow till and not a lodgement till, are aligned in the dominant north-west to south-east direction. This suggests that during the later glacial period, ice following a south-east course parallel to the local direction of Nithsdale ice, exerted a greater influence in the foothill zone along the south and south-west margin of Area II, than did ice moving south-south-west from the Lowther Hills.

MORAINES. The only morphological expression of glacial deposition to be found within Area II, apart from the sloping benches of till which/...

which descend from the lower valley flanks towards the present streams in scattered localities, is found in the upper parts of several of the valleys which drain the high ground linking Lowther Hill to Dungrain Law. On the valley floors and lower valley flanks of the Lang Cleuch, Riccart Cleuch and Upper Peden Burn are found a series of hummocky mounds (Figs. 4.4, 4.13). The irregular assemblage of mounds is similar to the moranic topography described in the Tail, Blackhope and Carrifran valleys of Area I, and the landforms in the Lowther Hills are also taken to represent moraines. As before, air photographs at a scale of approximately 1:10,000 of the valleys containing moraines were examined stereoscopically and then taken into the field where the landform pattern was checked by detailed field mapping.

Moraines in the Lang Cleuch Valley. The Lang Cleuch Valley is a steep-sided glacial trough with a narrow floor, and a well-developed cirque at its head. The morainic mounds are not found at the cirque head, but extend along the floor and lower valley sides between approximately 396 - 488 m.o.d. (Fig. 4.13; Plate 4G). By nature of their location, the moraines are generally neither well-developed nor particularly distinct, and it looks very much as if some mounds were destroyed by fluvial erosion or hidden by the processes of mass wastage down the steep valley flanks. The mounds which remain are found on both lower flanks near their upper valley limit, but become restricted downvalley to a narrow belt just over one kilometre in length along the northern side of the stream, (Fig. 4.13). Individually, the mounds range between 2 - 6m in height and 20 - 100m in length. They are generally/...

generally steep-sided only along the flank which faces downslope towards the stream, and often merge imperceptibly upslope into the valley side. Although it is difficult to generalise on the distribution of this moundy spread, it would appear that in the upper part of the valley the more elongate forms are aligned downslope at a high angle to the contour pattern, towards the Lang Cleuch. Moving downvalley, the mounds tend to be aligned parallel to the contour pattern. Occasionally between, and in places cutting through, the mound forms there is evidence of small-scale fluvioglacial erosion; the channels generally 1.5 - 4m in depth with floors 1 - 1.5m in width.

Incision by the Lang Cleuch into the side of one of the mound forms at Site 4K (Fig. 4.13), reveals their internal composition. There is no apparent bedding and mainly angular clasts are found in a loose, brown, gritty matrix. Numerous fines less than 2cm in diameter are present, but a wide variety of clast sizes, including angular boulders 1.5m in diameter are scattered together. All of the clasts are of local origin.

The importance of slope processes in the modification of the morainic topography is thought to have been considerable. Numerous angular blocks and boulders up to 2m in diameter, have slumped down the northern side of the valley against the morainic mounds near their downstream limit (Fig. 4.13). On the steeper southern flank of the valley the affects of mass wastage are more extensive. Scree slopes extend down to the Lang Cleuch along the valley side, while near the valley head terraces of unconsolidated slope deposits cover the lower flanks and abut against the morainic forms.

Overall/...

Overall, the morainic mounds of the Lang Cleuch Valley are generally indistinct and dispersed in their distribution. It would appear that their original morphology and extent have been greatly modified by the processes of mass wastage down the steep valley flanks.

Moraines in the Riccart Cleuch Valley. The Riccart Cleuch Valley lies one kilometre to the north-east of, but runs parallel to, the Lang Cleuch Valley (Fig. 4.13). The Riccart is also a steep-sided glacial trough, the only difference between the two valleys being that there is no evidence of cirque development at the head of the Riccart. By contrast, the valley head merely descends abruptly from the upland surface in the vicinity of Green Lowther.

The distribution of morainic mounds in the Riccart Valley is similar to that in the Lang Valley, (Fig. 4.13). The mound forms are again concentrated along the valley floor and lower valley slopes between approximately 396 - 488 m.o.d., although more mounds are evident, and they are generally more sharply-defined, in the Riccart Valley. As before, there is evidence to suggest that the processes of mass wastage were active down the steep valley flanks.

The moraines were again best-developed in a narrow belt which extends down the northern side of the valley for approximately one kilometre in length. Individually, these mounds are readily identifiable as steep-sided, sharply-defined forms up to 8m in height and 80m in length. However, once more the steeper side to the mound is that which faces downslope towards the stream, the upslope side again often merging imperceptibly into the valley side. At site 4L, (Fig. 4.13), the steeper southern side of one particular mound was incised by stream activity to reveal numerous angular and sub-angular/...

angular clasts of local origin, generally less than 3 - 4 cms in diameter, in a loose, brown, gritty matrix. Once again, there is no evidence of bedding and larger blocks 30 - 60cms in diameter are incorporated in the deposit.

There are few elongate forms within the moundy spread, but collectively the mounds appear to be aligned downslope towards the stream at a high angle to the local contour pattern. Where mounds are particularly concentrated, as along parts of the northern flank, several forms have coalesced to encircle kettle holes which attain depths of 5m in places. Evidence of small-scale fluvioglacial erosion is again present, the meltwater generally channelled towards the present stream course.

As in the Lang Valley, the most extensive evidence of mass movement in association with slope processes in the Riccart Valley is found down the southern flank. Near the downvalley limit of the mound forms, there is an extensive spread of scree material along the southern valley side (Fig. 4.13). An exposure in this material, Site 4M (Fig. 4.13), reveals 8 - 10m of angular clasts in a very loose, gritty matrix. The majority of the clasts are less than 2cm in diameter, although larger blocks up to one metre in diameter are also present. The more elongate clasts tend to have their long axes aligned directly downslope towards the stream. Along the northern valley side, several small alluvial fans, post-dating the deposition of the moraines, have transported blocks up to 2m in diameter, against and on top of the mound forms.

The moraines in the Riccart Valley are more readily identifiable and concentrated in their distribution than the forms in the Lang, but the location and extent of morainic mounds in the two valleys/...

valleys is basically similar.

Moraines in the Upper Peden Valley. The Peden Burn also occupies a well-developed glacial trough, but the valley sides here are not as steep, nor the floor as narrow, as in the Lang and Riccart Valleys (Fig. 4.13). Similar to the Lang Valley however, a well-developed cirque is found at the head of the Peden Valley.

The moraines of the Peden Valley are found some distance from the valley head, across the lower and less-steep valley slopes between 375 - 427 m.o.d. (Fig. 4.13). The moundy spread is concentrated into a small area less than $300m^2$ which extends down both sides of the stream, although in this case the moraines are best-developed on the southern flank of the valley. The mounds are easily distinguished and stand out as sharply-defined features up to 8m in height and 100m in length. However, by the nature of their location, the steepest side to the mounds is once again that which faces downslope towards the stream.

Several exposures reveal the internal constituents of the mounds to be basically similar to previous descriptions. At Site 4N, (Fig. 4.13), numerous angular and sub-angular clasts, all of local origin, are found in a brown gritty and in places slightly clayey matrix. There is no bedding and the majority of the pebbles are less than 4cm in diameter, although larger blocks up to one metre in diameter are also found.

There is evidence of quite extensive meltwater activity in close association with the moranic mounds. Most of the channels are small, less than 4m in depth with floors 1 - 2m in width, and rum between the mound forms, generally parallel or at a low angle/...

angle to the local contour pattern for much of their length. However, all of the channels eventually curve downslope towards the Peden Burn near the head of their course. Collectively, the mounds themselves also appear to be aligned generally parallel, or at a low angle, to the local contour pattern along both valley sides. There is little indication of mass movement of slope material in the vicinity of the Peden Valley moraines (Fig. 4.13), a fact which strongly reflects the gentler slope conditions found here in comparison to the Lang and Riccart Valleys.

The moraines of the Upper Peden Valley are concentrated into a comparatively small area at slightly lower altitudes than the forms in adjacent valleys, but they are basically similar in terms of morphology and internal composition.

Formation of Moranic Mounds in Area II. As in the Tweedsmuir Hills (Area I), the moraines in the 3 main valleys which drain eastwards from the Lowther Hill-Dungrain Law ridge are believed to relate to a recurrence of colder conditions either after or during the main period of deglaciation. A Zone III age for this cold period was previously suggested. On the basis of the distribution of the moraines, the former presence of small glaciers occupying the floors and lower flanks of the Lang, Riccart and Peden Valleys during this period, can be inferred (Fig. 4.14).

4.6 FLUVIOGLACIAL EROSION

Landforms of fluvioglacial erosion are unevenly distributed and developed in Area II (Figs. 4.4, 4.15). The highest meltwater channels are found on the spurs leading down from Lowther Hill at altitudes exceeding 570 m.o.d., but the densest concentration of/...

of channel forms is found below 450 m.o.d. along the southern margin of Area II. Closely interlinked channel systems are not typical of Area II as a whole however, and away from the southern margin, meltwater channels are often found individually, or in closely spaced but unlinked groups.

Almost all the channel forms are incised into bedrock, but they still vary considerably in their form and dimensions. Many are small depressions only 1 - 2m in width and less than 2m deep throughout their length. At the other end of the scale, however, are the forms which begin unimpressively, but develop into V-shaped notches incised over 30m into the surrounding terrain. Between these extremes are a multitude of forms exhibiting various characteristics of form and size.

Within Area II, channels are best-developed across the crests of spurs and in cols along the regional watershed. Figure 4.15 locates the main channel systems more accurately and indicates, from the dominant slope of the channel floors, the principal direction of meltwater flow responsible for channel formation.

It becomes readily apparent from an examination of figures 4.4 and 4.15, that channel systems are best-developed in the peripheral parts of Area II, and that along the north-north-west, south-south-west, and eastern boundaries, the systems are indicative of 3 distinct, but different, directions of meltwater flow. Similarly, in the central part of the area also, a characteristic pattern to the landforms of fluvioglacial erosion can again be identified. Channel systems in each of the 4 areas mentioned will be examined individually/...

individually, in an attempt to clarify the local conditions of fluvioglacial erosion and hopefully aid in the better understanding of the pattern of deglaciation over Area II as a whole.

CHANNEL SYSTEMS IN AREA II.

(a) Channels along the North and North-Western Boundary. All of the channels in this area were incised by northward flowing meltwater. However, by altitude it is possible to distinguish between the forms found below 450 m.o.d. along the upland edge adjacent to the Nith valley, and the forms incised into spurs and cols in the upland core, generally above 520 m.o.d. (Fig. 4.15).

Of the group of channels which are developed along the north-west upland edge of the Lowther Hills, (Fig. 4.15), the forms which comprise system B, (Fig. 4.16), are the best-developed (Plate 4H). Channel B1, (Fig. 4.16), with its in-take at approximately 404 m.o.d., occupies the floor of a north-east to south-west aligned glacial breach. The channel starts abruptly, is deeply-incised into bedrock and follows a sinuous course northwards downslope to terminate at 350 m.o.d. Where best-developed, it is incised 16 - 18m into bedrock with only a narrow floor (3 - 4m), but near the outlet the width of the channel floor increases to 10 - 14m. Channel B2, like B1, also originates in the floor of a glacial breach and follows a deeply-incised, sinuous course downslope in the northerly direction. There is evidence to suggest a concentration of meltwater in the vicinity of this breach, with two feeders

on/...

on the floor of the breach leading to the channel in-take (at 440 m.o.d.) and a hanging meander, 7m above the floor on the eastern side of the channel. Where best-developed however, the channel is ravine-like, over 24m deep with steep bedrock sides rising from a floor only 3m in width.
The outlets for channel B2 are found at approximately 366 m.o.d., but it is likely that the poorly-developed form B3 was also incised by meltwater from channel B2, and consequently the final termination of meltwater flow in this part of the system was also at approximately 350 m.o.d. B4 is a small chute-form developed on the northern side of the spur between 457 - 427m. o. d. Channel B5 is similar to forms B1 and B2 in that it too commences in the floor of a well-developed glacial breach. The channel in-take is at approximately 440 m.o.d. and it follows a short, sinuous course downslope, terminating at 400 m.o.d. It is incised over 15m into the floor and northern flank of the breach, the width of channel floor varying between 4 - 6m.
The higher group of channels in the core of the Lowther Hills is represented by system Z (Figs. 4.15, 4.17). Channels Z1 and Z2, (Fig. 4.17), are incised across the crest and northern flank of the spur linking Dun Law to Kneesend. Z1 begins on the crest of the spur, at approximately 540 m.o.d. and runs down the northern flank in chute-like form, terminating at 518 m.o.d. The channel is thickly infilled with peat, but although initially indistinct it developes downslope/...

downslope to become incised over 7m into bedrock with a floor 5 - 7m in width. Channel Z2 was incised completely across the crest of the spur, but again the southern portion of the channel is partly obscured by peat. The channel however, is best-developed where it leaves the crest and starts to run down the northern flank of the spur. In this vicinity it is incised to a depth of 9m, with a floor 4 - 5m in width. When followed further downslope the channel gradually loses its form, terminating at approximately 530 m.o.d..

Channels Z3, Z4 and Z5 (Fig. 4.17) originate on the floor of the glacial breach known locally as Big Windgate Hass at an altitude of 570 m.o.d., and lead down from here in a north-west direction. Z5, the lowest channel in the system, terminates at approximately 470 m.o.d..

(b) Channels along the South and South-Western Boundary. The densest concentration of meltwater channels is found incised across the spurs which form the upland edge along the south and south-west boundaries of Area II. More than 120 channel forms, the majority of which slope down in a south-east direction, are found in a narrow band 7km in length and 2km in width (Figs. 4.15, 4.18). In places the channel forms are incised in close association with landforms of fluvioglacial deposition (Plate 4I).

On the most westerly of the spurs examined in detail, (Spur N Fig. 4.18), the highest channel N1, is found across the crest and south-east side of the spur, having its in-take at 600 m.o.d. and its outlet at 549 m.o.d.. This channel is

incised/...

incised 11m into bedrock and has a floor 8 - 11m in width where best-developed, but its dimensions gradually diminish when followed down the south-east flank of the spur. On the steeper south-west end of the spur, channel forms are generally not as clearly defined (Fig. 4.18). However, channel N3 is an exception. It is a large chute with a semi-circular plunge-pool in-take, that is incised 14 - 16m into the spur end. The chute is a fairly short feature however, and runs downslope for only 40 - 50m. Channels N5, N6, N7 (Fig. 4.18) all have up-down profiles, with short, poorly-developed, uphill sections in the westerly direction, and comparatively long, deeply-incised courses to the south-east. Below 366 m.o.d., the lowest channel forms of system N are mainly concentrated in the floor and along the lower slopes of the glacial breach which separates Garroch Fell from Auchenleck Hill. The majority of these channels are small, generally incised 5 - 8m into bedrock with narrow floors 2 - 3m in width, but form complex interlinking systems, particularly on the north-west side of the breach, (Fig. 4.18). It is worthy of note that above an altitude of 366 m.o.d., which is approximately the altitude of the floor of the breach, meltwater channels in this vicinity are wholly directed in a south-east direction. However, at approximately 366 m.o.d. there was a fundamental change in fluvioglacial conditions. Although channels on the south-east side of the breach (e.g. N8, N9, Fig. 4.18) indicate a continuation of meltwater flow in a south-east direction, channel forms on the north-west side of the breach indicate meltwater flor in a north-west direction/...

direction (Fig. 4.18). Channel N11, (Fig. 4.18), is in fact a large up-down channel, best-developed on the floor of the breach, which was perhaps utilised by meltwater which flowed first south-east, but then at a later stage in deglaciation reversed its direction to follow a north-west course.

The highest channel on the spur on which system O is developed, O1 (Fig. 4.18), begins at 535 m.o.d. and is again incised partly across the crest but principally down the south-east side, terminating at approximately 495 m.o.d. The channel is heavily infilled with peat but incised into bedrock to an apparent depth of 9 - 10m, the flat channel floor varying between 15 - 25m in width. Channel O2 (Fig. 4.18), is similarly best-developed on the south-east flank of the spur, but preference for such a location is more strongly indicated by channels O3 - O10 (Fig. 4.18). These mainly small channels are all developed solely on the south-east flank of the spur between 450 - 430 m.o.d. Below this altitude, the channel forms are mainly found across the spur end, parallel or at a low angle to the local contour pattern, in a south-east direction (Fig. 4.18). The bench O21 (Fig. 4.18), is typical of these forms, although slightly more continuous than is generally the case. It is incised 8 - 9m into bedrock and runs across the spur end for 600m varying in width between 15 - 30m, but varying little in altitude about 396 m.o.d. The alignment and altitude of O21 suggests that it may mark the/...

the continuation of the meltwater course which incised channel N5. To the south-east of the bench outlet a series of small chute forms, 020 022 (Fig. 4.18), follow short courses directly downslope. At 320 m.o.d., the chute forms are in turn replaced by south-east trending channels which again mainly parallel the contour pattern, although occasionally they swing downslope at their outlets. Channel 028 (Fig. 4.18) is the largest of these lower forms, incised 12 - 15m into bedrock with a floor 15 - 25m in width. The in-take of the channel is marked by a well-developed plunge-pool.

Channel system P is incised across the spur which lies on the eastern side of the Kenriva Burn (Fig. 4.18), and is similar in many respects to system O. There is however, evidence of fluvioglacial deposition in association with system P. The highest channel of system P, P1 (Fig. 4.18), is a well-developed up-down form incised across the crest of the spur at approximately 480 m.o.d. The western, uphill section to the channel is approximately 80m in length, but the downhill eastern part of the course is two to three times this length, and more deeply-incised. A ridge of sand and gravel begins 100m beyond the outlet of channel P1, at approximately 473 m.o.d. Channel P2 (Fig. 4.18), is similar in dimension to P1, but developed solely on the eastern side of the spur crest with no uphill section in its course. Again there is evidence of fluvioglacial deposition in the vicinity of the channel outlet, just below 427 m.o.d. (Fig. 4.18).

Fluvioglacial depositional activity is also evident at the outlet of channel P6 (Fig. 4.18), at approximately 396 m.o.d.

Downslope from P6 on the spur end, there are several well-developed channel forms which trend parallel to the contour pattern in a south-east direction for a short distance and then plunge downslope in the form of subglacial chutes (Fig. 4.18). Channel P10 exhibits this well, its course parallel to the contour pattern disrupted by sections which plunge directly downslope. By contrast, channel P12 (Fig. 4.18) follows the contour pattern round the spur end continually for a distance of 1.2km, varying between channel and bench form throughout its length (Plate 4J, 4K).P12 begins at approx. 335 m.o.d. as a southward trending bench, 14m in width. The bench is replaced by a well-developed channel form, incised 12m into bedrock with scree-covered slopes, 150m along its course. The channel swings south-eastwards for a distance of 300m, but in turn is replaced by another larger bench 40m in width, for the next 300m. Channel form is once again regained at a marked step in the floor, 18m in height, which leads down to a large and well-developed plunge-pool. A certain amount of meltwater left this plunge-pool in a southerly direction via channel P16, but most of the meltwater flow continued south-eastwards to descend a second step, 8m in height, to a second plunge-pool a further 100m along the channel length. Meltwater leaving the second plunge-pool also continued in a south-east direction, running across the regional slope to gradually/...

gradually fade away at approximately 290 m.o.d. Once again there is evidence of fluvioglacial deposition, in this case as a terrace form, at the channel outlet. It is interesting to note that to the east of the outlet of channel P12 there are a series of small, deeply-incised chute forms (P17 - P19, Fig. 4.18), most of which have plunge-pool in-takes, that trend directly downslope to also terminate at 290 m.o.d., at the depositional terrace form (Plate 4L,4M). Channel P21 (Fig. 4.18), also has a depositional terrace form at its outlet, but at the slightly higher altitude of 310 m.o.d.

Channel system Q is the most easterly of the systems which are incised across the upland edge of the Lowther Hills within this southern part of Area II (Fig. 4.18). The highest channel in the system, Q1, is found at approximately 470 m.o.d. in the floor of the glacial breach which separates Queensberry Hill from Wee Queensberry. The channel is aligned in a south-east direction and incised to a depth of 13m into bedrock, with a flat, peat-filled floor 8 - 10m in width. As indicated on figure 4.18, most of the channels below the highest form parallel its south-east alignment, although they tend to be concentrated across the crests and down the lee sides of the two spurs which flank the Bran Burn.

Two of the lowest forms, Q13 and Q14 (Fig. 4.18), are developed around either side of the conical hill, "The Law", both channels leading into the Bran Burn Valley. Q13, the slightly higher of the two, has its in-take at 290 m.o.d. and leads south-east from the Capel Burn Valley. The channel floor is 20 - 30m in width but heavily peat-infilled. Channel Q14, with/...

with its slightly lower intake at 282 m.o.d., also carried meltwater south-east from the Capel Burn Valley. It is believed that both channels formed in close association with the extensive terrace developments at the mouth of the Capel Burn Valley.

(c) Channels along the Eastern Boundary. All of the channels along the eastern boundary of Area II were incised by meltwater following a broadly eastward course (Fig. 4.15). Evidence of fluvioglacial erosion is found between 390 - 549 m.o.d., although the channels vary in their exact location, and are present on both the floors and flanks of glacial breaches, as well as across ridge and hill crests. The nature of the meltwater activity is well-illustrated by channel system U (Fig. 4.19).
The highest channels in system U (U1 and U2) are found at approximately 480 m.o.d., incised in a north-east direction across the ridge crest linking Beld Knowe to Mount Joe.
At slightly lower altitudes, between 411 - 457 m.o.d., channel forms U3 - U6 (Fig. 4.19), are incised across the western flank of Beld Knowe in an east-south-east direction, towards the glacial breach at the head of the Shiel Burn. These lower forms are only incised 3 - 4m into bedrock, with wide peat-filled floors 15 - 25m in width. Channel U7, developed across the crest of Earlside (Fig. 4.19), is a more obvious feature and is incised 6 - 7m into bedrock, with a flat floor 20 - 30m in width. U7 is aligned in an easterly direction towards the glacial breach which separates Mosshope Fell from Gill Knowe. The floor of this breach has been deeply-incised/...

incised by meltwater activity (Channel U8, Fig. 4.19), the degree of incision increasing eastwards. Where best-developed the channel is incised over 30m into bedrock with a wide, flat floor exceeding 60m in width. Although there is no direct evidence of feeder channels leading into U8, there are indications of fluvioglacial erosion across the spur flanking the glacial breach on its southern side, between 430 - 480 m.o.d. (Channels T1 - T8, Fig. 4.19). These channel forms are mainly small, the largest and lowest, T8 at 432 m.o.d., incised 7m into bedrock with a floor 12 - 15m in width. All of the channels in system T indicate an eastward movement of meltwater and it is suggested that lateral migration of englacial streams in the manner described by Clapperton (1968), resulted in the concentration of fluvioglacial erosion in the floor of the glacial breach. Regardless of the main source of meltwater however, there can be little doubt that the large and well-developed channel U8 was a major routeway for eastward flowing meltwater across the watershed.

(d) Channels in the Central Part of Area II. The meltwater channels of this area do not differ dramatically in their dimensions or altitude from forms described in other parts of Area II. However, with regard to the size of the area examined, channels are comparatively fewer in number, and whereas individual channel forms and channel systems in each of the peripheral zones generally possessed a common alignment/...

alignment, this is not the case in the central part of Area II (Fig. 4.15). A fundamental distinction can be made within this central area however, between the channel forms above and below 396 m.o.d. Of the channel forms above 396 m.o.d., it is intended to examine systems F, K and R (Fig. 4.15), in detail.

Channel system F is found in the vicinity of Wether Hill, a spur leading down from Lowther Hill, and consists of only three channel forms (Fig. 4.20). The highest of these channels, F1 at 560 m.o.d., is incised into the flank of the glacial breach at the head of Dinabid Linn. The channel is 8 - 9m in depth, with a narrow floor 2 - 3m in width; the floor sloping down in a south-west direction. Channel F2, with its in-take at approximately 550 m.o.d., is a larger form, found across the crest and down the western flank of the spur, terminating at 503 m.o.d. The channel is best-developed across the crest of the spur, where it is incised more than 11m into bedrock and has a flat floor 20 - 25m in width. Once again, the channel is aligned in a south-west direction. Channel F3, (Fig. 4.20), the lowest of the group, is also the most spectacular. As before, this form is incised across the crest and down the western flank of the spur, having its in-take at 515 m.o.d. and outlet at 457 m.o.d. The channel has a wide, open in-take but narrows westwards across the spur, such that although incised 20 - 25m into bedrock, the floor is only 4 - 5m in width near/...

near the western outlet. Movement of meltwater in a south-west direction from a north-east source is again indicated. Channel systems G, H and J flanking the Carron Valley (Fig. 4.15), to the south and east of system F, also indicate a south-west movement of meltwater.

Channel system K consists of two well-developed channels incised into the upland ridge linking Ballencleuch Law with Durisdeer Hill (Fig. 4.21). K1, at 608 m.o.d., is the higher of the two channels and is incised 7m into bedrock, with a flat peat-filled floor 7 - 8m in width. The channel floor is humped in profile, but the dominant slope is undoubtedly in a south-east direction. Channel K2 is found at an altitude of 545 m.o.d. and is larger than K1; it is incised 10 - 12m into bedrock with a flat floor 20m in width. The channel again possesses a slightly up-down profile across the spur crest, but formation by meltwater following a south-west course is strongly indicated. Therefore, although both incised across an upland ridge within 2km horizontally and 50m vertically of each other, the two well-developed channel forms K1 and K2 trend in strongly divergent directions.

To the south-east of system K, the channels of system R (Fig. 4.22), indicate 3 fundamentally different directions of meltwater flow. The highest forms incised across Earncraig Hill and at the head of the Daer Water (R1, R2, R3, Fig. 4.22), indicate a southerly movement of meltwater across the watershed.

The/...

The slightly lower channels incised across the crest of the spur at approximately 480 m.o.d. (R4, R5, Fig. 4.22), in contrast indicate an easterly flow of meltwater. In turn, the lowest form (R6, Fig. 4.22), which falls into the second category of channels found in this central area as it is developed entirely below 396 m.o.d., was incised by meltwater following a northerly course. Beyond the outlet of channel R6 there is also evidence of fluvioglacial deposition.

As with channel R6 (Fig. 4.22), all of the channels in system X (Fig. 4.23), are developed entirely below 396 m.o.d. Channel system X consists of three forms incised across the crest and western flank of the spur which leads northwards from Coom Rig (Fig. 4.23). X1, at 370 m.o.d., is incised solely across the crest of the spur to a depth of 7m. The floor of the channel is 4 - 5m in width and slopes down in a west-north-west direction. Channel X2 is the best-developed of the three forms. The in-take of the channel, on the eastern flank of the spur, is at approximately 362 m.o.d. and the channel follows a sinuous course from here across the crest and down the western flank, to terminate at 340 m.o.d. The channel is incised to a depth of 9 - 10m throughout its length, but floor width decreases westwards from 16m to 9m. X2 was incised by meltwater following a west-north-west course. Channel X3 (Fig. 4.23), is a short form which starts and stops abruptly. As with channel R6, it is interesting to note that there is evidence of fluvioglacial deposition along the lower western flank of the spur on which/...

which channel system X is incised, approximately 30m below the altitude of the outlets of channels X2 and X3 (Fig. 4.23).

It is difficult to summarise the affects of fluvioglacial erosion over the central part of Area II. However, above 396 m.o.d. there appears to be an almost radial channel pattern leading out from the higher parts of the area, with widely-spaced channels aligned in south-westerly, southerly, south-easterly and easterly directions (Fig. 4.15). The few channel systems which occur below 396 m.o.d. have no obvious pattern to their distribution, their only common characteristic being that they tend to be found in close association with fluvioglacial deposits.

By bringing together the information obtained from the four local areas, it is possible to speculate upon the main sources of meltwater, and fluvioglacial conditions generally at the time of channel formation for different parts of Area II.

GLACIAL CONDITIONS LEADING TO THE ESTABLISHMENT OF THE MELTWATER CHANNEL PATTERN IN AREA II. In attempting to explain the uneven distribution and highly varied alignment of meltwater channels in Area II, it is important to consider the factors that influence meltwater flow. As previously mentioned, it is generally agreed from observations in many parts of Britain and Scandinavia, that the alignment of meltwater channels across an area gives a general indication of surface slope of the ice mass and therefore closely corresponds to the former directions of ice movement as depicted by striations, roches moutonnees and transport of erratics, (J Gjessing 1960; Sollid 1963/64; Sissons 1967a; Sugden 1970; Clapperton 1970, 1971a, 1971b; Price/...

Price 1973; Sugden and John 1976). Over Area II, it was suggested in previous sections that ice built up locally over the higher ground and moved radially outwards from here to cover much of the area. However, along the west and south-west boundary of Area II, local ice merged with external ice descending the Nith Valley in a south-east direction. Consequently, with the onset of deglaciation, meltwater channel network became established in association with two highly individual, but confluent ice masses, each with differing ice gradients, on both the local and regional scale. For this reason, meltwater channel formation in association with Nithsdale ice will be examined separately from that in association with Lowther ice.

(a) Fluvioglacial Erosion in Association with Nithsdale Ice

The channels which fall into this category are developed along the north-west, south and south-west margins of Area II, in the Lowther foothills flanking the Nith Valley, and are represented by systems A, B, C, E, I, L, M, N, O, P, Q, (Fig. 4.15). A ready-made subdivision within the Nithsdale group separates those channels which are aligned in a northerly direction, across the upland edge, from those forms aligned in a south-east direction, parallel to the upland edge.

The channels which indicate a northerly movement of meltwater are restricted to the north-west corner of Area II and depicted by systems A, B and C (Figs. 4.15, 4.16). In all three cases, the channels are located at low points on broadly east-west orientated spurs, at altitudes ranging between 366/...

366 - 450m.o.d.

The tendency for the channels of this group to be most marked on convexities in the underlying topography reflects, ".... the primary control of active ice movement in their formation" (Sugden and John, 1976, P.303), and by definition such channels are ice-directed. Evidence relating to the direction of ice movement in this vicinity, in the form of striations, alignment of cols etc, is indecisive and indicates either a south-west or north-east passage of ice (Fig. 4.5). The channel alignments suggest an ice surface sloping down in a northerly direction from a southerly centre in the general vicinity of the Nith Valley. The overspillage of Nithsdale ice across the upland edge and into the Lowther foothills is therefore strongly indicated.

Although it can be stated that the ice surface gradient sloped down in a northerly direction and that meltwater paralleling this direction incised a channel pattern on transversely aligned bedrock convexities, the exact mode of channel formation can only be speculated upon. Once again, it is not possible to state conclusively whether these ice-directed channels were incised by the superimposition of supraglacial and/or englacial streams, or by subglacial meltwater flow beneath active ice. The tendency for development on the lee side of spur crests perhaps lends greater support to the latter postulation (Shreve 1972). However, regardless of the exact mode of formation, there is no evidence of ice-directed meltwater drainage in the north-west part of Area II below/...

below 366 m.o.d. This suggests that at approximately this altitude, the regional northerly movement of meltwater across the upland edge was replaced by drainage down local valley systems.

Away from the north-west corner of Area II, it is more typical for the channel systems produced in association with Nithsdale ice to follow a south-east course. This alignment is well-illustrated by systems E, I, L, M, N, O, P, Q (Fig. 4.15, 4.18). The channels of this group range in altitude between 305 - 600 m.o.d. and as before there is a strong development of ice-directed forms across bedrock convexities, although in this area ice movement has paralleled the upland edge.

Channel systems E and I (Fig. 4.15), are incised across the crests of spurs along the western boundary of Area II,but the greatest density of channels possessing the south-easterly alignment is found along the south-west boundary. The highest channel forms of systems N, O, P, Q (Fig. 4.18), generally above 427 m.o.d., are incised across the crests and lee slopes of spurs that slope southwards to the upland edge. The altitude of the highest channel on each spur also decreases in the south-easterly direction. At lower altitudes across the spur ends between 330 - 427 m.o.d., channels still tend to follow south-east courses but at a relatively shallow angle to the local contour pattern (Fig. 4.18). Below 330 m.o.d., although there are a few channels which still run across the spur end, paralleling the contour pattern, the majority tend to run more directly downslope (Fig. 4.18). The channels below 427 m.o.d./...

427 m.o.d. are collectively, representative of forms which were produced in marginal and sub-marginal environments.
The highest and ice-directed group of channels (above 427 m.o.d.), tend again to be represented by individual forms. Occasionally these channels are incised completely across the spur crest, e.g. P1 (Fig. 4.18), with its well-developed up-down profile, but more commonly begin on the crest and run down the eastern, lee side of the spur, e.g. N1, O1, O2, P2, P4 (Fig. 4.18). Other forms are developed solely on the lee side of the spur crest, e.g. O3 - O11 (Fig. 4.18). Once again, it is impossible to state conclusively whether such forms were incised by wholly subglacial meltwater flow or by superimposition. However, the presence of plunge-pool in-takes for some of the channels, e.g. N3, Q6 (Fig. 4.18), indicates that these forms at least were not produced by meltwater following a wholly subglacial course. Nevertheless, it is not possible to state on the basis of these two channel forms alone, that all the channels above 427 m.o.d. were incised by the superimposition of englacial and/or supraglacial streams.
The channel forms developed across the spur ends between 330 - 427 m.o.d. are also ice-directed, in that they follow a generally south-east course parallel to the former direction of ice movement. However, by the fact that they also tend to parallel the local contour pattern, it is suggested that they relate to formation near a glacier margin, in this case the margin of the Nithsdale ice mass. As in Moffatdale, where similar/....

similar dense channel patterns are found, it cannot be stated conclusively that a particular form was incised in a truly marginal or sub-marginal environment. It was previously suggested, as a result of work by Sissons (1961 a), that channels with gradients less than 1 : 50 may be marginal. On this basis, the more continuous bench form O21, the bench-channel form P12 and others such as Q9 and Q12 (Fig. 4.18), were perhaps incised at the ice margin itself. However, the more common solitary forms, which run downslope at an oblique angle to the contour pattern, and anastomosing patterns, with channel segments running at relatively gentle gradients along the spur end separated by segments running more directly downslope, are more likely representative of combined marginal and sub-marginal meltwater flow, or formation entirely beneath the ice margin. Both two-sided channel and one-sided bench forms are present, with perhaps a slight preference for bench development along the south-west spur margins (Fig. 4.18). The concentrated but discontinuous channel pattern which is developed across successive spur ends along the south-west margin of Area II, was incised in a similar fashion to the pattern in Moffatdale. A dense network of englacial and supraglacial streams occupying lateral positions in the Nithsdale ice mass and following generally south-east courses, impinged upon the spurs for short periods during downwastage. The depth of incision is once again believed to have been controlled by an englacial water-table./...

table.

The concentration of channels which trend directly downslope in the form of subglacial chutes below 330 m.o.d., (e.g. channels 026 - 030, P.17 - P.21, Q15, Fig. 4.18), and the fact that many of these channels possess plunge-pool intakes, suggests that there was a fundamental change in the control of fluvioglacial conditions within the Nithsdale ice mass at this altitude. It is suggested that the zone of meltwater penetration which controlled the superimposition of englacial and supraglacial streams collapsed at approximately 330 m.o.d. As a result, meltwater plunged directly downslope to incise the chute forms. The high frequency of plunge-pool in-takes clearly indicates that superimposition of meltwater streams was taking place and that the marginal channel pattern along the south-west boundary of Area II was not incised by wholly subglacial flow beneath active ice. It would appear however, that the collapse of the zone of meltwater penetration was not total, as there is evidence in the form of extensive fluvioglacial terrace remnants at concordant altitudes of 290 m.o.d. at the mouth of the Capel Burn, to suggest its re-establishment. The termination of many of the chute forms, (e.g. P17, P18, P19, P21, Fig. 4.18), and indeed marginal forms (e.g. P12, Fig. 4.18), at the altitude of these terrace remnants, reinforces this belief.

The reason for the initial collapse of the englacial water-table/...

table is not readily apparent. However, it is interesting to note that in the vicinity of Backhill Moss, on the north-west side of the glacial breach which separates Garroch Fell from Auchenleck Hill (Fig. 4.18), the direction of meltwater flow was reversed at approximately 360 m.o.d., the altitude of the floor of the breach. As a result, meltwater which formerly followed a south-east course through the glacial breach towards channel systems O, P and Q, changed direction to flow down the north-west side of the breach (channels N10, N11, N12, N13, Fig. 4.18). It is possible that the reduction in the supply of meltwater from a north-west direction, as a result of the zone of meltwater penetration falling below the altitude of the breach, was responsible for the collapse of the englacial water-table controlling marginal drainage along the upland edge, further to the south-east.

All of the channels which trend in a south-easterly direction along the south-west margin of Area II have been up to now attributed to the erosive action of meltwater streams associated with Nithsdale ice only. However, as it is believed that the Nithsdale and Lowther ice masses merged over the foothills in this vicinity, it is possible that the alignment of channel forms relates not solely to formation in association with one particular ice mass, but to the dominant direction of ice movement across this area (Fig. 4.24). It was earlier stated that at the glacial maximum, the south-east course followed by Nithsdale ice was dominant in this vicinity.

Consequently/...

Consequently, Lowther ice breaching the southern part of the watershed in a generally southward direction swung round to a south-east course on merging with the more powerful Nithsdale ice mass. As a result, although the higher ice-directed channel forms which follow a south-easterly course were attributed to formation in association with Nithsdale ice, it might be more accurate to state that they formed in association with an ice mass paralleling the course of Nithsdale ice. That is to say, that the higher meltwater channels, N1, O1, O2, P1 (Fig. 4.18), were perhaps incised by meltwater streams originating on Lowther ice (Fig. 4.24).

With the onset of deglaciation, downwastage and marginal recession would eventually result in the partition of the two confluent ice masses. However, at early stages in the deglacial period, the principal direction of meltwater drainage along the western margin of the Lowther ice mass was south-west (systems F, G, H, J, K, Fig. 4.15, Fig. 4.24). Such a course must have channelled vast amounts of meltwater from the Lowther Hills onto, into and against ice occupying the Nith Valley (Fig. 4.25 A). In addition, with downwastage, the upper parts of the Glenbuith, Kenriva and Capel valleys would become ice free before the lower parts (Fig. 4.25 B). Extraglacial meltwater moving down these valleys therefore further supplemented existing marginal flow in the Nithsdale ice. The concentration/...

concentration of meltwater drainage along the north-east flank of the downwasting Nithsdale ice mass, in the manner described above, was obviously an important factor in the establishment of the dense channel networks across the spurs which delimit the south-west boundary of Area II.

There is depositional as well as erosional evidence to substantiate the claim of partition of the two ice masses and the ice-free nature of the southward trending valleys. At the mouth of the Capel valley, ground vacated by ice became flooded by a glacial lake which was ponded to the south by Nithsdale ice. Terrace forms were deposited in this lake by systems of meltwater channels from the Nithsdale ice, augmented by extraglacial meltwater flow down the Capel valley (Fig. 4.25 C). It seems likely that an englacial water-table controlled the level of deposition. The Capel Lake is examined in greater detail in the section devoted to fluvioglacial deposition.

(b) Fluvioglacial Erosion in Association with Lowther Ice

The channel systems attributable to formation in association with ice derived locally in the Lowther Hills, are found over the central and western part of Area II (systems D, F, G, H, J, K, R, W, X, Fig. 4.15), and along parts of the eastern and northern margins (systems S, T, U, V and Y, Z, respectively, Fig. 4.15). It is difficult to detect common trends within this complex pattern of channel systems, but as previously stated, a fundamental distinction can be made on/...

on the basis of altitude between forms occurring above and below 396 m.o.d.

The higher group of channels, above 396 m.o.d., is by far the more dominant and is represented by a series of widely spaced, generally individual forms, incised across bedrock convexities and into the floors and flanks of glacial breaches. Channel systems F, G, H and J (Fig. 4.15), are all aligned in a south-west direction and although incised completely across convexities in places, more commonly begin on the crest and run down the lee slope of spurs for a short distance (e.g. F2, F3, Fig. 4.20). Locally there is a tendency for channels to seek out the low points in ridge and spur crests.

Channel K2 (Fig. 4.21), also has a south-west alignment, and is again best-developed on the lee side of the ridge crest, but nearby K1 is aligned in a south-east direction. The highest channels of system R (R1, R2, R3 and R4, R5, Fig. 4.22), are aligned in southerly and easterly directions respectively.

Channel systems S, T, U, V (Fig. 4.15), are all incised across the watershed in a broadly eastward direction and again generally favour low points in the divide, mainly glacial breaches. The channels of system Z (Figs. 4.15, 4.17), are similarly located, but aligned in north and north-west directions.

All of the channels which comprise this higher group tend to be aligned parallel to the suggested directions for ice movement over this area (Figs. 4.9, 4.25). (Based upon previously/...

previously mentioned findings on the occurrence of striations, roches moutonnees, distribution of erratics etc.). When taken into consideration with the fact that the channels also tend to be most marked on convexities in the underlying topography and in glacial breaches, it seems likely that all of these higher forms are ice-directed in character and again "..... reflect the primary control of active ice movement in their formation" (Sugden and John, 1976, P.303). Consequently, the almost radial alignment of the higher channels in the Lowther Hills, strongly indicates that the surface gradient of the Lowther ice mass sloped down in all directions from a source in the vicinity of the Lowther Hill - Dungrain Law ridge (Fig. 4.15, 4.25).

As before, it is not possible to be conclusive on the exact mode of formation of the radial channel pattern. Formation by subglacial meltwater flow at the base of active ice cannot be overlooked as a possibility, but the discontinuous nature of the channel pattern, the ruggedness of the terrain and the proximity of the local ice centre, suggest that the majority of this higher group of meltwater channels were incised by the superimposition of supraglacial and/or englacial streams during downwastage. The direction of meltwater flow was determined by the ice gradient and the depth of incision by the zone of meltwater penetration. The comparative scarcity of channel forms found in association with the Lowther ice mass generally, but particularly near the local centre of ice dispersal, can be attributed to meltwater drainage utilising the pre-existing valley network, as in the central part of the Cheviot massif (Clapperton, 1970, P. 121).

The/...

The channel forms found below 396 m.o.d., (R6, X1, X2, X3, Z6, Z7, Z8, Z9, Figs. 4.15, 4.17, 4.22, 4.23), are similar to the higher group in that they too have no specific alignment, but fluvioglacial erosion of these forms occurred at a stage in downwastage when regional controls over meltwater drainage were superseded by local relief and meltwater considerations. At varying altitudes between 360 - 396 m.o.d. in different parts of the Lowther Hills, there was a fundamental change in the control of fluvioglacial conditions within the downwasting Lowther ice mass. Where locally the height of the englacial water-table controlling fluvioglacial erosion fell below the level of the watershed or other bedrock convexities, the pattern of meltwater flow was disrupted and re-directed downslope under the control of local relief conditions. In the case of channels X1, X2, X3 and R6 (Figs. 4.22, 4.23), this resulted in the re-direction of meltwater back towards the main source area, but with channels Z6 - Z9 (Fig. 4.17), collapse of the water-table merely forced water directly downslope and several of the channels have plunge-pool in-takes. Localised fluvioglacial deposition also occurred at this time, but much of this late-stage meltwater drainage probably left Area II in a northerly direction, along the pre-existing valley network.

The pattern of meltwater channels produced in association with the Lowther ice mass reinforces the belief that a local centre of ice dispersal was present over the higher parts of the Lowther Hills during the last major glaciation to affect the area.

(c) SUMMARY. There can be little doubt that the complex channel pattern in Area II (Fig. 4.15), was established in association with two highly individual ice masses which merged over the area. Channels along the west and soth-west margin were incised by meltwater flow controlled by Nithsdale ice, which spilled across the upland edge into the Lowther foothills (Fig. 4.25). Elsewhere in Area II however, the almost radial pattern of channel development suggests formation in association with a local centre of ice dispersal over the higher parts of the Lowther Hills themselves (Fig. 4.25). Deglaciation, subsequent downwastage, and marginal recession, resulted in the partition of the two ice masses. However, south-west flowing meltwater from the Lowther ice mass augmented the existing meltwater drainage along the north-east margin of the Nithsdale ice mass and contributed to the dense channel network found along the foothills which delimit the south-west margin of Area II.

4.7 FLUVIOGLACIAL DEPOSITION

Evidence of fluvioglacial deposition in Area II is restricted to small pockets of sand and gravel which occur in widely scattered localities (Fig. 4.26). There is no readily apparent pattern to the occurrence of the fluvioglacial deposits, but they do appear to be slightly more extensive along the south-west margin of the area, where the greatest density of meltwater channels is also to be found. A better understanding of the distribution pattern of the fluvioglacial deposits, their mode of formation and the nature of deglaciation generally, may be facilitated by a detailed examination of the morphology and character of the deposits at several of the localities indicated on figure 4.26.

Capel/...

<u>Capel Valley</u>. The Capel valley, in the southern part of Area II (Fig. 4.26), runs southwards from the watershed, with a gently inclined western flank leading down from Hard Hill - Haggie Hill, but steeply sloping eastern flank leading up to Queensberry Hill (Fig. 4.27). The fluvioglacial deposits, morphologically represented by a series of mound, ridge and terrace forms, are concentrated along the western flank of the valley and at the valley mouth, where it leaves the foothill zone (Fig. 4.27). As previously mentioned, fluvioglacial deposition in the Capel Valley was closely linked to fluvioglacial erosion, and the numerous meltwater channels which are incised across adjacent spurs.

The most northerly evidence of fluvioglacial deposition in the Capel valley takes the form of four discontinuous mounds which extend down the western flank between 435 - 360 m.o.d. (AA, Fig. 4.27). The mounds vary in length from 25 - 70m and in height from 4 - 11m. However, there is a general increase in both length and height as the mounds are followed downslope, the lowest being the best-developed of the four forms. The internal constituents of the mounds are not well-exposed, but appear to be a coarse gravel. There is no evidence of fluvioglacial erosion in the immediate vicinity of the mounds. Despite this last factor however, the four mounds are believed to represent the remains of an esker ridge which was implaced by englacial or supraglacial meltwater following an easterly course. Further south, the ridge form BB (Fig. 4.27), again emerges from the hillslope at approximately 435 m.o.d., but in this case runs continuously downslope for 250m in a north-north-east direction, before/...

before fading away at approximately 415 m.o.d. Where best-developed the ridge exceeds 12m in height, with a crest width of 9m. Again there are no good sections in the ridge, but small exposures indicate that it consists of sub-rounded and sub-angular clasts (1-4cm in diameter), in a sandy matrix and as such is also taken to represent an esker. The feeder channel for the fluvioglacial ridge is readily apparent and has its outlet 100m to the west of where the esker begins. This channel, P1 (Fig. 4.27), is incised to a depth of 17 - 18m across the crest of the spur and has a well-developed up-down long profile.

There is slight evidence of fluvioglacial deposition, in the form of two small terraces 3 - 4m in height at the outlets of channels P2 and P3, at approximately 427 m.o.d. (Fig. 4.27). However, continuing the movement south down the Capel valley, a more obvious indication of fluvioglacial deposition is the sinuous, discontinuous ridge CC (Fig. 4.27), which follows a south-east course across the valley side. The main part to this ridge, which begins at 402 m.o.d., consists of four segments. The two most northerly are mounds over 10m in height, but dimensions fade southwards, the last segment being only 4m in height and terminating at 335 m.o.d.

Small exposures reveal that this discontinuous ridge in turn also consists of sand and gravel and as such is again taken to represent an esker form. It is possible that the course of the esker may have originally continued further downslope and that the short ridge DD, (Fig. 4.27), at 320 m.o.d., represents the former continuation of this. Channels P2 and P3, again incised across the crest of the spur linking Hard Hill to Haggie Hill, but without the up-down long-profile/...

profile of P1, were the main feeders for esker CC (and DD). The depositional form EE, at approximately 375 m.o.d., is a large steep-sided terrace, the flat surface of which is 100 - 120m in width. The steep eastern face of the terrace is 20 - 22m in height and small exposures in this vicinity indicate that the feature consists of numerous sub-rounded and sub-angular pebbles, in a coarse, gravelly matrix. On the basis of its morphology and constituents, EE is taken to represent a kame terrace. Three small mound forms, all less than 4m in height and 40m in length, are found on the southern flank of the terrace. All three mounds are aligned downslope in a south-south-east direction and also believed to consist of sand and gravel, although no exposures are visible. The main feeder for the kame terrace, and probably also the adjacent mound forms was channel P6 (Fig. 4.27). Flanking the Capel Burn itself, at approximately 305 m.o.d., there is another well-developed terrace form (FF, Fig. 4.27), the steep eastern face of which is 16 - 18m in height. This terrace was at least partly deposited by meltwater following the oourse of channel P21 (Fig. 4.27), which blends into the surface of the terrace itself. However, the largest and most spectacular terrace forms are found flanking the mouth of the Capel Valley where it leaves the foothill zone (Plate 4L & 4M).

The terrace GG (Fig. 4.27), is found along the western flank of the foothills at an altitude of approximately 290 m.o.d. The flat-surface to the feature, which extends out from the hillslope, is over 70m in width, while the steep south-east face is 30 - 35m in height. Exposures revealed by the incision of small streams into the/...

the steep face of the terrace, indicate that it consists of numerous sub-rounded and sub-angular pebbles, mainly the former, in a loose, gravelly matrix. A wide variety of clast sizes, from 1 - 30cm in diameter, are found jumbled together with no indication of stratification. An isolated mound of sand and gravel protrudes 3 - 4m above the otherwise flat surface of the terrace. Numerous channel forms both marginal/sub-marginal and subglacial chutes terminate at the altitude of the terrace (Fig. 4.27).

On the eastern side of the mouth of the Capel Valley, a similar extensive terrace form, HH (Fig. 4.27), also at 290 m.o.d., is apparent. This terrace generally rises 40m above the Capel Burn itself, but the southern part has been incised by fluvial activity and lies at the slightly lower altitude of 275 m.o.d. The constituents of this eastern terrace are similar to those of terrace GG and it would appear that the two terraces may formerly have merged, to form a continuous spread of sand and gravel across the mouth of the Capel Valley. There are no indications of feeder channels leading to the terrace HH.

In attempting to explain the landforms of the upper Capel Valley, Charlesworth (1926 b, P.17) termed the ridge forms (AA, BB, CC, DD, Fig. 4.27), "lateral moraines", but their internal constituents and close association with adjacent meltwater channels, leave little doubt that the features described above are indeed fluvioglacial in origin and are therefore eskers. Consequently, a more accurate explanation of the mode of formation of the depositional landforms in the Capel Valley must pay due consideration to the mode of formation/...

formation of the adjacent, and closely interlinked, landforms of fluvioglacial erosion.

It is stated in the previous section that the channel pattern across spur crests and spur ends along the south-west margin of Area II was incised by englacial and supraglacial streams, occupying lateral positions in the Nithsdale ice mass, as they impinged upon the sub-ice surface during downwastage. The superimposition of these streams, all following a broad south-easterly course, was controlled by a zone of meltwater penetration or englacial water-table. Across the Hard Hill - Haggie Hill spur, on the western flank of the Capel Valley, such streams first became incised between 457 - 480 m.o.d. (P1, P2, P3, P4,Fig 4.27). Continuing on a south-east course, the streams became englacial over the Capel Valley itself, but were again superimposed onto the Queensberry-Wee Queensberry spur at the slightly lower altitude of 450 - 457, (Q1, Q6, Fig. 4.27; Stage 1, Fig. 4.28). However, it would appear that when locally the water-table fell below the level of the major channels Q1 and Q6, approximately 450 m.o.d., the Queensberry - Wee Queensberry spur in effect acted as a temporary barrier to meltwater drainage. Meltwater crossing the Hard Hill - Haggie Hill spur was unable to follow a through route across the Capel Valley and out of Area II, and consequently, meltwater velocity declined on the eastern side of the spur and deposition of eskers AA, BB, CC (Fig. 4.27), occurred. The fact that all three ridges begin at approximately the same altitude, 435 m.o.d., suggests that the englacial water-table became stabilised at this altitude for a period and that the englacial channel responsible for esker AA and channels P1, P2, P3 and P4

(Fig. 4.27)/.....

(Fig. 4.27), all carried meltwater at this time. It is impossible to state conclusively whether the eskers were deposited in an englacial or subglacial environment. However, the fact that esker CC follows a very sinuous course, finally terminating at some altitude between 320 - 335 m.o.d., suggests that the englacial theory of formation and subsequent lowering onto the sub-ice surface with continued downwastage is more likely, at least in this case, (Stage 2, Fig. 4.28). Continued lowering of the water-table resulted in the meltwater drainage over the Capel Valley adjusting to a more southerly course; channels Q7 and Q8 (Fig. 4.27), were incised over a lower part of the Queensberry - Wee Queensberry spur and the through-flow of meltwater was re-established.

The alignment of the Capel Valley, transverse to the direction of regional ice movement and surrounded by ridges exceeding 457 m.o.d. in altitude on all but its southern side, suggests that it would become cut off from its source of supply early during downwastage of an ice sheet, and that ice in the valley would stagnate in situ, further facilitating fluvioglacial deposition, (Stage 3, Fig. 4.28). The ice mass occupying the Upper Capel Valley certainly appears to have wasted away more rapidly than the main Nithsdale ice mass which lay over the foothill zone at the valley mouth. As a result, ponding of meltwater from Nithsdale ice, augmented by extraglacial meltwater moving down the Capel Valley itself, took place against the main Nithsdale ice mass at the mouth of the valley. Initially such ponding occurred at approximately 305 m.o.d. and a small lake extended up the Capel Valley (Stage 4, Fig. 4.28). This lake drained either subglacially or extraglacially via channel Q13 (Fig. 4.27), into the/...

the valley of the Bran Burn, and left the delta-kame terrace (FF, Fig. 4.27), perched on the western valley side. A second lower but larger ice-dammed lake appeared at the mouth of the Capel valley at approximately 290 m.o.d.. Along the western margin, this lower lake appears to have extended, at least initially, into the Nithsdale ice mass itself, where extensive deposition by a series of subglacial chutes and marginal channels was carried out. This source of meltwater was also probably supplemented by extraglacial flow coming down the Capel valley, (Stage 5, Fig. 4.28). The lower lake also appears to have drained or at least overflowed in a south-east direction, in this case via channel Q14 (Fig. 4.27). The subsequent drainage of the temporary lake and incision of the deposits which accumulated there by postglacial fluvial activity, has left delta-kame terraces GG and HH (Fig. 4.27), perched on either side of the mouth of the Capel valley. Charlesworth (1926b) also supported the establishment of an ice-damned lake at the mouth of the Capel valley, but believed that the main source of meltwater was supplied by an actively retreating glacier at the head of the valley. "The water issuing from this glacier was apparently impounded to form a lake south-west of "The Law", by a glacier standing in the valley of the Garroch Water (Nithsdale Ice)" (P.17).

<u>Backhill Moss.</u> This area also lies in the foothill zone along the south-west margin of Area II and as the name suggests is heavily infilled with peat (Fig. 4.26). The fluvioglacial deposits are again identified primarily by their distinctive morphology, protruding through the peaty floor as a series of mounds and ridges, although small exposures revealing/...

revealing sand and gravel also testify to their character. Two main groups of mounds can be identified, a northern group at the head of the Kettleton Burn and a southern group in the vicinity of the Cample Water (Fig. 4.29).

The northern group of mounds (Fig. 4.29), vary in their dimensions from 2 - 7m in height and 30 - 50m in length. Small exposures in the flanks of several of the forms reveal numerous sub-angular and sub-rounded clasts in a coarse, gravelly matrix. However, despite the fact that there are 15 mounds in this group, there is no obvious preferential alignment to the mound crests, and a haphazard distribution is indicated.

The southern group consists of two mounds and a short ridge form, separated from each other by the Cample Water (Fig. 4.29). The two mounds on the western side of the Cample Water are aligned in a north-west to south-east direction and are both 5 - 7m in height and 50 - 60m in length. The more continuous ridge on the eastern side of the stream, although originally following a similar alignment, swings more directly southwards and bifurcates near the end of its course. The ridge is approximately 250m in length and varies from 8 - 10m in height. Small exposures in all three forms reveal numerous sub-angular and sub-rounded clasts, generally less than 2cm in diameter, in a loose, reddish-brown sandy matrix. It is believed that the three mound/ridge forms were formerly continuous and together represent an esker ridge, the ridge supplied by meltwater from a north-west or south-east direction.

The foothill zone in the vicinity of Backhill moss was crossed by south-east trending Nithsdale ice during the last major glaciation (Fig. 4.9)/...

(Fig. 4.9). With the onset of deglaciation, meltwater drainage followed a similar south-east course at higher altitudes, as indicated by channels L1, L2, M1, M2, (Fig. 4.29). However, as previously stated, with continued downwastage and descent of the zone of meltwater penetration below an altitude of approximately 360 m.o.d., the height of the floor of the breach on the south-east side of Backhill Moss which separates Garroch Fell from Auchenleck Hill, the direction of meltwater drainage was reversed (Figs. 4.18, 4.29). Meltwater which formerly flowed south-eastwards across this area reversed its course to flow north-west down into Backhill Moss, as indicated by channels N11, N12, N13, (Figs. 4.18, 4.29). It was at this later stage that the north-west to south-east trending esker ridge flanking the Cample Water was deposited.

On the north-west side of Backhill Moss there is another glacially-breached col again at an altitude of approximately 360 m.o.d., in this case separating Glenleith Fell from Rottencraig Head (Fig. 4.29). There is no evidence of fluvioglacial erosion on the slopes leading down from this latter breach. The presence of these two glacial breaches, and the associated uplands, which together encircle Backhill Moss, strongly suggests that with continued downwastage, this depression aligned transversely to the direction of regional ice movement would be occupied by a mass of stagnating ice, which wasted away in situ. Such a situation is ideal for the concentration of meltwater and formation of fluvioglacial landforms, (Sugden, 1970). All of the landforms of fluvioglacial deposition and some of the landforms of fluvioglacial erosion in the vicinity of Backhill Moss, were produced in association with this stagnant ice mass, meltwater finally/...

finally escaping the area south-westwards via the Kettleton and Cample Valleys.

In the central upland area of the Lowther Hills, conditions during deglaciation were basically similar to those in the peripheral area, as exemplified by the landforms and deposits in the vicinity of the Daer Reservoir and Nether Fingland (Fig. 4.26).

Daer Reservoir. In the vicinity of the Daer Reservoir (Fig. 4.30), fluvioglacial deposits, again identified by their distinctive morphology, are found at the mouths of the Carsehope Burn and Kirkhope Cleuch. Charlesworth (1926b, P.15), interpreted the mounds as moraines, to be more specific, the "Nether Fingland Series" of moraines, formed during the retreat of the "Upper Clydesdale Glacier". However, exposures in the flanks of the mounds reveal coarsely bedded sands and gravels, which, when taken into consideration with their often close relationship with adjacent meltwater channels, makes a fluvioglacial origin more likely.

At the mouth of the Carsehope Burn, a well-developed ridge of sand and gravel, 5 - 7m in height, follows a north-south course parallel to the main Daer Valley for 350m (Fig. 4.30). The ridge, found at approximately 366 m.o.d., is steepest on its eastern flank where it was incised by meltwater action paralleling its course. Beyond the northern limit of the ridge and close to the mouth of the meltwater channel there are a series of mound forms, some almost conical in shape, resting against the regional slope. These mounds, found between 350 - 366 m.o.d., are generally steep-sided and vary between 6 - 9m in height. There is no obvious pattern to the occurrence/...

occurrence of the mounds.

At the mouth of the Kirkhope Cleuch (Fig. 4.30), the evidence of fluvioglacial deposition is even less spectacular. Two mound forms, again aligned in a north-south direction, are found along the shore of the reservoir at approximately 330 m.o.d. The mounds are 6 - 8m in height and 40 - 50m in length. Exposures, revealed by wave action, indicate numerous sub-rounded and sub-angular pebbles mainly 1 - 4cm in diameter, in a coarse sandy-fine gravelly matrix. Larger more angular blocks, 30 - 50cm in diameter, are also present along the lower flanks of the mounds. It is believed that the two mounds were originally continuous and formed a small esker ridge. There is no evidence of fluvioglacial erosion in this vicinity.

Other landforms and deposits relating to fluvioglacial deposition in this vicinity were either hidden or destroyed in the formation of the Daer Reservoir. However, a series of borings carried out prior to the construction of the dam give some indication as to the nature and thickness of drift deposits at the northern end of the reservoir (Figs. 4.30, 4.31). It can be seen from figure 4.31, that below 310 m.o.d. several metres of gravel overlie the basement rocks, particularly along the more gently inclined western valley flank. It is suggested that gravel deposits underlie much of the Daer Reservoir, particularly below 325 m.o.d.

With the regional movement of Lowther ice across this area in a broad easterly direction, as indicated by roches moutonnees on figure 4.30, the Upper Daer Valley, aligned north-south and surrounded by high ground, is believed to have retained a mass of stagnant ice which wasted away in situ during downwastage; a similar situation to that previously/...

previously described in Backhill Moss. At higher altitudes over this area the regional direction of meltwater flow was also in an east-south-east direction (Fig. 4.15). However, as indicated by channel R6 (Fig. 4.30), and the adjacent esker form, towards the later stages of deglaciation the direction of meltwater drainage was reversed and re-directed northwards into the Daer Valley itself, where fluvioglacial deposition was concentrated. Many of the fluvioglacial landforms in the vicinity of the Daer Reservoir were probably destroyed prior to the construction of the reservoir itself with the re-establishment of the northward drainage pattern in the postglacial period.

Nether Fingland. The fluvioglacial landforms on the eastern side of the Potrail Water at Nether Fingland (Fig. 4.26), were also termed moraines by Charlesworth (1926b, P.15), who believed this to be the type-site for the previously mentioned "Nether Fingland retreat stage" of the "Upper Clydesdale Glacier". However, once again exposures clearly indicate the fluvioglacial character of the landforms and this is confirmed by their close association with meltwater channels incised across Pin Stane (Fig. 4.23; Plate 4N).

A large sinuous ridge, starting gradually at approximately 320 m.o.d., runs initially downslope in a westerly direction, but swings southwards near its junction with the Potrail Water floodplain (Fig. 4.23). Exposures in the steep, western face of the ridge reveal numerous sub-rounded and sub-angular clasts 1 - 2cm in diameter, although larger forms up to 30cm in diameter are also present, all in a coarse, gravelly matrix. The ridge is approximately 300m in length, and

10/...

10 - 11m in height when viewed from the floodplain. On swinging southwards near where it terminates, the ridge appears to have almost enclosed a marshy terrace area 100 - 120m in width. This terrace stands 8 - 9m above the present river floodplain and can be seen from small sections to consist of numerous pebbles in a gravelly matrix. A large marshy hollow is found in the surface of the terrace.

The sinuous fluvioglacial ridge is another esker form, in this case found in association with a small kame terrace, the surface of which is pitted with a marshy kettle hole. The esker and associated forms were deposited by meltwater following the courses of channels X1, X2, X3 (Fig. 4.23), but particularly the largest form X2, which was the main feeder for the esker itself.

As the regional direction of ice movement and consequently meltwater drainage at higher altitudes was broadly eastwards over this vicinity, westward-trending channel system X and its associated fluvioglacial deposits must have formed during a later period in downwastage, possibly when stagnating ice occupied the adjoining, north-south aligned, Potrail and Daer Valleys. Concentration of lateglacial and postglacial drainage in the pre-existing river valley destroyed any other fluvioglacial deposits formerly present in the Potrail Water, and has undercut the existing deposits to produce the steep face which flanks the floodplain at the present day.

<u>SUMMARY</u>. The patchy distribution and relatively limited extent of fluvioglacial deposition in Area II is a direct result of the complex interrelationship between glaciological and relief conditions during deglaciation. The/...

The irregular upland topography of Area II placed major restrictions on the deposition of characteristic sand and gravel forms. Sugden and John (1976) believed that fluvioglacial deposits were less common in glacial troughs in uplands, "...because valley glaciers often remain active during retreat, inhibiting the survival of subglacial or englacial meltwater streams and allowing fluvioglacial landforms to persist only in ice-marginal and pre-glacial situations" (P.333). Certainly, over the central part of Area II, which was covered by locally derived ice from the Lowther Hills, meltwater channels and corresponding fluvioglacial deposits are poorly developed. Similarly, the best-developed fluvioglacial landforms, both erosional and depositional, are found along the south-west margin of Area II where Lowther ice and externally derived Nithsdale ice were confluent. With deglaciation, downwastage and partition, fluvioglacial activities were concentrated along the marginal zone of these two ice masses, particularly the Nithsdale ice mass.
A closely-linked factor also influencing fluvioglacial deposition was the direction of regional ice movement. Originating over the higher ground of the Lowther Hills, initially much of the dispersing Lowther ice followed the pre-glacial valley network. However, with increasing distance from the source, the direction of ice movement became more independent of the underlying relief, crossing valleys, spurs and ridge crests transversely. During the period of deglaciation, ice masses occupying valleys and depressions transverse to the direction of ice movement became isolated from their source of supply and downwasted in situ. As mentioned, these conditions are highly conducive to the concentration of meltwater

and/...

and formation of fluvioglacial landforms, but there is comparatively little evidence for this having taken place over the irregular topography of Area II. The patchy distribution of sand and gravel forms in potentially suitable localities suggests that stagnation and downwastage in situ did occur, but that many of the meltwater features which were deposited on the relatively narrow valley floors were destroyed, or buried, by pro-glacial and/or postglacial drainage.

4.8 CONCLUSIONS

The glacial geomorphology in Area II is dominated by landforms of erosion, both glacial and fluvioglacial in origin. From the study of these landforms and associated though more limited evidence from glacial and fluvioglacial deposits, the sources and directions of ice movement can be inferred and the nature of ice dissipation over this essentially upland area suggested.

1. Area II was occupied by ice from two main sources (Figs. 4.5, 4.9).

   Most of the area was crossed by a locally derived ice mass which radiated outwards from the high ground in the vicinity of Green Hill - Lowther Hill - Dungrain Law. However, along the foothills which represent the west and south-west margin of Area II the dominant source of ice was external.

2. Evidence from the erratic content of tills and till fabrics (Figs. 4.10, 4.11, 4.12), indicates that the external ice mass moved down Nithsdale in a predominately south-east direction, but only overspilled into the marginal uplands of Area II itself where local relief and ice conditions permitted. The presence of erratics derived solely from local/...

local Lower Palaeozoic rocks in tills over most of Area II, reinforces the belief that the higher parts of the Lowther Hills, like the Tweedsmuir Hills, were a primary centre of ice dispersal during the last major glaciation to affect Scotland. Geikie (1871) stated, " It appears that the high grounds ranging from the sources of the Afton north-eastwards through the Lowther and Leadhills to the Clyde have served as a central axis of dispersion for the ice of the glacial period" (P.38), a view that is supported by Charlesworth (1926 b , P.23).

As in the Tweedsmuirs, the higher surfaces of the Lowther Hills supported an ice cap or ice dome, from which outlet glaciers flowed radially, guided initially by the upper reaches of the principal valleys. However, on escaping these constraints, continued outward movement of ice was fan-like, particularly in the easterly direction, to eventually cover most of Area II and overspill across the eastern boundary into Area I.

3. The Lowther and Nithsdale ice masses became confluent over the west and south-west margins of Area II, together following a south-easterly course controlled by the more powerful Nithsdale ice mass at the glacial maximum.

4. Evidence of glacial breaching and fluvioglacial erosion are found at altitudes exceeding 610 m.o.d. which, in association with the glacial moulding of hill and ridge crests, strongly suggests that Area II was completely covered by ice, either internally or externally derived, during the last major glaciation.

5./...

5. Fluvioglacial landforms and deposits produced during downwastage are poorly developed in Area II as a whole, but evidence of concentrated fluvioglacial activity is found in the vicinity of the zone of confluence of the Lowther and Nithsdale ice masses.

6. As in Area I, evidence of fluvioglacial erosion is best-developed across spurs and bedrock complexities aligned transverse to the regional direction of ice movement, in association with both Lowther and Nithsdale ice. Most of the meltwater channels were incised by the superimposition of ice-directed supraglacial and englacial streams onto the underlying topography as the ice surface downwasted, the depth of meltwater incision controlled by a zone of meltwater penetration or englacial water-table. However, a few of the channel forms may represent formation by subglacial meltwater flow at the base of an active ice mass.

7. The pattern of meltwater channels produced in association with the Lowther ice mass radiates outwards from the higher uplands in a similar fashion to the landforms of glacial erosion (Fig. 4.25). Such regional control over fluvioglacial erosion applies only to channels above 396 m.o.d. however, as below this level local relief considerations played a more important role in governing channel formation, principally because of the disruption of the englacial water-table during the later stages of downwastage. Comparatively few channels were produced in association with the Lowther ice mass, much of the meltwater drainage taking place down the existing valley systems. As a result of this latter factor, many fluvioglacial deposits/...

deposits produced during the terminal stages of downwastage in association with stagnant ice masses occupying valleys transverse to the direction of regional ice movement, were destroyed or re-worked by meltwater activity.

8. Fluvioglacial activity in association with the Nithsdale ice mass is more complex (Fig. 4.25). Over the north-west part of Area II the gradient of the Nithsdale ice mass locally sloped down in a northerly direction and meltwater channels paralleling this course were incised across the upland edge of the Lowther Hills. More commonly however, the gradient of the Nithsdale ice mass reflected the dominant direction of ice movement along the west and south-west margins of Area II and sloped down in a south-east direction. In this respect, the term "Nithsdale ice mass" also refers to confluent Lowther ice which similarly followed a south-east course in this vicinity. Regional ice gradients concentrated both Nithsdale meltwater drainage and south-south-west flowing Lowther drainage along the margin of the Nithsdale ice mass, and accounts for the enhancement of fluvioglacial activity along the south-west margin of Area II. The englacial water-table controlling regional fluvioglacial erosion collapsed in this area at approximately 330 m.o.d., and meltwater was re-directed downslope.

9. With downwastage below the level of the regional watershed, and partition of the two ice masses, Nithsdale ice remained longer over the south-west margin of Area II than did Lowther ice. As a result, the upper parts of southward trending valleys in the foothill zone became ice free. Ground vacated by ice at the mouth of the Capel Valley was flooded by glacial lakes/...

lakes which were ponded to the south by Nithsdale ice. Deposition in the lakes was carried out by channels from the Nithsdale ice mass itself, but also by extraglacial meltwater flowing down the Capel Valley. The altitude of deposition was controlled by the presence of an englacial water-table which extended into the decaying ice mass itself.

10. In places along the south-western foothill zone, patches of ice became detached from their source of supply and downwasted in situ, in a similar fashion to the final stages of dissipation in the central part of the Lowther Hills.

11. The absence of fluvioglacial features below 290 m.o.d. indicates the establishment of a "subglacial escape route" at a comparatively early stage in decay which effected the rapid drainage of meltwater from the area.

12. The presence of moraines in the valleys which drain the higher parts of the Lowther Hills, indicates that there was a return to colder conditions after or during the main period of deglaciation. Similar morainic forms in the Tweedsmuir Hills were attributed to deposition during the Zone III period, and the moraines of the Lowther Hills are believed to be of comparable age. Small, narrow glaciers were re-established in the Lang, Riccart and Peden Valleys. The limits of these glaciers, indicated by the extent of the morainic mounds, are not always well-defined as a result of periglacial slope processes.

CHAPTER 5

AREA III

5.1 INTRODUCTION : LOCATION AND EXTENT

Area III is the western part of the thesis area and its boundary lines were drawn in such a fashion that it delimited a substantial length of the Upper Nith valley (Fig. 5.1). As a result the area, which is approximately 195km^2 in extent, is shaped like a narrow parallelogram, the river Nith running down the middle of the figure. The northern limit of Area III is represented by the east-west grid line NS 17, to its junction with the Strathclyde/Dumfries and Galloway Regional boundary at NS 723170. The regional boundary is then followed south-west as it swings across the Nith to McCrierick's Cairn, NS 668101. Both the western and eastern limits of Area III are represented by lines drawn parallel to the course of the river itself, linking together local hill crests. The western boundary connects McCrierick's Cairn (556 m.o.d.), Corserig Hill (393 m.o.d.) and Cairn Hill (339 m.o.d.) to grid reference NS 800050, whereafter the north-south grid line NS 80 is adopted for the southern part of the limit. The east-west grid line NS 00 represents the southern boundary of Area III from NS 800000 to its eastern junction with the upland edge of the Lowther Hills, (Area II), at NS 902000. The eastern boundary to Area III is the previously referred to western limit of Area II, which follows the upland edge of the Lowther Hills as a line connecting the crests of East Morton, Black Hill, Auchensow and Knockenhair, to the Crawick Water at NS 785140. The most northerly part of the eastern boundary is represented by the course of/...

of the Crawick Water itself to its junction with grid line NS 14 at NS 806140.

The boundaries of Area III enclose the upper part of a mature valley system, in which there is extensive evidence for the development of landforms relating to the glacial period. In contrast to Area II, landforms of glacial erosion are not well-developed in the Upper Nith Valley and it is essentially a low-lying area where depositional processes, both glacial and fluvioglacial were dominant.

5.2 RELIEF AND DRAINAGE

Area III is divided into two halves by the River Nith, there being a fundamental distinction in terms of relief between the northern and southern valley flanks (Fig. 5.2). North of the river, the valley side generally rises steeply from the floodplain onto a local structural surface between 229 - 259 m.o.d. before rising again, but much more abruptly, into the Lowther foothills.

The upland northern part of Area III lies mainly between 350 - 520m.o.d., the principal summits being Halfmerk Hill (451 m.o.d.), Kirkland Hill (509 m.o.d.), Todholes Hill (480 m.o.d.), Polholm Rig (491 m.o.d.) and Shiel Hill (486 m.o.d.). Locally, relative relief values exceed 270m along the fault line edge of the hills, but the uplands generally represent an area of smoothed and rounded ridge and hill crests only occasionally deeply-incised by fluvial activity.

South of the river there is a gentler but continuous increase in altitude, with no sudden breaks in slope, despite the fact that the highest summit within Area III, McCrierick's Cairn, is found along the southern margin. Generally however, the terrain along the/...

the southern flank rises little above 366 m.o.d. and local relief values are less than 80m.

The drainage of Area III is naturally dominated by the river Nith, but the character of the river itself varies considerably (Plate 5A). Between the north-west boundary of the area and Kirkconnel, the river follows a broad easterly course and occupies a narrow floodplain, less than 150m in width, incised into glacial drift (Fig. 5.2). Between Kirkconnel and Mennock the Nith, now following a south-east course, is joined by two of its major tributaries, the Kello Water and Euchan Water, and the floodplain, again flanked by extensive deposits of glacial drift, increases considerably in width to 500 - 600m. Downstream from Mennock, there is a steepening of the river gradient as it swings more directly south to leave the area via a narrow and steep-sided gorge, more than 80m deep. This part of its course is broken by numerous small falls and rapids. The constriction in valley width is attributed to local geological conditions by George (1955), and to glacial breaching, by Highland ice descending the Nith Valley, by Sissons (1967a. P42). There is extensive evidence of glacial and fluvioglacial deposition not only along the lower flanks of the Nith, but also at depth beneath the river, where Lumsden and Davies (1965) have detected a buried channel, possibly a former course of the Nith itself, containing 10 - 30m of glacial drift.

The two major southern tributaries, the Kello Water and Euchan Water, represent the principal elements of a rich tributary system that follows a broadly north-east course to join the Nith. The stream density south of the Nith far surpasses that to the north, where three/...

three large rivers, the Mennock Water, Crawick Water and Carron dominate the tributary system. The Crawick Water is the most continuous within Area III, following a southerly course along a deep, steep-sided valley to its junction with the Nith. This river, like many of the southward draining streams to the Nith, has a steep gradient, which accelerated headward erosion and facilitated piracy (George 1955). Drift terraces are found along the flanks and at the mouth of the Crawick Water. The Mennock Water, like the Crawick, follows a steep, deeply-incised course, but the Carron by contrast, on leaving the Lowther foothill zone occupies a wide, shallow-sided valley flanked with drift deposits.

5.3 GEOLOGY

Although rocks of Ordovician and Silurian age are again most abundant in area III, they underlie 50 - 55% of the total area, the geology of the Upper Nith Valley is dominated by two disconnected basins of younger Carboniferous and New Red Sandstone strata (Fig. 5.3). The differences between the Upper and Lower Palaeozoic rocks in terms of susceptibility to erosion and tectonic control, is strongly reflected in the contrasting relief conditions of Area III described above.

The Lower Palaeozoic rocks, Silurian and Ordovician greywackes, grits, shales and siltstones, are more resistant to erosion within Area III and constitute the uplands which border the river Nith along its higher northern and southern flanks. Rocks of Ordovician age are most extensive, Silurian outcrops being restricted to the south-west of the area, but as before rocks of both ages are essentially similar in character and highly faulted and folded in the north-

east/...

east to south-west direction. There is also evidence for contemporary volcanic activity, Bail Hill in the Lowther foothills consisting of vent agglomerates of Ordovician age (Fig. 5.3).

The only rocks of Devonian age within Area III are also igneous in origin and outcrop along the extreme north-west margin (Fig. 5.3). Andesites, basalts and lava conglomerates all lie on the north-west, downthrown side of the Southern Uplands fault and were formed in association with local volcanic centres at Spango Hill and Polshill, both outside the thesis area. The fault itself originated in Late Silurian - Early Devonian times, but there is evidence to suggest re-activation and displacement along the fault-line of a much more recent nature (Lumsden and Davies, 1965). There is however, no readily apparent surficial expression of the Southern Uplands fault in Area III.

Upper Palaeozoic rocks rest unconformably as outliers on the Lower Palaeozoic rocks in Area III, the two main areas of occurrence being the Sanquhar Basin in the north-central part of the area and the Thornhill Basin in the south-west (Fig. 5.3). The Sanquhar outlier underlies an area of about 45km^2 along the floor and lower flanks of the Nith Valley and consists almost entirely of strata of Carboniferous age. The rocks are in fact mainly Upper Carboniferous of the Coal Measure Series and consist of sandstones, siltstones, mudstones, shales, coals and seatclays. However, much of the sequence on the northern side of the Nith was subjected to secondary reddening by oxidation to locally produce the Barren Red Measures. As indicated on Figure 5.3, the strata of the Sanquhar Basin are downthrown along a series of faults marking the edge of the Lowther Hills. The faultscarps are readily apparent in the landscape and contrast markedly with the gentle slopes along the southern edge of the basin where there are no major faults.

In the Thornhill Basin, which is aligned down the Nith Valley in a north-south direction, the Carboniferous beds crop out in a fringe around the strata of New Red Sandstone age. They are mainly red and purple in colour and consist of cyclic sequences of sandstone, siltstone, mudstone and seatclay of the Coal Measure Series. Coals which were formerly present were removed by oxidation, which also gave rise to the secondary reddening of the associated strata.

The New Red Sandstone rocks rest unconformably on top of the Carboniferous strata and are found only in the Thornhill Basin (Fig. 5.3). They consist of olivine-basalt lavas, overlain by red sandstones and breccias deposited in a desert environment.

Igneous intrusions of Tertiary age represent the youngest solid rocks in Area III. Five dolerite dykes with the characteristic north-west to south-east Tertiary trend are found in the Sanquhar Basin (Fig. 5.3). There is also a more extensive sill of similar composition found in close association with the dykes. As before, there is little surface expression of the Tertiary outcrops.

5.4 GLACIAL EROSION

Landforms of glacial erosion are not well-developed in Area III. Only in the Lowther foothills and other generally upland localities within the area is there scattered evidence of glacial erosion. Elsewhere, and particularly along the floor and lower flanks of the Nith Valley, glacial and fluvioglacial deposits mask any erosional/...

erosional landforms which may be present (Fig. 5.5).

<u>GLACIAL TROUGHS</u>. Few of the valleys in Area III show large-scale modification of their form by glacial action. Indeed, only those occupied by the Glenaylmer, Crawick, Kello and Euchan streams (Fig. 5.5), resemble the glacial troughs found in the uplands of Area II.

The Crawick trough follows a sinuous north-east to south-west course of approximately 5km in length within Area III, terminating at the edge of the Lowther foothills. It is characterised by steep slopes rising 182 - 243m above a fairly narrow, flat floor and it possesses the typical parabolic cross-profile (Plate 5B). The flat floor is the result of glacial and postglacial depositional infilling to an unknown depth, depositional terrace forms also being found along the flanks and at the mouth of the valley. There is no indication of cirque development in the vicinity of the trough or indeed anywhere within Area III. Although the head of the Crawick trough lies outside the thesis area, Mciver (1947) points out that, ".... there is a real contrast between the Crawick and Mennock valleys in that the latter merely leads up to a high level col ...... whereas the Crawick leads up to a beautiful through trough, which it could never have excavated but which provides an easy route through the waterparting and so to the valley of the Duneaton Water and the Clyde Basin" (P.80). This strongly suggests that the Crawick trough was a major routeway for ice through the Lowther Hills during the last glaciation, the principal direction of movement being either south-west or north-east/...

east. The lower portion of the Spothfore valley, which joins the Crawick from a north-west direction, also shows evidence of glacial moulding along its flanks, but the valley itself is left hanging 20 - 30m above the floor of the main trough (Fig. 5.5).

The Glenaylmer trough is also aligned in a north-east to south-west direction, but it is much shorter and straighter than the Crawick. The trough extends for less than 2km in the Lowther foothills, terminating at the sharply-defined upland edge. However, throughout its length the Glenaylmer trough is characterised by steep, craggy slopes which rise 122 - 152m above a narrow floor. The head of the trough also rises abruptly, in this case through a vertical distance of 76m, to a well-developed col, the col having a similar alignment to the trough itself. As before, the Glenaylmer trough was formed by ice following a north-east or south-west course

Along the south-west margin of Area III, the form of the Kello and Euchan valleys is also indicative of large-scale modification by glacial erosion. However, the deeply-incised nature of these troughs gradually diminishes on approaching their junction with Nithsdale and as such is not maintained for any distance within the thesis area itself. Nevertheless, both the Kello and Euchan, aligned in north-east to south-west directions, would appear to have acted as major routeways for the transportation of ice into Area III during the last major glaciation to affect the area.

GLACIALLY-BREACHED COLS. Fifteen glacially-breached cols were identified in Area III, 13 of the forms/...

forms occurring in the northern part of the area in the Lowther foothills (Fig. 5.5). The altitude of the col floors ranges between 290 - 457 m.o.d. which, when taken into consideration with the fact that most of the summits in the area exhibit some degree of ice moulding, strongly suggests that Area III was completely covered by ice during the last glaciation. As was previously found to be the case, the cols tend to be flat-floored, often with concave sides and are generally catenary in cross-profile. The alignment and altitude of all glacially-breached cols within Area III is indicated on figure 5.6. Two main concentrations are readily apparent. A major group of cols, 10 in number and found between 290 - 457 m.o.d. in altitude, are aligned in a north-east to south-west direction. A second smaller group extend over a similar altitudinal range, but are aligned in a north-west to south-east direction.

The larger north-east to south-west aligned group are concentrated along the edge of and within the upland zone which represents the northern margin of the Nith valley. The cols parallel the alignment of the troughs in this area, but other adjacent landforms of glacial erosion, i.e. striations or roches moutonnees do not clearly indicate whether the principal direction of ice flow was to the north-east or south-west. However, research by Holden (1977) in the area immediately to the north-west of Area III, indicated that the high-level landforms of glacial erosion along the northern margin of the Nith Valley were formed by an ice-mass following a north to north-east course. This suggests that within the thesis area itself ice occupying the Nith Valley also/...

also overflowed into the Lowther foothills in a north-east direction, as was found to be the case in the north-west of Area II. The lowest cols along the upland edge were incised by diffluent ice, but the higher forms in more central parts of the uplands were formed under conditions of glacial transfluence, when the regional direction of ice movement along the northern margin of the area was also broadly north-eastwards. The only col found on the south side of the Nith valley is also aligned in a north-east to south-west direction, but in contrast to the forms described above was most likely incised by ice following a south-west course.

The smaller north-west to south-east aligned group of ice-breached cols is focused along the watershed which represents the north-west margin of Area III, separating Nith drainage from that of the Lugar Water. These cols reflect the dominant movement of ice down the Nith valley in an east to south-east direction and as such were most likely incised under conditions of glacial transfluence. The only form incised across the upland edge along the south-east margin of the area, which also possesses this orientation, was also incised by Nithsdale ice, and is further testimony to the importance of the Nith valley as a major routeway for ice movement in Area III.

STRIATIONS AND ROCHES MOUTONNEES. Twelve striations were recorded in Area III (Fig.5.5). Their main concentration is along the gentler south-west flank of the Nith valley, with only one form found on the north-west side of the river, along the upland edge. Ten of the striations are aligned in a north-west to south-east direction parallel to the Nith valley itself/...

itself. Of the two anomalous forms, one is found in the southern part of Area III aligned in a north-south direction parallel to the local trend of the Nith, but the second striation is found in the floor of the north-east to south-west trending Euchan Water valley and possesses an alignment parallel to this valley. The only striation on the northern flank of the Nith valley is also aligned north-west to south-east parallel to the main valley, despite the fact that it occurs at the mouth of the Crawick trough.

Twelve roches moutonnees were also identified in Area III (Fig. 5.5), but these tend to be more randomly distributed than the striations, although both erosional forms are occasionally found in close proximity. Six roches moutonnees are found to the north of the river Nith, and 6 to the south, but in both areas the landforms are represented by generally small mounds, less than 4m in height and 30m in length.

Along the northern flank of the Nith, three distinct groups of roches moutonnees are readily identifiable, each group consisting of two mounds. The forms vary in altitude between 305 - 381 m.o.d., but in all cases the smoothed stoss side of the mound faces north-west and the shattered lee side south-east, indicating a south-east movement of ice down this part of Nithsdale. No roches moutonnees are found in the uplands along the northern margin of Area III.

On the southern flank of Nithsdale, the roches moutonnees are again found in three distinct groups of two, but at generally lower altitudes between 228 - 305 m.o.d.. The alignment of the bedrock mounds parallels the alignment of adjacent striations and is again indicative of a south-east movement of ice down the Nith valley.

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The most southerly of the roches moutonees forms do however, suggest that locally ice movement was more directly eastwards. The roches moutonees on both the northern and southern flanks of the Nith valley and similarly aligned striations, all found below 381 m.o.d., indicate that Nithsdale was a major routeway for ice during the last glacial period and that the direction of ice movement was strongly controlled, at least initially, by the alignment of the Nith valley itself.

SUMMARY. The limited evidence available from the landforms of glacial erosion in Area III, suggests that there were two main directions of ice movement across the area. The dominant movement of ice was directed in a south-east direction down the Nith valley itself. Initially the main ice mass was restricted to the confines of the valley supplied by glaciers from a west to north-west source descending the Euchan and Kello troughs, as well as the Upper Nith. It was at this stage that the majority of the lower striations and roches moutonnees was produced. The increasing thickness of the ice mass over the valley floor resulted in the overspill of ice across the upland edge, via ice-breached cols, into the Lowther foothills in a dominantly north to north-east direction. Most of the valleys in this part of the Lowther Hills are aligned transverse to a northward direction of ice movement and consequently, were not greatly modified by ice action during the glacial period. However, this was not the case with the pre-existing south-west to north-east aligned Crawick Valley, which acted as a major routeway for ice through the Lowther Hills into the Upper Clyde Basin.

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The formation of the Glenaylmer trough is more difficult to explain, but was perhaps the result of erosive processes being concentrated along a line of weakness produced in association with the adjacent fault-scarp. At the glacial maximum, the dominant south-east direction of ice movement extended beyond the confines of the Nith valley into the foothill zone, and it was at this stage that the highest roches moutonnees and striations were produced (Fig. 5.7).

The directions of ice movement depicted on figure 5.7 are similar to those postulated by Holden (1977, P. 149 - 173), for the region to the north-west of Area III. Holden suggested a south-east movement of ice down the Nith valley, although in his area fed from a dominantly southerly source, and the northward movement of ice across the higher northern flanks of Nithsdale. He further suggested that the northward movement of ice was forced north-eastwards by the presence of "Highland Ice" (the main source of which was the West Highlands of Scotland) encroaching upon the north-west foothills of the Southern Uplands.

5.5 GLACIAL DEPOSITION

Evidence pertaining to the depositional affects of glaciation is much more prominent than that for glacial erosion in Area III. Glacial deposits are extensively developed along the floor and lower flanks of the Nith valley, often in close association with deposits of a fluvioglacial origin. Till covers approximately half of the surface area of Area III (Fig. 5.4), the remainder being occupied by sands and gravels of fluvioglacial and fluvial origin, peat, solid rock and debris derived from mass wastage.

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The greatest till thicknesses are attained along the floor of the Nith valley, where approximately 30m of the deposit is found (Lumsden & Davies, 1965). However, as indicated on figure 5.8, till thins rapidly upslope from the valley floor, with little evidence of the deposit above 274 m.o.d. in Nithsdale itself. At higher altitudes till is restricted to isolated pockets, generally less than 10m in thickness, along the floors and lower flanks of valleys in the Lowther foothills. Even here however, there is no indication of the deposit above 400 m.o.d. and with increasing altitude it again becomes increasingly difficult to differentiate between till and other superficial material produced by mass wastage.

The extensive occurrence of Upper Palaeozoic rocks and the generally more varied geological character of Area III (Fig. 5.3), in comparison with Areas I or II, has led to a greater variety in till composition and colour. Across the higher flanks of the Nith valley and in the Lowther foothills, the tills contain a large admixture of Lower Palaeozoic erratics and are coarse and gritty, due to the dominance of greywackes, grits and siltstones. As before, these tills are generally dark brown in colour. Over the Carboniferous outliers, the till assumes a much darker tint, becoming dark brown/ dark grey or occasionally black in colour, and the matrix is more clayey and tenacious. Although Lower Palaeozoic erratics are still dominant, there is a higher percentage of shales, mudstones and sandstones in the deposit. However, where the Barren Red Measures of the Carboniferous series are present at the surface, to the north of Kirkconnel on the northern flank of the Nith Valley, the till becomes redder in colour. In the Thornhill Basin, a similar

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tenacious brick red till was derived from Permian sandstone outcrops. Regardless of the colour of the deposit, the shape of the included clasts remains generally constant; angular and sub-angular clasts dominating, although sub-rounded and even rounded forms are also present in certain localities.

It is generally the case that only one till is found overlying bedrock in Area III. However, at some exposures a second thin till is revealed overlying the main unit, while at depth, distinct till units are occasionally separated by thin lenses of sand and gravel (Fig. 5.8). At various localities, till can also be seen to both rest upon, and be overlain by, sand and gravel deposits.

More detailed examinations of till characteristics were completed at the best-exposed sites in Area III, in an attempt to aid the description of this highly varied deposit and determine whether more than one basal unit was present in the area. The more detailed analyses also enabled the origins and former directions of ice movement responsible for till deposition, to be determined more accurately. Seven exposures of till were examined (Fig. 5.4, Exposures 5A - 5G; Table 5.1), and as before the nature of the deposit and dimensions of the included clasts were described, and preferred-stone orientation, particle-size and erratic count data depicted in tabular form. The results obtained from each of the sites are summarised on figures 5.9, 5.10 and tables 5.1, 5.2, 5.3 and 5.4.

The rose diagrams for preferred-stone orientations at the scattered till sites suggest a highly varied pattern of ice movement in Area III (Fig. 5.9; Table 5.2). The alignment of the long axes of clasts contained within the till at Site 5A (Polneul Bridge), near

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near the head of Nithsdale, indicates a north-west or south-east movement of ice, broadly parallel to the valley itself. Sites 5B (Glengap Burn) and 5C (Shiel Rig), in contrast, indicate a north-east or south-west movement of ice either into or out from the Lowther foothills. The orientation of the clasts at Site 5D (Whing Burn Ford) and 5E (Old Mains), similarly suggest a north-east or south-west movement of ice into or out from the Nith Valley, although in the case of Site 5E, a large number of clasts are also aligned parallel to the valley itself. The two most southerly exposures, Sites 5F(Burnsands Burn) and 5G (Cairn Burn), both indicate either a north or south movement of ice, again broadly parallel to the Nith Valley itself. In the more upland areas of the Lowther foothills (Sites 5B, 5C), and also on the southern flank of Nithsdale (Sites 5F, 5G), the orientation of the long axes of the clasts was strongly controlled not only by the direction of regional ice movement, but also by the nature of local relief conditions and particularly the pre-glacial alignment of local valley systems.
The erratic content of tills in the vicinity of Area III greatly helped in the accurate identification of the pattern of ice movement. A considerable amount of work on directions of ice movement in south-west Scotland, based upon the identification of erratics derived mainly from several igneous sources, was carried out by Charlesworth (1926 a) and Simpson and Richey (1936). Although none of the main igneous masses lie in Area III, their distinctive erratics were identified at sites within the Upper Nith valley and in other areas adjacent to this (Fig. 5.10). It should be noted however, that the arrows on figure 5.10 indicate the generalised routes followed by the ice,

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which were often far less direct in reality. For example, the pebbles of Loch Doon granite found in the Upper Nith valley were deposited by ice moving south-east down the Nith Valley (Eyles et al, 1949). Similarly, the erratics of kylite identified in till sections near Sanquhar also indicate a south-east movement of ice down Nithsdale via the valley head (Simpson and Richey, 1936). The radial distribution pattern of Spango granite erratics is more difficult to account for, but Charlesworth (1926 a)attributed this to oscillations of a confluent Southern Upland-Highland ice mass. However, from a wider study of the occurrence of other erratics in this area, Charlesworth too reached the conclusion that, "In Nithsdale there was a general south-east transport of drift", (Charlesworth, 1926 a , P. 7). In addition to the identification of igneous erratics, Charlesworth also found erratics of Carboniferous sandstone in the Upper Crawick valley, suggesting a north-east movement of ice from the Nith valley.

Despite the fact that neither of the granites, nor kylite, were found among the erratics at the till exposures examined in detail (Table 5.3), although identified at other till exposures in Area III, the erratics which are present still indicate a south-east movement of ice down Nithsdale (Fig. 5.10; Table 5.3). Principal among this latter group of indicator stones are erratics of lava conglomerate, Old Red Sandstone lava and tuff, which all outcrop along the northern flank of the Nith Valley but are found at Sites 5A and 5E in the valley floor to the south-east (Fig. 5.10). The tuff erratics were possibly derived from an alternative, smaller outcrop on the southern flank of Nithsdale (Fig. 5.10), but even if this was the/...

the case, a general south-eastward movement of ice is still indicated. Similarly, the only felsite outcrop in the vicinity of Area III is found beyond the western boundary of the area and therefore the presence of felsite in the till at Site 5D suggests an east to north-east movement of ice into the Nith valley (Fig. 5.10).

The predominance of erratics derived from Lower Palaeozoic outcrops at all the sites in Area III (Table 5.3), and the restriction of Upper Palaeozoic erratics to sites at lower altitudes in the vicinity of the valley floor, reinforces the belief that greywackes, grits and siltstones are more resistant to erosion during transport than sandstones and shales. It also indicates that ice movement was strongly controlled by the alignment and relief of the Nith valley itself. In summary therefore, the erratic content of tills in and around Area III strongly suggests that during the last major glaciation, ice from a west to north-west source entered the area at several points along its western margin, but was channelled principally down the Nith valley itself in a south-east direction. Along the southern margin of Area III this ice mass turned more directly south to again parallel the alignment of the Nith valley. Only along the northern margin, where ice overflowed into the Lowther foothills in a north-east direction, is there any indication of the overall pattern of ice movement strongly diverging from the general south to south-east course.

The erratic content of the tills and their differing resistances to erosion are also reflected in the particle-size characteristics of the till units (Table 5.4). It is generally the case, that the/...

the till units found in close association with the Upper Palaeozoic outcrops have a lower percentage of cobbles and boulders in the matrix than those derived entirely from Lower Palaeozoic strata, but a higher percentage of particles in the sand and silt-clay fractions. As a result, the tills containing Upper Palaeozoic erratics are generally more tenacious. Furthermore, it is suggested that the consistently high percentage of gravel-sized particles in the tills of Area III reflects the general dominance of Lower Palaeozoic erratics in all the tills (Tables 5.3, 5.4), but that the higher percentage of the finer fractions in the tills containing Upper Palaeozoic erratics is a further reflection of the greater susceptibility of these to comminution during transport. In a similar context Flint (1971) stated, "Shales yield till that is chiefly clay. The stones present are mainly rocks other than shale and are derived from elsewhere" (P. 181).

From table 5.1, it can be seen that at certain of the sites examined, a second till was identified overlying the lower basal unit. This upper till is best exposed at Site 5E (Old Mains), where it consists almost entirely of sandstone blocks, varying in size from 30cm - 1m in diameter, in a very sandy-slightly clayey matrix (Plate 5C). The blocks tend to be equidimensional and as such unsuitable for stone orientation analysis. Similarly, the generally large size of the blocks and their tendency to crumble on excavation prevented accurate particle-size analysis. There is evidence of bedding in sandy layers within the till, and some of the larger blocks were apparently dropped into these bedded deposits shortly after their deposition, as the beds can be seen to curve round the base/...

base of the blocks as continuous units (Plate 5D). Intercalated lenses of sand and fine gravel, 15 - 20cm in thickness, are also present in the till, and on closer examination indicate deposition by meltwater following a generally southerly course. There is no obvious orientation to the sandstone blocks or other smaller clasts in this upper till unit and they all appear to be randomly distributed. The upper till, which varies between 1.5 - 4m in thickness, is overlain by 3m of poorly bedded sands and gravels. The upper till unit at Old Mains is believed to represent an ablation till (Fig. 5.11). "Ablation till is deposited from drift in transport upon or within the terminal area of a shrinking glacier. As the ice melts inward from terminus, top and base, this drift slides, flows, is dumped or subsides onto the ground. The resulting till is therefore loose, noncompact, and nonfissile, and its clasts are less strongly abraded than those in lodgement till. During the process of settling, fines are washed away selectively, and all particles are reorientated by settling as their matrix of ice melts". (Flint, 1971, P. 171 - 172). The presence of stratification in the till unit at Site 5E (Old Mains), indicates that at the time of deposition the water content of the till was very high and that a large amount of movement or flowage of the deposit occurred. In this respect, Boulton (1968, P. 43), differentiated between flow till and melt-out till under the general category of "ablation tills". It would appear, that the upper till at Site 5E is mainly a flow till, but it is impossible to state conclusively that the entire unit was formed in this manner.

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The high concentration of sandstone blocks in the upper till indicates that the erratics were not transported far before deposition, and that the direction of ice movement prior to their deposition was south-east down Nithsdale, across the Upper Palaeozoic outcrops. When considered in association with the rose diagram for Site 5E (Fig. 5.9), this suggests that the basal unit, with comparatively few sandstone clasts, was deposited at an early stage in glaciation by ice following a north-east course into the Nith Valley. At the junction with the main valley this ice mass curved south-eastwards. As the glacial period continued, Nithsdale became a major routeway for ice flow and this change in the dominant direction of ice movement is reflected in the substantially higher percentage of sandstone clasts and blocks in the upper unit, derived mainly from the head of the valley.

The upper till at Site 5D (Whing Burn Ford) is only 2m in thickness (Table 5.1), and is not as well-exposed as that at Old Mains. Nevertheless, it can be seen to consist of a loose, brown, earthy matrix, in this case containing mainly greywacke clasts and blocks, but again the clasts have no readily apparent orientation. This upper unit at Whing Burn Ford is also believed to represent an ablation till, formed in a similar manner to that depicted on figure 5.11, but because of the poorly-exposed nature of the section, flowage of this till prior to deposition cannot be readily ascertained.

Although difficult to prove conclusively that there is not more than one lodgement till present at depth in the Nith Valley (Fig. 5.8), the/...

the irregular occurrence of the sand and gravel deposits which separate the till units, their limited thickness, and the similarity in descriptions applied to tills above and below the fluvioglacial deposits, strongly suggests that the depositional sequences indicated relate to one till unit. The interstratified sands and gravels merely represent breaks within a single process of glacial deposition.

DRUMLINS. As in Upper Annandale (Area I), glacial deposition in parts of Nithsdale is morphologically characterised by distinctive drumlinoid forms (Plate 5E). Groups of drumlins are found along both lower flanks of the Nith valley, generally at altitudes between 170 - 240m.o.d. (Fig. 5.12). Table 5.5 indicates the number of forms to be found in each group, the dimensions of the drumlins and their postulated constituents. Borehole evidence from Upper Nithsdale indicates that few of the forms consist wholly of drift deposits and that, as previously mentioned, with movement upslope from the valley floor the thickness of till overlying bedrock gradually diminishes, although the shape of the drumlin mounds remains basically the same. Less than 1½m of till overlies bedrock at drumlin A1, while at the slightly lower D1 the drift thickness is 3m (Table 5.5; Figs. 5.4, 5.12). Only in the immediate vicinity of the valley floor itself, for example at drumlin C2 where there is a till thickness of 13m, can it be said with any degree of certainty that the drumlins are formed entirely of drift. Further down the Nith valley from group C, borehole evidence is scarce and any assessment of the internal constituents of the drumlins must be based upon limited natural exposures. In drumlin swarm F (Fig.5.13)/...

(Fig. 5.13), where numerous drumlinoid forms are found together, such exposures again suggest that only a thin veneer of drift overlies bedrock.

Although there would appear to be great variety in the ratio of drift to bedrock representing the internal composition of individual forms, drumlin shape by contrast remains generally homogeneous. With only a few exceptions, the steeper stoss end to the mounds point up the Nith valley in a north to north-west direction and the gentler lee slope tapers south to south-eastwards. The drumlins therefore, are in agreement with other indications of the direction of ice flow in suggesting a south-east movement near the head of the Nith valley, curving more directly south further downvalley, to follow the changing alignment of Nithsdale itself.

The longest, largest and most streamlined drumlin forms are found in groups A and D near the head of the valley (Figs 5.4, 5.12; Table 5.5). Chorley (1959), associates the greater elongation of such forms with more powerful ice flow. By contrast, the smallest forms are found further down Nithsdale (Group F, Figs 5.12, 5.13; Table 5.5), which by definition suggests that as a result of relief constrictions and/or other factors, the rate of ice movement diminished as it curved more directly southwards.

There is no indication of the formation of moraines within the boundaries of Area III.

5.6 FLUVIOGLACIAL EROSION

Although/...

Although landforms of glacial erosion are poorly represented in Area III, landforms of fluvioglacial erosion by contrast are extensively developed and form complex patterns across both flanks of the Nith valley (Fig. 5.4). The distribution and development of meltwater channels varies considerably however, the highest and best-developed forms being found incised into bedrock in the Lowther foothills up to altitudes exceeding 427 m.o.d., while near the valley floor channels only a few metres in depth and width are incised wholly into drift deposits. The channels developed in bedrock, although larger, tend to occur individually, whereas the forms across the lower valley flanks are often interlinked to form complex anastomosing patterns. Figure 5.14 indicates the location of the main channel systems in Area III and from the dominant slope of the channel floors, the principal direction of meltwater flow responsible for channel formation. Two dominant groups of channels can be distinguished by altitude :-

(a) A higher group of ice-directed channels, found generally above 300 m.o.d., incised across spurs and into cols.

(b) A lower group of channels, below 300 m.o.d., whose formation was apparently greatly influenced by local relief conditions.

CHANNEL SYSTEMS IN AREA III.

(a) Higher Group of Channels above 300 m.o.d. The limited amount of Area III which lies above 300 m.o.d. (Fig. 5.2), has restricted the location of these channels to peripheral zones, but two main sub-groups can be identified along the northern and south-eastern margins. Most of the channels along the northern margin of the area were incised by meltwater/...

meltwater following a north to north-east course; those along the south-east margin by south to south-east flowing meltwater. The northern group of channels is represented by systems D, E, F, G, H (Figs 5.4, 5.14), of which System G (Fig. 5.15), is the best-developed. Channel system G is incised across the north-west to south-east trending spurs which flank the Back Burn, a tributary of the Crawick Water (Plate 5F). Channel G1 (Fig. 5.15), occupies the floor of a glacial breach and has a well-developed up-down long profile. The in-take of the channel is at approximately 366 m.o.d., the high point along the channel floor at 373 m.o.d. and the outlet at 355 m.o.d. The channel attains its greatest dimensions down the north-east side of the breach, where it is incised 22 - 25m into bedrock, with a flat floor 10 - 14m in width. The channel swings more directly east near its outlet. G2 (Fig. 5.15), is incised across the crest of the same spur, but at approximately 330 m.o.d.. This channel also follows a north-east course and again has a slightly up-down profile. Where best-developed however, this form is only incised 14m into bedrock. Channel G3 (Fig. 5.15), is similar in alignment to both G1 and G2, but is only incised across the crest of the spur to a depth of 6m.

On the north-east side of the Back Burn, channels G4 and G5 are found in the glacial breach which separates Castle Hill from Cruereach Hill (Fig. 5.15). G4 is one of the largest channels in Area III, being incised into the floor of the breach to a depth exceeding 30m, with a peat-infilled floor 10 - 15m in width. The channel has its in-take at approximately 366 m.o.d. and runs across/...

across the floor of the breach in a north-east direction. G5 is incised into the northern side of the breach and although initially represented as a bench form, when followed north-eastwards it takes on channel proportions and is incised 10 - 11m into bedrock. This channel swings downslope towards the floor of the breach, but terminates 6 - 8m above the floor of G4. Channels G6 - G10 (Fig. 5.15), all found in close association, are incised into the spur end. The main channel, G6, has a plunge-pool in-take at 305 m.o.d. and runs across the spur end in a north-east direction. It is incised 10 - 12m into bedrock and has a flat floor 12 - 15m in width. A short chute form, G7 (Fig. 5.15), 100m in length, leads directly downslope from the main channel to terminate at 298 m.o.d.. Two hanging meanders begin at this altitude, where the steep spur end flattens slightly, (G8, G9, Fig. 5.15), but there is no obvious connection with channel G7. The two meanders are both deeply-incised to a depth of 16 - 17m into bedrock, with floors 4 - 5m in width, but even these are not noticeably linked. Channel G10 (Fig. 5.15), is a small form which also trends in a north-east direction. By their altitudes and similar alignments, it seems highly likely that channel forms G6 - G10 were incised by north-east flowing meltwater also responsible for the incision of channels G1 and/or G2.

The tendency for the channels of system G to be located across convexities in the underlying topography and to be most marked at low points along spur or ridge crests, indicates that such channels are ice-directed. It was previously suggested that Nithsdale ice moved across this part of the Lowther foothills and

up/...

up the Crawick Valley in a north to north-east direction. This direction of ice movement is supported by the similar alignment of the meltwater channels, which indicate that locally the ice surface gradient sloped down to the north-north-east from the vicinity of the Nith valley.

It would appear that the channels were mainly incised by the superimposition of supraglacial and englacial streams. The presence of semi-circular plunge-pool in-takes, as for example with channel G6 (Fig. 5.15), has been previously taken to be an indication of superimposition, and the hanging meanders G8 and G9 (Fig. 5.15), suggest a similar mode of formation. Sharp (1947), Hoppe (1950), Common (1957) and Price (1973) all believe that such crescentic or in-out channels, as they are also termed, were formed, ".... by meandering supraglacial or englacial streams that cut down through the ice on to the slope beneath" (Price, 1973, P. 113 - 114).

There is little indication of northward trending meltwater channels below 300 m.o.d., which suggests that regional control over meltwater drainage in this vicinity was replaced by drainage down local valley systems at approximately this altitude. Overall, the location and alignment of meltwater channels along the northern margin of Area III supports the suggested north-east direction of ice movement across this area and the importance locally of the Crawick valley as a major routeway for ice.

Two other channel systems A and B (Figs. 5.4, 5.14), located along the north-west margin of Area III adjacent to the Nith Valley, also lie/...

lie above 300 m.o.d., but were incised by meltwater following a south-east and not a northerly course. In this respect, systems A and B are more similar to systems L and T (Fig. 5.14), near the south-east margin of the area, and as such will be examined in this wider context.

Channel system T (Fig. 5.16), is incised across the upland edge of the Lowther foothills which separate Area III from Area II. T1 (Fig. 5.16), the highest channel in the system, is aligned across the crest of a ridge in a south-east direction, at approximately 320 m.o.d. The channel is 5m deep, with a flat peat-infilled floor 5 - 6m in width. The other channels in system T (T2 - T7, Fig. 5.16), are all incised into the flanks or floor of the north-west to south-east aligned glacial breach which separates East Morton Hill from Morton Mains Hill. The largest channel, T6 (Fig. 5.16), occupies the floor of the breach and is incised 9 - 10m into bedrock, with a floor 6 - 7m in width. All of the channel forms are located on the eastern side to the breach at its junction with the Kettleton valley and slope down in a south-east direction. Although not all of the channels and benches are wholly incised above 300 m.o.d., their common alignment and obvious close relationship resulted in their inclusion in the higher group.

By their location the channel forms of system T are similar to those of the previously mentioned system G, and as such are ice-directed. Once again superimposition of supraglacial and englacial streams, their depth of incision controlled by a zone of meltwater penetration, seems the most likely method of channel formation.

There/...

There can be little doubt that as previously, meltwater erosion was concentrated at a low point in the upland topography, with the largest channel found in the floor of the col as a result of lateral migration of meltwater in the ice (Clapperton 1968). The location and alignment of channel system T and also system L (Figs. 5.4, 5.14), indicate formation in association with an ice mass moving south-east down the Nith Valley. Adjacent channel systems with a similar alignment, but incised across the upland edge in Area II (Systems L, M, N, O, P, Q, Fig. 4.15), have been previously attributed to formation in association with Nithsdale ice, (Chapter 4). Consequently, channel systems T and L and indeed A and B in the north-west of Area III (Fig. 5.14), are also attributed to formation by supraglacial and englacial streams of the main Nithsdale ice mass, where ice overspilled into the Lowther foothills.

The high altitude channels of system X (Figs. 5.4, 5.14), also relate to formation in association with the Nithsdale ice mass, but in this vicinity the ice followed a south to south-west course. However, further east, the ice-surface gradient responsible for the formation of channel system P (Figs. 5.4, 5.14), was fundamentally different from that responsible for nearby system T. The channel floors of system P slope down in a westerly direction, indicating formation in association with ice emanating from the Lowther Hills into the Nith Valley in this vicinity.

Generally therefore, the higher group of meltwater channels in Area III, found above 300 m.o.d., are ice-directed in character and/...

and with the exception of system P, indicate formation by the superimposition of supraglacial and englacial streams produced in association with Nithsdale ice. Along the northern margin of the area, the surface gradient of the Nithsdale ice mass sloped down in a north to north-east direction across the Lowther foothills. However, within the main part of the Nith valley the dominant surface slope of the ice mass was south to south-east, parallel to the alignment of the valley itself. Locally, along the south-east margin in the vicinity of system P, channel formation took place in association with a Lowther ice mass.

(b) Lower Group of Channels Below 300 m.o.d.. The greater availability of meltwater at the later stages in downwastage of an ice mass, is well-illustrated by the fact that the majority of meltwater channels within Area III lie below 300 m.o.d.. However, the channel pattern is also much more complex at lower altitudes, for with the zone of meltwater penetration falling below the altitude of the flanking uplands, local relief conditions, as opposed to regional ice sheet conditions, have exerted the greater control over fluvioglacial erosion. The importance of relief in the development of channels at lower altitudes is clearly indicated by systems S and J (Fig. 5.14).

Channel system S (Fig. 5.16), is found along the south-east margin of Area III at the base of the steep scarp to the upland edge, across which channel system T is incised. The in-take of channel S1 (Fig. 5.16), at 213 m.o.d., is represented by a spectacular, steep-sided plunge-pool which is hollowed to a depth of /...

of 16 - 18m into bedrock (Plate 5G). Escaping meltwater left the plunge-pool downslope in a westerly direction, but after a short distance curved northwards across the regional slope in a channel 7m deep. The main channel is joined by a tributary, S2 (Fig. 5.16), which also possesses a well-developed plunge-pool. In this case however, the plunge-pool is found a short distance beyond the channel in-take at 213 m.o.d., but is only 6 - 7m in depth. S2 runs south as a steep-sided narrow form incised 10 - 12m into bedrock, but is left hanging 8 - 10m above the main channel floor at its outlet. Channels S3 and S4 (Fig. 5.16), both trend directly downslope from the main channel, at approximately 172 m.o.d., in the manner of subglacial chutes, the former terminating at 152 m.o.d., but the latter continuing further downslope to 128 m.o.d. S5 (Fig. 5.16), represents the continuation of the main channel S1 across the regional slope in a northerly direction. The floor of S5 has a slightly up-down profile, the channel form gradually fading away completely at approximately 178 m.o.d..

The location of channel system S vertically below system T, is a direct result of the disruptive influence of the north-south aligned upland edge on the meltwater drainage pattern during downwastage. As previously mentioned, channel system T was incised by the superimposition of south-east trending supraglacial/englacial streams into the floor and flanks of the glacial breach separating East Morton Hill and Morton Mains Hill. The depth of incision was controlled by an englacial water-table and lateral migration/...

migration of channels within the ice resulted in the concentration of incision into the floor of the breach itself (Stages A and B, Fig. 5.17). With further downwastage and the descent of the zone of meltwater penetration below the level of the lowest point along the upland edge, that is the floor of the glacial breach, the scarp in effect acted as a barrier to the through flow of meltwater. As a result, the water-table collapsed and concentrated meltwater flow plunged directly downslope to the foot of the scarp, where it encountered the underlying topography with considerable force and incised the plunge-pools mentioned above (Stage C, Fig. 5.17). Initially, this re-aligned system T, or system S as it is now known, flowed across the regional slope, but with further ice decay meltwater flow was re-directed downslope once more, towards the Carron valley floor.

Channel system J is also incised across the upland edge of the Lowther foothills, but in this case along the eastern margin of Area III, where the Mennock valley joins Nithsdale (Figs. 5.14, 5.18; Plate 5 H). The highest channel in the system, J1 (Fig. 5.18), is a deeply-incised chute form which runs down the steep northern flank of the Nith valley. The channel in-take is at 295 m.o.d. and it terminates abruptly downslope at 152 m.o.d.. Throughout its length the chute is incised to a depth of 16 - 18m, with a very narrow floor 2 - 3m in width. Moving west along the scarp face which overlooks the river Nith, channel J2 (Fig. 5.18), is very similar in character to J1. J2 has a gradual in-take at 235 m.o.d. and runs south across the edge and down the scarp face

as/...

as a chute form, to terminate again at approximately 152 m.o.d.. J3 (Fig. 5.18), represents a series of small interlinked channel forms incised across the crest of Druidle Hill in a southerly direction at approximately 243 - 250 m.o.d.. The channels are generally less than 4 - 5m in depth, 4m in floor width, and terminate either at the scarp edge or a short distance downslope.

Two of the largest and most spectacular channels in Area III are represented by J4 and J5 (Fig. 5.18). Both channels are deeply-incised into the low-lying area which separates Overtown Hill from Druidle Hill in a south to south-west direction. Channel J4 has its in-take at approximately 205 m.o.d. on the southern side of the Auchensow Burn. However, J6 on the northern side of the burn by its altitude and alignment, is believed to represent a former up-channel continuation of J4 and consequently the original in-take for the channel was slightly higher, at approximately 213 m.o.d.. Along the northern part of its course J4 has an up-down profile, but is only 6 - 8m in depth, with shallow sides and a flat floor 13 - 15m in width. At approximately 200 m.o.d. however, the channel floor abruptly descends 16m to a large plunge-pool. Down-channel from this plunge-pool the course is much more spectacular, being incised 25 - 30m into bedrock with a flat-floor 20 - 25m in width. This larger part to the course of J4 continues south-west for 450m. Evidence of large-scale meltwater erosion in association with the channel finally terminates at approximately 145 m.o.d., although smaller channel-forms are found below this altitude down to 130 m.o.d. (J8, Fig. 5.18).

Channel/...

Channel J5 (Fig. 5.18), has a twin in-take, both origins occurring at approximately 205 m.o.d. and both located on the southern side of the Auchensow Burn. In this case, there is no large-scale evidence for a continuation of meltwater incision in association with channel J5 on the northern side of the burn, although some of the minor forms of J7 (Fig. 5.18), were perhaps feeders. The long-profile of J5 is smooth in comparison to that of J4, with no abrupt steps in the floor of the channel. Instead, there is a gradual increase in the depth of incision as the channel is followed south-west. Where best-developed, J5 is also incised 25 - 30m into bedrock, with steep-sides and a floor 15 - 25m in width. The channel terminates abruptly at approximately 155 m.o.d., 9 - 10m above the floor of J4, the two channels linked by only a small, steep-sided gorge. J9 and J10 (Fig. 5.18), represent a series of small channel forms incised across the crests of Overtown Hill and Mennock Hill Heights, at approximately 213 m.o.d.. The two groups of channels, both trending south-westwards and generally less than 4 - 5m in depth, were probably incised by the same meltwater streams. The lowest channel in the system, (J11, Fig. 5.18), is deeply-incised into bedrock between Overtown Hill and Kiln Hill, again in a southerly direction. The channel in-take is at approximately 155 m.o.d. and it terminates at 137 m.o.d.. Although short in length and of limited altitudinal range, J11 is incised to a depth of 20 - 30m and has a steeply-sloping floor 20 - 25m in width.

The channels of system J follow a fundamentally different course

from/...

from that previously identified as being typical of Nithsdale as a whole. Generally, at higher altitudes, and also at lower altitudes as indicated on figure 5.14, the meltwater channels of the Nith valley follow courses between east and south, parallel to the alignment of the valley itself and the direction of ice movement. However, the channels of system J are aligned at right-angles to the majority of the channels in Nithsdale and follow a south to south-west course. There are two possible reasons for this :-

(1) Locally during downwastage, the ice-surface gradient over this part of the Lowther foothills, which was adjacent to the zone of confluence between the Nithsdale and Lowther ice masses (Fig. 4.25), sloped down in a south-west direction.

(2) South-east trending meltwater in Nithsdale ice, occupying channels located beyond the upland edge at altitudes generally below 300 m.o.d., was forced more directly southwards and indeed south-westwards by the manner in which the Lowther foothills just out into Nithsdale itself at this constricted part of the valley. The north-south aligned Auchensow Hill - Dalpeddar Hill ridge which lies entirely above 315 m.o.d. would, with the lowering of the zone of meltwater penetration, effectively act as a barrier to the continued south-east flow of meltwater (Figs. 5.2, 5.4, 5.19).

It may well be that both factors have worked together in the establishment of system J. Furthermore, it seems likely that at the later stages of downwastage, extraglacial meltwater descending the Mennock valley also augmented the existing southerly flow.

However/...

However, as before, it is suggested that most of the channels were incised subglacially by the superimposition of supraglacial/ englacial drainage onto the underlying topography. As indicated on figure 5.19, with the initial re-direction of meltwater drainage southwards, the highest channels were incised by a series of small independent streams (Stage 2, Fig. 5.19). With continued down-wastage and the lateral migration of the drainage network downslope in a generally westerly direction, meltwater became concentrated into the two large channels J4 and J5, which occupy a low point along the scarp edge between Overtown Hill and Druidle Hill (Stage 3, Fig. 5.19). The depth of incision of all these early channel forms was apparently controlled by an englacial water-table at approximately 152 m.o.d.. At a later stage in deglaciation, meltwater drainage was concentrated over the Mennock valley itself. Channel J11 (Fig. 5.18), between Kiln Hill and Overtown Hill, represents the most direct route from the Mennock to the Nith valley for southward flowing meltwater and was incised by englacial and extraglacial streams during this late-period (Stage 4, Fig. 5.19).

Local relief conditions were also of fundamental importance in the establishment of channel systems Y and Z (Figs. 5.4, 5.14), along the south-west margin of Area III. The generally downslope alignment of these channel systems and their close association with fluvioglacial depositional landforms, indicated that the Druidhill and Burnsands valleys respectively were occupied by stagnant ice masses which wasted away in situ. However, the fluvioglacial landforms in these valleys, both erosional and depositional, are examined/...

examined in greater detail in the section devoted to fluvioglacial deposition.

In the Nith valley itself, there is also ample evidence of channel development towards the later stages of downwastage in close association with drift deposits. As indicated on figure 5.14, both lower flanks of the valley below 182 m.o.d. are scarred by numerous short and generally discontinuous channel forms. However, even at this late-stage in downwastage, local relief conditions exerted a strong influence on channel development, with by far the greatest concentration of channels found on the gentler sloping southern flank of the valley. Channel system BB (Fig. 5.20), typifies the forms which are found here (Plate 51).

Two of the highest channels in the system, BB1 and BB2 (Fig. 5.20), share the same in-take at 185 m.o.d.. BB1 runs across the regional slope in an easterly direction for a short distance. It is only incised to a depth of 3 - 4m and it terminates abruptly at 175 m.o.d.. BB2 runs more obliquely downslope and is 6 - 7m deep with a flat floor 7 - 8 m in width. The higher southern side to this channel is incised into bedrock, but the less steeply-inclined northern flank appears to be incised wholly into till. BB2 terminates at 170 m.o.d., but 100m beyond this outlet, the similar altitude and alignment of channel BB3 (Fig. 5.20), strongly indicates that meltwater flow continued its easterly course downslope via this channel. BB3 is a larger form than BB2, being incised to a depth of 8m, with a floor 12 - 15m in width. As before, the southern flank of the channel is the more deeply-incised. BB3 is also a fairly short form/...

form, and after running obliquely downslope for 450m, terminates at 159 m.o.d.. Once again however, only a short gap separates the outlet of BB3 from the in-take of BB4 (Fig. 5.20), and the latter channel has continued meltwater drainage down to the floor of the Nith valley. BB4 is the most deeply-incised of the 4 forms in this discontinuous series, with 5m of drift revealed overlying 4m of bedrock in the channel sides. Several outlets for the main channel are found incised between/through mounds of till and sand and gravel adjacent to the Nith floodplain, these being utilised at different periods during ice decay.

Channel BB5 (Fig. 5.20), is very similar in its alignment, but much more continuous in its form to the channels immediately upslope. The principal in-take to the channel is at 167 m.o.d. and as before, meltwater has followed an oblique course downslope in an easterly direction towards the Nith valley floor. Meltwater was also supplied from a more northerly source via channel BB6. Although a continuous form, both sides to the channel are not evident throughout its length, with only the more deeply-incised southern flank represented in places. Throughout its length the channel appears to be entirely incised into drift deposits. Along the lower part of the channel course, meltwater flow was again concentrated between/through till and fluvioglacial mounds, evidence of incision finally terminating as before at the Nith floodplain.

Channels BB7 - 8 and BB9 - 10 (Fig. 5.20), are very similar to the forms previously described. As before, the channels have their in-takes at altitudes between 167-182 m.o.d. and run obliquely/...

obliquely and discontinuously downslope, gradually increasing in size to finally terminate at the Nith floodplain. The channels are incised into drift deposits throughout most of their length and adjacent to the floodplain itself again follow courses between/through glacial and fluvioglacial mounds. Parts of the channel courses, often near the in-take, are represented by bench and not channel forms. Therefore, the alignment and altitude of all the channels in system BB suggest that they were incised under similar conditions at approximately the same period during deglaciation.

Channels of a similar nature to those in system BB are not as common on the northern flank of the Nith valley, but can still be identified at several scattered localities, as for example at the mouth of the Crawick valley (System I, Fig. 5.21). The higher channels of system I, although initially running parallel or at a low angle to the local contour pattern, tend to be mainly directed downslope towards the valley floor. I1 (Fig. 5.21), with twin in-takes at 180 and 195 m.o.d., is deeply-incised through till into bedrock to a depth of 8m, with a flat floor 10 - 15m in width. The channel terminates abruptly at approximately 159 m.o.d. where it joins I3 (Fig. 5.21). I3 is a well-developed up-down form which runs at right-angles to I1, curving in a south to south-east direction across the regional slope. It is incised mainly into till around a large bedrock/till mound and where best-developed is over 9m deep, with a flat, peat-infilled floor 15 - 20m in width. The in-take of channel I3, at approximately 152 m.o.d., lies 4 - 5m above the floor of the larger channel I5 (Fig. 5.21). The channel/...

channel outlet lies only a few metres below this altitude, but near the outlet the channel curves more directly downslope towards the valley floor. Channel I4 (Fig. 5.21), is similar to I3 in a number of ways. I4 also curves across the regional slope, around a large mound, in a south-east direction and possesses an up-down long profile. Furthermore, the channel in-take is at approximately 156 m.o.d., 3 - 4m above the floor of I3, and the outlet of I4 occurs at 145 m.o.d.. As before, meltwater flow was focused more directly downslope towards the valley floor near the channel outlet. I4 is incised 6m into till and has a flat floor 10 - 15m in width.

Adjacent to the Crawick Water itself, I5 (Fig. 5.21), is also very similar in character to I3 and I4. This channel has its in-take at 145 m.o.d. and runs south-east across the regional slope from the remnants of kame terrace forms flanking the Crawick valley at approximately the same altitude. The channel is incised to a depth of 10m, mainly into drift, with a wide, flat floor 30 - 40m in width. Once again this channel curves around a large bedrock/till mound, to terminate at approximately 137 m.o.d. in the floodplain of the river Nith. Other minor channels, I6, I7, I8 (Fig. 5.21), are found directed downslope in the manner of subglacial chutes between fluvioglacial mounds and kettle holes.

Basically, the channels of system I are similar in character to those of system BB and were produced at approximately the same period in downwastage. However, there was a greater tendency for meltwater to be directed down, rather than across, the steeper and more irregular topography of the northern valley flank.

Channel/...

Channel systems BB and I, and the other similar forms incised across the lower flanks of the Nith valley (AA, CC, DD, EE Fig. 5.14), are described by Simpson and Richey (1936) as, ".... numerous well-defined marginal drainage channels sloping down to the east and formed along the sides of the valley glacier as it retreated westwards" (P. 94). Working in the Nith valley to the south of the thesis area, Stone (1957, 1959) also attributed the formation of channels "... which flow almost parallel to the contours ..." to "... meltwater flowing along a glacier margin...." and speculated that "... successive channels appear to represent stages in downwastage, each halt in recession marked by a channel cut through drift and solid rock" (Stone, 1959, P. 168). Although there is some disagreement as to the exact mode of retreat of the ice mass, both Stone and Simpson/Richey concur with the belief that the channel patterns were incised in close proximity to the ice margin. The possibility of such channels being produced in an entirely marginal location however, has been previously discussed in relation to Area I, and consequently it seems more likely that the majority of the forms found over the lower slopes of Nithsdale were incised submarginally. The oblique alignment of the channels downslope and their general discontinuity, both well-illustrated by system BB, tend to reinforce this belief.

In the light of previously related findings in Areas I, II and III, as well as in other parts of Scotland, the theory of general downwastage (as suggested by Stone), as opposed to backwastage (as suggested by Simpson/Richey), is the more acceptable. However, with the uncertainty over the exact environment of channel formation, it/...

it is not possible to correlate successive channels running across a hillslope with stages during downwastage.

Consequently, all of the channels across the lower flanks of the Nith Valley were incised in the marginal zones of a decaying ice mass during the later stages of downwastage, most likely by combined supraglacial/englacial and extraglacial meltwater flow. As mentioned, local relief conditions were again important, the greatest channel concentrations found across the gentler southern flank of the valley. As Sissons (1967a) stated, "... on till-covered slopes of gentle or moderate gradient, small channels may occur in great numbers and form complex interconnected systems" (P. 103).

The principal direction of the submarginal drainage at this late-stage was obliquely downslope towards the valley floor in a generally easterly direction, which indicates that throughout the period of downwastage, meltwater flow over much of Nithsdale was directed in an east to south-east direction, parallel to the alignment of the valley itself. Furthermore, the similar outlet altitudes of several channels along the northern side of the valley, J1, J2, J4, J5 (Fig. 5.18) and I1 (Fig. 5.21) all terminate at approximately 152 m.o.d., suggests that the depth of incision of streams flowing towards the valley floor was controlled by an englacial water-table. At the mouth of the Crawick valley, control of fluvioglacial activity by an englacial water-table is further supported by the occurrence of kame terrace forms, also at 152 m.o.d.. In fact, it would appear that channels I3, I4 and I5 (Fig. 5.21), acted as overflow channels for the temporary lakes in which the terraces accumulated, as indicated on figure 5.22 (Plate 5J))./...

(Plate 5J).

On the southern flank of the valley however, there is more limited evidence of an englacial water-table controlling fluvioglacial processes at 152 m.o.d.. Small terrace forms are found at this altitude at the outlets from two channels in system AA (Fig. 5.4), but the evidence from other channel forms is less convincing. Where the direction of meltwater flow was oblique to the hillslope, there is generally only a short gap in the channel form, the replacement of a channel with a bench, or occasionally no indication at all of any control over fluvioglacial erosion at an altitude of 152 m.o.d. (System BB, Fig. 5.20). It can only be assumed that as a result of relief and/or glaciological conditions, the meltwater streams aligned more directly downslope on the northern valley side became incised to the altitude of 152 m.o.d. at an earlier stage in downwastage than those trending obliquely across the southern flank. Consequently, by the time that many of the meltwater streams on the gentler southern flank descended to this level, any control over the depth of incision was severely weakened, or had disappeared altogether, such that incision continued through/between fluvioglacial and glacial deposits to the valley floor. Alternatively, some of the more continuous channel forms, such as BB5 and BB7 (Fig. 5.20), were perhaps incised by supraglacial or extraglacial streams descending the Euchan valley at a late-stage in ice decay, well-after the collapse of the englacial water-table.

Despite the uncertainty over the amount of control exerted by an englacial water-table in the final stages of ice decay, there is little doubt that throughout the later stages of downwastage meltwater/...

meltwater was directed downslope through the ice mass towards the floor of the valley itself. It therefore seems likely that as in Moffatdale, the subglacial and englacial drainage network formed a three-dimensional tunnel pattern within the ice, leading down to a subglacial master tunnel which ran along much of the length of Upper Nithsdale. Although in Moffatdale there were no borehole records to support or refute the former existence of a master tunnel, the situation in Upper Nithsdale, with the presence of coal seems in the underlying Carboniferous strata, is entirely different. Geikie et al (1871), first made reference to, ".... former river courses .... found under the drift in the course of mining operations ...... In the valley of the Nith to the west of Kirkconnel, a series of borings showed the existence of a deep trench worn out of the Carboniferous rocks and filled up with boulder clay (till)...... A little to the east of Sanquhar a similar buried water-course was encountered...... and in this instance sand was found to lie between the boulder clay and the rocks below" (P. 39). More recently, Lumsden and Davies (1965) mapped the extent of the "buried channel of the river Nith" from the borehole date available (Fig. 5.23). The channel, which extends across the Southern Uplands fault is generally a few hundred metres across, although it widens to a kilometre around New Cumnock. It is infilled with drift deposits to a maximum thickness of 53m, these consisting mainly of sands and gravels varying in thickness up to 40m and overlain by till as much as 20m thick. Lumsden and Davies consider, but dismiss, glacial erosion as the cause of the buried feature and conclude instead that/...

that it is a preglacial river course. They further believe, from the gradient of the base of the buried channel (Fig. 5.23), that movement of the Southern Uplands fault, with downthrow to the north-west of 50 - 60m, occurred late in the history of the Nith river system but prior to the last glaciation of the area.

However, the downslope alignment of channel forms along the lower flanks of Upper Nithsdale towards an unknown base-level in mid-valley allows an alternative mode of formation to be suggested; that the portion of the buried channel that lies to the east of the Southern Uplands fault was incised by concentrated subglacial meltwater activity. It would certainly appear that if not entirely the result of subglacial fluvioglacial erosion, the buried Nith channel was at least modified by such action. The fact that south-east flowing meltwater incised a channel which, to the east of the fault, is most prominent in the Sanquhar Basin itself, tempts the suggestion that the less resistant Carboniferous strata have facilitated fluvioglacial erosion. Alternatively, the proven extent of the buried channel, depicted on figure 5.23, may merely reflect the distribution pattern of boreholes in Upper Nithsdale. It may well be the case that the two portions of the buried channel developed independently; the larger and wider portion to the west of the Southern Uplands fault reflecting after all the influence of glacial erosion, as originally suggested by Lumsden and Davies. However, Holden (1977) indicated a similar east to south-east movement of meltwater to that in Area III for the area to the west of New Cumnock. This tends to suggest that the two parts of the buried channel may indeed have been linked and formerly occupied by a major/...

major subglacial master channel into which meltwater from Upper Nithsdale was focused.

SUMMARY. Regional control over fluvioglacial erosion was much more limited below 300 m.o.d. than at higher altitudes. With the descent of the englacial water-table below the altitude of the flanking uplands, local relief conditions played a much more important role in the establishment of the meltwater channel pattern. As a result, the lower group of channels is not as strongly ice-directed in character as the higher group and locally follow courses fundamentally different from the regional directions of ice and meltwater movement. This local re-alignment of meltwater flow is most evident in the more rugged topography along the north and south-west flanks of Nithsdale. However, over a large part of the valley the direction of meltwater flow remained south to south-east, generally parallel to the direction of ice movement, throughout the period of downwastage. Such channels are best-developed across the more gently sloping southern flank of the Nith valley, while the superimposition of supraglacial and englacial streams supplemented by extraglacial meltwater took place. Once again there is evidence to suggest that the depth of meltwater incision was controlled by an englacial water-table, but only down to an altitude of approximately 152 m.o.d.. At the later stages of downwastage, with the collapse of the englacial water-table, extraglacial, supraglacial, englacial and subglacial drainage became concentrated in a subglacial channel at the base of the stagnant ice mass occupying the floor of Nithsdale. All of the channels below 300 m.o.d., with the possible exception of system J (Fig. 5.14), were incised in association with Nithsdale ice. Figure 5.24 indicates the general pattern of meltwater drainage both above and below 300 m.o.d. over Area III.

5.7 FLUVIOGLACIAL DEPOSITION

Fluvioglacial deposits and depositional landforms in Area III, like their glacial counterparts, are best-developed along the floor and lower flanks of the Nith valley (Figs. 5.4, 5.25). In Nithsdale, there is abundant evidence of sand and gravel deposits between 137 - 243 m.o.d. and particularly below 182 m.o.d., often in close association with the previously mentioned dense channel network. Away from the principal valley, more limited accumulations of sand and gravel are found at similar altitudes in certain of the tributary valleys to the Nith (Fig. 5.25), again in close association with channel forms. As before, in an attempt to aid explanation of the distribution pattern of the fluvioglacial deposits, their mode of formation and the nature of deglaciation over Area III as a whole, more detailed examination of the character and morphology of the deposits at several of the sites depicted on figure 5.25 will be made. In this respect, the smaller accumulations in the tributary valleys will be briefly examined prior to the main spread in Nithsdale itself.

Burnsands Valley. Fluvioglacial deposits in the Burnsands Valley (Figs. 5.4, 5.25), although limited in extent, are typical of all the tributary valleys, and clearly indicative of the nature of ice wastage during the later stages of deglaciation (Fig. 5.26). The depositional landforms depicted on figure 5.26 consist solely of a kame terrace and an esker ridge. The kame terrace (Terrace A, Fig. 5.26), is found on/...

on the southern side of the valley at approximately 213 m.o.d.. The surface to the terrace is 80m wide and it has a steep north face 7 - 8m in height. Small exposures in this face reveal numerous sub-rounded and sub-angular clasts in a loose, gravelly matrix. A second terrace (Terrace B, Fig. 5.26), is also perched along the lower southern flank of the valley again 7 - 8m above the floodplain of the Burnsands Burn, but at the slightly lower altitude of 190 m.o.d.. However, this lower terrace differs from terrace A in two major respects. Firstly, exposures in the face of terrace B indicate that it consists of a stiff, reddish-dark brown till, and secondly, terrace B has an esker ridge running across its surface (Fig. 5.26). The esker in fact begins further upslope, emerging from the valley-side at approximately 216 m.o.d.. It runs almost directly downslope, gradually increasing in size, and only becomes sinuous across the surface of the terrace itself (Plate 5K). Where best-developed, the esker stands more than 8½m above the till terrace and is incised by the Burnsands Burn to reveal numerous sub-angular and sub-rounded pebbles in a coarse, gravelly matrix. A high percentage of the clasts are sub-angular in shape and tend to be less than 1 - 2cm in diameter, although forms up to 60cm in diameter are also present.

The depositional landforms have developed in close association with channel system Z, incised across the southern flank of the Burnsands valley (Fig. 5.26). All of the channels in this system start/...

start abruptly, with their in-takes between 195 - 274 m.o.d. and trend either directly or obliquely downslope towards the valley floor. Several of the in-takes are characterised by deeply-incised semi-circular plunge-pools, for example Z1, Z8, Z10, Z11, (Fig. 5.26), while Z3 has a plunge-pool part of the way along its length. Channel Z1 (Fig. 5.26), the largest in the system, is incised into bedrock to a depth of 20 - 22m, but as with adjacent forms Z2 and Z3, meltwater incision terminated downslope at approximately 213 m.o.d.. Similarly with channels Z6, Z7, Z8 and Z9 (Fig. 5.26), meltwater erosion terminated abruptly at approximately 213 m.o.d.. Channel Z5 (Fig. 5.26), directly upslope from the esker ridge, also appears to have initially terminated at this altitude, but then continued downslope to the valley floor at a later date.

The landforms of both fluvioglacial erosion and deposition in the Burnsands Valley are strongly indicative of formation in association with a stagnant and decaying ice mass, which downwasted in the valley itself. The direction of ice movement and meltwater drainage at higher altitudes in this vicinity was generally south to south-east (Figs. 5.7, 5.24). However, with the onset of deglaciation and descent of the zone of meltwater penetration below the altitude of the uplands flanking the Burnsands valley, the englacial water-table collapsed and locally, free downslope movement of meltwater onto the less steep southern flank of the valley was established. This resulted in the characteristic subglacial chute-form exhibited by all of the channels/...

channels in system Z, in places accompanied by plunge-pool in-takes. However, the similarity in altitude of many of the chute outlets with that marking the upslope limit of fluvioglacial deposits, strongly indicates that locally an englacial water-table was re-established at approximately 213 m.o.d.. Kame terrace A was apparently supplied by channel Z3 (Fig. 5.26), while channel Z5 was the main feeder for the esker ridge at this time. The ridge itself is typical of previously mentioned subglacially-engorged or slope eskers in that it represents the infilling of a subglacial chute (Embleton and King, 1975, P. 476). Such forms are generally produced, ".... at an advanced stage of ice disintegration when their orientation is controlled above all by local topography .... They are shorter and straighter than normal eskers and because of their situations, they are seldom destroyed by proglacial meltwater erosion ......" (Sugden and John, 1976, P. 331). With the final collapse of the englacial water-table, meltwater in the residual ice mass was directed towards the valley floor, as indicated by channels Z5, Z10, Z11 (Fig. 5.26), and no doubt left the valley in an easterly direction. Meltwater drainage late in the glacial period and in postglacial times may well have destroyed other depositional landforms, glacial as well as fluvioglacial. Consequently, the fluvioglacial landform assemblage in the Burnsands Valley is essentially the result of local relief conditions disrupting the regional pattern of ice down-wastage and leading to the detachment of a residual ice mass which decayed in situ.

The/...

The fluvioglacial landforms and deposits in the three tributary valleys, Marr, Druidhill and Carron (Figs. 5.4, 5.25), indicate that conditions of ice wastage at each of these localities were essentially similar to those described above for the Burnsands valley. As a result of local relief conditions, stagnant ice masses again became detached during the later stages of downwastage in each of the three valleys and wasted away in situ. Consequently, the fluvioglacial landform assemblages found here owe their distinctive morphological characteristics to the control exerted by local topography over meltwater conditions in extensively decayed ice masses.

Similar conditions of downwastage to those described in the tributary valleys were responsible for the deposition of the fluvioglacial landforms in the Nith valley itself. For the purposes of more detailed examination, the isolated accumulations along the northern flank of the valley will be looked at separately from the more continuous spread along the floor and lower southern flank (Figs. 5.4, 5.25).

Todholes. At Todholes(Fig. 5.25), which lies at the foot of the scarp slope delimiting the upland edge of the Lowther Hills along the northern flank of the Nith valley, there are two well-developed kame terrace forms (Fig. 5.27). The higher of the terraces (Terrace A, Fig. 5.27), at approximately 250 m.o.d., is a narrow form which extends across the slope parallel to the upland edge for 600m. There is no clearly distinguishable ice-contact slope to the terrace as locally deposition has taken place against a bedrock mound, but exposures indicate/...

indicate that 6 - 7m of sand and gravel are present. The pebbles are mainly sub-rounded forms, less than 4cm in diameter, in a coarse, gravelly matrix. The lower terrace (Terrace B, Fig. 5.27), has a sloping surface and extends more down than across the regional slope, between 235 - 213 m.o.d.. It is approximately 650m in length, but also 200 - 250m in width. There is a steep south-west face to the terrace, 6 - 7m in height, and the nature of the deposits is well-exposed here along the course of the Spout Sike. Numerous sub-rounded and sub-angular pebbles are revealed, again in a coarse, gravelly matrix. The majority of the pebbles are less than 4cm in diameter, but forms up to 15 cm are also present. The pebbles are poorly-bedded, but lenses of sandy-clay and fine gravel are also exposed in the face. By their alignment, such features indicate that meltwater responsible for deposition flowed from a north-east direction.

Both terraces A and B formed in small lakes at the margin of the downwasting Nithsdale ice mass. Their altitude and location at the upland edge, indicate that they were laid down at a fairly early stage of decay when a considerable mass of ice still remained in the centre of the valley. The depositing meltwater streams may have been supraglacial, englacial or subglacial, but the deeply-incised nature of the Spout Sike and Grain Burn across the upland edge strongly suggests that extraglacial meltwater following these courses was also of major significance. There is no clear indication as to how the small lake in which terrace A was deposited drained but, an indistinct channel leading south-east from the terrace suggests that if meltwater did not escape directly into the ice itself, it followed/...

followed this more marginal route. The deeply-incised nature of the Spout Sike beyond the southern edge of terrace B, strongly suggests that in this case meltwater escaped subglacially, towards the present course of the Polbower Burn.

Nith Valley Floor. Fluvioglacial deposits near the Nith valley floor extend discontinuously down both sides of the river for approximately 16km from the north-west margin of Area III (Figs. 5.4, 5.25). As previously mentioned, these are best-developed on the more gently-sloping southern flank of the valley and also where the valley floor is widest, disappearing completely downstream of Mennock, where the floor width is drastically constricted. The landorm assemblage depicted on figure 5.4, is basically similar in character, although more extensive in distribution, to the irregular topography of mounds, ridges and meltwater channels in the Burnsands and/or Carron valleys. However, although more extensive, it remains equally difficult to distinguish any pattern to the depositional landforms, and indeed it is often difficult to be certain that a particular mound or ridge form consists wholly of sand and gravel.

As indicated in table 5.1, the basal till deposit exposed over the floor and lower valley flanks of Nithsdale is occasionally overlain by a second till unit, which is generally less compact than the lower unit and contains a higher percentage of clasts. With limited field exposures, this upper or ablation till is often difficult to distinguish from unstratified and unsorted sands and gravels, particularly where there is a high percentage of sandstone/...

sandstone clasts in the matrix, as at Old Mains (Site 5E, Fig. 5.4; Table 5.1). To further complicate matters, the ablation till overlies sand and gravel accumulations in some localities, a fact referred to by Stone (1957) further down the Nith valley, "Above the stratified drift there is often 1 - 3 feet (35cm - 1m) of superglacial till (ablation till)....." (P. 54). Consequently, the limits of fluvioglacial deposits depicted on figures 5.4, 5.25, often based on morphology alone, are by definition tentative. It would be wrong however, to assume that the floor and lower flanks of Nithsdale are entirely covered by a thin layer of ablation till and it should be stressed that the extent of this deposit is highly localised.

Good exposures of sand and gravel are nevertheless visible in this area. At Site 5H (Fig. 5.28), a large, terrace feature bounded by a steep ice-contact slope on its northern side, is incised by the Polmeur Burn to reveal 5 - 6m of poorly-bedded pebbles in a gravelly, in places slightly clayey, matrix (Plate 5L). Most of the pebbles exhibit some degree of rounding and are generally less than 3cm in diameter, although forms up to 20cm are also present. Nearer the valley floor, at Site 5J (Fig. 5.28), incision by the Polneul Burn has similarly revealed 4 - 6m of sub-rounded and sub-angular clasts in a coarse, sandy matrix. The pebbles at this exposure are unsorted and unstratified, but generally less than 2cm in diameter, although larger forms up to 30cm in diameter can be found. At Site 5J, the fluvioglacial deposits overlie a stiff dark brown till.

The borehole information, depicted on figure 5.8, gives further insight as to the occurrence and thickness of fluvioglacial deposits/...

deposits near the valley floor. This diagram would appear to suggest that generally only a thin layer of sand and gravel overlies till. However, it also re-stresses the complicated interrelationship of the drift deposits along the valley floor and reveals that the greatest thicknesses of fluvioglacial deposits are found at depth. A maximum thickness of 19m of sand and gravel is found below the Nith valley floor in this area. Returning to the landform assemblage across the floor and lower southern flank of the Nith depicted on figure 5.28, although no pattern is identifiable, individual landforms can be readily distinguished. Near the upslope limit of the fluvioglacial deposits, a discontinuous ridge form (Ridge A, Fig. 5.28), runs obliquely across the valley flank in a north-east direction for several hundred metres. The ridge begins abruptly at 230 m.o.d. and as it is followed downslope bifurcates, both segments terminating at approximately 213 m.o.d.. It is 8 - 10m in height and sections revealed by stream incision show that it consists entirely of badly slumped, poorly-bedded sands and gravels resting upon bedrock. The majority of the pebbles are sub-rounded in shape and less than 3cm in diameter. The morphology and internal constituents of ridge A indicate that it is an esker. The eastern section of the esker terminates just below the previously referred to large fluvioglacial terrace. The terrace (Terrace B, Fig. 5.28), extends across the slope for approximately 900m, varying in width between 100 - 300m. The surface of the form slopes only slightly northwards at 2 - 3^{o}, but the northern edge is marked throughout its length by a steep ice-contact slope 7 - 9m in height.

Along/...

Along the north-west edge of the terrace, closest to the esker ridge, 4 kettle holes 2 - 4m in depth disrupt the otherwise fairly level nature of its surface. This extensive landform is another kame terrace which has accumulated in a small lake along the southern margin of the decaying ice mass over Nithsdale. A meltwater stream following the course of the esker, ridge A, would appear to have supplied at least part of the sediment which accumulated in this lake. The absence of meltwater channels in the vicinity of the kame terrace suggests that drainage of the lake took place through the ice mass itself. This large kame terrace is the most extensive of several widely scattered forms found along both flanks of the Nith.

Along the floor of the valley, generally below 182 m.o.d., the fluvioglacial deposits are concentrated between and across the lower flanks of the larger drumlin forms found here, as irregular spreads or groups of small hummocky mounds (Figs. 5.4, 5.28). The relative relief values in this kame and kettle-like topography are generally less than 4m. Meltwater flow was also concentrated between the drumlins however, but in such an irregular landscape it is impossible to state conclusively whether the role of meltwater at a particular locality was erosional or depositional. Nevertheless, although the topography in the immediate vicinity of the valley floor is chaotic, it is still readily apparent that there are no clearly-defined crescentic trends to the mound forms as suggested by Charlesworth (1926 a). Charlesworth stated, "Sand and gravel moraines cover the broad floor of the Nith valley over the stretch between Sanquhar and New Cumnock. Below Sanquhar the/...

the crescentic and concentric ridges curving along the hillside are convex to the south, while between Old and New Cumnock they are convex to the north; the change in the direction of convexity appears to take place east of Kirkconnel" (P. 14). Charlesworth attributed these supposed moraine ridges, his "Kirkconnel Series", to the "... Minnoch stage of retreat of the Nith glacier" (P. 14). All of the ridges in the vicinity of the Nith valley floor are short esker forms, believed to relate to a general period of downwastage, and not a specific stage in backwastage. As mentioned previously, there is no indication of moraines anywhere in Area III. Indeed all of the fluvioglacial landforms and deposits in this area relate to an advanced stage in the decay of the downwasting ice mass over Nithsdale. The early stages of downwastage were marked by the marginal terrace accumulations at Todholes and along the higher southern flank of the Nith valley, but it is only when the zone of meltwater penetration in the extensively decayed and crevassed residual ice mass collapsed, at an altitude of approximately 152 m.o.d., that meltwater was directed freely downslope and widespread fluvioglacial deposition could occur (Plate 5M). The fluvioglacial mounds and hollows which developed at this late-stage in ice decay are termed "ice-disintegration features" by Clayton (1964), and have been similarly described by other authors (J. Gjessing 1960; Sollid 1963-64; Sissons 1967a, P. 108-124; Sugden 1970; Sugden and John, 1976, P.333 - 336). They formed in ice-marginal, subglacial, englacial or supraglacial situations, wherever cavities happened to be available for the receipt of water-borne sediment. As a result, it is not surprising to find that such landforms/...

landforms tend to accumulate in close association with deposits of ablation till and that there is, "... often so much mixing of till and fluvioglacial materials..... that differentiation becomes impossible" (Sugden and John, 1976, P. 333). However, the concentration of meltwater downslope towards the valley floor did not always result in deposition. Extensive erosion of the fluvioglacial deposits also took place at this time and this is a major reason for their present discontinuous distribution and often limited thickness. Although the englacial water-table had collapsed, the low base-level of the master channel along the floor of the Nith valley resulted in incision and not deposition over parts of the lower flanks, as evidenced by the extensive channel networks developed in drift deposits.

Further support for the Nith Valley as a major focus of meltwater drainage during the later stages of downwastage and also for the presence of a residual ice mass occupying the floor of the valley at this time, is supplied by Simpson and Richey (1936). "At Sanquhar, abundant pebbles of Spango granite in the gravels derived from the Crawick valley, show that the materials here were to some extent obtained from sources in the hills adjoining the Nith valley which must have been in part at least, free of ice during the retreat of the Nith glacier" (P. 94). Indeed, several stages in downwastage are indicated by kame terrace forms in the Crawick valley, the altitude of the terraces increasing with movement north-east up the valley from its confluence with the Nith (Figs. 5.4, 5.21, 5.25).

SUMMARY. The fluvioglacial deposits along the Nith valley/...

valley floor, as in other parts of Area III, relate to formation in association with a stagnant ice mass which downwasted in situ. At the time of greatest deposition, an extensively decayed and crevassed residual mass of ice extended for several kilometres along the Nith Valley bottom. The most wide-spread accumulations of sands and gravels were laid down on the gentler valley slopes and in hollows between drumlin forms. However, meltwater flow directed towards the valley floor was also concentrated in such localities, and as the Nith valley remained an important routeway for the dispersion of meltwater throughout the later stages of ice decay, the survival of fluvioglacial deposits was strongly dependent upon the length of time that a particular channel was utilised. In some localities, the fluvioglacial deposits were completely removed to be re-distributed further down-valley and as a result scoured basal till now represents the surface deposit.

5.8 CONCLUSIONS

As in Areas I and II, the glacial and fluvioglacial landforms and deposits of Area III indicate the main sources and directions of movement of the last major ice sheet to cross the area. The increased diversity of geological conditions in and around Area III and the extensive development of drift deposits in this essentially low-lying area, enabled a far greater use to be made of distinctive erratics in the determination of the pattern of ice movement. The nature of ice wastage from its maximum extent is also suggested.

(1) Almost all of Area III was crossed by ice from an external source following an east to south-east course, much of this ice entering the area via the head of the Nith valley (Fig. 5.7)./...

(Fig. 5.7). Along the northern margin of the area however, ice streams followed a north to north-east course across the Lowther foothills and into the Upper Clyde drainage basin. From the alignment of landforms of glacial erosion and the occurrence of erratics in drift deposits, the main source for the ice mass appears to have lain in the western Southern Uplands, in the hills surrounding Loch Doon (Sissons 1967a, 1976; Holden 1977).
Locally, along the south-east margin, a small part of Area III may have been crossed by Lowther ice following a generally southerly course (Fig. 5.24). Any such Lowther ice merged with the main Nithsdale ice mass over Area III to flow south-eastwards.

(2) Glacial striations, roches moutonnees (Fig. 5.5), and evidence from the erratic content of tills and till fabrics (Figs. 5.9, 5.10), all indicate that the Nith valley was the major routeway for ice crossing Area III, the direction of ice movement generally following the alignment of the valley itself. This dominantly south to south-east movement of ice extended beyond the confines of the Nith valley into the foothills of the flanking uplands.

(3) Evidence of glacial breaching and fluvioglacial erosion are found at altitudes exceeding 457 m.o.d. which, when taken into consideration with the fact that most of the hill and ridge crests flanking Nithsdale are streamlined in form, strongly indicates that Area III was completely covered by ice during the/...

the last major glaciation.

(4) There is extensive evidence of deposition both glacial and fluvioglacial in Area III. Borehole information indicates that both till and sand and gravel are thickest at depth below the floor of the Nith valley. Only one basal till is found in the area, but at localities near the valley floor, a thin layer of ablation till occasionally overlies this lower unit.

(5) The meltwater channel pattern over Area III is dense (Fig. 5.14), but can be divided into two distinctive groups on the basis of altitude. A higher group of channels, found above 300 m.o.d. are ice-directed in character and best-developed in glacial breaches and across bedrock convexities. The majority of these channels indicate formation by the superimposition of supraglacial and englacial streams as the surface of the Nithsdale ice mass downwasted. As in Areas I and II, the depth of incision was controlled by a zone of meltwater penetration. Consequently, most of the higher channels are aligned in a south to south-east direction, although along the northern margin of Area III, where ice overspilled from the Nith valley, it is more common to find a north-east alignment. Only locally along a small part of the south-east margin of the area is there a significantly different channel pattern, produced in association with Lowther ice (Fig. 5.14).

(6) With the lower group of meltwater channels, below 300 m.o.d., regional control over fluvioglacial erosion was much more limited/...

limited. As the ice surface downwasted and the zone of meltwater penetration continued to drop correspondingly, local relief conditions played a more important role in the establishment of the channel pattern. As a result, channels in the lower group locally follow courses fundamentally different from the regional directions of ice and meltwater movement. Most of the channels below 300 m.o.d. were incised submarginally or subglacially, again by superimposed supraglacial and englacial streams supplemented by extraglacial meltwater. Control over the depth of meltwater incision exerted by the englacial water-table ceased to apply below 152 m.o.d.. At the final stages of downwastage, meltwater drainage was focused downslope towards a subglacial master channel at the base of the stagnant ice mass which occupied the floor of Upper Nithsdale. The subglacial channel is thought to be at least partly responsible for the erosion of the drift-filled trench that extends for several kilometres along the valley floor.

(7) The most extensive fluvioglacial sand and gravel accumulations are found in close association with the lower group of meltwater channels. Over most of Area III deposition of this kind took place against, on top of, within or at the base of relict patches of ice, isolated from their source of supply, which stagnated and downwasted in situ in the Nith, Carron, Burnsands, Marr and Druidhill valleys. Many of the fluvioglacial landforms produced during the final stages of decay were destroyed and their deposits re-distributed by postglacial meltwater activity.

CHAPTER 6

CONCLUSIONS

6.1 MODELLING THE LAST MAJOR GLACIATION AND DEGLACIATION IN UPPER NITHSDALE AND ANNANDALE

The main purpose in using models is to provide a simpler explanation than that offered by the real world. As defined by Chorley and Hagget (1967), a model is, "... a simplified structuring of reality which presents supposedly significant features or relationships in a generalized form", and that, "... as such they are valuable in obscuring incidental detail and in allowing fundamental aspects of reality to appear" (P.22). In this section therefore, an attempt will be made to summarise, in simplified form, the main processes involved in the build up of, and landforms resulting from, the last glacial system over a part of Southern Scotland. However, it must be recognised that Upper Nithsdale and Annandale cannot be examined in isolation, but must be considered in association with other areas affected by the last ice sheet, at both the regional and national scale.

Numerous theories invoking climatic change have been put forward to explain the initiation of glacial periods during the Quaternary. However, no one interpretation has yet gained general acceptance and it would appear that the true explanation lies in the combination of two or more of the six theories most frequently advanced, (Flint, 1971, P. 804 - 805) :

1. Variations in solar emissivity.
2. Veils of cosmic dust.

3./...

3. Geometric variations in the earth's motions.
4. Variations in transmissivity and absorptivity of the earth's atmosphere.
5. Lateral and vertical movements of the earth's crust.
6. Changes in the system of atmosphere/ocean circulation.

The above factors (and others) have interacted by a series of positive and negative feedbacks to produce multiple periods of glaciation in the British Isles during the Quaternary (Shackleton and Opdyke 1976). Consequently, the landforms and indeed landscapes which characterise the initial stages in ice accumulation and outward movement reflect a net landscape response to moulding during a number of successive glacial episodes. As such, unlike the pattern of glacial deposition, it can only be assumed that ice accumulation and advance were similar during each of the main glacial periods when ice penetrated far south across Britain. As Price (1973) stated, "The landforms and deposits that develop during one glaciation will affect the build-up and expansion of any subsequent ice mass and the landforms and deposits it develops" (P. 198). However, it is impossible to measure this affect.

The onset of the last glacial period was most likely characterised by only a relatively slight cooling but substantially increased precipitation, "... fluctuations of the mean annual temperature of the order of 5 - 8^{o}C seem to be generally agreed" (Sparks and West, 1972, P. 7). Snow, and eventually ice, began to accumulate in situations where they were/...

were able to collect and survive from one year to the next.
In the British Isles the morphological and climatological conditions most suitable for the build-up and retention of ice were found in the mountains and uplands of Scotland, Northern England and Wales. In each of these areas the form of the pre-glacial (or pre-last glaciation) surface determined the nature of the initial ice form and its subsequent development (Fig. 6.1).
The first snow accumulation often occurred in a valley head, but with continued deterioration of climate and falling snow-line it was likely that the, "... snow bank in the valley head will grow both in extent and thickness and a "cirque glacier" will develop ...... Once the ice mass becomes so large that movement begins to take place within it then the term "valley glacier" can be applied" (Price, 1973, P. 181); (Fig. 6.2A).
Alternatively, valley glaciers may originate from ice sources on upland surfaces above valley heads. In such situations continued climatic deterioration led to the establishment of "plateau glaciers" or "ice caps", the valley glaciers descending from here to fill the drainage network of the upland concerned (Fig. 6.2B). Within the British Isles, and in the particular context of the thesis area, existing evidence suggests that initial ice accumulation took place in <u>both</u> cirque and plateau glaciers, dependent upon local upland morphology.
In Upper Nithsdale and Annandale 20 cirques were identified, the majority of these in the Lowther Hills. As previously described, the Lowther Hills are generally heavily dissected with/...

with only limited development of upland surfaces above the valley heads. Cirques in this area are found incised into the east and south-east flanks of the uplands and are "open cirques" (Penck, 1905, P.16), at the head of major troughs. Such cirques are indicative of the extension of initial cirque glaciers into valley glacier forms as the glacial period progressed. In the Tweedsmuir Hills by contrast, there is more limited evidence of cirque formation, "open cirque" forms being particularly scarce. Several of the cirque forms in these uplands are found on the flanks of glacial troughs, but have had their dimensions trimmed by more powerful erosive action associated with ice occupying the trough itself. In the Tweedsmuir Hills therefore, unlike the Lowthers, it would appear that the local cirque forms were not the main source of ice supply. The fairly level upland surface of the Tweedsmuir Hills which lies above 610 m.o.d. and stretches for 7 km in a north-west to south-east direction, seems from other evidence to have nourished a plateau glacier or ice cap and as such acted as the major local ice source during the last glaciation. Manley (1955) stated that it may be reasonable to assume that, "... in a disturbed temperate climate a summit 1,000m broad is likely to retain a snow cap and form a "dome" (of ice) if it rises 200m above the local firn line" (P. 455). With such a broad summit, the Tweedsmuir Hills are likely to have developed an ice dome (or plateau glacier) when the firn line was considerably less than 200m from the summit. Once a permanent dome of ice had become established, it would continue to grow higher and higher above the snow-line with

continued/...

continued availability of precipitation, its surface gradient would increase and eventually outlet glaciers spread down towards the lower ground, channeled via pre-existing valley heads.

Outlet valley glaciers of this type, also known as "Icelandic" (Linton, 1963, P. 9), have steep rounded trough heads and in the thesis area flowed south-west from the Tweedsmuir Hills (Plate 6A). Evidence from the northern and eastern flanks of the Tweedsmuir Hills (Price 1960), indicated that similar trough forms are found here also and imply that there was a generally radial outward movement of ice from the Tweedsmuir ice cap (dome).

It seems highly likely that with the climatic deterioration at the onset of the last glacial period other broad summits in the thesis area and throughout Southern Scotland as a whole supported ice domes. Furthermore, it is evident that cirque glaciers, either individually or in groups, developed where morphological conditions restricted the development of ice domes. However, within Upper Nithsdale and Annandale the evidence from glacial striae, erratics, meltwater channels, roche moutonnees and large scale features of glacial erosion, suggests that there were only two <u>major</u> centres of ice dispersal, the aforementioned Tweedsmuir ice cap and an amalgam of smaller ice domes and cirque glaciers in the Lowther Hills. A third centre of dispersal, external to the thesis area but of major significance in terms of ice movements affecting the area, lay beyond its western boundary in the uplands surrounding Loch Doon. Ice from these three centres is termed Tweedsmuir,

Lowther/...

Lowther and Nithsdale respectively, and a postulated early stage in the build-up of the three ice masses in the thesis area is indicated on figure 6.3.

Although initial ice movement outward from the accumulation area was strongly controlled by local morphology, with increasing ice thickness and distance from the source a stage was reached where ice movements often disregarded the nature of the underlying relief and followed courses dictated by climatic conditions in the fashion of Flint's (1971) theory of "highland origin and windward growth" (Figs. 6.1 and 6.4). As a result, the principal directions of ice movement across the thesis area on nearing the glacial maximum were broadly southwards (Manley 1959), although interaction between ice streams also exerted a strong influence on the regional flow of ice (Fig. 6.5). With the coalescence of the three major ice masses over Upper Nithsdale and Annandale, ice from the more powerful Nithsdale and Tweedsmuir sources greatly restricted the movement of Lowther ice and concentrated its flow almost directly southwards (Fig. 6.5). Similarly, the presence of an ice mass of Scottish Highland origin along the northern margin of the Southern Uplands, in conjunction with the Lowther dispersal centre over the central uplands, forced part of the Nithsdale ice stream north-eastwards along the upland margin (Fig. 6.5). Even at this advanced stage in the glacial period however, the principal directions of ice movement within this enlarged Southern Upland/...

Upland ice mass paralleled the alignment of the two major valleys in the area, Nithsdale and Annandale, such that the role of the underlying topography cannot be completely discounted (Fig. 6.1).

Eventually, ice from the three sources affecting the thesis area, other major sources in Scotland and upland centres in England and Wales coalesced and thickened, such that at the maximum of the last glaciation a British ice sheet covered most of of the country and was confluent with ice of Scandinavian origin (Fig. 6.6). The presence of ice-breached cols and meltwater channels at altitudes exceeding 732 m.o.d. in the thesis area suggests that at least in the vicinity of Upper Nithsdale and Annandale, the landscape was totally submerged by an ice cover at this time. The summit height for the ice sheet as a whole is estimated at 1,800m (1,700m over the Southern Uplands, which supports the above statements), with a speculated total volume of 346,000 km^3 (Boulton et al, 1977). At the glacial maximum, Boulton et al (1977) also suggest that the British ice sheet was characterised by an outer zone of melting where ice was at or above the pressure melting point, succeeded up-glacier by a zone where basal temperatures were below the melting point. In terms of glacial erosion, where ice velocity is of major importance (Boulton 1975), it becomes readily apparent that conditions under the centre of ice outflow e.g. Scottish Highlands, Southern Uplands etc, characterised by low ice velocities and possibly sub-melting point temperatures if the above assumption is correct, "... would not be conducive to high rates of erosion by any process" (Boulton et al, 1977, P. 240).

As/...

As such, it is suggested that the landscapes of intense glacial erosion, which generally characterise the dispersal centres, although admittedly only locally developed in the central Southern Uplands, were not primarily achieved at or near the last or a previous glacial maximum. Instead, it is proposed that the greatest erosion took place, "... during periods of much more limited glacierization, when these (source) areas merely maintained local ice-caps and valley glaciers and when high local ablation gradients produced rapid local glacier movement" (Boulton et al, 1977, P. 240). It is speculated that the landscape of the Southern Uplands dispersal centre is not as deeply eroded as that underlying other major sources, "... because of its lower elevation compared with the other centres of outflow, which did not enable it to support as much active local ice during the periods when no large British ice-sheet existed. It suffered less erosion during these periods and the smaller erosional intensity that it shows compared with surrounding areas is a product of this and low erosional rates beneath source areas during periods of more intensive ice-sheet glaciation" (Boulton et al, 1977, P. 240-241).

Sissons (1979a, P 199 - 203), also believed that glacier development in the Southern Uplands was retarded during the initial stages of the glacial period in comparison with other major accumulation centres. Sissons however, attributed this to climatic factors, in particular the availability of precipitation associated with the location of the Polar Front in the Atlantic Ocean./...

Ocean. He suggested that the zone of maximum precipitation shifted southwards from the West Highlands of Scotland with the migration of Polar Water, causing optimal conditions of glacier accumulation during ice sheet growth to pass over the Southern Uplands, but at a stage when extensive expansion of ice masses had already occurred further north. The southward movement of this front was a major factor in the growth of the British ice sheet to the glacial maximum during the last prolonged cold period.

Climatic amelioration following the maximum of the last ice sheet initiated the period of deglaciation. The rate of ablation in the ablation area of the ice sheet exceeded the rate of replenishment in the accumulation area and so with the establishment of a negative mass balance, rapid downwastage and marginal recession took place. Information concerning the rates of retreat of the last British ice sheet is very limited although Price (1980), after studies in areas of contemporary glaciation, suggested that "... during deglacierization it is ... reasonable to expect that land will emerge from beneath ice at the rate of between 10-100m per year depending upon local conditions" (P. 82). It is however, generally believed that its break up into streams largely controlled by the underlying topography probably occurred fairly early in the period of deglaciation (Price, 1973, P. 210). Indeed, the nature of the underlying relief conditions became of increasing importance as ice-wastage progressed, particularly in upland areas (Fig. 6.1).

It/...

It is during the period of recession of an ice mass that the importance of meltwater and fluvioglacial processes in the glacial system become increasingly apparent. In this respect, the temperature of the ice mass gains priority. If the ice mass lies below the pressure melting point, no meltwater can exist within the glacier in liquid form. Temperate glaciers by contrast can contain meltwater throughout their mass. Although it was previously suggested that at the glacial maximum the basal temperature of the ice sheet underlying the centres of outflow in the British Isles lay below the pressure melting point (Boulton et al 1977), such conditions are not believed to have prevailed throughout the period of deglaciation. The abundant evidence of landforms indicative of fluvioglacial erosion and/or deposition up to the highest altitudes in Upper Nithsdale and Annandale and other adjacent areas, (Price 1960; Mclellan 1967; Sissons 1967a; Clapperton 1970; Holden 1977), strongly suggests that the decaying ice sheet was at the pressure melting point throughout much of the period of its dissipation, at least over a large part of Southern Scotland.

During ice wastage, meltwater activity developed in association with each of the three confluent ice masses which covered the area. The fluvioglacial landform patterns therefore indicate not only the nature of deglaciation over the area as a whole, but more specifically the changing interrelationship of these three ice masses during this period.

The close association of the alignment of many meltwater channels/...

channels (and fluvioglacial ridge forms) with former directions of ice movement has frequently been referred to, (Flint 1971; Gjessing 1960; Sissons 1967a; Clapperton 1971a; Price 1973). This relationship is taken to indicate the strong control exerted by the regional slope of the ice surface over the regional direction of meltwater drainage; such channels which parallel the former directions of ice movement have been termed "ice-directed" (Clapperton 1971a). Ice-directed meltwater channels and deposits are common throughout Upper Nithsdale and Annandale, particularly at higher altitudes and as suggested, have developed independently in association with each of the three major ice masses, as a comparison of figures 6.5 and 6.7 indicates. Such channels are found incised across spurs and bedrock convexities aligned transversely to the regional direction of ice movement, and are best-developed above 250 m.o.d. Both single forms and complex channel systems are apparent, the greatest concentrations occurring in the areas of confluence of ice streams from the major centres. In the thesis area, regional surface slopes focused meltwater activity onto the terrain delimiting part of the southern boundary. South and south-west flowing meltwater from the Lowther ice mass augmented the existing south-east trending meltwater drainage along the margin of the Nithsdale ice, to concentrate erosional and to a lesser extent depositional activity in this vicinity. The vast majority of the ice-directed channels here and indeed throughout the thesis area were incised by the superimposition of supraglacial and englacial streams as the ice surface downwasted, the depth of meltwater incision being controlled by a descending zone of meltwater penetration. Although in the case of the Lowther ice mass much of the meltwater produced during downwastage appears to have been channelled into the pre-existing radial valley system, the regional directions of meltwater drainage over the area as a whole did not change dramatically until the zone of meltwater penetration became increasingly disrupted by the underlying relief. A tentative figure of 250 m.o.d. is suggested for the widespread disruption of ice-directed drainage in the thesis area (Fig. 6.7), but in reality this altitude varied considerably on the local scale and was strongly controlled by the nature of the topography in different parts of the area. In the generally upland terrain which characterises Upper Nithsdale and Annandale, disruption of the regional meltwater drainage pattern obviously occurred at higher altitudes than would be the case where the emerging topography had local relief values of only tens of metres.

Therefore, the ice-directed channels and of more limited development eskers, in Upper Nithsdale and Annandale represent the earliest phases of deglaciation (Sugden 1970) and to reiterate, indicate that during this period meltwater drainage essentially paralleled former directions of ice movement.

With continued downwastage and marginal recession, areas where several ice masses were confluent are often the first to become ice free and in such localities small and temporary ice-dammed lakes may develop (Clapperton 1971b). On a similar theme, Price (1973) stated that, "... such lakes may develop in tributary/...

tributary valleys because of differential rates of retreat in different glaciers" (P. 205), and this was in fact the case in part of the thesis area. The thinning and associated marginal retreat of the Lowther ice mass caused its southern terminal area to part from its confluence with the more powerful Nithsdale ice at the mouth of the Cairn Valley and withdraw a short distance northward; the ground vacated by the ice became flooded by a small glacial lake. The altitude of this lake was apparently controlled by the local stabilisation of the englacial water table, but its existence was only short-lived, overflowing initially across low points along the valley flanks into adjacent ice-free valleys, before finally draining subglacially into/through the Nithsdale ice-dam itself. Other small ice-dammed lakes formed in valleys tributary to the Nith during the period of partition of the Nithsdale-Lowther ice masses, but there is no evidence to suggest the formation of similar lakes in the zone of confluence of the Lowther/Tweedsmuir ice during downwastage, mainly because the ice streams here followed parallel courses prior to converging. The final stages of deglaciation were characterised by the balance in the complex interrelationship between ice cover and underlying topography and their oscillating influence over glacial and fluvioglacial processes, swinging strongly in favour of the emerging landscape (Fig. 6.1). With continued thinning of the ice cover, mountains and hills gradually appeared above the ice surface, underlying valley systems became dominant in determining the flow lines within the ice

and/...

and the end result was that emerging interfluves cut off some glaciers from their accumulation areas. In such situations, "... all forward motion ceases.... the ice mass becomes stagnant and ablation rates are the sole determinant of rates of thinning and marginal retreat" (Price, 1973, P. 200). The most suitable locations for the retention of stagnant masses of ice, often hundreds of metres in thickness and several kilometres in length (Flint, 1929), appear to have been troughs and other depressions aligned transversely to the direction of regional ice movement. However, in addition to these, as indicated on figure 6.8, major remnant ice masses also became detached and stagnated in situ in the Nith and Annan valleys themselves. Stagnation and downwastage in situ provided ideal situations for the concentration of meltwater and hence the formation of suites of fluvioglacial landforms (Sugden 1970). It is principally upon the occurrence of these characteristic landform assemblages that the main areas of ice stagnation and downwastage are identified. Ablation till often supplements the fluvioglacial material and covers a wide area of stagnant ice either supraglacially or englacially. Consequently, a complex ice-contact environment of deposition evolves as downwastage continues. The end product is a confused landscape of mounds, hollows, ridges and terrace forms with little or no apparent orientation, consisting mainly of fluvioglacial deposits although flow and melt-out tills are often intricately intercalated with these (Boulton 1967). Such an environment also produces characteristic channel forms. These commonly plunge directly downslope, a consequence of the re-direction/...

re-direction of meltwater upon the collapse of the zone of meltwater penetration at the onset of stagnation. Whatever the exact alignment of channel forms produced in association with stagnant ice, unlike the higher indications of meltwater drainage, their occurrence is always strongly controlled by local topographic conditions. As previously implied, channels formed under conditions of strong topographic as opposed to glaciological control are found mainly below 250 m.o.d. in the thesis area (Figs. 6.1, 6.8). Therefore, in the final stages of deglaciation, ice lingered longest in valley floors and basins, with the possible but by no means definite exception of a few plateau snowfields (Fig. 6.8). This final period of dissipation resulted not only in the chaotic dead-ice landscape described above, but also in the concentration of late-stage meltwater activity in pre-existing valley floors. In the context of the thesis area the late-stage meltwater drainage pattern, like the present fluvial drainage pattern focused flow in the two main valleys, Nithsdale and Annandale. Although initially such concentrated meltwater activity may have led to spectacular erosion, as in the case of the buried valley in Upper Nithsdale, depositional processes gradually became dominant and both Nithsdale and Annandale are extensively floored with fluvioglacial as well as glacial deposits. With particular reference to the latter fact, it is assumed that throughout the period of deglaciation, (and also perhaps prior to this) extensive glacial deposition took place in the form of lodgement till, fluted ground moraine and/or drumlins wherever conditions were suitable. The survival of the glacial deposits and their

retention/...

retention of a morphological expression however, were heavily dependent upon the time and location of their deposition in relation to subsequent glacial, and more particularly fluvioglacial activity.

During the course of the shrinkage and disappearance of the British ice sheet, it has been suggested that, ".... small ice caps or valley glaciers will be left on highlands if net accumulation remains in these areas" (West, 1977, P. 19). It is however, difficult to be certain whether or not such remnants of the ice sheet were retained in Upper Nithsdale and Annandale during the last stages of deglaciation. There is certainly evidence in the form of hummocky moraines to suggest that small glaciers did exist in certain localities within the thesis area (Fig. 6.9), and other parts of Britain after the main period of ice wastage. However, whether these forms relate to a period of re-advance of ice or separate advance post-dating the total removal of ice from the landscape, is not yet completely clear, although existing evidence from various parts of the country tends to support the latter theory. (Sissons 1976, 1979a; Gray and Lowe 1977). In the context of the thesis area, the location of the morainic topography indicates that the major areas of ice accumulation during this subsequent cold period were essentially the same as during the initial stages of ice build-up associated with the growth of the last ice sheet itself.

6.2 CHRONOLOGY AND CLIMATIC IMPLICATIONS

The build up of the last Quaternary ice sheet to cover the thesis area referred to in the previous section, is believed to have taken place/...

place in Late Devensian times, beginning approximately 25,000 years ago, reaching its maximum 18,000 years ago and wasting away either partially or completely by approximately 12,500 years. Between approximately 11,000 and 10,000 years B.P., there was a return to colder conditions and the re-advance or re-establishment of glaciers in the more upland parts of the British Isles (Sissons 1967a, 1976, P. 79 - 90); Penny et al 1969; Bowen 1977; Gray and Lowe 1977). As suggested on several occasions there is still considerable debate as to whether the ice sheet disappeared completely at the end of the last major glaciation or remained in patches throughout the Scottish Lateglacial period. (Gray and Lowe (1977) define the Scottish Lateglacial as consisting of the Lateglacial Interstadial, "The period between the start of the apparently rapid thermal improvement that occurred between about 14,000 and 13,000 B.P. and the beginning of the marked thermal decline that took place around 11,000 B.P."; and the Loch Lomond Stadial, "The period between the start of the marked thermal decline that occurred around 11,000 B.P. and the international chronostratigraphic boundary for the beginning of the Flandrain, viz. 10,000 B.P." (PXiii).)

Peacock (1971, 1977); Sugden (1970, 1973a, 1973b, 1974); Sugden and Clapperton (1975), hold with the belief that a major active ice sheet existed throughout the Lateglacial, and that morainic landforms attributed to an independent advance of ice during this period merely reflect a minor fluctuation during the decline of the ice sheet. The opposing viewpoint, that total deglaciation of the last ice sheet to cover the British Isles

occurred/...

occurred prior to the subsequent re-advance has been led by Sissons (1967a, 1972, 1973a, 1973b, 1974a, 1976 ; Sissons and Grant 1972). Over 60 Lateglacial pollen sites in Scotland indicate that large areas of the country were deglaciated during the Lateglacial Interstadial and therefore support the latter theory. Several of these sites are in Southern Scotland, and one within the thesis area itself, at Sanquhar.

The exposure containing vegetation remains, at the Sanquhar Brickworks quarry, was first described by Simpson and Richey (1936), who discovered, "... a bed of peat resting on sands and gravels ..... overlain by, apparently, boulder clay (till)" (P. 94).

	Ft.	Ins.	M.	Cms.
Soil	1	0	0	30
Stiff Dark Clay with Stones up to a foot in length (? Boulder Clay)	3	4	1	2
Alternating Layers of Silt and Peat	0	6	0	15
Peat with much coarse Vegetable Debris, containing Wing-Cases of Beetles, and with small patches of Vivianite (Hydrous Ferrous Phosphate locally plentiful)	1	3	0	38
Yellow sand with a bed of grey Silt	2	0	0	61
Sandy Gravel with small pebbles, many of Spango Granite, resting upon rock	1	3	0	38

(Simpson & Richey, 1936, P.94)

Simpson and Richey concluded from the above section that, "... this evidence .... favours a glacial origin for the supposed boulder clay (till), and in consequence a readvance of the ice must be postulated after a period when the sands and gravels/...

gravels were deposited and the peat was formed" (Simpson and Richey 1936, P. 94). No date was suggested for this re-advance. The same vegetation site was re-examined by Bishop and Coope (1977) who decided that the peat bed was overlain not by till but, ... by about 1m of solifluction on which a soil profile had developed", and that on the basis of, "... faunal and stratigraphical grounds there can be no doubt that the deposits here are of Lateglacial age" (P. 82). No material was removed for radiocarbon dating from this site and as the quarry has since been filled, the possibility of now obtaining a date for the vegetation remains seems unlikely. However, Bishop and Coope (1977) estimated the age of the peaty layer on the basis of several considerations :

"Stratigraphically this deposit must surely post-date the retreat of the ice from this part of the Southern Uplands. The peaty horizon, though somewhat compacted, does not bear the intense compressional features characteristic of peats that have been overriden by ice sheets .... The deposit is plainly overlain by a layer of solifluction that includes clay with stones that might well be mistaken for a till .... The most appropriate time interval for this solifluction deposit is during the Loch Lomond Stadial. The insect faunas from this deposit would also support a Lateglacial age for these deposits" (P. 83). A more exact date for the vegetation layer was suggested as, "between 13,000 - 12,000 B.P." (Bishop and Coope, 1977, P. 85). However, although the lowlands of Upper Nithsdale were apparently ice-free between approximately 13,000 - 12,000 B.P., this does not completely rule out the possibility that the surrounding Uplands could/...

could have retained substantial glacier remnants. Nevertheless, faunal and floral climatic implications suggest that this is unlikely.

The morainic landforms and deposits found in the more upland parts of the Lowther and Tweedsmuir Hills (Fig. 6.9), would therefore appear to relate not to a halt or re-advance associated with the dissipation of the last ice sheet, but to a separate and limited advance of ice after the period of general retreat and climatic amelioration. The altitude, location and morphology of the morainic accumulations suggest that they relate to the Loch Lomond Stadial (Gray and Lowe 1977), the limits of which have been well mapped in other parts of the country (Sissons 1979a). There is at present still considerable uncertainty about the timing of the build up of the Loch Lomond Advance glaciers with Sissons(1979a) suggesting that, ".... glaciers may have begun to develop .... by 11,500 B.P." and subsequent ".... attainment of glacier maxima - C.10,800 B.P., markedly out of phase with much other evidence" (P. 202).

The deterioration of climatic conditions associated with the Loch Lomond Stadial resulted not only in the formation of the morainic topography, but also in more widespread periglacial action away from the immediate proximity of the re-established glaciers themselves. Many of the products of mass wastage, in particular the sloping solifluction benches which descend from both valley flanks towards the present stream in parts of the uplands, are believed to have formed either partially or completely during the Lateglacial period. There is no apparent pattern to the occurrence of benches of this type, but their total/...

total absence from any of the valleys which contained glaciers during the Loch Lomond Stadial strongly suggests that the major period of bench formation, and by definition periglacial activity, occurred before and/or during this advance of ice. Similarly, the presence of a fossil ice-wedge in kame terrace gravels at the mouth of Moffatdale (Fig. 3. 32) is further testimony to severe climatic conditions during and/or after the decay of the last ice sheet. The ice-wedge cast implies the former existence of permafrost in this area, the thickness of which was at least as great as the length of the cast (Flint 1971). Mean annual air temperature at the time of formation of the ice-wedge was in the region of -6 to -8° centigrade (Pewe 1966, 1973). Sissons (1979a, P.200) also refers to fossil frost wedges within the limits of the Loch Lomond Advance near sea level in Scotland, thus emphasising the wisespread occurrence of permafrost during this period. It is not generally possible to give an exact date for the formation of fossil periglacial features, but Sissons (1976) stresses the importance of the Lateglacial period in this respect. "Some of the fossil periglacial features on the Scottish mountains may have been formed when the lower ground was still covered by the downwasting ice sheet, but the severe climatic conditions that accompanied the Loch Lomond Re-advance(Stadial) were of major importance " (Sissons, 1976, P.110). Tentative support for Sissons belief is supplied by the section containing vegetation remains at Sanquhar. If the peaty layer was indeed formed during the Lateglacial Interstadial as suggested by Bishop and Coope (1977), then one metre of soliflucted debris has slumped on top since approximately 12,000 years B.P.; the

vast/...

vast majority of deposition undoubtedly taking place during the period of the Loch Lomond Stadial. By implication, a similar if not greater thickness of material derived from mass wastage can be assumed to have accumulated across the lower slopes of the uplands flanking Nithsdale, in closer proximity to the glaciers themselves. This also has the wider implication that extensive re-modification of the morphology and nature of the drift deposits in the thesis area may have taken place since their formation during the main period of ice sheet decay. However, such studies of post-depositional modification, as have been carried out in other parts of Scotland (Dickson et al 1976), are outwith the scope of this thesis.

6.3 RELATIONSHIP OF FINDINGS TO PREVIOUS RESEARCH IN ADJACENT AREAS.

In the last two decades the Southern Uplands and West-Central Scotland have figured largely in research undertaken by former or present staff and/or students in the Geography Department at Glasgow University. To reiterate, Price (1961) worked in Peebleshire and was responsible for the initiation of subsequent research by Mclellan (1967), in West-Central Lanarkshire; Gemmell (1971) in Arran; Ward (pers. comm. 1975) in Renfrew and North Ayrshire; Holden (1977) in Central Ayrshire, and the present work in Southern Lanarkshire and Northern Dumfriesshire (Fig. 6.10). Although, as indicated on figure 6.10, total coverage of this substantial area has not yet been achieved, it is possible to combine the information gathered to date and distinguish the main source areas and directions of ice movement to have affected a large part of West-Central and Southern Scotland during the last major glacial period (Fig. 6.11).

Ice/...

Ice from the West Highlands and the Southern Uplands became confluent over this area (Fig. 6.11), and all of the authors are in agreement that at the maximum stage of the last ice sheet, this part of Scotland was entirely covered by ice. Highland ice entered the area from sources to the north-west, but was deflected south-west down the Firth of Clyde and north-east towards the Firth of Forth on encountering the Southern Uplands ice mass. Three major source areas for the southern ice mass were identified, the uplands surrounding Loch Doon, the Lowther Hills, and the Tweedsmuir Hills.

The Loch Doon centre was the largest and most important. At the glacial maximum there was a radial outward movement of ice from here, although ice flowing directly northwards was deflected north-eastwards by the presence of the Highland ice mass.

Of particular importance to much of the thesis area was the presence of eastward flowing Loch Doon ice which, in association with Highland ice to the north, restricted the pattern of outward ice movement from the smaller centres over the Lowther and Tweedsmuir Hills. However, at the ice sheet maximum a major axis of ice dispersal in the Central Southern Uplands lay over and linked the Lowther and Tweedsmuir Hills. Ice to the north of the axis, confluent with Loch Doon ice and Highland ice, flowed in a generally north to north-east direction; to the south movement was almost directly southwards, except in the area adjacent to Nithsdale where the pressure from Loch Doon ice enforced a south-east course.

In 1901 Geikie stated, "From the direction of striae it is evident that the Southern Uplands formed another centre of dispersion/...

dispersion, for the southern part of the Scottish ice-sheet. (To speak more accurately there were several distinct centres of movement of the ice that lay on these uplands") (Geikie, 1901, P. 341-343). The main findings of this thesis strongly reinforce Geikie's beliefs, but in addition, have enabled several of the main dispersal centres to which he refers to be identified and the varying influence which they have exerted during the last period of glaciation and deglaciation to be assessed.

APPENDIX I

PARTICLE-SIZE ANALYSIS OF SEDIMENTS

Particle-size analysis of tills was carried out to enhance the description of individual exposures and to aid in the identification of the origin and direction of movement of the ice mass by which they were deposited. All exposures of till selected for particle-size analysis were at least 3 metres in thickness. At each site the face was cleared of slumped or loosened material and a sample of 50kg. collected from several random localities across the exposure. The sample weight was ascertained using a spring balance. The sample was then passed through a set of sieves (in the field) and the amount of material retained on each sieve was weighed using the spring balance. The sieves used had mesh sizes of 8cm, 4cm and 3cm. About 10kg. of the material which passed through the 3cm sieve was then taken back to the laboratory for further analysis.

It is generally accepted that for the purpose of particle-size analysis of till deposits, wet sieving is a more accurate method than dry sieving. For this reason wet sieving by the method advocated in British Standard Publication B.S. 1377, was used for the fraction coarser than and including 63µm, with sieves at the British Standard Size Range of 63µm, 125µm, 250µm, 500µm, 1200µm, 2000µm, 3350µm, 6350µm, 12700µm and 25700µm. The coarseness of the till deposit throughout the thesis area meant that the hydrometer method of particle-size analysis for the fraction finer than 75µm was not utilised.

PROCEDURE

1) The sample (of approximately 10kg) was oven-dried at a temperature of 100-120 C for 24 hours.
2) The dried sample was then lightly crushed with a rubber-headed pestle and mortar. Great care was taken not to crush individual particles.
3) 3,000gm of material was then weighed to 0.01gm and placed in glass beakers where it was covered with distilled water containing a dispersing agent (Sodium hexametaphosphate). This was warmed, mechanically stirred for 15 minutes and then

left for 30minutes.

4) The sample was then washed through a nest of sieves (3350µm, 6350µm, 12700µm, and 25700µm) using wet sieve apparatus connected to the sink. Great care was taken not to flood any of the sieves as this could lead to the loss of some material.

5) The sieves were removed and oven-dried at 50 C. A piece of paper was placed beneath the sieves to collect material falling through during the drying process.

6) When dry, the sieves were nested and shaken mechanically for 20 minutes. The sample in each sieve was then carefully brushed onto a sheet of paper, emptied onto the balance and weighed to 0.01gm. The amount of material in the gravel fraction was thus ascertained.

7) A 200gm. sample of the material passing through the 2000µm mesh sieve was placed in a glass beaker and a dispersing agent again added. This was warmed, stirred mechanically for 30 minutes and left for one hour.

8) A nest of sieves between 63µm and 2000µm (63µm, 125µm, 500µm, 1200µm and 2000µm) was placed on the wet sieving apparatus and the sample again washed through.

9) The sieves were oven-dried at 50 C, again resting on a piece of paper to collect material passing through, nested and mechanically shaken for 20 minutes. The samples were then carefully brushed from the sieves onto a large piece of paper, emptied onto a balance and weighed to 0.01gm. This enabled the amount of material in the sand fraction to be ascertained.

CALCULATIONS

The weight of material retained on each sieve was used to determine the percentage weight retained and then the percentage weight passing each sieve size. These figures only applied to the two sub-samples, but were related to the initial sample collected in the field so that the cumulative percentage weight passing each sieve size could be calculated. Any gross errors in weighing were determined by adding together all the weighings of materials retained on each sieve and the weight of material retained in the bottom tray.

It is felt that the above procedure gave a fairly accurate assessment of relative particle-size. The relative proportions of cobbles-boulders, gravel, sand and silt-clay were used in simplified form to distinguish important differences between exposures in different parts of the thesis area (Tables 3.2, 4.3, 5.4).

APPENDIX II

PREFERRED - STONE ORIENTATION

As indicated in the text, the purpose of preferred-stone orientation analysis on tills in the thesis area is to indicate the direction of movement of the ice mass by which they were deposited.

PROCEDURE In the field, those exposures whose potential usefulness for the determination of former ice movements in both a local and regional context was greatest were chosen for examination.

1) The exposure was cleaned and the outer 0.3m removed in case of disturbance (Andrews, 1971). The sampling was generally carried out on vertical exposures, nearly entirely the result of fluvial incision.

2) Avoiding the top 0.5m of the exposure in case of disturbance, 5 trenches were cut at random intervals into the vertical face to provide horizontal working faces. These trenches were slowly excavated with a trowel until a suitable stone was located. A suitable stone was one which had a "a" axis to "b" axis ratio of at least 3:2. That is to say, all of the stones examined were clearly longer than they were broad, and the direction of elongation could be readily identified. It was common, with the exception of the upper deposit at exposure 5E Area III (Old Mains), for there to be sufficient silty-clay in the matrix of the till for the stone to be carefully removed leaving its cast. A non-magnetic rod (in this case a wooden cocktail-stick) was inserted into the cast exactly duplicating the dip and orientation of the stone for measurement purposes. Stones that lay adjacent to large boulders or touched each other were avoided.

3) The orientation of the stones was measured using a Suunto fabric compass. However, as it is generally considered that such readings are only accurate to $\pm 5^\circ$, regardless of the care taken during measurement, the readings were merely recorded to the nearest 5° orientation.

4) The measurement of the dip was completed by measuring the inclination of the non-magnetic rod representative of the former dip of the "a" axis. Both the orientation and the dip were recorded for 50 stones at each exposure examined (10 stones from each of the 5 pits excavated in the face of the exposure).

APPENDIX III

ANALYSIS OF RESULTS FROM PREFERRED-STONE ORIENTATIONS

The results of the preferred-stone orientations have been portrayed both graphically and statistically. In diagrammatic form the recorded data is represented on rose diagrams (Figs. 3.12., 4.10; 5.9). With these, the orientations are grouped into 20 class intervals from $0^\circ - 360^\circ$. The 20° class intervals are in turn grouped through 180° to produce an identical appearance either side of the mean (Andrews, 1965, 1971). The rose diagrams have been used in the text to give a clear and instantly identifiable summary of the orientation data obtained from each site.

In terms of statistical analysis of the data, a mean stone orientation was calculated using the following formula

$$\bar{X} = Xa + C\,\frac{uf(x)}{f(x)}$$

Where Xa is the middle point of the distribution, and C is the interval between classes. This calculation has been carried out on the data recorded for exposure 4A in Area II in order to aid understanding. In this example the model frequency is just east of south and the data will be tabulated from 60° to 240° with opposite 20° cell units summed together (Table IIIA).

TABLE IIIA

Mean Orientation of Till deposit at Exposure 4A.

Class (Degrees)	Frequency(f(x))	u Scale	uf(x)
60-79, 240-259	1	-4	-4
80-99, 260-279	3	-3	-9
100-119, 280-299	4	-2	-8
120-139, 300-319	4	-1	-4
140-159, 320-339	8	0	0
160-179, 340-359	12	1	12
180-199, 360-19	9	2	18
200-219, 20-39	4	3	12
220-239, 40-59	5	4	20
	50		37

$$X = 150 + 20 \cdot \frac{37}{50}$$

$$= 150 + 14.8 = \underline{164.8^\circ}$$

The Chi-squared test is calculated to provide a numerical value for the orientation-strength and the dip-strength. "Statistical analysis requires that 1) the sample data be tested against a null hypothesis and that 2) the probability that the distribution differs from that of the null hypothesis is tested at a particular level of significance. If a confidence limit of 95% is accepted, this implies that such a difference is due to chance. In the analysis of the till fabric data, the null hypothesis is that the observed distribution (O) of orientations and dips of the "a" axis of elongate pebbles is uniform. The distribution of the "a" axes ranges from 0 - 360°. Chi-squared consists of testing an observed distribution (O) against the expected distribution (E) which in this case is uniform" (Andrews, 1965, Appendix A). For acceptable Chi-squared results, the expected frequencies have to be at least equal to 5 (Andrews, 1971). Therefore, orientations are divided into 9 x 40 classes, 0° - 39°, 40° - 79°,........, and the number of pebble orientations (O) recorded for each class (Table IIIB). As 50 pebbles were examined, the expected uniform distribution for each class is therefore 50/9 (i.e. total number of observations/number of class groups) or 5.55 pebble orientations for every 40° division. Chi-squared is determined by using the following formula:-

$$X^2 = \frac{(O - E)^2}{E}$$

TABLE IIIB

Chi-square for Orientation of till deposit at Site 4A

Central value	Observed Frequency (O)	Expected Frequency (E)	(O-E)
0	8	5.55	2.45
40	3	5.55	2.55
80	0	5.55	5.55
120	8	5.55	2.45
160	12	5.55	6.45
200	8	5.55	2.45
240	4	5.55	1.55
280	3	5.55	2.55
320	4	5.55	1.55

$$X = (2.45)^2 + (2.55)^2 + (5.55)^2 \ldots\ldots + (2.55)^2 + (1.55)^2$$

$$= \frac{108.25}{5.55} \qquad = \underline{19.50}$$

There are (N - 1) degrees of freedom, where N is the number of class groups. The Chi-square tables indicate that with (N-1) = 8, the 95% confidence level is 15.51. The calculated value for 4A is 19.50. As this is greater than 15.51 it can be said that there is a significant difference between the observed distribution of the "a" axis orientations and the expected uniform distribution. Therefore, the null hypothesis that the pebble orientations are evenly distributed can be rejected. "Obviously the figure becomes larger the more observations are concentrated within specific class divisions. Thus orientation - strength is a measure of concentration or isolation (Andrews, 1965; Appendix A).

The Chi-squared test was also used to give a dip-strength value of the stones in the till fabric. It is obtained by dividing the observed stone fabric into halves at right angles to the mean orientation. "The null hypothesis is that it is expected that the pebbles lie uniformly on either side with equal numbers dipping up - or down - glacier. Thus the Chi-square(d) tests are an attempt to gauge the departure from a pattern which shows no influence of being affected by preferred orientation or dip". (Andrews, 1965; Appendix A). If there are no horizontal pebbles, then the expected distribution of the dips would be 50/2 = 25, but if 2 horizontal pebbles are present, the expected value is 48/2 = 24. In the case of the till deposit exposed at Site 4A, no stones are horizontal. There are 18 pebbles dipping up-glacier and 32 pebbles dipping down-glacier. The Chi-square value is therefore:-

$$\frac{(18-25)^2 + (32-25)^2}{25} = \frac{98}{25} = \underline{3.92}$$

With (N - 1) degrees of freedom the tabulated value at the 95% confidence level is 3.84. As the calculated value exceeds the tabulated value the null hypothesis is rejected (i.e. there is a significant difference between the observed and expected distributions).

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