Contributions to the geomorphology of the North York Moors.

by

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ABSTRACT

This thesis is a geomorphological study of Eskdale, a drainage basin in the North York Moors. The aims of the study are to examine the potentiality of the technique of morphological mapping as a basis for quantitative study in geomorphology, to consider some of the factors which affect angle of slope and to elucidate the development of the physical landscape within the drainage basin.

There is a general relationship between angle and area of slope in a drainage basin; as angle increases above one degree the area of slope decreases. A regression is derived to express this relationship. Distributions of angle of slope plotted against area of slope for certain controlled conditions are obtained and compared with the results from the drainage basin framework.

Eskdale was drained by a major eastward - flowing consequent stream in early Tertiary time which was superimposed upon the underlying geological structures. Three planation surfaces were produced after the mid - Tertiary earth movements. During the production of the most recent of these, which developed in two parts as partial peneplains, specific drainage changes occurred and these are analysed in detail. The Quaternary sequence of stages in valley development is considered for the main valley.

The mode of decay of the last ice sheet in the area is examined. Stagnant ice formed throughout the area during deglaciation but its formation was preceeded by two stages of ice - marginal drainage in eastern Eskdale.

The major landforms introduced by periglaciation are considered and the variation of angle of slope with different values of orientation analysed. This shows that not one direction, but several, suffered oversteepening after the last glaciation. Finally, an analysis of mass movements which occurred during 1960 - 1961, largely as a result of exceptionally high rainfall, is made.

CONTENTS

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During fieldwork in Yorkshire many people were of assistance and the help given by the members of the Whitby Naturalists Club and particularly the honorary secretary, Miss M.C.Walker, is gratefully acknowledged. To the farmers of Eskdale who willingly allowed me to have access to all of the fields in the area I also record my thanks. Finally I am grateful to the typist Mrs E.E.Bates for the efficient way in which she has dealt with the typescript.

CHAPTER 1.

ESKDALE IN PERSPECTIVE.

The North York Moors may be described as a topographical and geological island. "The region forms one of the most natural divisions of Yorkshire possessing its own special physical and geological features, and being well - defined by distinct physical boundaries" (Elgee, 1912, p.1). This 'island region' is bounded on the west and north by an escarpment which occasionally reaches an amplitude of 1000 feet, and on the south by a steep dip slope to the Vale of Pickering. The eastern margin is the coast, generally cliffed and sometimes rising to heights of 600 feet. Circumscribed as it is by the Vales of Pickering, York and Mowbray and the Tees valley, the North York Moors are a 'relief island'. The region is distinguished geologically on the west and north by the Jurassic - Triassic boundary and on the south side to a lesser degree by the junction of the Corallian of the Tabular Hills with the Kimmeridge clay of the Vale of Pickering. Several workers have suggested that the North York Moors have not always been so topographically isolated (Reed, 1901; Kendall & Wroot, 1924) but were continuous with the Pennines and drained by easterly flowing rivers during the Tertiary.

The island of the North York Moors is a distinct physical unit which includes considerable diversity. Several physical regions may be recognised, each with its own character, yet again, within these regions a second level of diversity may be recognised mainly as a result of the variable geological succession and the different processes shaping the landscape. Eskdale, the drainage basin of the Esk and its tributaries is a distinct region unified by the east - flowing river. North of the Esk a glaciated region falls gently to the Tees valley, to the south east is a similar glaciated coastal region including Robin Hood's Bay and the anomalous Derwent drainage. The Tabular Hills, developed on the Corallian and defined by a pronounced scarp on the northern side, comprise a fourth region whilst the Hambledon Hills form a fifth unit. The remainder of the North York Moors comprises the area south of Eskdale and north of the Tabular Hills, drained by south - flowing rivers including the Dove and the Severn. This region was probably an unglaciated enclave (Linton, 1952) during the last glaciation.

Eskdale (Fig.1) is drained by the only major east - flowing river between the Tees and the Humber. The drainage basin has a relief of 1489 feet as the watershed includes Burton Howe, the highest point of the North York Moors. Eskdale has a compound landscape; one fashioned fundamentally under the control of river base level, but whose development has been interrupted by ice at least on two occasions and part of Eskdale has been further etched and modified by the impact of periglaciation. The diverse geological succession is expressed in the detail of the landscape and many years ago it was noted that "In no part of England is the relation of the surface topography to the nature of the underlying rocks more instructively displayed than in this district; the strata being nearly horizontal and little disturbed by dislocations, the valleys radiating from the tableland can be traced out as the results of erosion with a precision and completeness unattainable in other parts of the country where the geological structure is less simple" (Geikie, 1898).

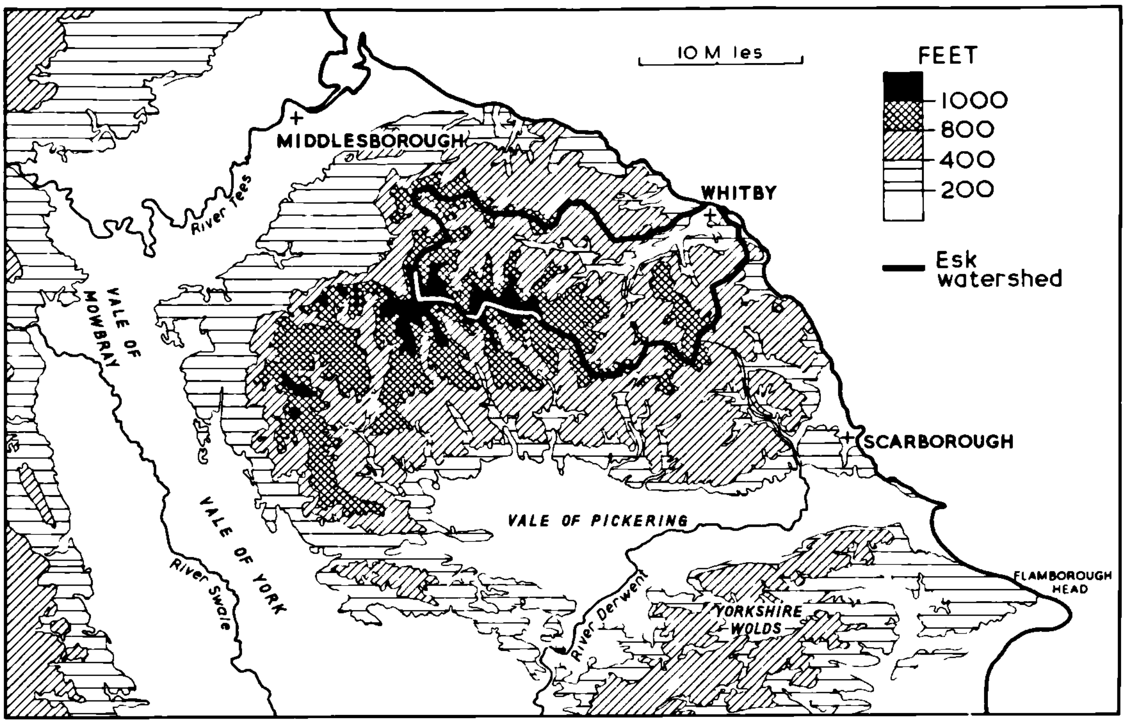
10 M les
FEET
1000
800
400
200
Esk watershed
MIDDLESBOROUGH
River Tees
WHITBY
SCARBOROUGH
VALE OF MOWBRAY
VALE OF YORK
River Swale
VALE OF PICKERING
River Derwent
YORKSHIRE WOLDS
FLAMBOROUGH HEAD

Fig 1.

The North York Moors were compared with the Weald as early as 1866 (Topley, 1866) but they have not been given the amount of attention devoted to the geomorphology of South Eastern England since that date. Research on the region has been rather sporadic and intermittent. The Geological Survey mapped the area and produced memoirs in 1885, 1886 and 1888. In 1901 the Sedgwick prize essay gave an account of 'The Geological History of the Rivers of East Yorkshire' (Reed, 1901) following Davis' paper of 1895 (Davis, 1895). Professor P.F.Kendall's now classic paper on 'The Glacier Lakes of the Cleveland Hills' appeared in 1902 and was important, not only to this area but to many other parts of glaciated Britain. This was followed by the 'Glacier Lakes of Cleveland' (Kendall, 1903a) and the 'Geology of Yorkshire' (Kendall & Wroot, 1924). A considerable and detailed literature exists on the structure of the North York Moors (Versey, 1929, 1931, 1937, 1947). Renewed interest in the problems of deglaciation was first shown in North East Yorkshire in 1956 (Best, 1956) and a thesis dealing with 'The development of the Eskdale (North Yorkshire) drainage system in relation to the geology of the area' also appeared in that year (Henry, 1956). A succinct summary of the geology and glaciation of the Whitby area was produced in 1958 (Hemingway, 1958) and the most recently published reference to part of Eskdale, again on the subject of deglaciation, referred to Glaisdale and the lower Stonegate valley (Sissons, 1961).

The relief and settlements of Eskdale are indicated on Fig.2. The Esk is a fifth order stream (Fig.3) which conforms to Horton's laws of drainage composition (Horton, 1945) (Fig.4). The hypsometric curve (Fig.4)

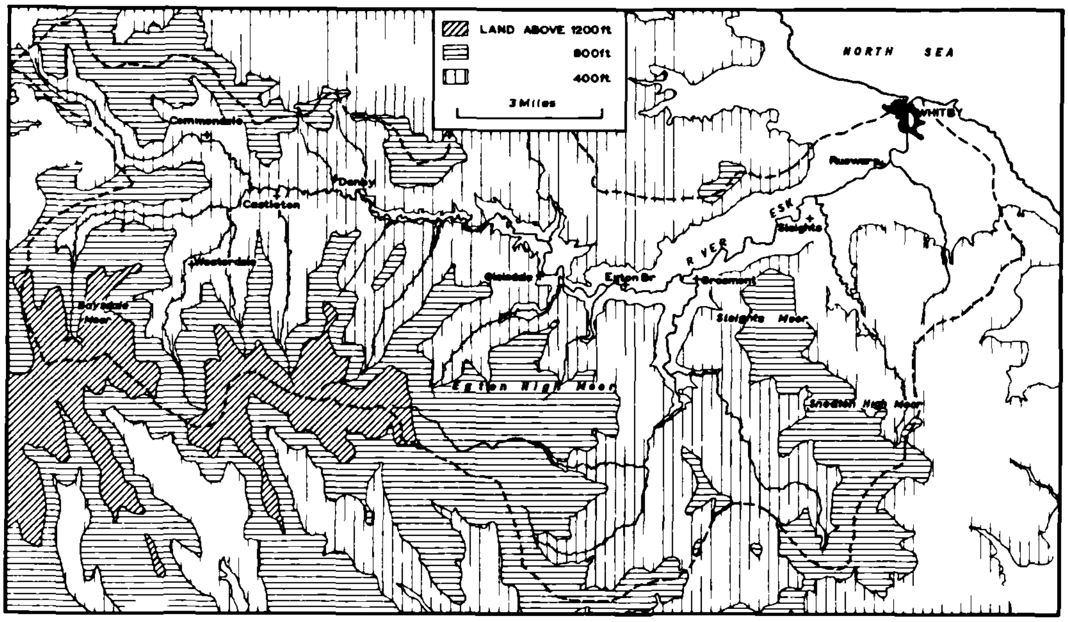
LAND ABOVE 1200ft
800ft
400ft
3 Miles
NORTH SEA
WHITBY
Ruswarp
Commondale
Danby
Castleton
Westerdale
Glaisdale
Egton Br
Grosmont
R VER
ESK
Sleights
Sleights Moor
Egton High Moor
Sneaton High Moor

Fig 2.

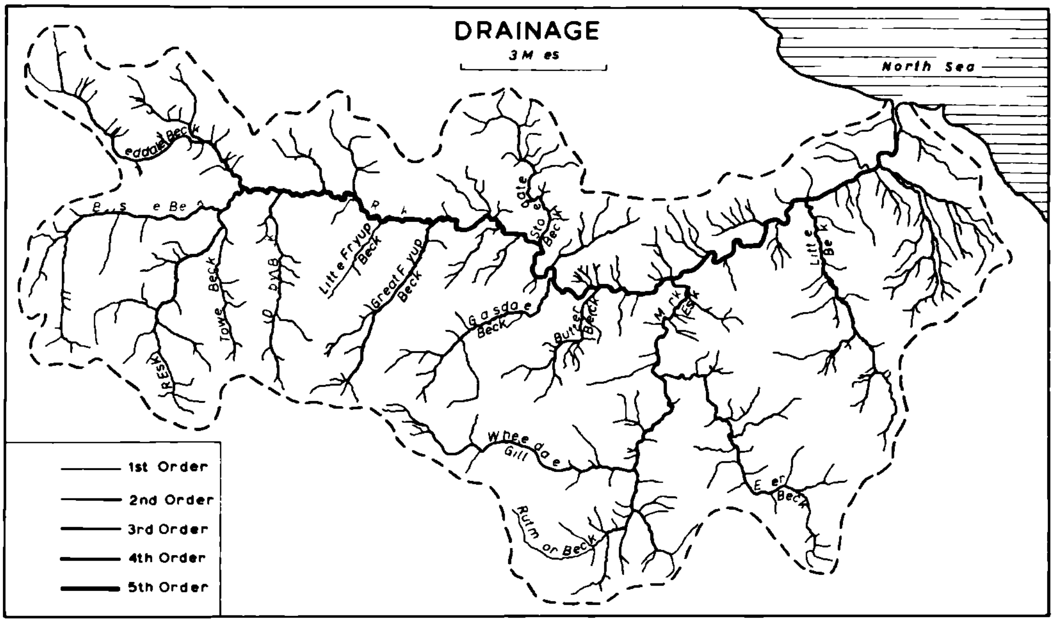

Fig 3. The drainage pattern of Eskdale and stream order.

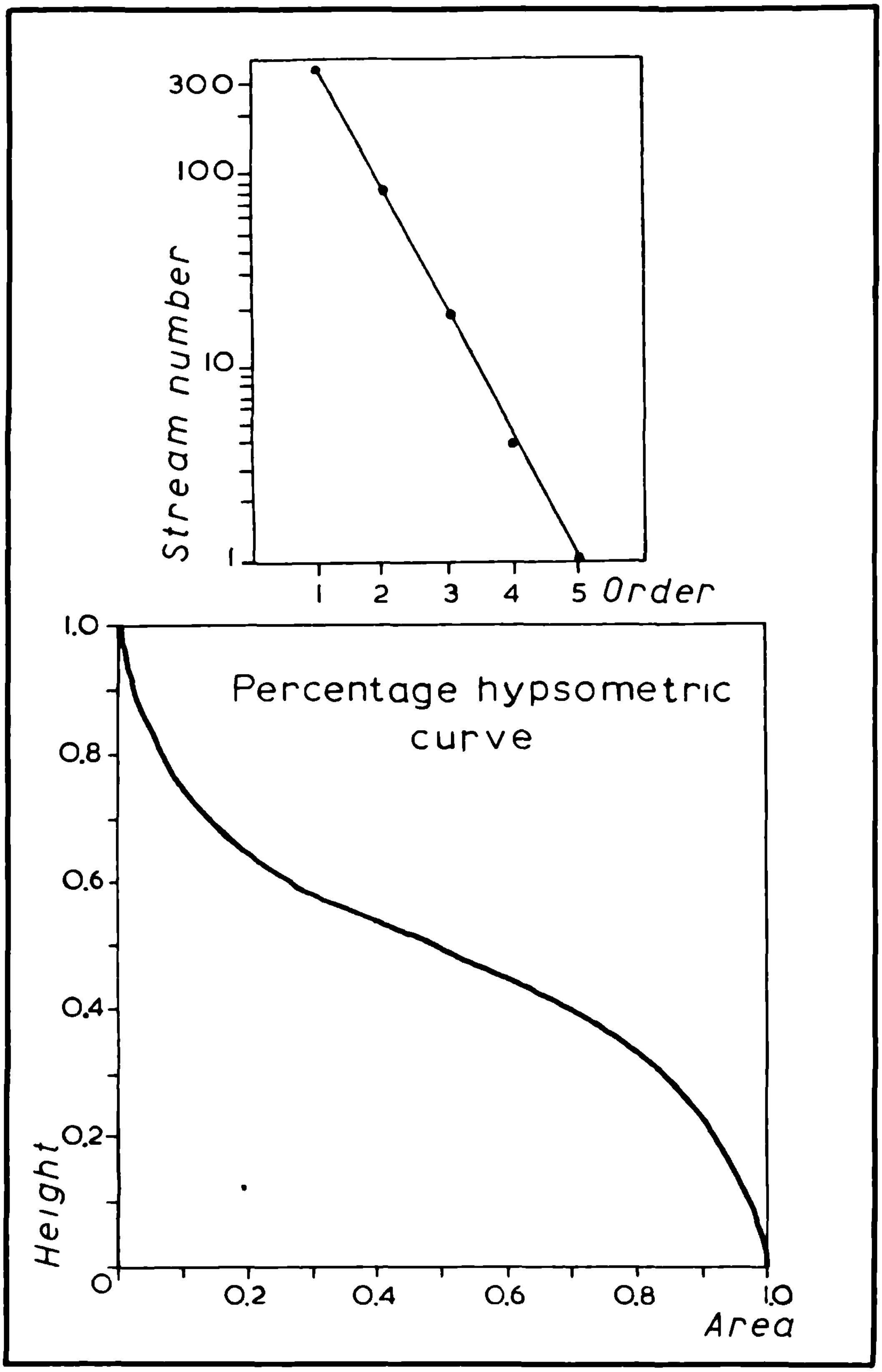

Fig 4. Cartographic analysis.

Based upon 1: 25,000 maps.

illustrates the fact that the basin is in an equilibrium state of development according to Strahler, (1952).

Morphological mapping (Waters, 1958) has been used as the main method of fieldwork in Eskdale and as Waters noted (1958, p.16) "....the construction of a morphological map is only the essential first stage in the study of a landscape. Recognition and delineation of slopes and flats must be followed by their analysis and classification; the empirically defined units of surface must be assigned a place in the genetic classification of landforms". When this technique of mapping is used and the map analysed quantitatively there are two parts to the study; the quantitative analysis of the present landscape and the study of its development. In this account the two themes have been co-ordinated; angle of slope is considered first, followed by an analysis of the constituent flat and slope facets, leading to a study of planation surfaces, glaciation and periglaciation - the influences which have shaped the contemporary landscape of Eskdale.

CHAPTER 2.

A METHOD OF APPROACH.

1) The development of Quantitative Geomorphology

Since 1945 there have been many attempts to find a firm basis for geomorphological research and this has been contemporaneous with increasing interest in slope study which demands a method of handling large volumes of data. The need for analysis has been expressed by Brown (1960a, p.43) : "The full understanding of the physical landscape presupposes a familiarity with some evidence which is not obtainable solely from field investigation. The study of a variety of maps of differing scales and the application of a growing number of analytical methods is a desirable, if not obligatory, aspect of geomorphological research today. Such cartographic labour is not a substitute for field work but may prove a very valuable adjunct to it". Bakker and Strahler (1956) have remarked that "Geomorphic science, at its present stage of development suffers from a lack of quantitative exactness" and A.A.Miller (1961) has emphasised a similar view: "....there is a third factor, the degree of slope. Here again is subject for quantitative work, begun in earnest by Strahler. But as long as the work of geomorphologists remains qualitative controversy will still proceed inconclusively on such things as peneplains and pediplains, convex and concave slopes, and the qualitative contributions of W.M.Davis, Walther Penck and Lester King". But the opposite opinion has been expressed by several geomorphologists including Baulig (1950): "The laws of geomorphology are complex, relative and rarely susceptible of numerical expression".

There is general agreement that more quantitative data and analysis are required before definite conclusions can be made.

Quantitative studies may be based on either existing or specially surveyed contour maps, or on fieldwork. The methods and limitations of the analysis of contour maps have recently been summarised (Clarke and Orrell, 1958). Some of these methods have been applied in Eskdale for the purpose of comparison with the results based on fieldwork. Bakker and Strahler (1956) have commented that "....full use of the modern morphometric - statistical methods for slope development can only be made if it is based on fieldwork", but in America and elsewhere much of the early work was based upon available contour maps. In Britain, where only small areas are available for research, it is very doubtful if any appreciable results would be obtained from the analysis of contour maps without fieldwork. The results obtained from contour maps or from fieldwork may be analysed by one of three methods:

i) quantitative - in which all the available data is collected and analysed as effected by Strahler (1956).

ii) statistical - where data is collected by sampling as exemplified by the studies of Strahler (1954, 1957), Miller (1953), Schumm (1956), Chorley (1957), Melton (1957), and Coates (1958).

iii) qualitative - when the material is collected and analysed descriptively (e.g. Gardiner, 1960). This method involves subjective interpretation on the basis of personal conclusions, and also necessitates the loss of much of the available data as a result of the sheer impossibility of analysing data without resort to either quantitative or statistical methods.

This increasing interest in quantitative geomorphology has been reflected in geomorphological publications of the last ten years. In America a publication by Horton (1945) led to the emergence of dimensional analysis; treated statistically by Strahler and others this was based initially upon contour maps and subsequently to an increasing degree upon fieldwork. In Europe, quantitative measurements have been treated statistically by French geomorphologists (e.g. Gloriod and Tricart, 1952) and in the Netherlands the problem of slopes has been treated mathematically by Bakker and others (e.g. Bakker and le Heux, 1947). In Eastern Europe development has been mainly quantitative within the field of dynamical geomorphology (Dylik, 1957). These developments in quantitative studies have largely proceeded along different lines but the various methods could be co-ordinated in one area either by combining or repeating the different approaches. To a certain extent the methods which can be applied will be dictated by the form of the area, the relationships within the area and also by the aims of the study.

2) The aims of the study

The original aim of the study, when first instigated, was to complete a geomorphological survey of part of the North York Moors. The main field technique adopted was that of morphological mapping (Waters, 1958)

From this beginning it is now hoped to realise an investigation into the potential of morphological maps as a basis for quantitative analysis. This involves a consideration of the areal dimension in landscape analysis, the relationship of integral parts of the landscape and also the correlation of the properties of these landscape constituents or facets[1]. The investigation necessarily leads to an examination of the possibility of integrating two themes; that of physical landscape evolution, hitherto often considered qualitatively and that of dimensional analysis which is treated quantitatively.

3) Mapping

Morphological mapping was formally described by Waters in 1958 although previously many experiments had been conducted using and developing this technique contemporaneously with the production of geomorphological maps in other countries such as Poland (Klimaszewski, 1961). The British Geomorphological Research Group has undertaken research into the variation in maps produced by different workers and also into suitable map scales (Reports 1 - 4). However, no study has so far been attempted designed solely to extract and relate information contained on the morphological map and so to suggest what possibilities the technique may afford. The chief advantage of this type of mapping is that the entire landscape is mapped and so a complete picture is obtained. This has been achieved in Poland by a more subjective type of mapping as noted by Klimaszewski (1961): "Geomorphological research in Poland has hitherto, in its attempts to present the relief of a region, and to enquire into its morphological evolution, limited itself to some isolated forms disregarding the totality of the forms investigated". The study of Eskdale included the production of a geomorphological map for the

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[1]In this thesis the area between adjacent changes or breaks of slope is always referred to as a facet; no other technical terms are used.

whole drainage basin; parts of this map have been analysed quantitatively and will be used as the core of the dimensional analysis.

A morphological map is constructed by delimiting and recording areas of fairly uniform slope in the field. The map produced for Eskdale is termed a geomorphological map because it includes features too small to map in terms of angle of slope, which are designated by symbols according to origin. This introduces the problem of the most suitable scale to use for field mapping which should preferably be a multiple of one of the existing scales of published Ordnance Survey maps. The 6 inch maps were found to be most suitable in Eskdale because they allow the recording of significant detail on the valley side slopes (found to be the most detailed) and are not too large for use in moorland areas. Use of a smaller scale, (1:25,000) would be adequate for the moorland areas, in many cases, but would not allow the inclusion of much of the significant detail from the sides of the dales. A larger scale map (1:2,500) would be difficult, if not impossible, to use in moorland terrain by one person working alone. The 1:25,000 maps could form the basis of a geomorphological map in areas where the relief is low and the geomorphological detail small, or where a map of features was required rather than a detailed representation of the form of the ground.

When the mapping scale has been selected the major variations within the area should be considered and several small trial maps produced for each of the major types of terrain. The writer found that at least three weeks mapping is required for the development of the method and adjustment to the area to be mapped. The mapping operation consists basically of delimiting breaks and changes of slope; when these have been defined the angle of slope between adjacent breaks or changes is measured down the line of steepest slope. Within any one facet which has an average slope of ten degrees or less the amount of angular variation is not permitte to exceed $1\frac{1}{2}$ degrees and usually it is 1 degree or less. Symbols are introduced whenever the features become too small to map in detail and also to represent certain types of mass movement phenomena for ease of analysis. The symbols are explained with examples in Appendix 1.

In Eskdale there is a fundamental distinction between the terrain of the valleys (usually enclosed by field boundaries) and that of the unenclosed moorlands. The map varies slightly as between these two areas because of difficulties of location on the moors. This is partly justifiab as the variation and detail is much smaller on the moorland tracts. Within limits of attainable accuracy, all significant detail was mapped in the hope that an exact knowledge of the morphology of the area would be helpful in determining the mode of evolution.

The enclosed areas are relatively easy to map as the system of field boundaries provides a convenient framework for location. In moorland areas considerable competence is attained with experience from a period of mapping (up to six weeks) in enclosed country which improves correct judgement of distance. In another context the difficulties of moorland mapping have been noted; "Here the enemies of the surveyor are the absence of good points of survey reference and the frequency of wind and rain which make observation difficult" (Phillips, 1961). Mapping in these areas was effected by short traverses up or down the line of steepest slope. With practise many landmarks shown on the 6 inch map may be used as base lines and base points and even old tracks now covered by caluna may be detected and used for the traverses (Fig.5). Other landmarks include howes, (tumulii), boundary stones, crosses, triangulation stations and streams. In North East Yorkshire a portion of moorland devoid of any of these features is very uncommon. The discrepancies which arise, especially in enclosed areas, due to soil creep are resolved for angular measurement into two components, above and below the change or break. Only when the depth of accumulated creep material achieves a sufficient thickness (above 5 feet) can a symbol be employed. All existing water courses are marked on the field map in blue with allowance for seasonal variation. The head of a first order stream is recorded to the apparent limit of recent activity.

In many cases smaller detailed studies may be needed to supplement the information afforded by the geomorphological map. In Eskdale height readings have been taken for major flats delimited on the map and small detailed studies undertaken, including the morphological investigation of glacial drainage channels and periglacial terraces. Field notes were constantly made during field work to record exposures and sections of interest and also to refer to the character and occurrence of specific landforms. Preliminary cartographic analysis affords a fourth supply of data but this is used mainly for the purpose of comparison with the results of the field mapping.

4) <u>A method of analysis</u>

A geomorphological map contains a vast amount of material and only by grouping, correlating and analysing this data can its true value

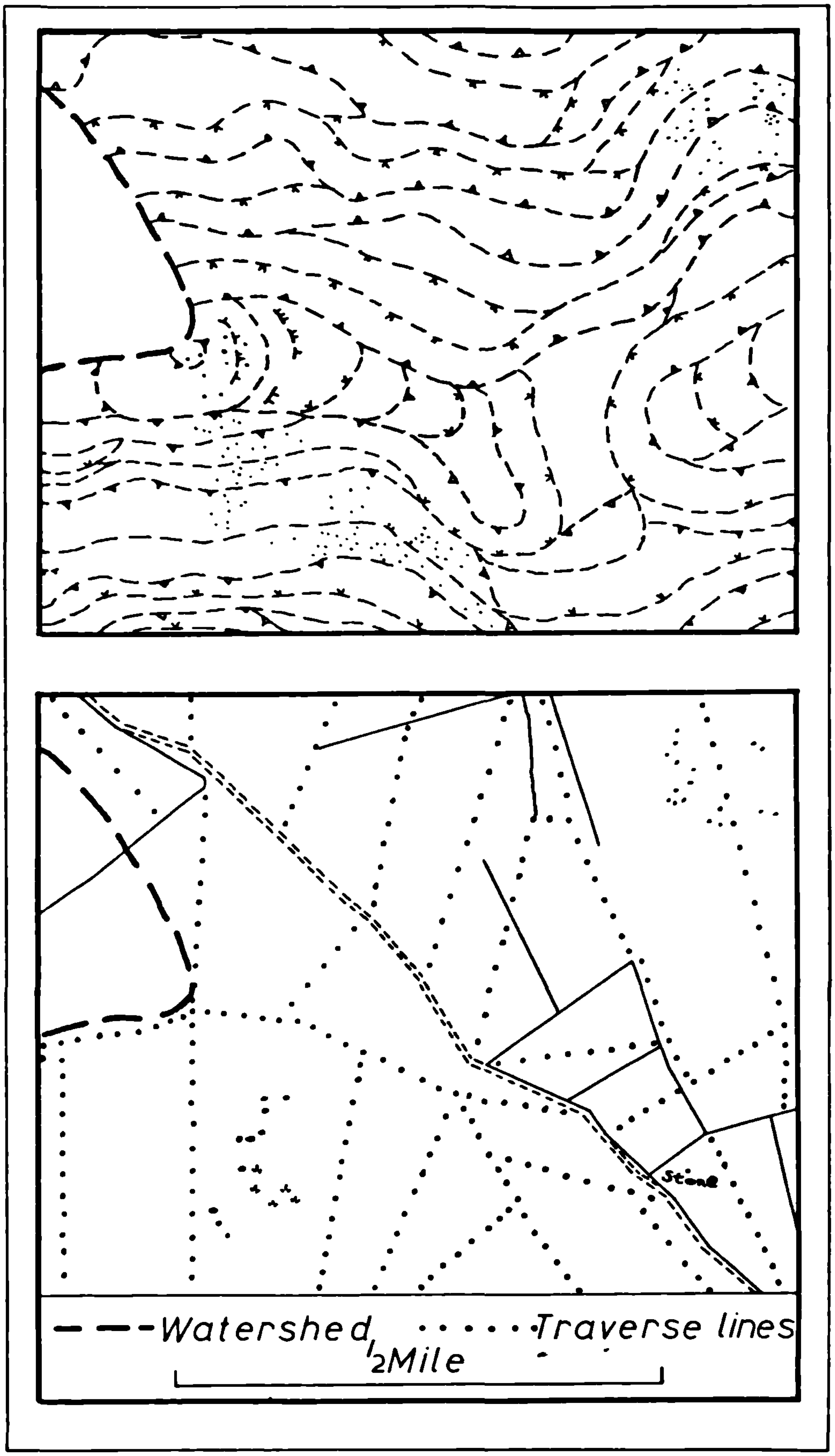

Fig 5. The method of moorland mapping.

be realised. As noted above, the information may be extracted and utilised, using quantitative, linear (statistical) or qualitative methods. Qualitative studies have been made by Gardiner (1960) and others, but necessarily incur great loss of available data which could be used as a basis for analysis. Statistical methods are based on profiles constructed from geomorphological maps and have been described by Savigear (1956). This method also results in loss of data and only certain profiles are selected for study by statistical or subjective sampling methods. Other workers have used profiles which have been surveyed directly thus dispensing with the geomorphological map (Savigear, 1960; Young, 1961). The quantitative method of analysis involves direct measurement of area and so for the area considered all the available information is used. This method has not, as far as is known, been attempted before.

A method of analysis was devised while mapping and only in the field can the problems and correlations be appreciated for the particular area. This scheme is one of several which could be devised but although more items could be added and the scheme amplified, few of the items used here could be replaced. Further records could include data for climate, soils and vegetation. The areal method of analysis could then be used to compare the morphology of different areas and would be one way of developing the method in accordance with Dury's suggestion that "....such analysis (statistical) may in time succeed in revealing the precise effects of rock type and rock structure in a given climate, and the contrasted effects of climate, soil and vegetation in regions of similar rocks, similar structures and similar erosional history" (Dury, 1960, p.43).

The geomorphological map consists of a network of facets; unique areas of fairly uniform (i.e. including variation between slope readings of each facet not greater than $1\frac{1}{2}$ degrees) slope. The data derived for each facet is of two types; apparent and deduced. The apparent are definite quantities whereas the deduced are based to a certain degree upon subjective definition. The apparent items include area of facet, angle of slope, height range, underlying rock formation, nature and approximate amount of drift cover, and orientation; the deduced items include relative slope, position on major slope type, origin, height above stream and drainage basin order.

a) The apparent items.

i) The area of each facet was measured using an Albrit polar planimeter. The area obtained is the horizontal equivalent and the area on the ground may be obtained by multiplying this area by sec x where x is the angle of slope of the facet.

ii) The angle of slope of each facet is calculated as the average of all the slope measurements made for the facet. This angular value is recorded to the nearest half degree because angular measurements in the field are made to this accuracy (limiting accuracy of the Abney level; $\frac{1}{2}$ degree). A test using $\frac{1}{4}$ degree values obtained by evaluating average slope showed too much random variation.

iii) The height range is recorded as two readings which indicate the absolute values of height between which the facet occurs. The height values are determined from the 6 inch maps (25 feet contour interval) and in some cases from aneroid readings. The height values are given to the nearest 5 feet.

iv) The rock type underlying each facet is noted by comparing the geomorphological map with the 6 inch geological survey sheets (Geological Museum, South Kensington). Where a facet transcends the geological boundaries the facet is subdivided accordingly.

v) The nature and thickness of the drift cover is based upon the geological survey maps, on the records incorporated in the survey memoirs (Fox - Strangways, Reid and Barrow, 1885) and on personal observation in the field. The main categories of drift are glacial clay (boulder clay), glacial sands and gravels, peat (blanket and channel), detrital material including landslip material, and alluvium.

vi) Orientation is defined as the aspect of the facet. It is measured with a protractor as the angle between the line of steepest slope of the facet and grid north. All readings were made to the nearest 10 degrees, from north recorded as 0 degrees, through east (90°), to south (180° and west (270°). In instances where the facet varies along its length it is subdivided by orthogonals; lines drawn down the line of steepest slope to isolate areas with uniform orientation. A summit facet, which does not possess a back, is not given an orientation but forms a distinct group.

b) The deduced items.

i) A dimension was required to represent relative slope[1] so that flats with varying angles of slope could be compared (Fig.6). The index would, it was hoped, indicate any differences and similarities between flats of different types and in different locations. The relative slope of a facet is noted only where the slope of the facet is less steep than the

1. The dimension was called relative slope rather than relative flatness because it could be calculated for all facets and not only for flat facets.

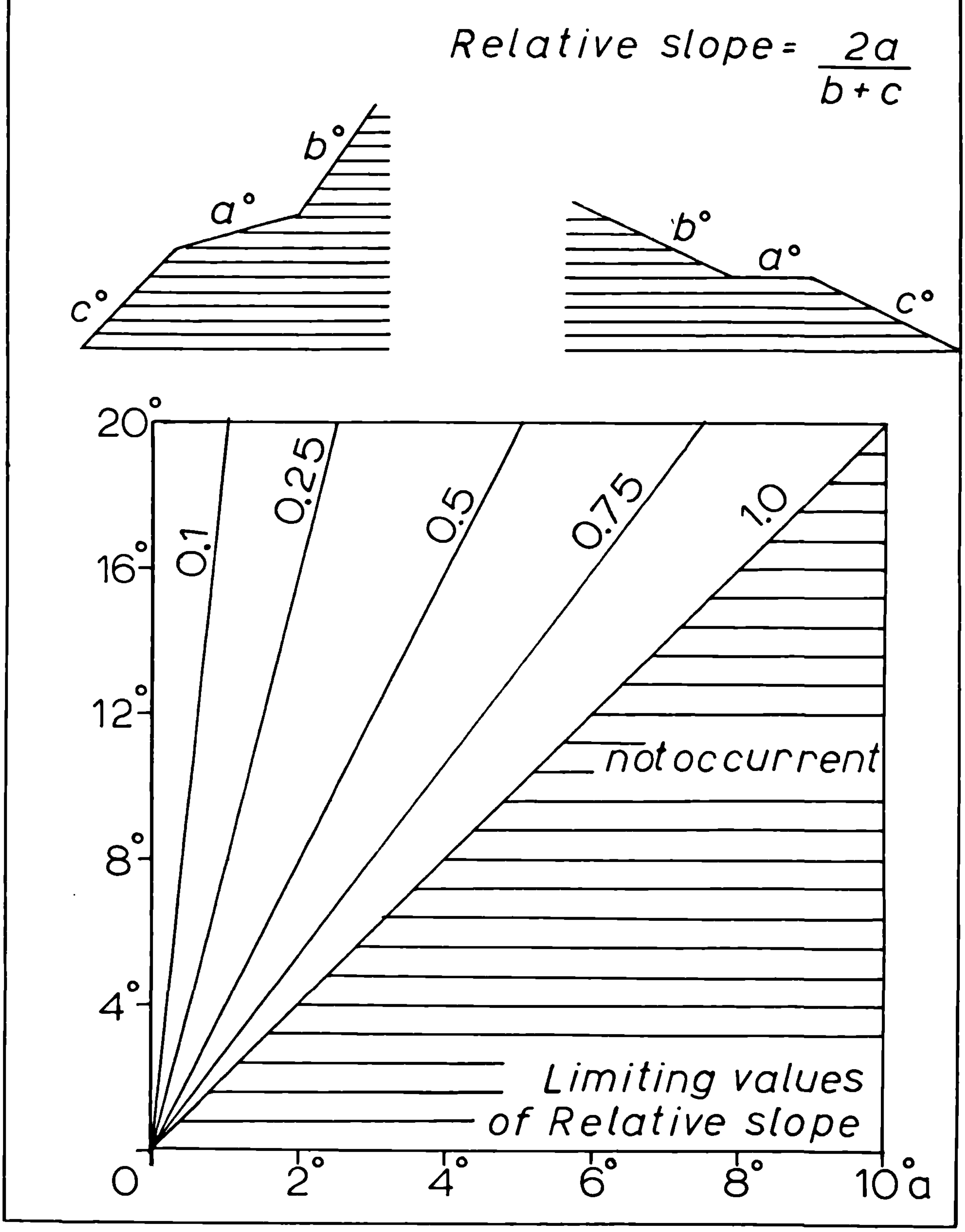

Fig 6. Relative slope (angle a plotted on x axis and b + c on y axis).

slopes immediately above and below.

ii) The position on major slope type was formulated so that the available information on slopes could be grouped and compared for large areas. On the basis of field experience three types of major slopes were recognised in Eskdale; summit slopes, valley side slopes and stream side slopes. If a free face occurs in the slope profile other than at the top, the valley side and stream side slopes were sometimes subdivided into upper and lower parts. A major free face in the valley side is taken to be included in a stream side slope. If a free face does not occur the slope adjacent to the stream will be described as stream side or valley side according to whether a stream side slope and associated free face occurs further downstream or not. The basis for the distinction of these three types of slopes is illustrated in Fig.7. When the slope type has been distinguished, the height (feet) of the lowest part of the facet above the slope base height (H_b) and the height (feet) of the highest part of the facet below the slope top height (H_t) are noted. The percentage position P of the facet in the slope type is then calculated as $P = \frac{H_b}{H_b + H_t + H} \times 100\%$ where H is the height range of the facet. This dimension is a modified quantitative expression of the qualitative description 'erosional environment' (Melton, 1960).

iii) The height above stream is difficult to calculate for all facets but was devised as a possible line of approach. The difference between the height of the base of the facet and the height of the nearest eroding stream is calculated and this gives a possible method of comparing

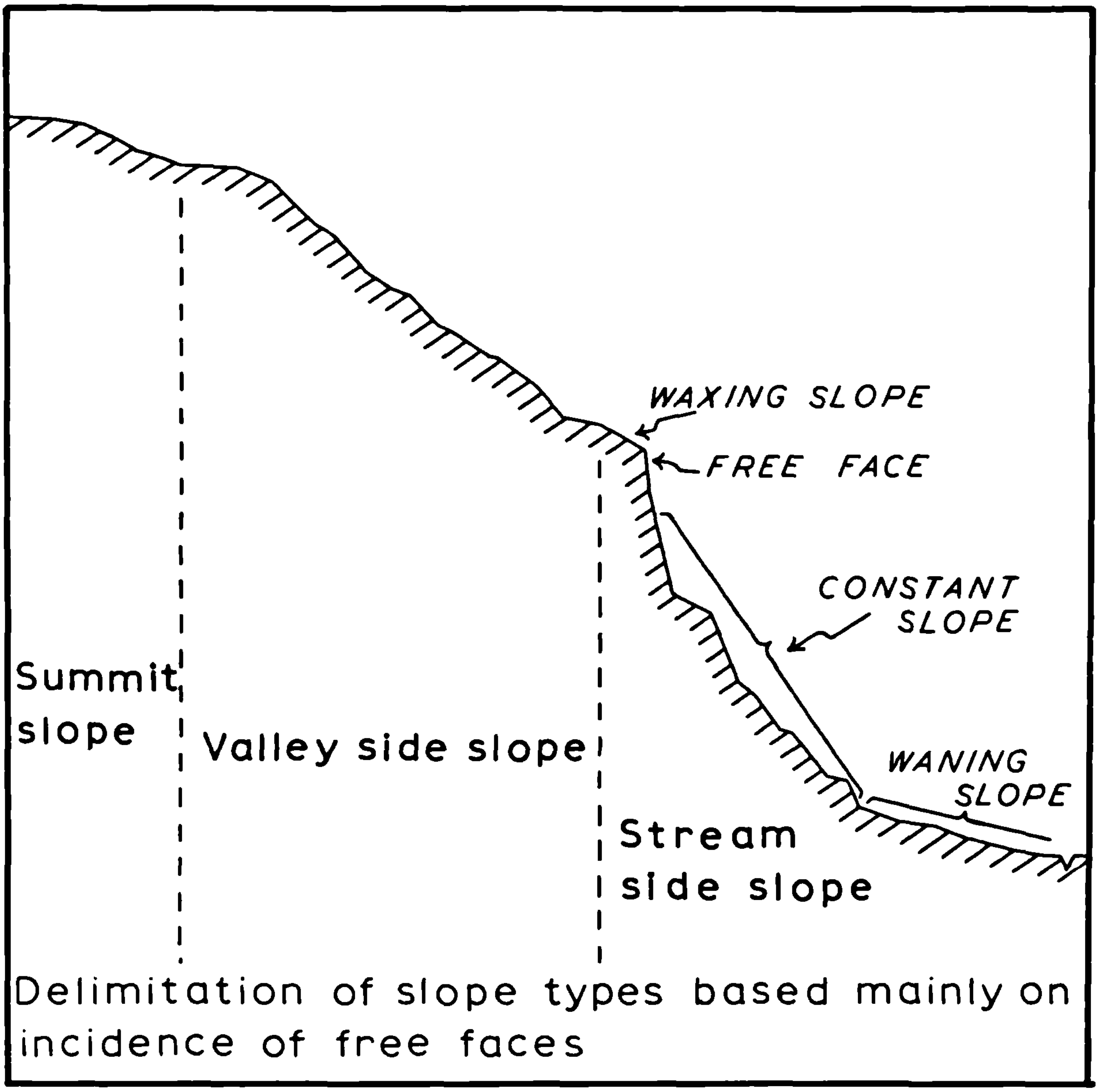

Fig 7. Slope types.

facets in relation to fluvial erosion. There are two main types of fluvial base above which the height of this dimension is calculated; the head of a first order stream or the appropriate section of a second or higher order stream. In the latter case the height above stream is measured down the line of steepest slope to the stream flowing approximately parallel to the facet.

iv) The origin of the facet is classified in two ways; the morphological origin is noted, as described above, for one of three slope types; and the genetic origin was noted for certain features. This classification is not comprehensive but small features are included for ease of analysis. Those included are flood plain, post - glacial, river terrace, rock - strewn terrace (altiplanation terrace), boulder - strewn ground, dry valley, erosion surface, glacial erosion feature, glacial deposition feature, landslipping (rotation form), and other types of landslipping.

v) Drainage basin order is based upon the definition of Horton (1945) with the later modification proposed by Strahler (1952). The drainage basins are defined in terms of facets and the junction of the valley side slope and the stream side slope is taken to represent the junctic of the main valley basin and a first order basin. Six types are recognised in Eskdale; first, second, third, fourth and fifth order basins and also the length of overland flow (Horton, 1945) which is the portion of land surface devoid of channel dr inage.

The scheme of analysis is designed to consider area and rel tionship of facets. Area is measured and so in every correlation absolute values of occurrence are available in terms of area on the ground. The entire landscape is mapped and so correlations may be made between constituent parts, and the relationship and effects of these examined. A typical sheet of records for twenty facets is shown in Fig.8. In the course of analysis subjective decisions have been made but as long as they are acceptable ones and are adhered to consistently the system is considered valid. Criticism has been levelled at the consistency of geomorphological mapping (Report Number 4 of the British Geomorphological Research Group) in that different workers may produce different results. However the author suggests that with experience (at least four weeks) workers could be trained to produce similar maps and, if the map is produced by one person, consistency will be attained after a trial period and similar problems resolved uniformly.

QUANTITATIVE ANALYSIS													
GRID. REF.	AREA	ANGLE	HEIGHT	R.S.	GEOL	LIAS	DRIFT	ORIENT -ATION	ORIGIN A	ORIGIN B	ABOVE STREAM	SLOPE POSITION	D_B ORDER
749075	011	000	37	00	3		5	00	3	1	00		
4 73	013		37		3			00	6		1	04	
747 72	06	35	041		3		1	36	6		04	5	
74807	0	06	03 5		3		1	00			01	07	
7 7071	02	01	0415	5	3		1	01	6		04	29	4
746071	038	030	0425		3		1	1	6		05	36	4
747070	37	1	043	27	3		1	1	6		07	46	4
747069	0	0	0445		3		1	34	6		07	0	4
7 7	00	06	04		3		1	13	6		00	00	4
748070	5	55	04 5		3		1	31	6		0		4
74 070	03	20	0	5	4		1	03	6		1	11	4
749 70	1				5		1	13	6		0	00	4
74 069	0	06	4				1	1	6		00	00	4
749069	010	080	04 0				1	34	6		2	54	4
4806	009	5	04				1	04	6			58	4
747 9	1	005	460	15	3		1	35	6		03	7	4
748068	006	0	047				1	3	6		5	01	
748068	1	5	490				1	34	6			7	4
74 067	00	0	0	3			1	35	5		08	00	4
748067	11	90	0 1				1	34					4

Fig 8. Records for 20 facets in the sample area.

CHAPTER 3.

THE MECHANICS OF ANALYSIS.

It is estimated that there are approximately 17,000 facets in Eskdale, an area of 135 square miles. For each of these facets 11 items of information could be recorded giving a total of approximately 190,000 items for analysis. The analysis of approximately one fifth of the total area (23.5%) took three months of concentrated effort and so as a result of the time taken to effect the analysis and the prohibitive cost it was decided to test the method of analysis for this sample area before embarking upon the complete project. If the scheme proves successful it could be applied to the entire drainage basin incorporating the modifications suggested by the analysis of the sample. In analysing the sample, which included 3228 facets, approximately 35,000 quantities are involved.

1) Sample analysis

The sample data chosen from the Eskdale drainage basin could be selected in one of two ways; statistically or by drainage basins. The statistical method would be effected by sampling facets quite freely throughout the area, using random numbers. This method would be disadvantageous at this stage because the sample would be taken to represent the whole drainage basin, the facets selected would not be related to one another in a direct way and a proportion of the facets would be selected from the eastern part of the area where glacial drift mantles the landscape and where glaciation has imposed many modifications. The total area was selected because it is a drainage basin, a self - contained unit which is fundamental in dimensional analysis. The drainage basin method was chosen because the eastern part of the area, which is complicated by the legacy of glaciation may be ignored. In a full analysis of the area the drift - covered area would be significant and could be used to illustrate the morphological variations imposed by glaciation through comparison with the drift - free area. However, unless the whole drift - covered area is analysed there would not be sufficient data for comparison. A further reason for adopting the drainage basin method is that the analysis primarily represents the drainage basins selected although it may also be taken to represent the entire area if desired. The probability that the sample chosen may represent the entire area is not greater than 28.48/135 = 0.24.

The drainage basins comprising the sample were selected from western and central Eskdale bearing in mind the need to include a sufficient variation of height range, of orientation and of drainage basin order and also a reasonable proportion of slope types. The slopes of this part of Eskdale are very well - defined and well - formed and so if the method may be effective for slope analysis these areas form an ideal base for initial work. The drift - covered slopes of the eastern part of the area could subsequently be studied in the light of the initial analysis and the variations and differences noted. The distribution of the selected drainage basins is shown in Fig.9.

The sample chosen consists of 3223 facets each with 11 items of information. Although this total is appreciably less than that for the whole area, the mechanical problem of handling this volume of data is quite considerable. The methods of analysing the data described in Chapter 2 depend upon selecting certain facets and then correlating two or more

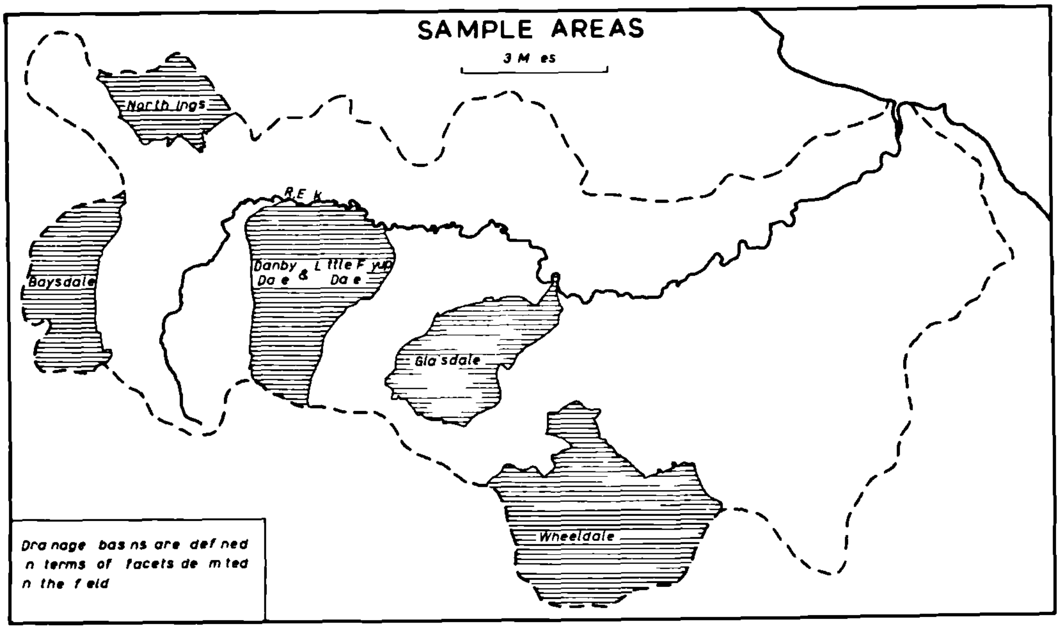

Fig 9. The distribution of drainage basins in the sample area.

values for these facets. The problem is mainly one of sorting followed by addition of areal values[1]. A general account of the methods available for 'Measurement in human geography' has recently been produced (Coppock and Johnson, 1962). There were three methods available for consideration which could be applied to the geomorphological analysis of Eskdale and these involve the use of desk calculating machines, an electronic computer (Ferranti Mercury) or punch card equipment.

Desk calculating machines speed up calculation but sorting of information must first be done by hand. These machines are given instructions interspersed with data and so with a large amount of data would lead to considerable human error in hand sorting. An electric desk calculator is most useful in doing rapid, simple calculations on results obtained from another source such as the calculation of percentage values which can be achieved by employing the memory, consisting of one register.

The possibilities and techniques of computer programming were studied[2] in the hope that this would afford a possible method of effecting the analysis. The London University Ferranti Mercury computer has two auxiliary stores each containing 8192 registers in addition to the main store of 480 - 32 registers giving approximately 17,000 registers for storag of the instructions and data. If the analysis of the sample was attempted in the computer by storing information and then effecting the program, at least two operations would be required. A more suitable method would be to program and then to read in the total data some of which would be

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[1]The author acknowledges the assistance of Dr E.H.Brown who suggested the application of mechanical means.

[2]Programming (Autocode) Course; University of London Computing Unit.

selected and used in each part of the program. However, a computer is designed to speed up calculation and not merely to effect sorting and to read the total information into the computer would take a large amount of time. The actual time taken for computation would be very small indeed, most of the time being spent upon input and output. Input to the Ferranti Mercury is achieved by punched paper tape but by using a computer which could take punch card input the obstacles would be removed. The great amount of data involved in sorting was regarded as too prohibitive to use a computer with paper tape input at this stage. If quantitative analysis is developed sufficiently the electronic computer may afford an extremely useful 'tool of geomorphological research' at a later stage, especially with punch card input. When the great volume of data has been sorted and general conclusions reached the computer could be used either to test the validity of these conclusions or to assemble the generalised data and to test it in inductive models. This is of particular application to slope studies; once the initial data has been analysed and digested, generalised mathematical models may be derived. Already some progress has been made in the use of a computer for this purpose (Scheidegger, 1961). A further line of potential development is afforded by data - plotting machines which may be coupled with a computer; this would allow the direct plotting of results on maps, rather than tabulation. This has been developed by the Computation Branch, National Meteorological Centre, U.S.A.

Punch card equipment is admirably suited to analysis of this type because each card may be punched to represent one facet. The information relating to each facet is therefore retained on a card and the cards may be sorted into groups according to the information recorded. The general details concerning the use of punch cards and their possible application to geographical methods have been discussed by Barry (1961). The equipment consists of three components; card punch, sorter and tabulator. The punch is used to record information on individual cards and then the sorter is employed to sort the cards into groups as required. Cards may be sorted at rates of 24,000 or even 36,000 per hour according to the machine used. The standard punch card has 80 columns and up to 12 items may be recorded in each column (values 0 - 9, X, Y). Letters may be represented by double punching. Once the cards have been sorted into relevant groups the tabulator may be used to add the total recorded values for any field (i.e. a group of columns).

2) Programming for punch card equipment

The data to be punched is first coded into a convenient form for punch cards. Whenever possible data is coded to numbers to avoid double punching and the use of a minimum number of columns is desirable. Thus if one category of information includes 15 items, as does the geology of Eskdale, it is better to use one column with a subdivision of two of the twelve groups in this column rather than two columns with numbers 1 to 15. This reduces the number of cards involved in sorting. The Geological types in Eskdale were therefore represented as Lower Lias - 1, Middle Lias - 2, Upper Lias - 3, Dogger - 4, Lower Deltaic - 5, Eller Beck Bed - 6, Middle Deltaic - 7, Grey Limestone - 8, Moor Grit - 9, Upper Deltaic - 0, Cornbrash - X, Kellaways - Y in column 19 and the Middle and Upper Lias were then subdivided on column 20 into Sandy series - 1, Ironstone series - 2, Grey shale - 3, Jet Rock - 4, Alum shale - 5. When the cards are sorted on the basis of rock type only one complete sort is required rather than two complete sorts which would be needed if the coding had been by numbers 1 to 1

Using the information analysed and described in Chapter 2 the following scheme for punching was finally adopted and inserted in the first 30 columns of 80 column cards[1].

Punch Columns	Information	Range	Comments.
1,2,3,4,5,6.	Grid Reference		A six figure reference is unique fo this part of the North York Moors. These cards could later be used for comparison with other areas by punching an index letter in column 31. The grid reference could also be used for automatic plotting.
7,8,9.	Area	001 to 200	These are planimetric units reduced to actual ground areas (square mile by multiplying by 200/640 and then by the sec. angle of slope.
10,11,12.	Angle of slope	000 to 500 (0° to 50°)	$\frac{1}{2}$ degree is represented by 5 in column 12. The maximum value recorded is $38\frac{1}{2}^{\circ}$ punched as 385. All free faces (not accurately measured in the field) are recorded as 50° (punched as 500).

[1]There is no appreciable difference in the cost of 30, 65 and 80 column cards and so 80 column cards are most frequently used.

Punch Columns	Information	Range	Comments.
13,14,15,16.	Average Height	0280 to 1480 in sample	The mean of two limiting heights is taken to the nearest 5 feet (upper value). In the analysis columns 15 and 16 are not used but may be used later for the whole are and for comparison with other areas
17,18.	Relative slope	00 to 60	The first two significant figures of the dimension are recorded. If no relative slope occurs the columr are left blank and so in sorting these would be placed in the reject pocket of the sorter.
19.	Geology	0 - 9,X,Y.	Coding as above.
20.	Lias Geology	1,2,3,4,5.	Coding as above. The divisions of the Upper Lias are not always recorded on the survey maps and so in some cases subdivision is not possible.
21.	Drift Geology	1,2,3,4,5.	Boulder clay (1), sand and gravel (2), detrital material (3), peat (4 alluvium (5).

Punch Columns	Information	Range	Comments.
22,23.	Orientation	00 - 35	Some cards representing summit fla with no orientation are left blank in columns 22,23. They will be placed in the reject pocket during sorting. Values are measured to the nearest 10 degrees and so 320 is punched as 32 and 20 as 02.
24.	Slope type	1 - 7	Summit slope - 1 Upper valley side slope - 2 Lower valley side slope - 3 Valley Side slope - 4 Upper stream side slope - 5 Lower stream side slope - 6 Stream side slope - 7.
25.	Origin	1 - 11	Flood Plain - 1 Post glacial - 2 River terrace - 3 Rock - strewn terrace - 4 Rock - strewn ground - 5 Dry valley or depression - 6 Erosion surface - 7 Glacial erosion - 8 Glacial deposition - 9 Landslipping, Rotation - X Landslipping (other forms) - Y.

Punch Columns	Information	Range	Comments.
26, 27.	Height above stream	00 to 60	This was originally calculated to the nearest 5 feet but now is reduced to the nearest (upper) 10 feet and so 55 becomes 60 and is punched as 06.
28,29.	Position on slope type	00 to 99	The percentage position above slop base was calculated and so 9% is punched as 09.
30.	Drainage basin	1 to 6	Including first order (1), second order (2), third order (3), fourth order (4), fifth order (5) and length of overland flow (6).

A punch card prepared according to this scheme is illustrated in Fig.10.

3) <u>The main program</u>

The program of sorting and tabulating must be devised bearing three factors in mind; the correlations which are required, the available number of cards and the cost involved. The fundamental aim of this study is to analyse the occurrence of slope angles and to see how they vary areally with factors such as geology, position and orientation. A sort into angular groups is therefore an essential part of each section of the program devised. The cards may be sorted according to geology or any other factor but then each of the groups obtained must be sorted into further groups according to angle of slope. The analysis for the entire drainage basin of Eskdale would allow intricate and complex sorts but when using a sample the program

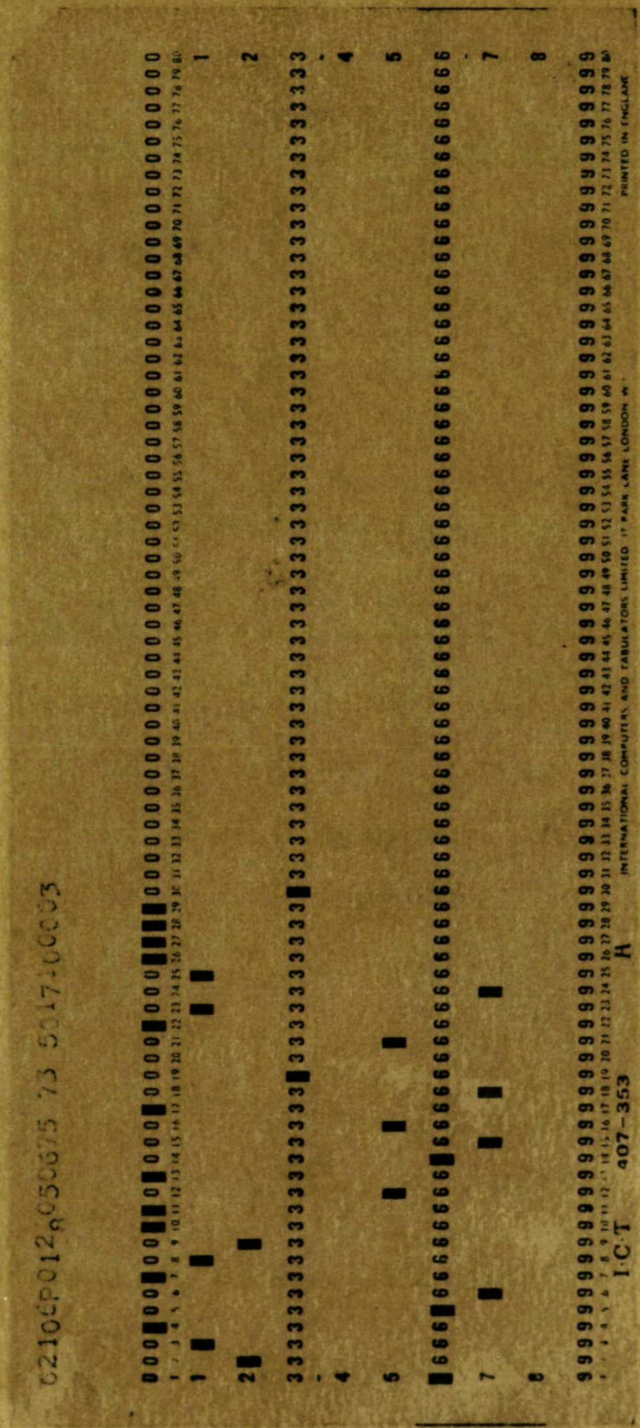

Fig 10. An example of the type of punch card used.

must be devised remembering that the final groups must always contain sufficient cards to justify tabulation. This problem may be resolved either by grouping angular values together after the first sort or by eliminating detail from other information. The former method was adopted because little is lost by considering groups of angular values whereas by considering orientation as 8 rather than 37 groups, a substantial amount of possibly significant detail would be lost. A basic initial program was devised to obtain the areal values of occurrence of every slope angle in the sample. On the basis of this, angular groups could be adopted for use in the remainde of the program. This basic initial program was devised as follows:

Basic Initial Routine.

1. Take all cards.
2. Sort into 6 groups using column 10 (values 0,1,2,3,4,5.) 6 groups
3. Sort the first 5 of these groups (values 0,1,2,3,4.) separately into 10 groups using column 11 (values 0,1,2,3,4,5,6,7,8,9.) 50 groups
4. Sort each of these 50 groups into 2 groups using column 12 (values 0,5.) 100 groups
5. Take each of these 100 groups and also the last group from 2 (value 5) and add the values of columns 789 giving 101 different totals
6. Yield up to 101 different results.

The basic routine afforded the total occurrence of each angular value. These results were first plotted as a simple histogram (Fig.11: i). The most striking feature of this diagram is that there are no great variations in the distribution of angular values. As would be expected,

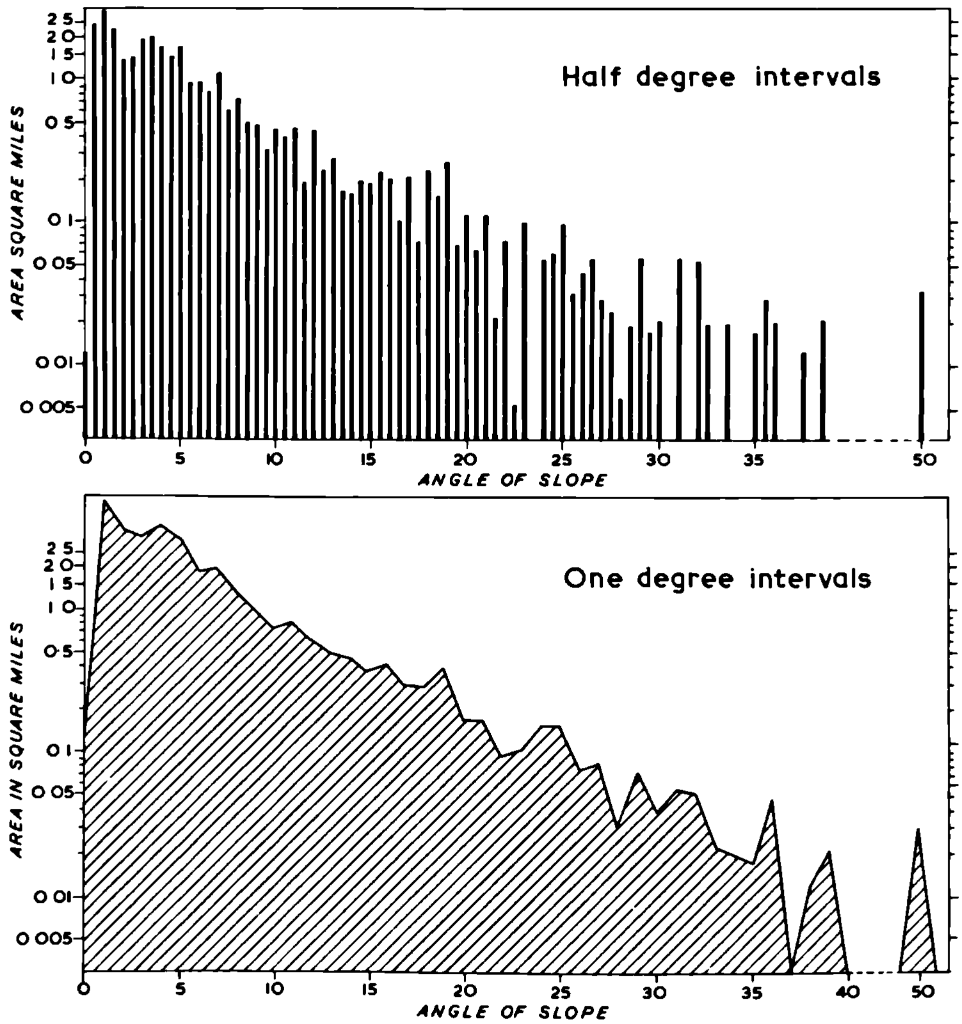

Fig 11. Results of the basic initial program.

there is a decrease of area as the angular value increases and a regression may be derived to express this relationship (Chapter 4). The two significant departures from the general pattern occur at 0 degree, which is a pronounced minimum and with values over 23½ degrees. The minimum at 0° is adjacent to a pronounced maximum at 1 degree. When the angular values exceed 23½ degrees certain angles are not represented at all. Above 16½ degrees there is a considerable amount of variation between adjacent ½ degree divisions. This seems to be the result of field observation as ½ degree values tend to be minimised with high angle slopes. To eliminate some of this variation a further histogram was compiled by combining the ½ degree value with the next highest whole degree value (Fig.11: ii). A method which may be adopted to eliminate random variation was used by Young (1961) and involves taking the mean of three adjacent values. This method is especiall suited to the analysis of statistical samples where the random variation may be very appreciable but with the Eskdale sample, which is not statistically selected, this type of diagram merely emphasises the lack of variation along the length of the distribution. The deviation of the minima in Fig.11 was considered and plotted by evaluating the percentage difference between each minimum value and the lowest of the two adjacent values (Fig.12). Although the first minimum occurs at 2 degrees it was thought necessary to subdivide this lowest group and so categories of 0 - ½ and 1 - 2 were chosen. On the basis of Figs 11 & 12 categories were chosen for use in the later analysis nd these are: 0 - ½, 1 - 2, 2½ - 4, 4½ - 6, 6½ - 9, 9½ - 11, 11½ - 13½, 14 - 17, 17½ - 21½, 22 - 27½ and over 28 degrees. The results of the basic initial routine are tabulated in Appendix 2.

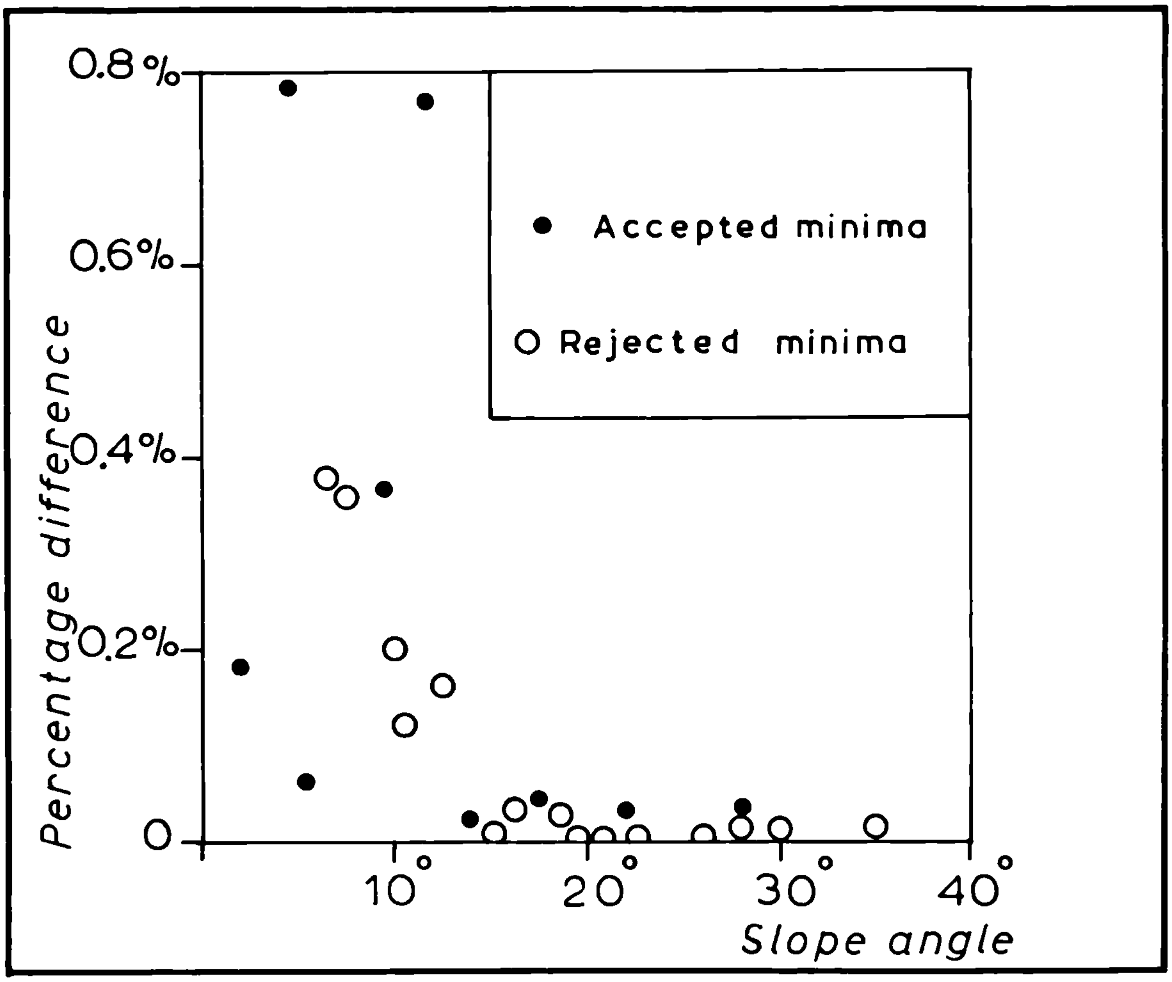

Fig 12. Graph showing all the minimum values of Fig 11.

The percentage difference is calculated by dividing the minimum value by the least of the two adjacent values.

NOTE: The key to the y axis should be multiplied by 100 to give real percentage values.

The main basic routine, to correlate angle and area, was determined using these categories as a basis and then this routine could be applied afte every stage of the main program. The main program and the main basic routin are given in Appendix 3. This program was devised with the size of the sample in mind. When two different sorts are effected prior to the angle - area sort, a degree of generalisation must be used to ensure that each final group contains some cards for tabulation. The punching, sorting and tabulating was completed on equipment at Senate House, University of London and the results recorded by operators on previously prepared sheets[1].

4) Consolid^tion of the results

When the mechanical difficulties have been resolved and the raw data assembled the question of presentation and interpretation must be considered. The data may be presented with respect to the sample area or for a particular group of the main program. Thus when considering geology, the angle - area relationship may be considered absolutely, by examining the distribution for each outcrop, or alternatively the relationship may be considered relatively by considering the extent to which the distribution for each outcrop deviates from the angle - area relationship for the total sample area. Furthermore, the areal values may be plotted as absolute or percentage values. In view of the substantial variation which may occur in total areal occurrence of groups within any part of the main program and also to f cilitate comparison with the average for the sample area as a whole the percentage method was selected but the absolute occurrence of individual values within any part of the program are always shown on an accompanying diagram.

[1]The author acknowledges the financial support provided by the Department of Geography, University College London and the help of Mr.Wicks and other Senate House staff.

The results may be plotted as line diagrams (Fig.11: i), graphs or histograms; and in each case the results may be plotted as normal or cumulative frequency distributions. These alternative methods are illustrat in Fig.13. The histogram, normal or cumulative, is favoured by Strahler (1954) because it gives a strict representation of the groups which are plotted. A line diagram is useful when a large number of values have to be plotted and for this reason was used to express the result of the basic initial routine (Fig.11: i). A graph is disadvantageous in that it suggests that the angular groups are of equal size and gives the impression of uniform distribution throughout the range and so histograms are usually used in preference to this method. Graphs may be used to plot more generalised data derived from the histograms of any one group of the main program (see Chapter 5). Other techniques may be used discriminately as required and where orientation of the facets is involved the results may be plotted as a modifie wind - rose diagram.

The histograms of any one group (e.g. Geology) may be considered comparatively by noting various characteristics of the individual distributions. The modal value indicates the most commonly occurring value and the range of the distribution illustrates the extent to which the available value are present or absent. The number of variates (N) cannot be given directly for any graph as the values are all calcul ted as percentage areas and so the number of variates strictly is 100, but each group of histograms is given wit an area of occurrence histogram which shows the relative areal significance of all other histograms representing the same type. The arithmetic mean ($\frac{\Sigma x}{N}$) is a useful statistic which may be used to compare distributions and

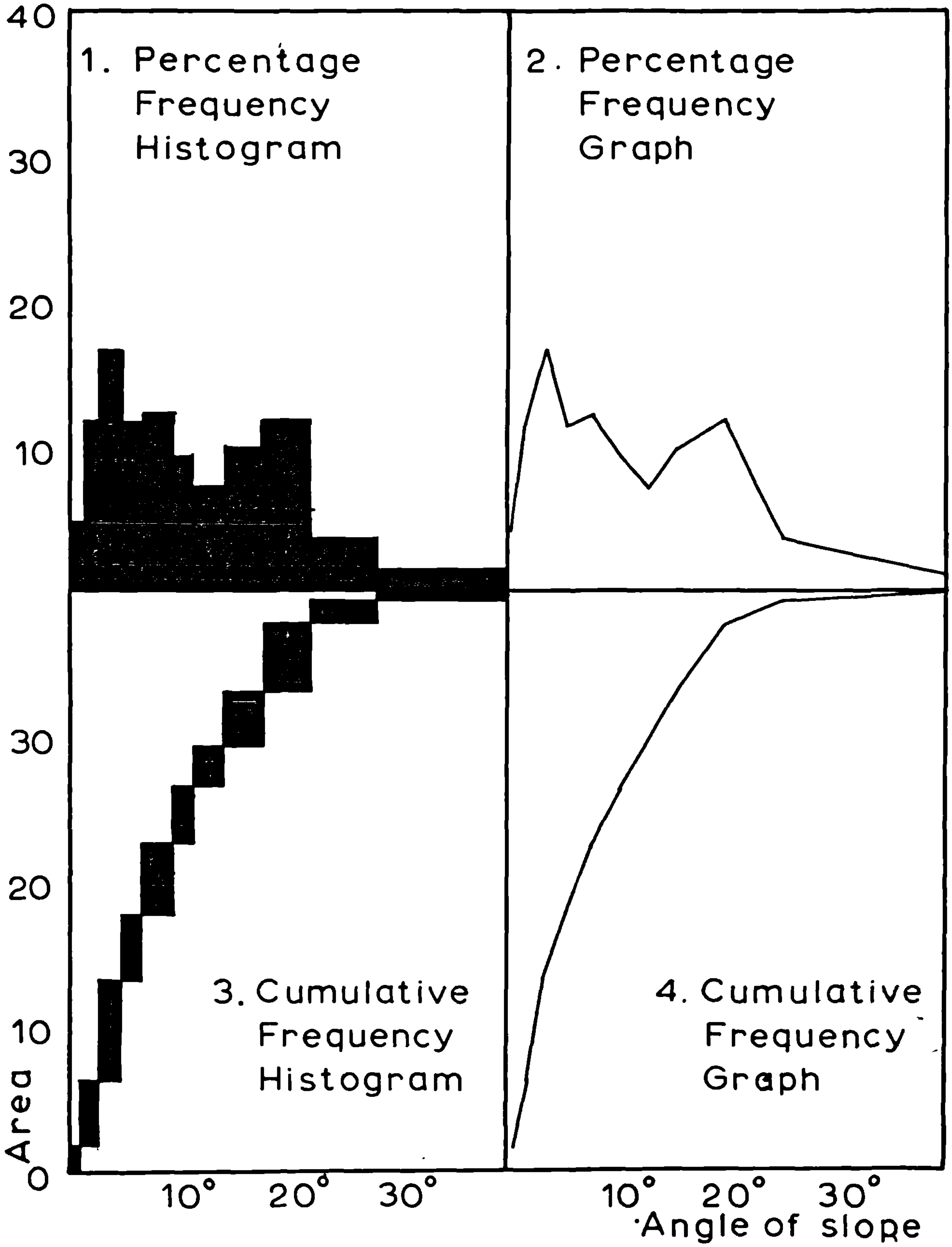

Fig 13. Methods of representing the results of quantitative analysis.

in some cases this may be developed to give standard deviation (s) where $s = \frac{\Sigma(x - \bar{x})^2}{N}$. This arithmetic mean represents the average percentage occurrence for any distribution and a more useful statistic is the <u>weighted arithmetic mean</u> (Kenney, 1939, p.33). This is calculated by multiplying the percentage value of area by the angular value, summing the products and dividing by the number of variates (100). Thus the weighted arithmetic mean $\bar{x} = \frac{\Sigma fx}{N}$. When deriving the weighted arithmetic means it would be inaccurate to use the central value for each of the 11 groups of slope angles in the calculation. Thus the third group, values 2½ to 4 degrees, is not represented by 3¼ degrees unless the population of the group is distributed evenly on each side of this median value. For the sample area the mean (weighted) was calculated, from the results of the Basic initial routine, for each of the 11 groups of slope angles and these values may now be used in other parts of the main program. These calculated values do not differ very substantially from the mid - values of the groups except in the case of group 11 where the mid point is 39 and the weighted arithmetic mean for the group is 33.19. The appropriate values are given below:

Group	Values	Percentage area of occurrence	Weighted arithmetic mean
1)	0 - ½	8.20%	0.25 degrees
2)	1 - 2	21.48%	1.36
3)	2½ - 4	21.98%	3.28
4)	4½ - 6	15.87%	5.14
5)	6½ - 9	13.41%	7.39
6)	9½ - 11	5.01%	10.29
7)	11½ - 13½	4.07%	12.41

Group	Values	Percentage area of occurrence	Weighted arithmetic mear
8)	14 - 17	3.91%	15.48 degrees
9)	17½ - 21½	3.32%	19.10
10)	22 - 27½	1.70%	24.53
11)	28 and over	1.07%	33.19

The main program affords data on the variations of the area of different groups of angles of slope according to major factors such as geology, orientation, height, position and drainage basin order. Within any one of these major groups statistics may be used to compare the distributions but additionally the same statistics may be derived for each major group and used to compare the difference imposed by such factors.

CHAPTER 4.

SLOPE ANGLE ANALYSIS.

The slope angle of a facet is an effect and a cause; an effect which is inherited through landscape evolution and a cause affecting process in the contemporary landscape. There is also a difference between those factors which initiate facets and those which merely modify an existing feature. Initiation is mainly a direct reflection of process whereas structure, minor processes and time comprise the modifying factors. In Eskdale facets were initiated largely as a result of planation, (controlled by fluvial base level), glaciation and periglaciation (mainly mass movement) and subsequent morphological variations have been imposed by structure, process, location and time. Angle of slope is affected by the dip of the beds as well as by lithology (Macar and Lambert, 1960), the process operating on the facet accounts for the degree of modification which the facet suffers but in turn the magnitude and significance of the process acting is in many cases determined by the location, while the time factor will allow for the amount of variation imposed. As noted by Smith (1958), "The value of a slope angle analysis depends upon the determination of the existing relationships between slope angle and the controlling factors in a given area".

1) The distribution of angular slope values

When angle of slope is plotted against area of slope for a drainage basin a general relationship emerges. In Fig.14 (1) log. percentage area is plotted against individual ½ degree values. This distribution is almost linear for angular values between 1 and 11 degrees but with higher angular values a considerable amount of variation occurs. As noted above, this stems from a preference to record whole degree rather than ½ degree values

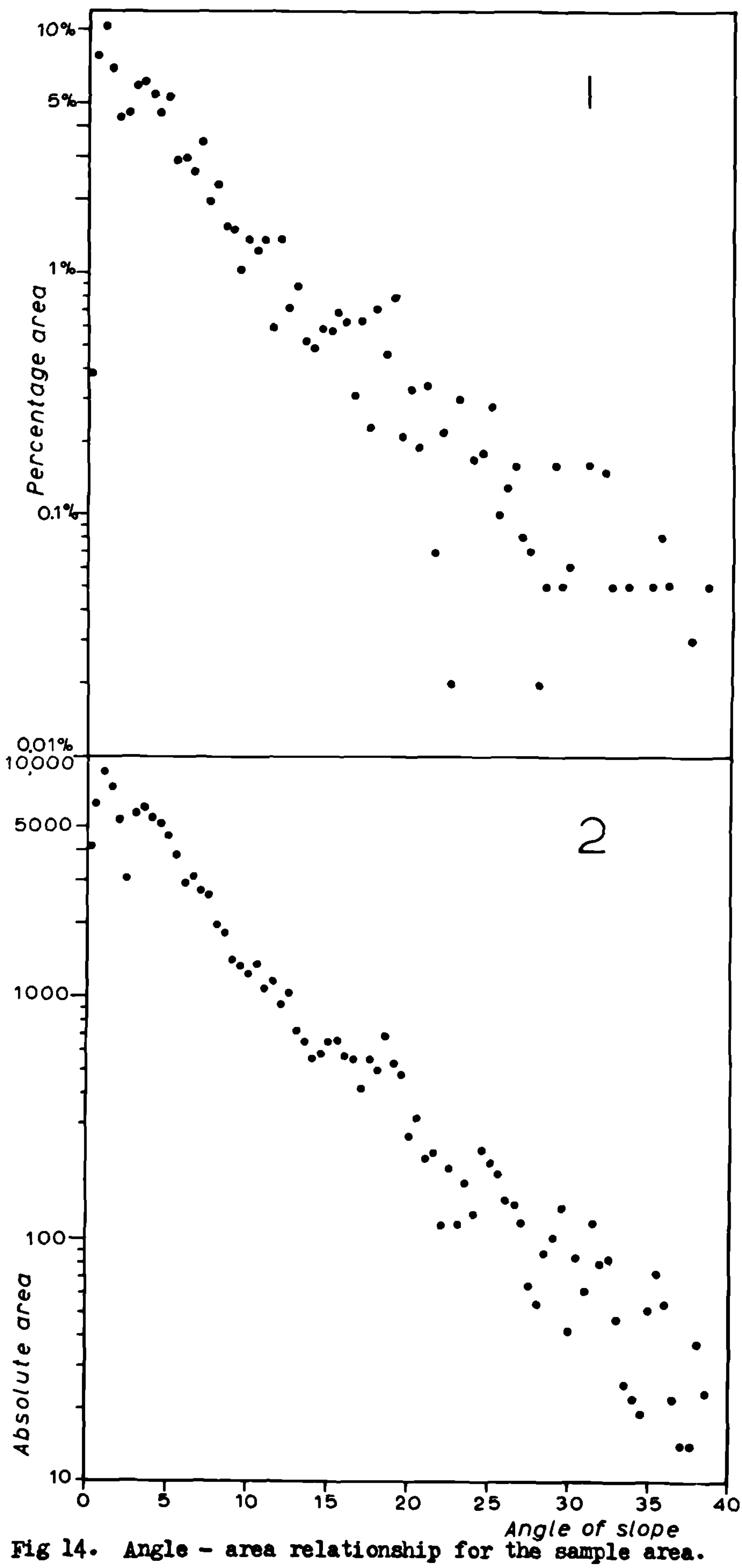

Fig 14. Angle - area relationship for the sample area.
(2 includes values calculated as running means)

on high angle slopes in the field. This deficiency is emphasised if the mean of the values recorded for each facet is averaged to the nearest $\frac{1}{4}$ degree. When measuring high angle slopes in the field slight irregularity, concavity or convexity tends to lead the observer to record whole degree values on these slopes (see Fig.11). In Fig.14 (2) the observer preference has been partly eliminated by finding the average of every three adjacent values by calculating the running mean values. This method gives a distribution which is more uniform than the normal distribution although variation still occurs for values greater than 27 degrees.

The most suitable method of expressing this relationship between angle of slope and area is to fit a curve to the distribution. The distribution is approximately linear and so first an equation of the form $\log Y = Ax + B$ was employed. The method of mean squares was applied to all the data represented in Fig.14 (2) and the following function obtained:

$$\log Y + 0.0665X - 3.8482 = 0 \qquad (1)$$

This function satisfactorily expresses the angle - area relationship for Eskdale and shows the degree to which area of slope increases as angle of slope decreases. A relationship of the same general form (i.e. with the same gradient) would be expected from other areas of this country although constants in the equation would vary according to the 'form of the ground' in the particular area. The dimensional studies in the United States have revealed different types of hypsometric curve representing equilibrium stage, inequilibrium stage, and monadnock stage of landscape development (Strahler, 1952). This angle - area relationship now affords a supplementary index of the general morphology of a drainage basin and the two correlations, one relating height and area and the other relating angle of slope and area, may be used to give the morphological index for any drainage basin.

The equation (1) derived above expresses the general relationship between angle and area of slope and may be used as a standard for the British Isles but in order to facilitate comparison with other areas of the world the position of the modal value of the curve must be noted. In Eskdale this occurs at 1 degree but in morphogenetic regions which have a different erosional history the modal value of the curve would probably occur at a different value and the gradient of the curve would also differ. This theoretical curve must have a peak at 1 degree and so the parabolic form $\log y = Ax^2 + Bx + C$ is a possibility. However this curve does not become concave for high values of x and so would not allow for the variation of the highest angles from one area to another. A more suitable form is given by $\log y = A + B \log x + C \log^2 x$ (Ezekiel, 1930, p.69). Using the mean square method the constants in this equation may be derived for the sample area and this becomes:

$$\log y = 0.948 + 0.086 \log x + 0.183 \log^2 x \qquad (2)$$

This equation now expresses the angle - area relationship in a form which can be readily available for comparison[1].

The area sampled contains seven small drainage basins and the two general equations are derived for this total area and therefore it is interesting to examine the variation within these basins. In Section 9 of the main program (Appendix 3) the area was divided into three groups

[1]Free faces are not included in the calculations to derive constants for equations (1) and (2) because these are arbitrarily represented as 50 degree when in fact the group comprises all the angles of over 38½ degrees, and also because this group covers only 0.1% of the total sample area.

consisting of (1) Baysdale ~nd North Ings

(2) Danby Dale, Little Fryup and Glaisdale

(3) Wheeldale and Rutmoor Beck group (See Fig.9).

For each of these three groups of drainage basins the angle - area correlati was calculated and used to produce Fig.15. The deviation diagram was drawn by plotting the percentage difference between the value recorded in each of the three groups and the corresponding value in the total sample. Area 1 (Baysdale and North Ings) includes two drainage basins which contain moderately well - defined valley side slopes, have generally V - shaped cros sections and also contain a large proportion of moorland planation surfaces. The distribution of angle - area would therefore be expected to resemble that for the entire sample but the mean angle would be slightly higher as the two drainage basins are both second order. This is illustrated by Fig.15 (1). Area 2 includes three dales (Danby Dale, Little Fryup and Glaisdale) all of which have very well - defined valley side slopes, broadly flat floors and are separated by comparatively flat moorland interfluves. The angle - area distribution for this section of the total sample is therefore distinct from that of the entire sample. With values up to 5½ degrees the population is definitely less than that of the entire sample whereas angles of slope above 6 degrees are always more significant in area 2 than in the total sample. The mean of this group is also significantly higher at 7.16 degrees than that for the total sample at 5.87. The third area has a deviation which is almost a mirror image of Area 2. The low angle values are well - represented but over 6 degrees the higher angle value are always areally less than the average. This is attributed to the fact

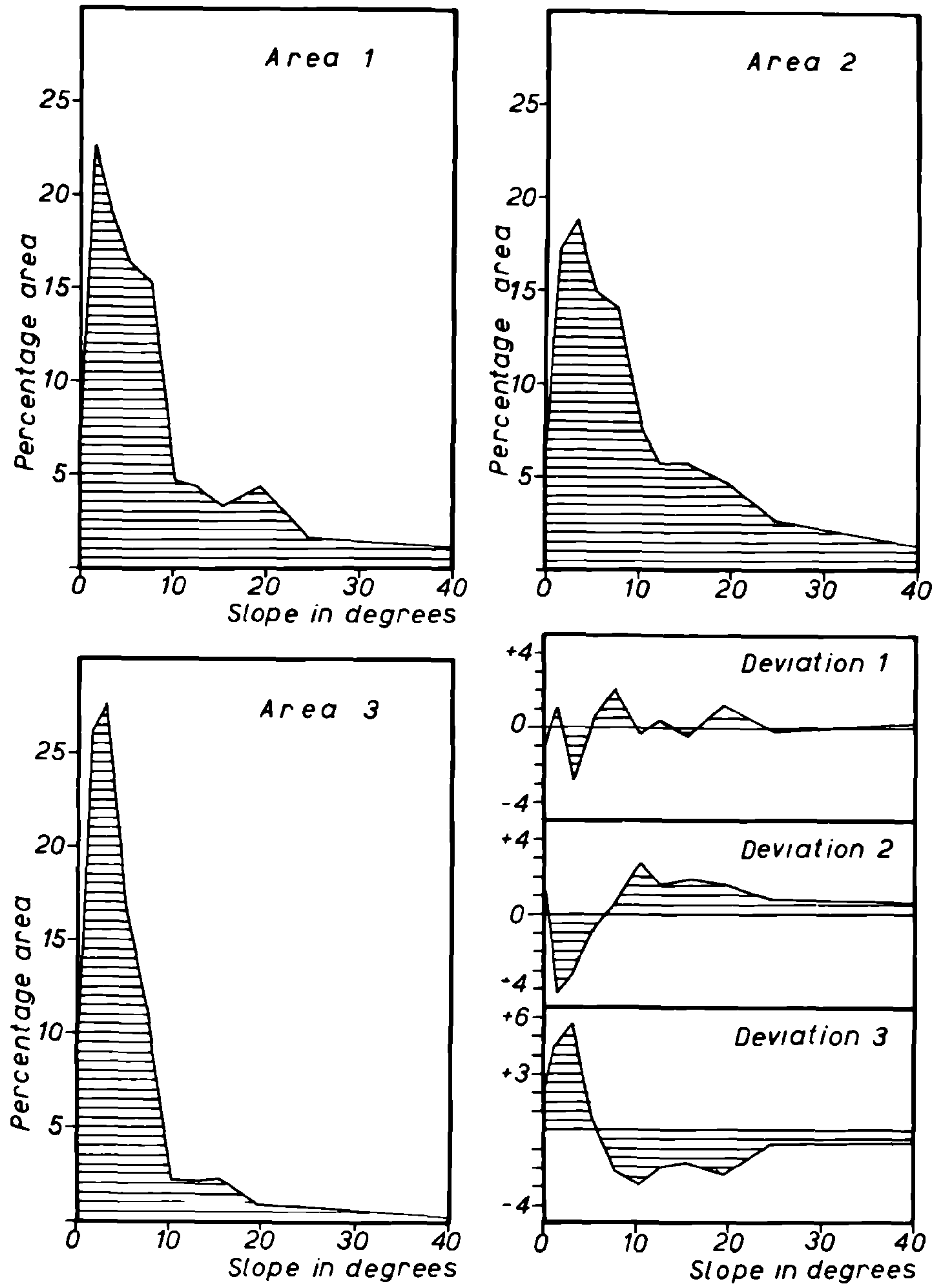

Fig 15. Angle - area relationship for three groups of drainage basins within the sample area.

Area 1 - Baysdale and North Ings,

Area 2 - Danby Dale, Little Fryup, Glaisdale,

Area 3 - Wheeldale and Rutmoor Beck.

that the valley side slopes of Wheeldale are usually only moderate or moderately steep and these drainage basins include a large amount of moorland which is little dissected. The mean is therefore very low with a value of 4.27 degrees. Throughout the three constituent areas the same general relationship between angle and area of slope is preserved; a unimodal distribution which varies in amplitude according to the order and morphology of the drainage basin.

2) The significance of area and drainage basin in the angle - area distribution

The two equations derived above are based upon analysis geared to the frame of the drainage basin and it is pertinent to enquire whether this relationship will be affected by abandoning the drainage basin framework. The analysis of an area of approximately 7 square miles bounded by grid lines and covering the upper part of one of the drainage basins included in the sample (Baysdale) revealed the relationship illustrated in Fig.16 (1) with random variation eliminated as before (Fig.16: 2). This distribution (1) is now bimodal with maxima at $1\frac{1}{2}$ and $5\frac{1}{2}$ degrees and a minimum value at $3\frac{1}{2}$ degrees. The largest of the two maxima is at $1\frac{1}{2}$ degrees and so very close to the 1 degree maximum for the drainage basin analysis. The original uniform relationship derived for the total area is destroyed by considering an area other than a drainage basin and this confirms the belief that the drainage basin is the fundamental framework for use in dimensional analysis.

The measurement of the area of all the individual facets in a drainage basin is a very laborious process and one alternative method is to use the numbers of facets. The differences between the results obtained by using number and area are illustrated for the total sample area in

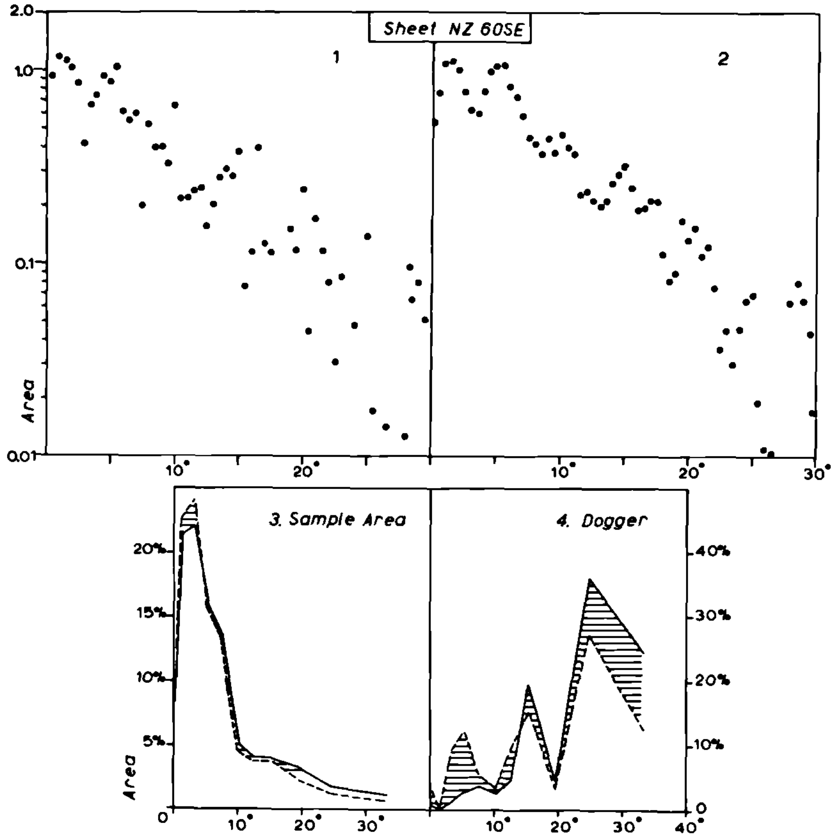

Fig 16. Variations in the angle - area relationship which arise when the drainage basin unit is not used.

1 & 2 are calculated for an area bounded by kilometr grid lines; 1 is obtained by plotting actual values and 2 derived by calculating running means.

3 & 4 illustrate the effect of the use of number of facets rather than area. In each case the solid line represents area and the broken line indicates number of facets.

Fig.16 (3). Although there is a broad correspondence between the form of the two distributions the use of number tends to emphasise low values at the expense of high values of slope angle. This is further illustrated by Fig.16 (4) where the discrepancy between area and number for the slopes on the Dogger outcrop is quite substantial and number again emphasises low rather than high angles. In this case the form of the distribution also differs particularly between 1 and 10 degrees. In certain other distributions the use of number not only distorts the value of the variates but it also ch nges the form of the distribution. In view of this discrepancy it is concluded that the use of area of facets rather than number is necessary.

3) Slope angle variation with height

Slope angle varies according to absolute and relative height; absolute height above sea level (O.D.) and relative height above the slope base or the dominant process level. In an area undergoing dominantly fluvial erosion, sea level provides the major base level but each slope develops with respect to a minor base level afforded by the main river or stream. It is this agent of transport, acting at a local base level, which controls erosion of the slope (vertically or laterally) and which facilitates trans ortation of debris.

Twelve groups, each of 100 feet interval, were used to consider the variation of slope angle with absolute height. The method is disadv ntageous in that by using only twelve groups, over - generalisations may occur and inaccuracies m y be introduced because the groups are taken from 300 to 399 feet and not say from 350 to 449 feet. This part of the main program (Appendix 3, Section 3) was des'gned with the size of the sample in mind; a more detailed height analysis could be effected using a larger sample area and more punch cards.

The results of the operation are plotted in Fig.17 which shows angle - area correlations for height groups. Above 500 and up to 1200 feet the complete range of angular groups occurs but above 1200 feet the population become increasingly restricted to lower angular values. At lower altitudes, between 300 and 500 feet the range is also incomplete. This shows a broad general relationship between angle of slope and height; increasing absolute height is associated with lower angles of slope and the range of slope values is largest in the height range from 500 to 1200 feet. The angle - area distribution for the entire sample area is a simple unimodal figure (Fig.14) but in Fig.17 some of the diagrams depart from this. The other groups show distributions which have more than one maximum although the second of these may, in some cases, be small; as between 600 and 700 feet for example.

The drainage basin has been shown to exhibit a simple relationship between angle and area of slope but when the ·ngl - area relationship is considered for an area other than the drainage basin framework the simple relationship is disrupted. The drainage basin is a balanced system, but when considering specific height groups certain maxima occur in the angle - area relationship because angles characteristic of specific types of facets predominate over others. There are two types of facet in landscape analysis; flats and slopes (Linton, 1951a). Under controlled conditions the flats will be characterised by one angular group and the slopes by a second one. This is il ustrated (Fig.17: 2) by the graph representing the area over 1400 feet.

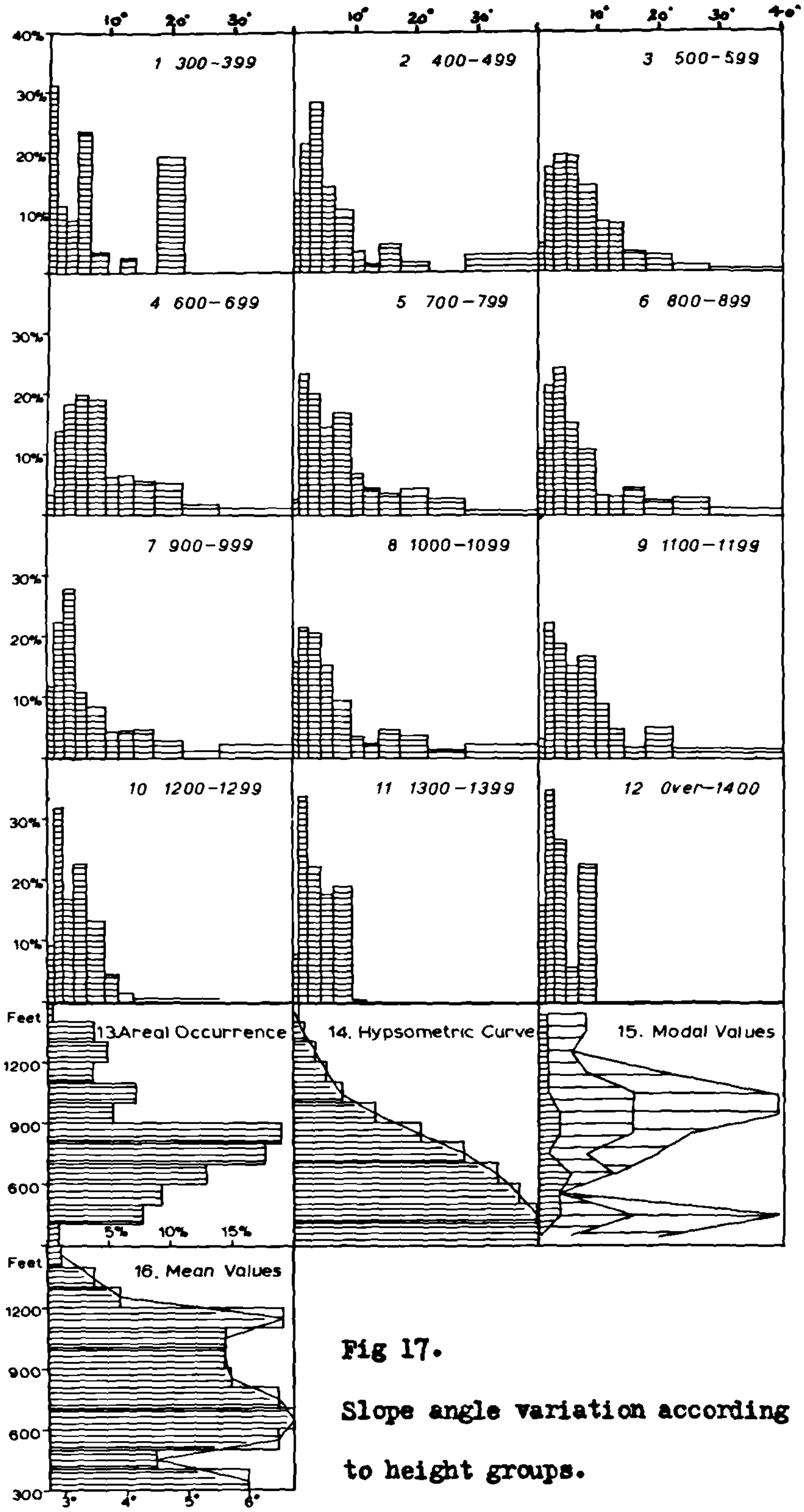

Fig 17.

Slope angle variation according to height groups.

The areal occurrence diagram (Fig.17: 13) shows that this area is comparativel small but the distribution (Fig.17: 12) shows two well - defined peaks. Thi small section of the drainage basin consists of flats (planation surfaces) an intervening slopes and there is no dissection at this height by streams. Th distribution shows that the characteristic angle of the flats lies between 1 and 2 degrees and the characteristic angle of the slopes occurs in the range 6½ to 9 degrees. This characteristic angle for slope facets is slightly higher than might be expected as a result of the incidence of the Moor Grit and Grey Limestone outcrops which inspire higher angles of slope. Although it is not possible to divide the histogram (Fig.17: 12) into two portions representing flats and slopes respectively, groups of characteristic angles may be recognised.

The next diagram (Fig.17: 11) representing the area between 1300 and 1400 feet also has a pronounced peak between 1 and 2 degrees and a maximum in the range 6½ to 9 degrees but this latter maximum is less pronounced than the corresponding one for the range above 1400 feet (Fig.17: 12). This is because the Moor Grit and Grey Limestone which occur particularly above 1400 feet give higher angles of slope than the Middle Deltaic Series which dominat in the area between 1300 and 1400 feet. Above 1200 feet the characteristic angle of the flats lies between 1 and 2 degrees and the characteristic angle of the slopes lies between 4½ and 6 degrees (Fig.17: 10). This is a reflection of the incidence of the broad planation surfaces which occur between 1200 and 1300 feet. In detail this planation surface (High Moor Surface) consists of small flats with characteristic angles between 1 and 2 degrees separated by slope facets characteristically having slopes between

$4\frac{1}{2}$ and 6 degrees (Chapter 6). The three diagrams (Fig.17: 10,11,12) show a gradually increasing range of angular values with decreasing height. Angles above 9 degrees do not occur above 1400 feet, between 1300 and 1400 feet there are no angles of slope greater than 11 degrees and the range 1200 to 1299 feet does not show angles of slope greater than 28 degrees. These restrictic indicate limiting angles (Young, 1961) which occur for specific height groups.

The height range 700 to 1199 feet (Fig.17: 5,6,7,8,9) gives a series of histograms each with three peaks. Two of these represent flats and slopes in each case but the third peak, reflecting increased dissection, consists of a group of high angle slopes which occur immediately above streams or in the upper part of the valley sides. The position of the lowest maximum varies according to the type of flat (Chapter 6) which occurs in the range. The flats are characterised by angles of 1 - 2 degrees between 1000 and 1200 fe t and also between 700 and 800 feet whereas between 800 and 1000 feet the characteristic angle of the flats lies between $2\frac{1}{2}$ and 4 degrees. This variation arises as a result of the incidence of planation surfaces, particularly between 700 and 800 and between 1000 and 1100 feet and also as a result of the occurrence of altiplanation terraces which tend to have higher angles of slope than the major planation surfaces. The characteristic angle of the slope facets in the range 700 to 1200 feet also varies. Between 700 and 800 and between 1100 and 1200 feet it is in the range $6\frac{1}{2}$ to 9 degrees whereas it is substantially higher, in the range 14 to 17 degrees, between 800 and 1100 feet. This indic-tes that certain angles are characteristic of specific environments. Between 700 and 800 feet the maximum group, representing the steep, stream side and valley side slopes has a characteristic angle between 17½ and 21½ degrees. The same group is represented by characteristic angles of 22 - 27½ between 800 and 900 feet and also between 1100 and 1200 feet and of over 28 degrees in the height range of 900 to 1100 feet.

The distribution for the range 600 to 700 feet is almost a normal curve with a maximum between 4½ and 6 degrees and a second very minor peak between 11½ and 13½ degrees. This height range group contains flats but they are so small areally that they do not produce a significant peak in the distribution. The two maxima probably represent two types of slope facet; the numerous facets which form the floors of the dales such as Glaisdale and the facets which occur in the steepened valley sides. In Fig.19 the two types of facet are illustrated; the lower angle group has a characteristic angle between 4½ and 6 degrees and the higher one has a characteristic angle between 11½ and 13½ degrees.

The height range of 500 to 599 feet is the only instance (Fig.17: 3 of a normal distribution although the height group immediately above (Fig.17: 4) closely approximates to it. These two diagrams represent a height range in which the content of facets must resemble that of the total drainage basin. This height range embraces a complete range of situations; it is also critical in that it represents the Pliocene - Pleistocene junction for the planation surfaces, it bore the brunt of modification by marginal glacial meltwater and in some cases, in eastern Eskdale, it is the zone between moorland planation surf ces and valley incision.

The low angle slope facets noted as occurring between 600 and 700 feet (above) are also represented between 400 and 500 feet by a characteristi angle in the range $2\frac{1}{2}$ to 4 degrees. A similar group of higher angle slopes also occurs in this height range (Fig.17: 2) characteristically with angles between 14 and 17 degrees. A third maximum occurs, with angles over 28 degrees, and this must represent the steep slo e angles bounding the streams (Fig.17: 5,6,7,8,9). The first height group, 300 to 399 feet, is restricted in area of occurrence (Fig.17: 13) but shows the three maxima equivalent to those of the 400 - 500 feet range. A fourth maximum occurs between 0 and $\frac{1}{2}$ degree representing valley bench and flood plain facets. The discontinuit of this distribution is probably a reflection of the size of the area of the sample lying between 300 and 399 feet; if a larger sample, with a larger proportion of area at this height, had been chosen angles would have been recorded between $9\frac{1}{2}$ and 11 degrees and also between 14 and 17 degrees but the peaks of the distribution would remain in the same positions.

The different modal values are summarised in Fig.17: 15 where each modal value is added to the previous value. The first maximum usually represents the characteristic angle of the flats at a particular height, the second modal value represents the characteristic slope facets between the flats and the third modal value represents the slopes which occur bordering streams (mainly post - glacial incision) and those in the free faces and constant slopes of the valley sides. The modal values show that the 500 to 699 feet range affords the most 'normal' distribution and heights aoove and below this show variations from the normal. The variation is summarised in a different way in Table 1.

Table 1. Characteristic and Limiting angles for 100 feet height groups.

Height Range	Flats	Slopes	High angle slopes	Very High angle slopes	Limiting angles
300 - 399	0 - ½	4½ - 6	11½ - 13½	17½ - 21½	22
400 - 499		2½ - 4	14 - 17	28 and over	
500 - 599		2½ - 4			
600 - 699		4½ - 6	11½ - 13½		
700 - 799	1 - 2	6½ - 9		17½ - 21½	
800 - 899	2½ - 4		14 - 17	22 - 27½	
900 - 999	2½ - 4		14 - 17	28 and over	
1000 - 1099	1 - 2		14 - 17	28 and over	
1100 - 1199	1 - 2	6½ - 9		22 - 27½	
1200 - 1299	1 - 2	4½ - 6			28
1300 - 1399	1 - 2	6½ - 9			11½
over 1400	1 - 2	6½ - 9			9

The hypsometric curve (Fig.17: 14) may also be plotted for this data and produces a curve conforming to the equivalent stage of landscape development (Strahler, 1952) as noted for the whole of Eskdale in Chapter 1.

The weighted mean values for each of the height groups are shown in Fig.17: 16. The salient feature of this diagram is the subdivision of the range above 800 feet into two groups by the mean of the 1100 - 1199 feet range which is introduced by the division between the High and Low Moor surfac described in Chapter 6. The low mean value between 400 nd 500 feet reflects the occurr nce of terraces and of moderate slopes (3 to 6 degrees) on the lower parts of the valley sides. The mean for the total sample is 5.87

degrees and this is exceeded between 300 and 399, 500 and 799 and also between 1100 and 1199 feet.

The angle - area correlation thus varies with height. Above 1200 feet limiting angles define the angular occurrence in the hundred feet groupings and the distribution becomes confined to lower angles of slope as height increases. The distributions are often peaked and the maxima must represent the angles characteristic of certain types of facets. Between 500 and 700 feet O.D. the angle - area relationship is most normal but above and below this height characteristic angles occur.

4) The geological skeleton

Geikie (1898) first noted the importance of rocks in the physical landscape of Eskdale. This landscape embraces three types of area; the Central Dales of Eskdale (Glaisdale, Little Fryup, Danby Dale, Westerdale and Central Eskdale) where the influence of geology is profound and the resistant bands dominate in free faces; the western dales where the same pattern is observed but with rounding, modification and more extensive planation surfaces, and f'nal y e stern Eskdale where the skeleton of relief is char cterised by fewer free faces and is often masked by glacial deposits.

The impact of geology on landscape may be considered under three headings; the influence of dis osition in so far as it affects occurrence of rocks, the influence of disposition of strata on angle of slope and the influence of lithology on angle of slope. The detailed pattern of relief is partly dictated by the outcrop of the succession and the mosaic of outcrops is largely controlled by the pattern of anticlines nd synclines (Fig.18). In Belgium the influence of dip has been shown to have a significant effect upon

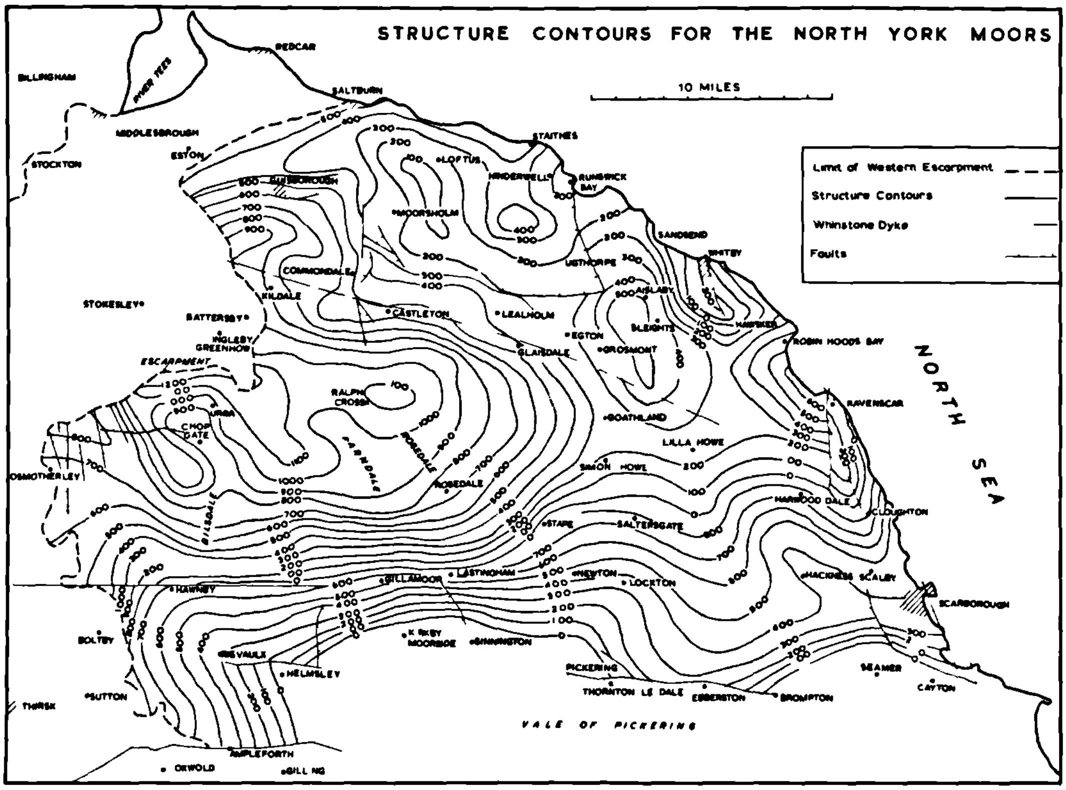

Fig 18. Structure contours for the North York Moors.

Contours drawn at the base of the Dogger in the north and at the top of the Oxford Clay in the south.

(Mainly based upon a map drawn by R. Agar).

angle of slope (Macar and Lambert, 1960). However no detailed quantitative analysis of the relationship of slope angle to angle of dip of the beds has been made in Eskdale because most of the valleys trend with the dip from south to north and so there is no extensive variation in the valley cross sections. A broad general relationship does occur along the east to west trending Esk valley. The structure of the North York Moors is broadly anticlinal and the river Esk, between Castleton and Glaisdale flows on the northern flank of this structure. The resistant bands in the succession outcrop at a higher level on the southern side of the valley than on the northern side; there is therefore a difference in the height of the dale side slopes and also in their morphology, (Fig.19). The lower parts of the Esk valley are developed across the Sleights anticline and so there is no appreciable difference in the macro detail on the two valley side slopes. The dales tributary to Eskdale in general flow across the strike of the outcrops and so although there are significant changes in the height of the rocks along the length of the dale the variations in cross section are slight.

The general skeleton of the area, determined by the occurrence and disposition of the particular outcrops, is further emphasised by lithology. In extreme cases the lithology of any particular bed determines the form of the landscape; on the south side of Eskdale the Dogger and the resistant Lower D ltaic Series occur at the top of the valley side slope, giving a steep, well - defined slope (Fig.19). In detail, lithology affects angle of slope in all cases and a study of the effects of particular outcrops against a background of the distribution of each type can be made.

The distribution of the rock types is shown in Fig.20 and a litholog

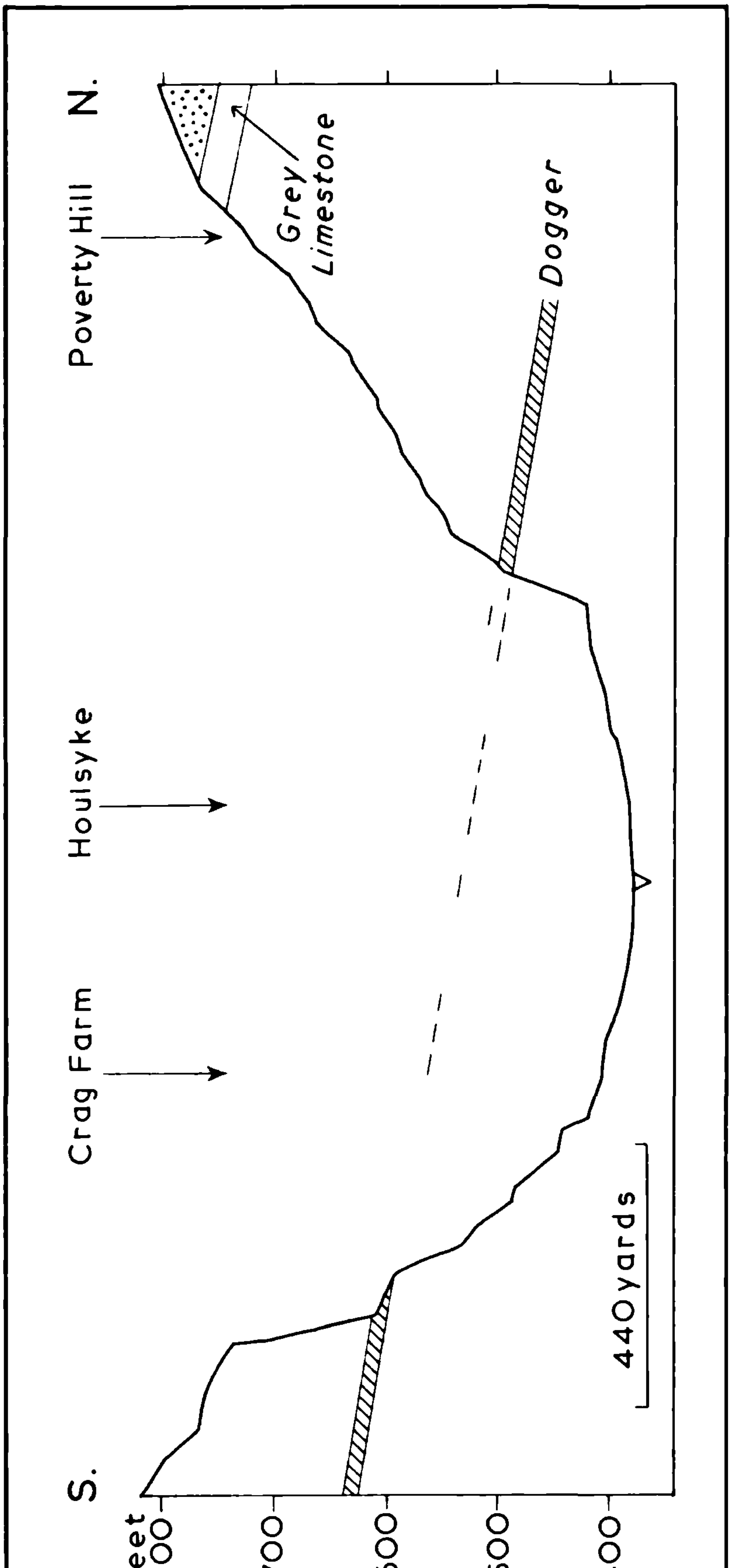

Fig 19. Cross section of the Esk valley at Houlsyke.

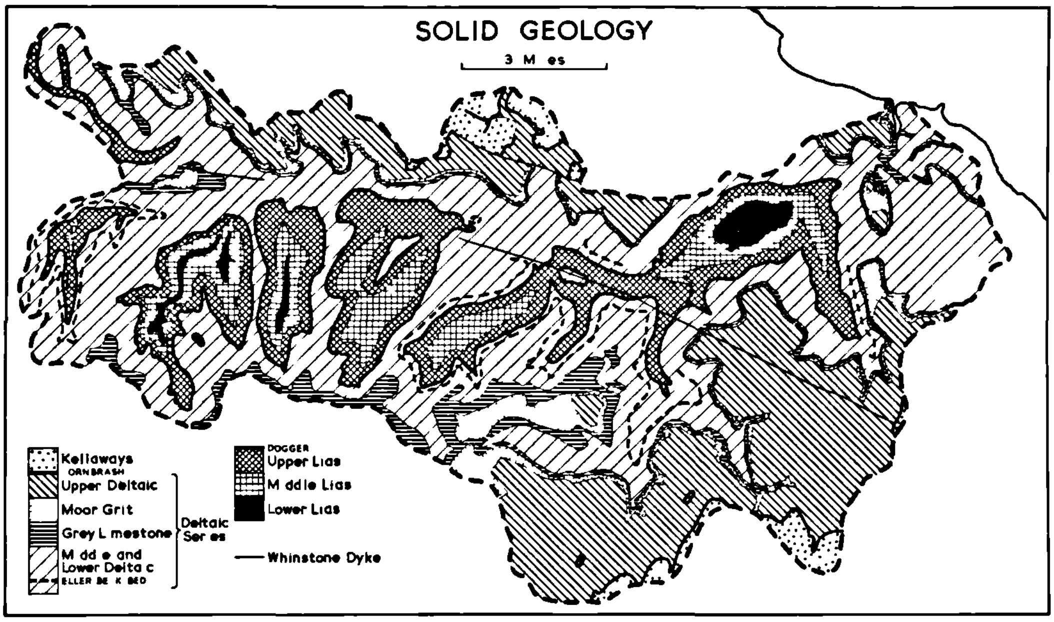
SOLID GEOLOGY
3 M es
Kellaways
ORNBRASH
Upper Deltaic
Moor Grit
Grey L mestone
M dd e and
Lower Delta c
ELLER BE K BED
Deltaic Ser es
DOGGER
Upper Lias
M ddle Lias
Lower Lias
Whinstone Dyke

Fig 20.

column (Fig.21) was compiled to illustrate the variation in thickness of the particular beds, the dominant lithology and the suggested resistance. The resistance, indicated as very high, moderate or low, was determined subjectively on the basis of personal observation in the field; by noting exposures and particularly the reaction of streams to the different types. The variation which may occur within any one rock type, laterally or vertically, is also included (based upon Fox - Strangways, Reid and Barrow, 1885). This diagram was compiled on the basis of field experience before the results of quantitative analysis by punch cards were known. Angle of slope is affected to a varying extent by different lithological types and this is illustrated by the results of Section 1 of the main program (Appendix 3) which gives an angle - area correlation for each outcrop occurring in the sample area. The Jet Rock of the Upper Lias is not always mapped by the Geological Survey and does not occur sufficiently in the sample area to permit the division of the Upper Lias into three zones. In a more complex program of sorting, using a larger number of facets and cards, it would be possible to sort on the basis of height and geology. Thus the variation which occurs at different heights, for example between 800 and 850 feet, could give a finer technique for detecting the influence of rocks on the 'form of the ground'.

5) Angle of slope and the geological skeleton

Cumulative frequency histograms were drawn for the various outcrops and may be compared with the normal curve for the total sample area (Fig.22). The strata above the Middle Deltaic (Fig.22: 8 - 13) have distributions which are lower than the normal curve (i.e. with a larger proportion of low angle values) and the strata below the Middle Deltaic, with the exception of the

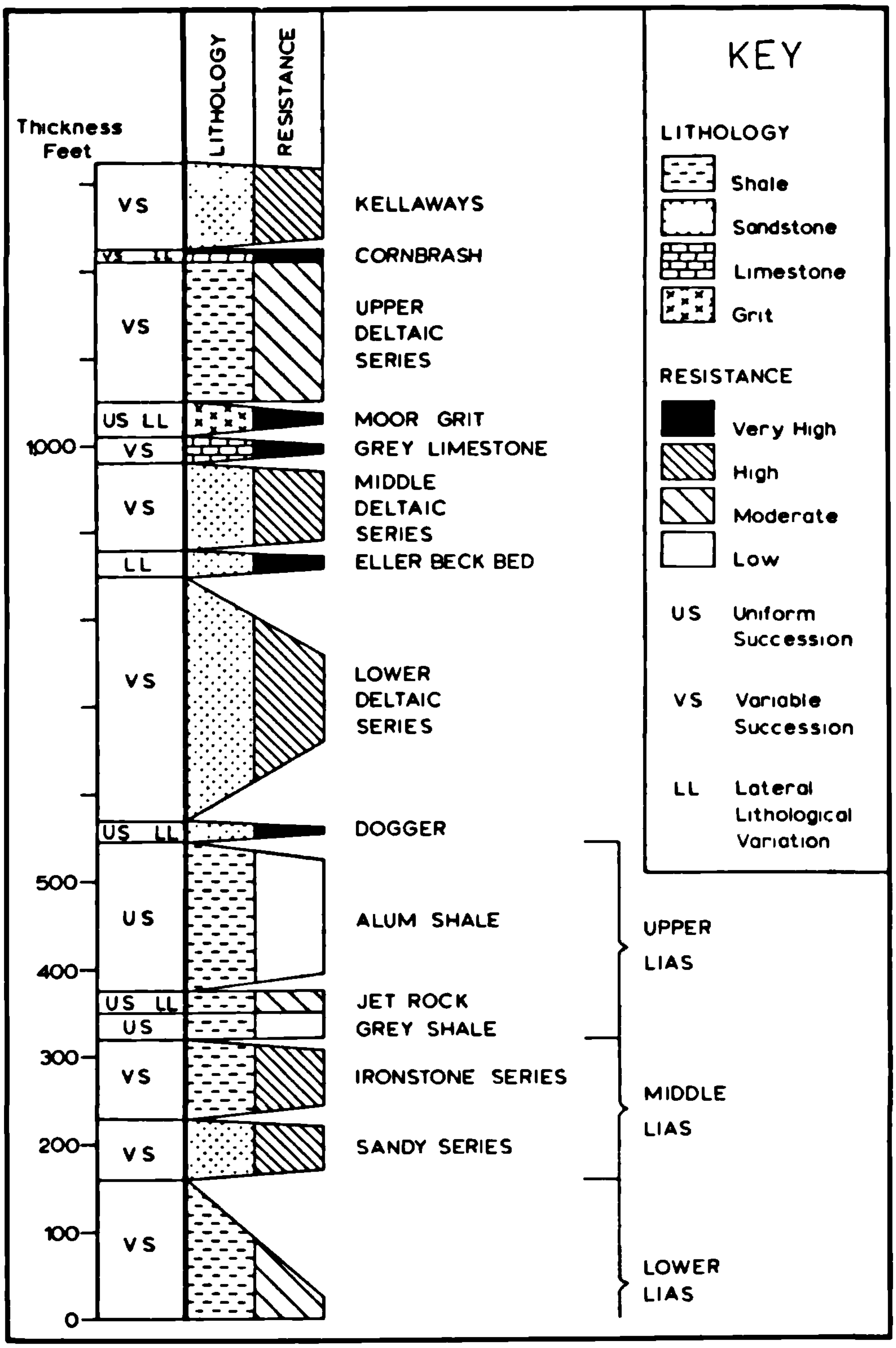

Fig 21. Lithology column for Eskdale.

Variation in thickness is indicated.

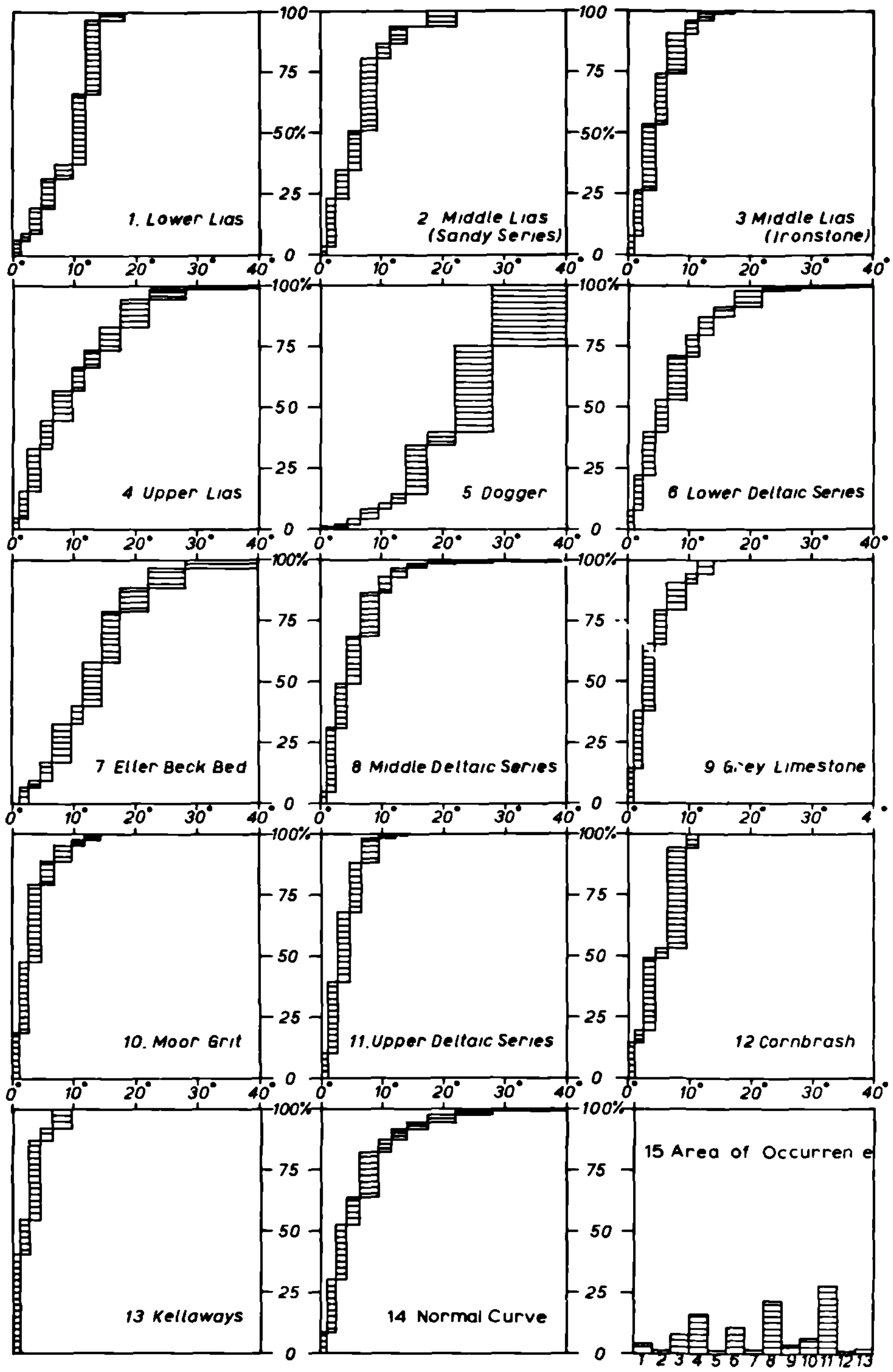

Fig 22. Cumulative frequency histograms for geological outcrops.

Sandy Series of the Middle Lias (Fig.22: 2) are higher than the normal curve. This is evaluated on the basis of the slope and composition of the distributions. The curves are all convex, like the normal curve, with the exceptior of the Lower Lias which is concave. This difference arises as a result of the restriction of the Lower Lias outcrop to the floor of Danby Dale. The sample area chosen generally shows higher angles of slope on the outcrops of the lower members of the geological succession, again with the exception of the Sandy Series of the Middle Lias. This is partly explained on a lithological basis. The Upper Deltaic Series consists of thin bands of shale wit occasional bands of hard - grained sandstone. The Grey Limestone and Moor Grit are both massive sandstones and apparently very resistant. The Cornbras a marine band similar to the Dogger and the Eller Beck Bed, is also resistant and prominent in some areas, including the slopes of Newton Dale where it forms many of the free faces in the upper part of the dale. The Kellaways Rock consists predominantly of soft sandstones which support low angles of slope. The pattern of a simple relationship between angle and area of slope found to occur for a drainage basin is destroyed when the angle - area distributions are drawn for specific geological outcrops (Fig.23). The distributions often have more than one peak; the Dogger shows four maxima (Fig.23: 5). The peaks suggest that certain angles are characteristic of specific types of facets and the range of the distributions may be used to determine the limiting angles for a particular outcrop.

The Lower Lias covers 4.1% of the sample area and is confined exclusively to Danby Dale. The outcrop is reflected in three types of facet flood plain, steep post - glacial stream side facets and low angle dale side

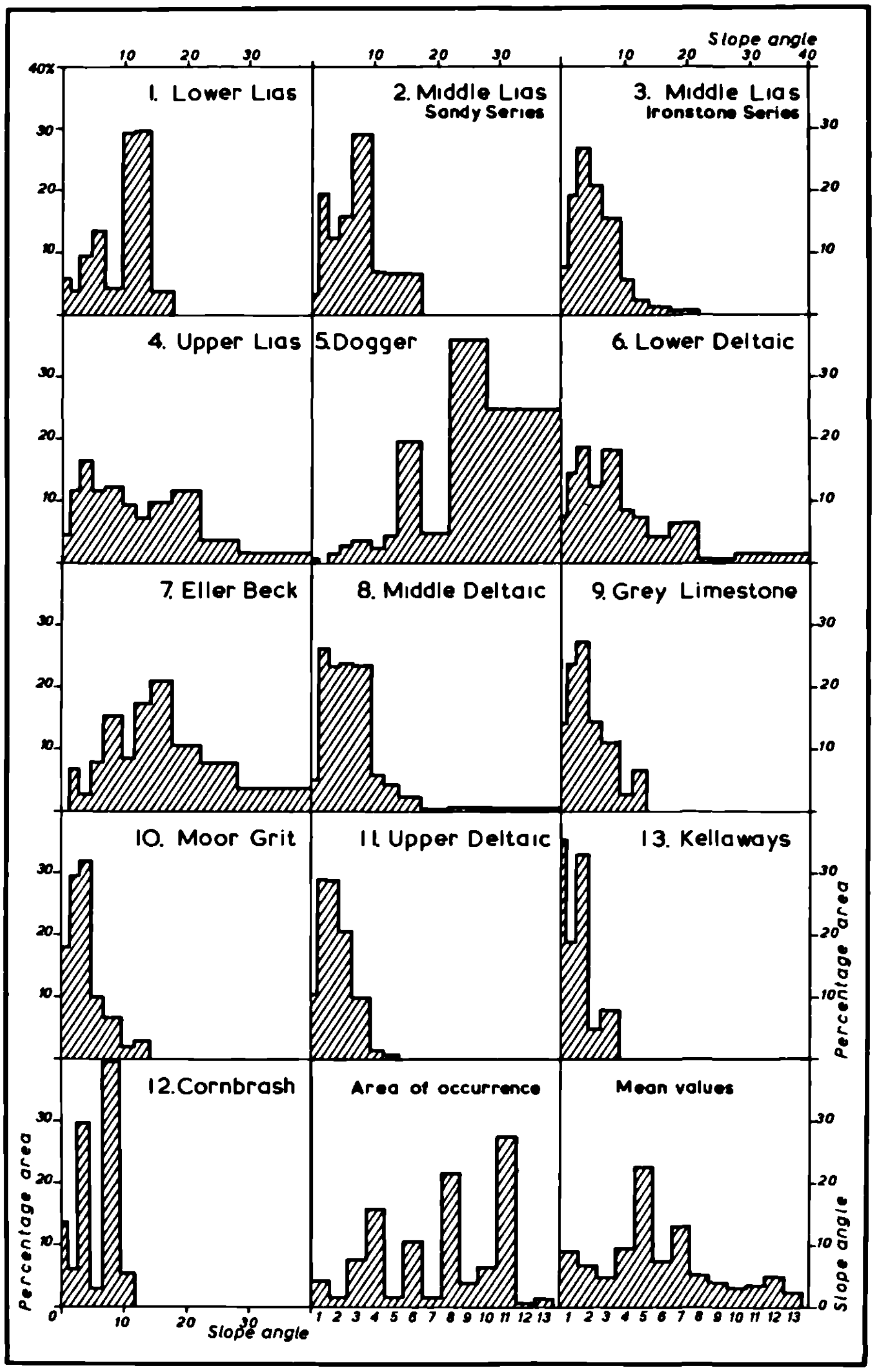

Fig 23. Histograms for geological outcrops.

facets. There are three maxima on the distribution coinciding with these three types of facets; the largest peak is represented by the steep, recently eroded slopes which occur between 11½ and 13½ degrees with a characteristic angle of 12.4 degrees. The second peak at 4½ to 6 degrees represents the dale side slopes; the flats and slopes of this zone are not distinguished as a result of the restricted area of the outcrop. The characteristic angle of the Lower Lias on the dale side therefore lies between 4½ and 6 degrees. The stream does not have a flood plain along its entire course but when this does occur the characteristic angle is between 0 and ½ degrees.

The Middle Lias (Sandy Series) is slightly smaller in area of outcrop and again is restricted to Danby Dale. The formation seldom occurs in the valley bottom and so does not include a flood plain group of facets in the distribution (Fig.23: 2). It includes two groups of facets; the slopes and flats of the lower part of the dale side. On this formation the characteristic angle of the slopes is between 6 and 9½ degrees and that of the flats is between 1 and 2 degrees.

The Middle Lias (Ironstone Series) occurs in Danby Dale, Little Fryup Dale and Glaisdale and in the latter two areas the outcrop occurs in the lower parts of the dales including the stream bed. The distribution for this outcrop is a skew unimodal form (Fig.23: 3) and so the area of the outcrop must include a balanced proportion of different types of facets. The outcrop occurs, in each of the dales, in the central portion of the dale side slopes and so a complete range of angular values is found. The modal value of the distribution is in the range 2½ - 4 degrees and this corresponds to the modal value of the sample area as a whole. In Glaisdale and in Little Fryup the steep slopes adjoining the streams are incised into the formation and show angles of up to 22 degrees but they are not prominent in the diagram (Fig.23: 3) as there is a gradation from these slopes into those of the dale proper.

The outcrops of the Lower and Middle Lias do not include a complete range of angular values of slope. The Lower Lias outcrop does not have any angles of slope greater than 17 degrees although this outcrop frequently occurs in the steep slopes bordering streams. The limiting angle of 17 degrees shows that the grey, earthy shale of the Lower Lias is unable to support angles of slope greater than this[1]. The Sandy Series also shows a limiting angle of 17 degrees and this also reflects its sandy shale with subordinate flaggy sandstones lithology. In Glaisdale the outcrop is covere by drift but the slopes bordering the streams, although capped by drift, are cut mainly into the Sandy Series. The Ironstone Series, an alternation of easily eroded shale and resistant ferruginous sandstones has a slightly highe limiting angle of 22 degrees reflecting the slightly increased resistance.

The <u>Upper Lias</u> includes the Grey Shale - easily eroded fine shales; the Jet Rock - an intermittently occurring bituminous band, and the Alum Shal which is finely laminated. The outcrop of the upper part of the Upper Lias is more extensive than that of the other two divisions as a result of the difference in thickness (Fig.21). The Grey Shale usually occurs in the side slopes of the dales and is characterised by angles between 2½ and 6 degrees

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[1]The succession of the Lower Lias consists of grey, earthy shale with beds of resistant doggers but in Danby Dale only the top two zones of the formation outcrop and these are easily eroded. The Lower Lias may also occur in the stream bed in Glaisdale but drift obscures any exposures (Fox - Strangways, Reid and Barrow, 1885, p.3).

whereas the Jet Rock, when it does occur, tends to form slightly higher angl of slope and sometimes underlies a narrow bench (e.g. at the head of Glaisda NZ 738030). The Alum Shale always occurs above the floor of the dale in Glaisdale, Little Fryup, Danby Dale and Baysdale but in the Esk valley the outcrop extends down to the river. This outcrop supports two types of slope facets; those in the gently sloping dale side (particularly on the eastern side of Danby Dale and along the Esk valley section) and those more steeply inclined facets which occur in the major slope immediately below the free faces afforded by the Dogger and the Lower Deltaic Series (Constant Slope). The Alum Shale is easily eroded but occurs beneath high angle facets simply as a result of the protection afforded by the free faces immediately above. The angle - area distribution (Fig.23: 4) has three peaks which may be interpreted in terms of three types of facets. The flat facets on the valley sides have a characteristic angle between 2½ and 4 degrees, the slope facets are characteristically between 6½ and 9 degrees whereas the steeper slopes below the free face (constant slopes) are characterised by the range 17½ - 21½ degrees. Although this range (17½ - 21 degrees) is areally the most characteristic, much higher angles do occur on the Alum Shale and with favourable conditions of position and orientation the formation supports angles of slope up to 38½ degrees over small areas below the free face. The importance of this outcrop in mass movement and the delicate balance between facets and angle of slope which exist upon it are examined in Chapter 7.

The Dogger, a very resistant marine band, generally consisting of sideritic sandstone, is very prominent in the Eskdale landscape although, as noted by Hemingway (1958, p.25), it is not always responsible for the free faces because the lower part of the Lower Deltaic Series is also very resistant. This is illustrated in the section at Houlsyke (Fig.19) where the free face is supported by the Lower Deltaic Series and a smaller feature occurs on the Dogger below. There are four types of facet beneath which the Dogger outcrop occurs:

a) a group of high angle slopes where it forms the only free face as on the western side of Danby Dale and part of the eastern side of Glaisdale. This group of angular values occurs in the range over 22 degrees and is probably represented by the maximum between 22 and 27½ degrees.

b) a group of facets which have slightly lower angles of slope because the main free face is formed by the Lower Deltaic Series and the Dogger outcrop occurs in the steep slope immediately below. The characteristic angle of this group of facets is represented by the range from 14 to 17 degrees.

c) a group of facets obtained when the outcrop occurs in the lower part of the main dale side slope. This situation arises on the south side of the Esk valley, between Castleton and Danby, and the Dogger clearly affects the angle of slope of the facets along part of its length at least. This type of facet is represented by the range 6½ to 9 degrees.

d) a group of flats which occurs immediately above the Dogger outcrop, particularly above a free face. The lowest peak of the distribution (Fig.23: 5) represents this group with a characteristic angle between 0 and ½ degree.

This distribution (Fig.23: 5) is distinct from all of the others and high angle slopes are much more significant on this outcrop.

The Lower Deltaic Series which includes 50 feet of very resistant basal sandstones surmounted by less resistant shales occurs in and above Baysdale, North Ings, Danby Dale, Little Fryup and Glaisdale. Several types of facet occur on the outcrop including those:

a) where the facet forms a major free face represented by the highest peak (Fig.23: 6) with angles greater than 28 degrees.

b) where the outcrop forms valley side slopes and the free face is supported by the Eller Beck Bed. This group is characterised by the range 17½ - 21½ degrees.

c) where the outcrop forms valley side and summit slopes; either where the major slope does not possess a free face or where the facet occurs at a lower level in the slope type. This group of facets is characteristically represented by an angle in the range between 6½ and 9 degrees.

d) where the outcrop occurs beneath planation surfaces the group is represented by a characteristic angle between 2½ and 4 degrees.

The Dogger is almost uniformly resistant and may be regarded as a uniform lithology but the Lower Deltaic Series includes two different lithologies; the very resistant sandstones in the lower part of the succession and the much less resistant shales above. If the lithology of groups b) and c) were uniform they would be combined into one group. The characteristic angle of the free faces on the Lower Deltaic Series is over

28 degrees but the free faces on the Dogger have a characteristic angle between 22 and 28 degrees. This again reflects the lithological difference between the lower part of the Lower Deltaic Series and the Dogger; the forme may be slightly more resistant and in addition the resistant part of the Lowe Deltaic is vertically more extensive than the Dogger.

The Eller Beck Bed, like the Dogger, is a marine sandstone but does not occur as frequently. It is found round Baysdale and Glaisdale and along part of the Wheeldale Gill valley. The facets which occur on this outcrop include the following types:

a) free faces with high angle slopes illustrated by the second free face which occurs round much of Glaisdale.

b) steep slopes developed on the outcrop at the top of a slope whic are not sufficiently distinct to be termed free faces. These types (a & b) are not distinct on the distribution (Fig.23: 7) but grade into one another and they possess a range of angular values generally over 11 degrees and characteristically between 14 and 17 degrees.

c) where the Eller Beck Bed occurs in valley side slopes at a lowe level in the constant slope and so possesses angles of slope les than either a) or b). This group is characterised by the range from 6½ to 9 degrees.

d) flats which are small in area and occur on the outcrop are represented by the characteristic range of 1 to 2 degrees and nc angle less than 1 degree occurs on the outcrop in the sample are

The Middle Deltaic Series is extensive in areal occurrence, comprising 21.4% of the sample area and including several types of facets:

a) valley side slope and summit slope 'slope' facets characterised by the range 4½ to 6 degrees.

b) valley side slope and summit slope 'flat' facets with characteristic angles between 1 and 2 degrees.

c) steep stream side facets are characterised by angles of slope over 28 degrees.

The proportion of high angle slopes is small on this outcrop but a maximum does occur in the highest group representing the facets adjacent to streams.

The Grey Limestone is commonly a coarse, resistant, calcareous or siliceous gritstone and the outcrop is frequently defined by altiplanation terraces or relatively steep, boulder - strewn facets. The steeper facets a the back of altiplanation terraces are characterised by angles between 11½ and 13½ degrees and the terraces themselves and other flats are characteristically represented by angles of slope between 2½ and 4 degrees. Although this formation is lithologically a resistant gritstone it does not support very high angles of slope and the limiting angle is 14 degrees. This limit is imposed by the position of the outcrop in the sample area rather than by the lithology; the formation seldom occurs below 800 feet and is frequently truncated by the relics of planation surfaces so that the only high angles possible on this formation occur at the backs of altiplanation terraces. Th Grey Limestone of Eskdale may be found in three types of situation; as a narrow outcrop which may have one or two altiplanation terraces developed on it, as a broad outcrop across which a series of low angle planation surfaces are cut as on Egton Moor (NZ 760010) or very occasionally as a free face in the side of a valley. The latter example is restricted and occurs in a free face with the Moor Grit in the Wheeldale valley near Wheeldale Lodge (SE 814984).

The Moor Grit is a very hard siliceous grit and although apparentl resistant it does not support angles of slope exceeding 14 degrees; again a a result of height of occurrence. The outcrop occurs in three types of facets; extensive summit flats as on Wheeldale Moor, the flats of altiplanation terraces (e.g. NZ 638119) and also in slope facets including those at the back of altiplanation terraces. The flats form one group in the distribution with a characteristic angle between 2½ and 4 degrees while the backs of the terraces and the slopes in which the Moor Grit occurs have a characteristic angle between 11½ and 13½ degrees. The Moor Grit, like the Grey Limestone, sometimes occurs in free faces and the two beds often combin to form one free face as at Wheeldale Lodge as noted above. Although this type of facet is not represented in the sample, the distribution would still not cover the complete range of angular values if it was included, because tl outcrop weathers into large angular blocks, giving a very irregular slope which is difficult to measure exactly and so is represented as a cliff (arbitrarily 50 degrees. See Fig.24).

The Upper Deltaic Series is the most extensive outcrop and extends over 27.6% of the sample area. The areal extent of this formation means that a considerable range of the different types of facet is included and so the distribution obtained by relating angle and area of slope is a balanced one (Fig.23: 11). The peak of the distribution is between 1 and 2 degrees but the range, unlike that of the sample area, is limited as a result of the

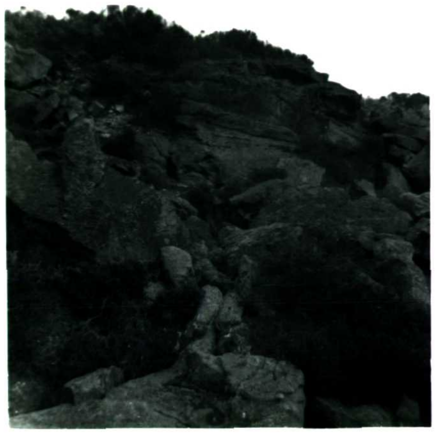


Fig 24. Weathering of the Moor Grit - Grey Limestone free face. (SE 816983)

height at which the formation usually occurs and also the low resistance; the beds are an alternation of thin sandstone and shales. The limiting angl found on this outcrop is 14 degrees.

The Cornbrash is a narrow marine band, composed partly of limestone and partly of sandstone, which supports facets with slightly higher angles than would be expected at the height at which it occurs. This is a result c the inherent resistance of the bed and also of the resistant bands of the base of the overlying Kellaways which promote relatively high angle slopes (Fox - Strangways and Barrow, 1915, p.46). The outcrop is restricted in the sample area to southern Wheeldale where it often forms a distinct feature, and to two outliers, Simon Howe and Ramsden Head. There are essentially three types of facet on this outcrop:

a) slope facets which occur in the summit slopes with characteristi angles in the range $2\frac{1}{2}$ - 4 degrees.

b) facets which occur in the valley side slopes characteristically between $6\frac{1}{2}$ and 9 degrees (also in the sides of the two outliers)

c) flats cut across the formation with low angles of slope between 0 and $\frac{1}{2}$ degrees.

The limiting angle of 11 degrees is lower for the Cornbrash than that shown by the Moor Grit and the Upper Deltaic Series.

The Kellaways outcrop is also confined to the southern part of the Wheeldale basin and although variable in composition, is usually well - represented by a bed of close - grained sandstone which is well - bedded and weathers to give a very dry soil (Barrow, 1888, p.58). The maxima on this distribution resemble those of the distribution for the Cornbrash although the limiting angle is now lower with a value of 9 degrees. The steeper slopes at the base of the outcrop are characterised by the range 6½ to 9 degrees and the facets on the valley side are represented by characteristic angles of between 2½ and 4 degrees (slope facets) and also between 0 and ½ degrees (flat facets). The characteristic angles for certain types of facets which occur in the distributions for different outcrops are tabulated in Table 2.

Table 2. Characteristic and limiting angles for geological outcrops.

CHARACTERISTIC ANGLES				LIMITING ANGL
Outcrop	Flat Facets	Slope Facets	High angle slope	
Lower Lias	0 - ½	4½ - 6	9½ - 14	17
Middle Lias:				
Sandy Series	1 - 2	6½ - 9		17
Ironstone Series	2½ - 4			22
Upper Lias	2½ - 4	6½ - 9	17½ - 21½	
Dogger	0 - ½	6½ - 9	14 - 17 (& 22-27½)	
Lower Deltaic	2½ - 4	6½ - 9	17½ - 21½ (& over 28)	
Eller Beck Bed	1 - 2	6½ - 9	14 - 17	not below 1°
Middle Deltaic	1 - 2	4½ - 6		
Grey Limestone	2½ - 4		11½ - 13½	14
Moor Grit	2½ - 4		11½ - 13½	14
Upper Deltaic	1 - 2			14
Cornbrash	0 - ½	2½ - 4	6½ - 9	11
Kellaways	0 - ½	2½ - 4	6½ - 9	9

The Upper Lias, Lower Deltaic, Eller Beck Bed and Middle Deltaic rocks cover the complete range of angular values but strata above and below this group have limiting angles. In the case of the Lower and Middle Lias the limiting angles reflect lithological control but in the case of strata above the Middle Deltaic the factor of location is also important. The Grey Limestone and Moor Grit are both resistant bands although the angle - area distributions for each of these outcrops are confined to values less than 14 degrees. The resistance of these two beds is indicated in Table 2 by the occurrence of characteristic angles between $11\frac{1}{2}$ and $13\frac{1}{2}$ degrees, close to the limiting angle. The use of weighted mean values does not indicate the resistance of these two beds.

6) Differential lithological resistance

The extent to which any particular rock type affects angle of slope varies according to a number of factors. However the relative significance of the various outcrops may be considered on the basis of the weighted mean values and modal values obtained for each angle - area distribution (Fig.25) and the results are compared by placing the different outcrops in order of significance in Table 3. The information collected in Table 3 allows the average effect of each geological outcrop to be calculated and the rock types, in so far as they affect angle of slope, may be arranged in the following order: Dogger, Eller Beck Bed, Upper Lias, Lower Lias, Lower Deltaic, Sandy Series and Middle Deltaic, Cornbrash, Grey Limestone and Moor Grit, Ironstone Series (Middle Lias), Upper Deltaic and Kellaways.

This order is based upon absolute data for the sample area, whereas certain outcrops are restricted to particular height ranges where the average

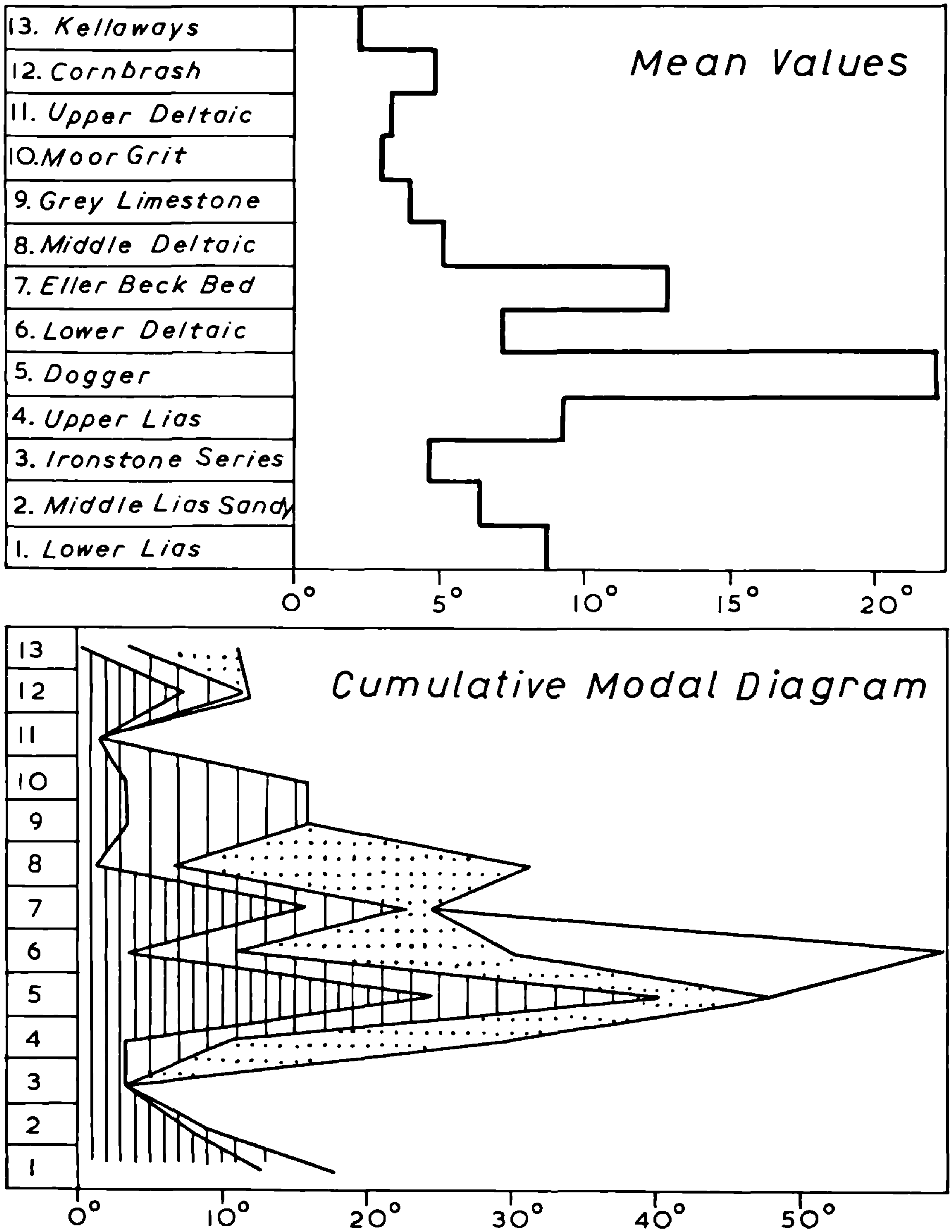


Fig 25. Mean values and modal values for the angle - area distributions obtained for geological outcrops.

angle of slope is greater than or less than the average for the total sample. This deficiency is partly eliminated by combining the data on variation with height with that for geology.

Table 3. Order of significance of geological outcrops based upon size of mean or modal values.

Outcrop	Mean Value	First Modal Value	Second Modal Value
Kellaways	13	13	10
Cornbrash	8	4	9
Upper Deltaic	11	11	13
Moor Grit	12	6	7
Grey Limestone	10	6	7
Middle Deltaic	7	11	2
Eller Beck Bed	2	2	5
Lower Deltaic	5	6	3
Dogger	1	1	1
Upper Lias	3	6	4
Middle Lias:			
Ironstone Series	9	6	12
Sandy Series	6	4	11
Lower Lias	4	3	6

A possible method is to deduce the height range of the particular outcrop and then to divide the mean angle for this range into the mean angle for the particular outcrop. A series of factors will then be obtained which will facilitate the comparison of the relative significance of individual strata within their local environments. The factors were evaluated and expressed in Table 4. This correction, applied for height, allows the various rocks to be re - grouped in order of significance and the order becomes: Dogger, Eller Beck Bed, Upper Lias, Lower Lias, Lower Deltaic Series, Sand Series (Middle Lias), Ironstone Series (Middle Lias), Middle Deltaic Series, Cornbrash, Grey Limestone, Upper Deltaic Series, Moor Grit and Kellaways. This sequence differs slightly from the one based upon modal and mean values on particular outcrops but the first six members are unchanged. The first eight members of this order are either sandstone or shale; angles are high on the sandstone because the lithology directly promotes a high angle slope whereas on the shales the high angle slopes are generally the result of location, either immediately below a free face or in slopes at the side of streams.

The concept of characteristic and limiting angles has been elaborated by Young (1961) who suggested that "characteristic angles of slope are those which most frequently occur, either on all slopes, under particular conditions of rock type or climate, or in a local region " but for the present purpose the term has been used in a more restricted form. Within any drainage basin there is a simple relationship between angle of slope and area of slope. This simple relationship is disrupted by considering any area other than a drainage basin. Characteristic angles are therefore defined as those which occur on specific types of facets under controlled conditions of geology, height, orientation or position etc. In the present analysis characteristic angular ranges have been used rather than characteristic angles as a result of the prohibitive size of the sample used.

Table 4.

Outcrop	Lithology	Height Range	1. Mean Height Range value	2. Mean angle for outcrop	2/1 value	2/1 ord
Kellaways	Sandstone	750 - 850	6.14	2.26	.37	13
Cornbrash	Limestone	750 - 825	6.14	4.92	.80	9
U.Deltaic	Shale	525 - 1025	6.34	3.36	.53	11
Moor Grit	Gritstone	500 - 1300	5.89	3.00	.51	12
Grey Limestone	Limestone	500 - 1400	5.63	3.92	.70	10
M.Deltaic	Sandstone	500 - 1300	5.89	5.03	.85	8
Eller Beck	Sandstone	500 - 1300	5.89	12.95	2.20	2
L.Deltaic	Sandstone	400 - 1300	5.74	7.11	1.24	5
Dogger	Sandstone	500 - 1250	5.89	22.24	3.79	1
U.Lias	Shale	Below 1100	5.97	9.32	1.56	3
M.Lias:						
Ironstone	Shale	Below 1000	6.02	4.59	.88	7
Sandy Series	Sandstone	Below 900	6.09	6.49	1.07	6
L.Lias	Shale	500 - 600	6.54	8.72	1.33	4

A more detailed analysis of angle of slope in relation to rock structure might follow one of three approaches. Firstly to examine mechanically the relative resistance of different rock types and to compare this with the topogra hic expression of the particular beds. Secondly to examine angle of slope strictly in relation to lithology; this would be a very intricate process and would involve subdivision of many of the existing geological boundaries so that the lower 50 feet of the Lower Deltaic Series would be considered separately from the remainder of the bed. A third alternative would involve the examination of slope angle variation under different height and orientation values but with constant lithology. Although a considerable amount of lateral and vertical variation occurs in the various rock types in Eskdale (Fig.21) the position of the resistant marine bands tends to emphasise the character of the intervening beds and so characteristic angles may be considered.

7) <u>The geological skeleton throughout Eskdale</u>

The above analysis of the significance of different lithologies with respect to slope angle may be taken as typical for the drainage basin as a whole. The only instance where a certain type of facet is not represented is in the case of the Grey Limestone and the Moor Grit which do not occur in a free face in the sample area. There are also two other significant omissions in the sample area; first the influence of superficial material imposed upon the underlying rock type - a situation which occurs throughout eastern Eskdale and secondly the outcrop of the Whinstone dyke. This Tertiary intrusion of augite andesite extends across Eskdale (Fig.20) but, although marked along its length by a narrow groove excavated by quarrying for road metal, there is only one instance where it significantly affects angle of slope; this is at Egton Bridge where the dyke underlies a terrace and promotes a very steep bluff in front of the terrace (NZ 802052).

Throughout eastern Eskdale the masking influence of the drift is two - fold; in some cases it obliterates fairly steep angles, as on the Lias of the Esk valley between Grosmont and Sleights, and in other cases it accentuates existing angles of slope as in the case of material deposited in ice - contact positions (Fig.26). The kame terraces at the southern end of

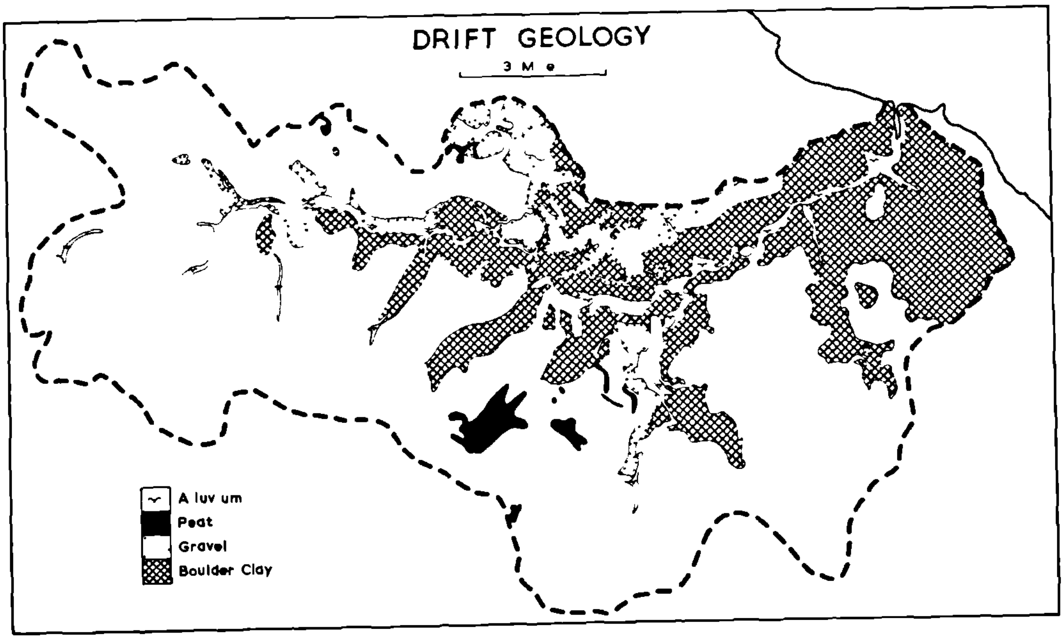


Fig 26.

the Stonegate valley have high angle slopes (up to 30 degrees) maintained on sand and gravel whereas the underlying slopes on the Upper Deltaic are less steep. On the more resistant formations the effect of lithology is maintained throughout. The influence of beds such as the Dogger, the lower part of the Lower Deltaic and also the Eller Beck Bed, is maintained despite the influence of drift. On the south side of the Esk valley between Grosmont and Sleights the effect of these resistant beds is as significant as within the sample area. This is the result of a two - fold influence; the angles of slope would be steep on these outcrops even pre - glacially, and so little glacial material would accumulate and persist, and secondly the high angle slope would facilitate periglacial weathering and removal of any material which did accumulate. In an examination of the influence of drift upon the slope angle, the thickness of the superficial cover is the critical factor; where the drift cover is thin the angle of slope is primarily determined by the underlying lithology but where the drift is thick the principal determinant is the lithology of the drift.

8) Conclusion

A unimodal distribution is obtained by plotting angle against area of slope in a drainage basin. If the drainage basin framework is not used, characteristic angles are represented on the distribution. The use of controlled conditions (such as geology, position etc.) gives a series of characteristic angles for specific types of facets. The modal values of different distributions cannot be related directly but should be interpreted with respect to the types of facets which can possibly occur within the range of the distribution. The morphological types of terrain which occur in the Condroz and the Appalachians have been noted by Bethune and Mammerickx (1960). In Eskdale there is primarily a contrast between flat and slope facets although secondarily, distinct groups of slope facets may be identified. The analysis indicates that there is a general decrease of structural influence as height increases; this could be firmly substantiated only by some form of mechanical analysis designed to compare the resistance of different formations to weathering, but the evidence points to the interpretation of landscape as a function of process, stage and structure (King, 1953) rather than structure, process and stage.

CHAPTER 5.

SLOPES.

Slope studies may be effected by either deductive or inductive methods but in each information on the mor hology of slopes is required. Inductive studies are often associated with studies of slope form over a large area while the deductive approach is often accomplished by concentrating on the evolution of particular slopes or particular slope sections. In this chapter the primary concern will be with the morphology of slopes and the information which this affords, concerning slope development, will then be assembled. The geomorphological map may be used for the study of slopes in three ways:

i) morphometric analysis of slopes in a drainage basin (Strahler, 1956).

ii) quantitative analysis based upon angle - area relationships of facets (as used in Chapter 4).

iii) profile analysis based upon profiles constructed from a geo orphological map and comparison of the results (Savigear, 1956).

The general constitution of a slope profile was described by Wood (1942) who recognised the presence of four ele ents; the waxing slope, free face, constant slope and waning slope. This general division has been widely recognised and followed by many workers including King (1957) who recognised a waxing slope, free face, talus or debris slope and a pediment.

1) Morphometric Analysis.

The analysis of 1:25,000 maps for the whole of Eskdale shows a definite relationship between stream order and stream number, illustrating Horton's first law (Horton, 1945), and gives a hypsometric curve indicating a mature state of dissection (Strahler, 1952) (Fig.4). An angle - area relationship was determined for the constituent drainage basins in the sample area (Appendix 3, Main program 4) and this information may be used in several ways.

Stream frequency for each order drainage basin (Horton, 1945) was calculated and plotted against stream number (Fig.27). This shows that the terms arrange themselves in the form of a geometric progression. The basin area of each order was plotted, for the sample area, against stream number (Fig.27) and the absolute area of first, second and third order basins occur in geometric progression. The fourth order total is below the line because the sample area is not large enough to include all the fourth order basins of Eskdale. If the area of overland flow is plotted on the same diagram the area of this also falls on the same straight line (Fig.27). Previous work (e.g. Schumm, 1956) has illustrated Horton's fourth law (Horton, 1945) by inference and shown a rel tionship between mean basin area and stream order. Morphometric studies of drainage basins based upon contour maps often encounte difficulty in the delimitation of first order basins; frequently the area of first order basins cannot be used to illustrate Horton's fourth law (e.g. Chorley, 1957b). This difficulty is removed when the areas are measured from a geomorphological map because the area of first order basins may then be defined in terms of facets. In the sample area in Eskdale there is apparently a relationship between absolute drainage basin area and stream order. The area of overland flow falls in the same series (Fig.27). This

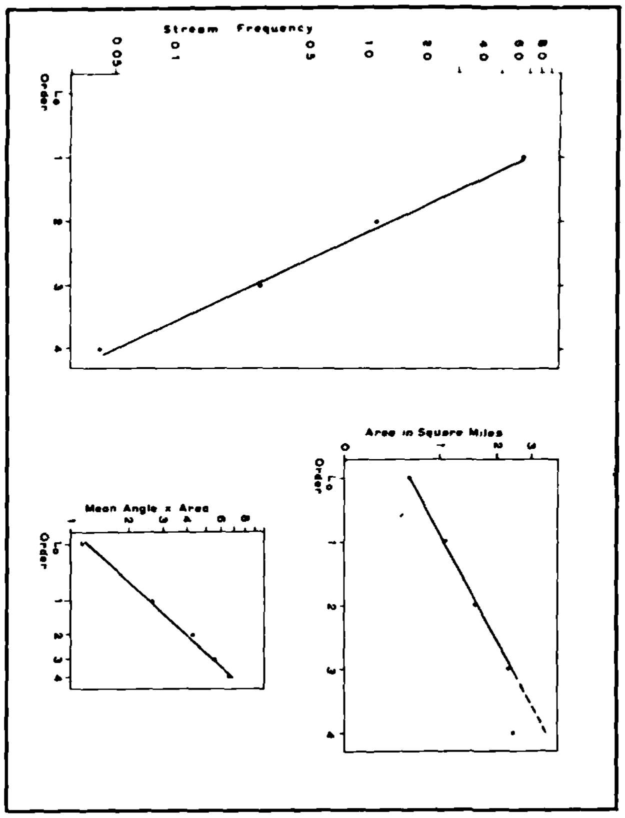


Fig 27. Morphometric analysis of the sample area.

suggests that Horton's fourth law is substantiated on a detailed scale by facet analysis; in any drainage basin the total area of specific order basins is related by a geometric progression and the area of overland flow is related to these areas by the same relationship. In a study of the central Appalachians Hack and Goodlett (1960) noted that 44% of the total area was occupied by slopes of first order valleys whereas in a 'typical lowland area', also drained by a fifth order stream, only about 33% of the total area was occupied by first order valleys. The sample area in Eskdale, which is part of a fifth order drainage basin, shows the following percentage areas for constituent drainage basins:

L_o	22.35%	
1st order	34.53%	44.51%
2nd order	71.19%	62.96%
3rd order	95.49%	94.27%
4th order	100.00%	100.00%
	Total area including L_o	Total area excluding L_o

The derivation of a relationship b tween mean slope angles for basi ns of a particular order was also considered. The weighted mean values for particular orders are:

L_o	3.06 degrees
1st order	4.78 degrees
2nd order	9.07 degr es
3rd order	7.97 degrees
4th order	7.02 degrees

The mean angular values for second, third and fourth order basins are in approximate geometric progression but the values for first order basins and for the area of overland flow do not lie in the same series. This is ascribed to the fact that first order basins and areas of overland flow are generally confined to the higher areas of the drainage basin where there is a smaller proportion of high angle slopes. The only relationship which could be derived was obtained by plotting the product of mean slope angle and drainage basin area against stream **order** hen a smo th curve w s obtained by using a semi - logarithmic plot. If this information is plotted using logarithmic scales for each axis the relationship is expressed by a straight line (Fig.27). Therefore the relationship between mean slope angle of drainage basins of successive orders, per unit area, may be expressed by a function of the form: $A \log y = B \log x + C$

2) Quantitative A alysis.

Quantitative analysis of slopes in the sample area was effected by considering the variation of the angle - area relationship according to various methods of repres nting rel^tive and absolute facet position. The methods adopted include:

i) Absolute (a) accordin to height groups.
(b) according to height above stream.
(c) according to drainage basin order.

ii) Relative (a) according to percentage position above slope base using only 'slope' facets.
(b) according to one of three major types of slope, again employing p rcentage position above slope base.

i) (a)

The angle - area relationship computed for height groups in the sample area, each of 100 feet vertical interval, was described in Chapter 4 (Fig.17; 14,15,16). The hypsometric curve (Fig.17; 14) indicates that the sample area, like the total drainage basin, is in an equilibrium state of development (Strahler, 1952).

i) (b)

The height of facets above the stream base was used to examine the relationship of facets according to their position above the base of the slope as defined by the position of a stream (Chapter 3). The analysis was effected in the main program (Appendix 3, Main program 7). Two types of slope are included in this analysis; that which occurs above a stream flowing parallel to the long axis of the constituent facets and that where the slope is considered to be based at the head of a first order stream. In a comprehensive examination the two types could be distinguished and the results of the analysis compared but the sample area was not sufficiently large to allow this and so the two types of slope combination were considered together. The essential difference between these two types is that the steep facets often occur at the foot of slopes in a drainage basin of second or higher order whereas low angle slopes occur at the base of the slope above a first order stream. The two profiles are basically similar but above a first order stream head the free face element and the steep facets at the foot of the slope are usually absent.

The angle - area relationship for the height of facets above stream base are plotted in Fig.28. The interpretation of this diagram is more

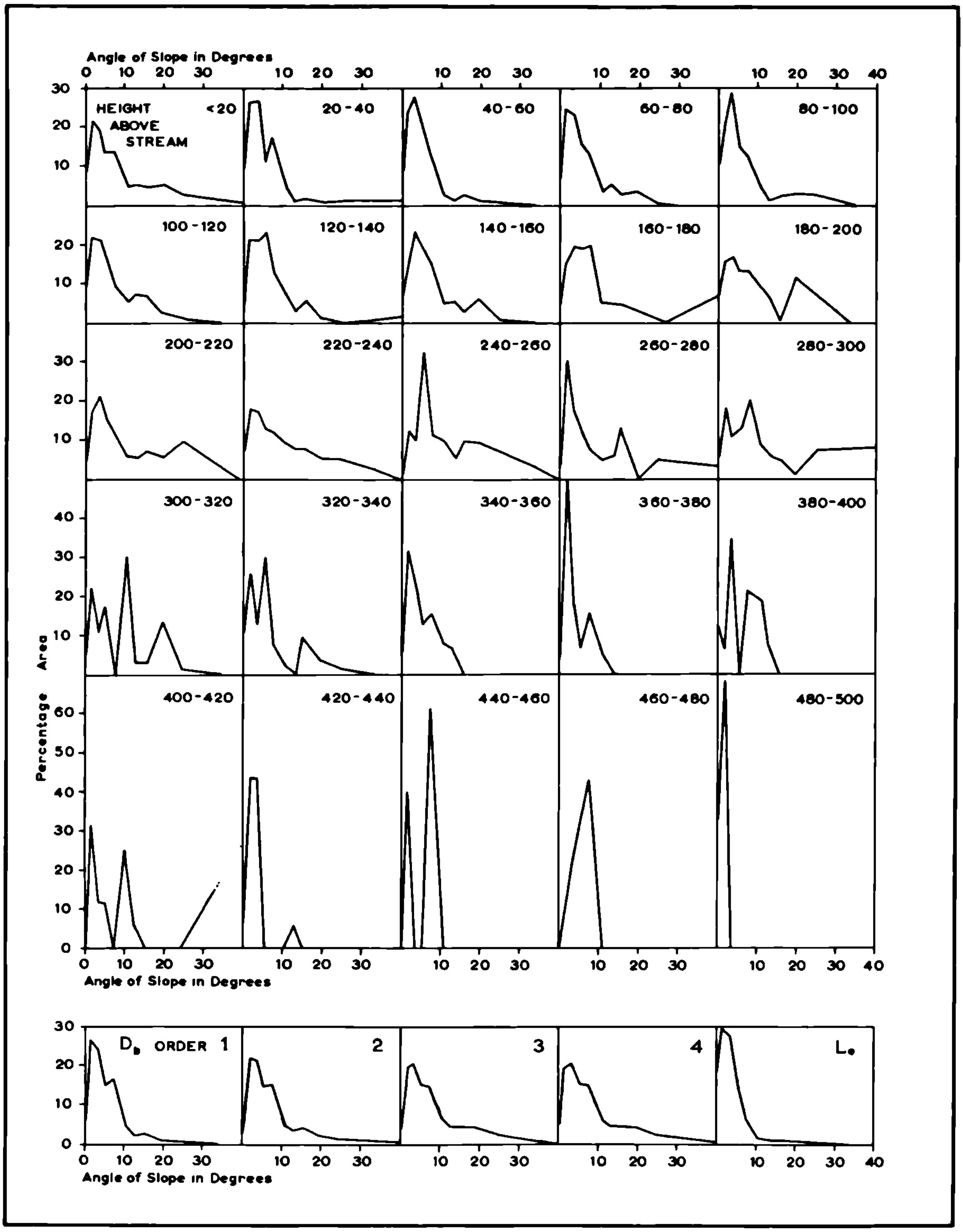


Fig 28. Angle - area distributions for facets according to height above stream and according to drainage basin order.

complex than that of those presented for different geological types (Chapter 4, Fig.23) because in addition to the different types of facet two types of slope are represented (i.e. above a first order stream head and above streams parallel to the facet). Below 220 feet the distributions generally have two marked maxima (Fig.28) which correspond either to the two types of slope or to groups of flat and slope facets. The latter possibility seems to be the most feasible in that both types of facet should occur in every 20 feet height group and so there will be at least two maxima on each of the distributions. The persistent occurrence of these two maxima indicates that flat facets and slope facets are both characterised by specific angular groups in particular slope positions. In the range 0 - 20 feet (Fig.28) there are three maxima which correspond to flat facets (1 - 2 degrees), gently - inclined slope facets at the foot of the slope ($6\frac{1}{2}$ - 9 degrees) and a third group representing steep facets bordering a stream ($17\frac{1}{2}$ - $21\frac{1}{2}$ degrees). The modal values of these distributions are plotted as characteristic angles in Fig.29. The flat facets always form a well - defin d group and the angle never exceeds 4 degrees except between 120 and 140 feet where true flats are probably not represented at all. Flat facets are generally characterised by angles of slope between $2\frac{1}{2}$ and 4 degrees up to 220 feet but between 220 and 380 feet the characteristic angle lies between 0 and 1 degrees. Free faces and high angle slopes are introduced above 120 feet above the stream base (Fig.28) and occur up to 300 feet but are represented by only one example above this height. The characteristic angles diagram (Fig.29) indicates the most frequent forms which occur and these incorporate the major elements already recognised as typical of slope profiles (Wood, 1942).

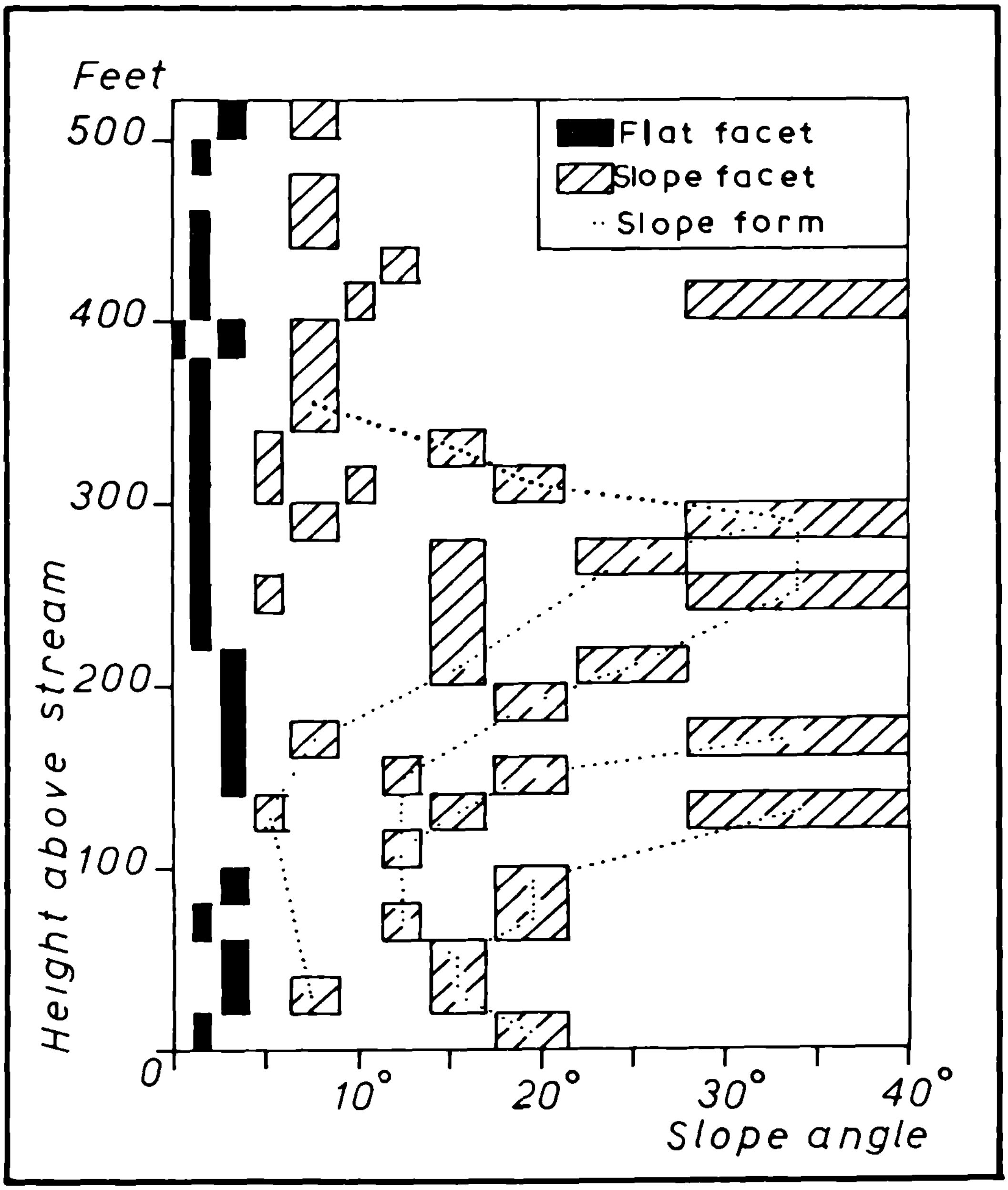


Fig 29. Characteristic angles above stream base.

In slope profiles without a free face the waning element is characteristicall between $4\frac{1}{2}$ and 9 degrees, the constant slope greater than 14 degrees and the waxing element has a value between 6 and 17 degrees. In slope profiles where a free face is present the waning element is characteristically betweer $11\frac{1}{2}$ and $13\frac{1}{2}$ degrees, the constant slope is over 14 degrees and the free face over 28 degre s while the waxing element has an angle of slope between 6 and 22 degrees.

The weighted mean values (Fig.30) calculated for each of the angle area distributions (Fig.28) indicate the form and general distribution of slope elements above the stream base. A high angle group of facets is typical of the base of the slope (0 - 20 feet) and is surmounted by the waning slope element (20 - 140 feet). The constant slope (140 - 220 feet and over) is succeeded by a free face element which may occur at any height between 220 and 380 feet above stream base (Fig.30).

This method, using height above stream base, as a basis for the recognition of slope types has possible applications. In a thorough analysi however, subdivision of the two major types (i.e. above head of first order stream and above other streams) would be required before the angle - area analysis could be effected. This could be achieved by sorting on the basis of colu n 30 (Chapter 3) on the present punch cards prior to the final analysis. A further dis dvantage is that absolute position has been used whereas, if devised, a percent ge of relative position might be more successful.

i) (c)

The relationship which exists in a drainage basin between angle

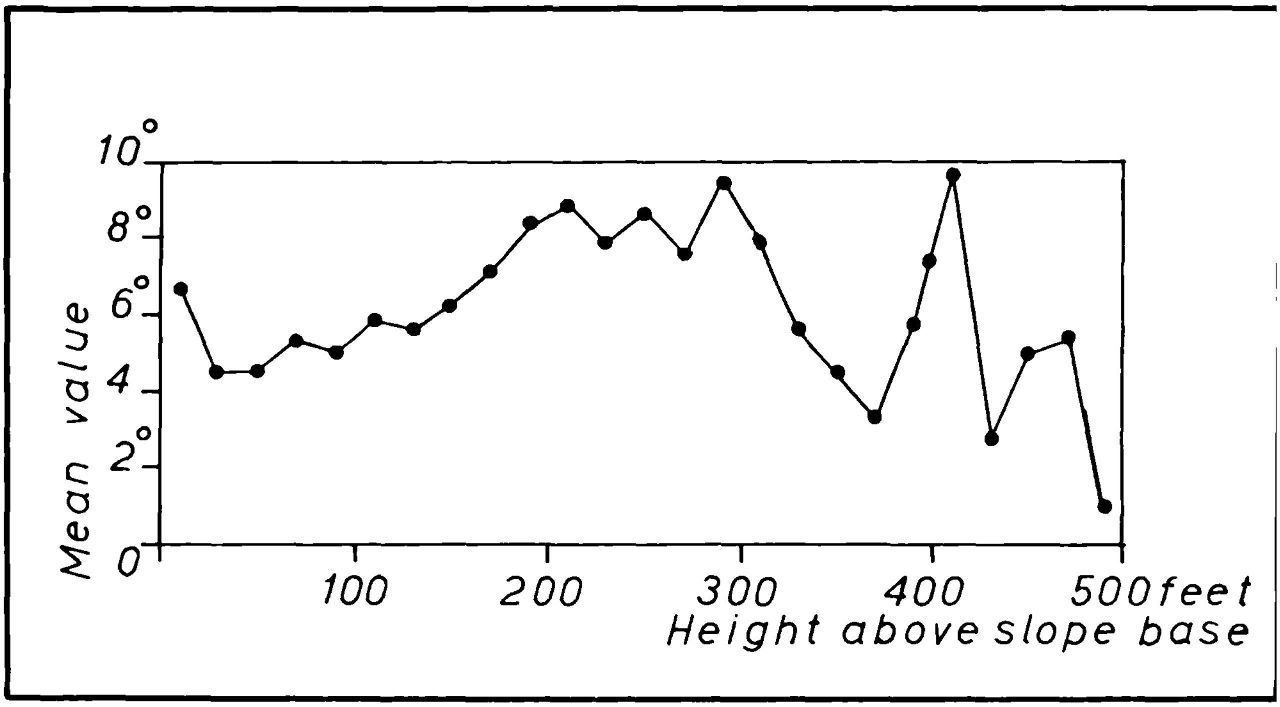


Fig 30. Mean values of slope angles above stream base.

of slope and area was noted above (Chapter 4) nd this is confirmed when the sample area is subdivided into drainage basins of each individual order (Fig. 28). The angle - area di tributions for basins of s ecific order and for the area of overland flow are in the form of simple unimodal rel tionships (Fig.28). The distribution for first ord r basins (Fig.28) shows a tendency to develop a second peak but otherwise the distributions are simple vari tion upon the major general rel tion hip (shown in Fig.7). The modal value of the angle - area distribution for the total sample area was 1 degree and the modal values of the distributions representing the constituent basins of specific ord r are enumerated in Table 6.

Table 6.

Order	Modal value: angular group
1	1 - 2 degrees
2	1 - 2 degrees
3	2½ - 4 degrees
4	2½ - 4 degrees
L_o	1 - 2 degrees

ii) (a)

In Eskdale facets were referred to one of three types of slope combination and these w re termed summit slopes, valley side slopes and stream side slopes (Chapter 3). Each facet in the analysis was given a ercentage position in one of these three types of slope. In the main program (Appendix 3; 6b) all the slope facets were considered together an analysed according to the osition above slope base r gardless of the type of slope. Angle - area distributions were lotted for 10 p rc ntage height gro ps (Fig.31). The first 10% (0 - 10%) h ve high angl s of slo e reflecting stream incision t the slope base. Betwe n 10 nd 30% slope position low angle values are d minant reflecting the pres nce of a waning slope. The distributions show two or more peaks between 30 and 70% while the free face usually occurs between 70 and 80%. Two lower maxima also occur betw en 70 and 80% (Fig.31, slope facets) indicating that a free face does not always occur in this position. Over 80% slope position the characteristic angles are lower and there is an increasing dominance of low angle values. This suggests the presence of five elements in the general slope profile; a fact further illustrated by the mean values plotted for each of the 10 percentage slope ositions (Fig.32). The five elements which may be recognised in a generalised profile are:

a) waxing slope - over 80% slope position.

b) free face or equivalent - 70 to 80% slo e position.

c) constant slo e - 30 to 70% slope position.

d) waning slope - 10 to 30% slope position.

e) stream side element - 0 to 10%. The presence of high angle values in some cases and low ones in others leads to the two peaks on the distribution (Fig.31 - slope facet

The modal values of the angle - are distributions for all slope facets (Fig.31) are plotted togeth r in Fig.33. Th se modal values represent characteristic a gular groups for particular slope ositions. The characteristic angular groups could be combi ed in several ways but in a slo e facet profile the char ct ristic angular group r a y sp cific ight must always be the same a or gre ter than h on b ow. Th c aract ris ic angles

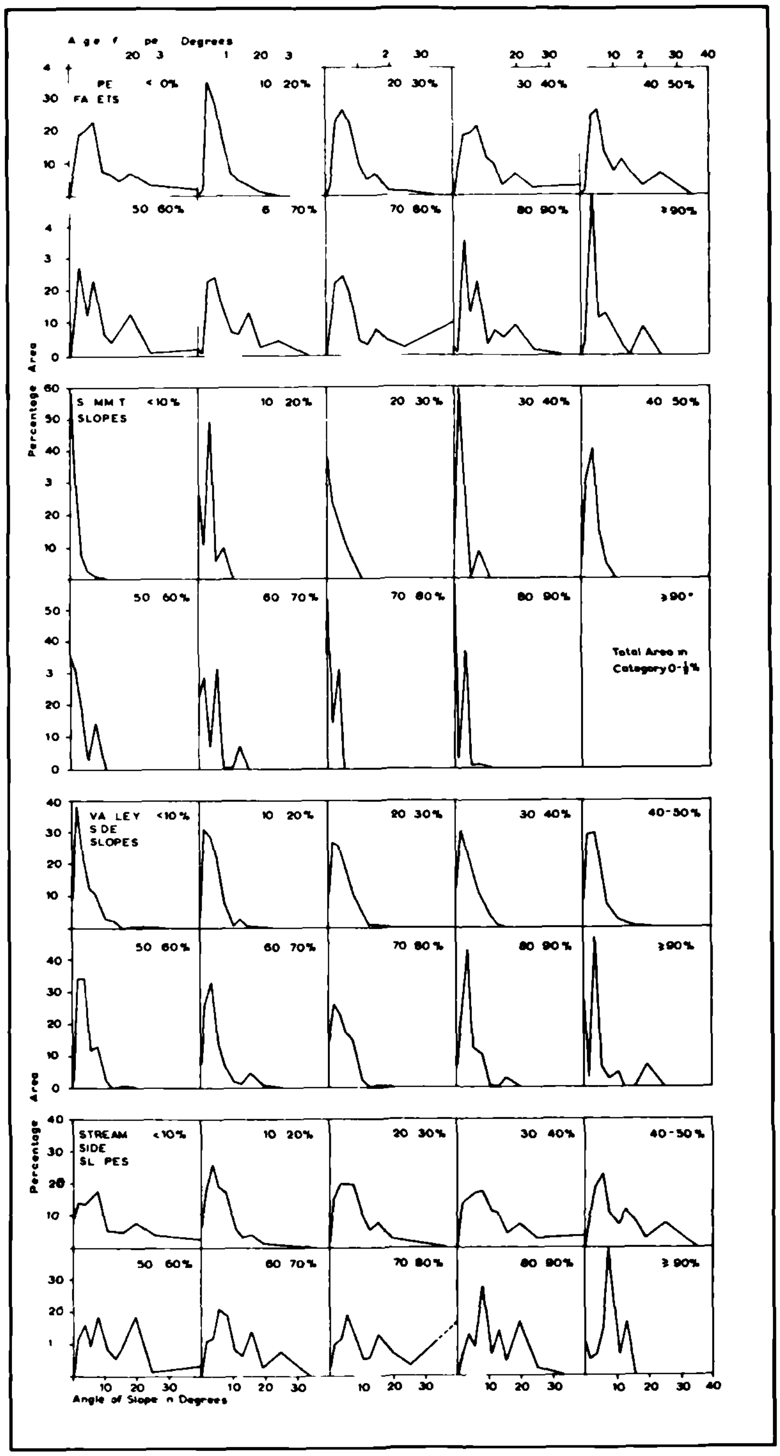


Fig 31. Angle - area distributions for slope facets and slope types.

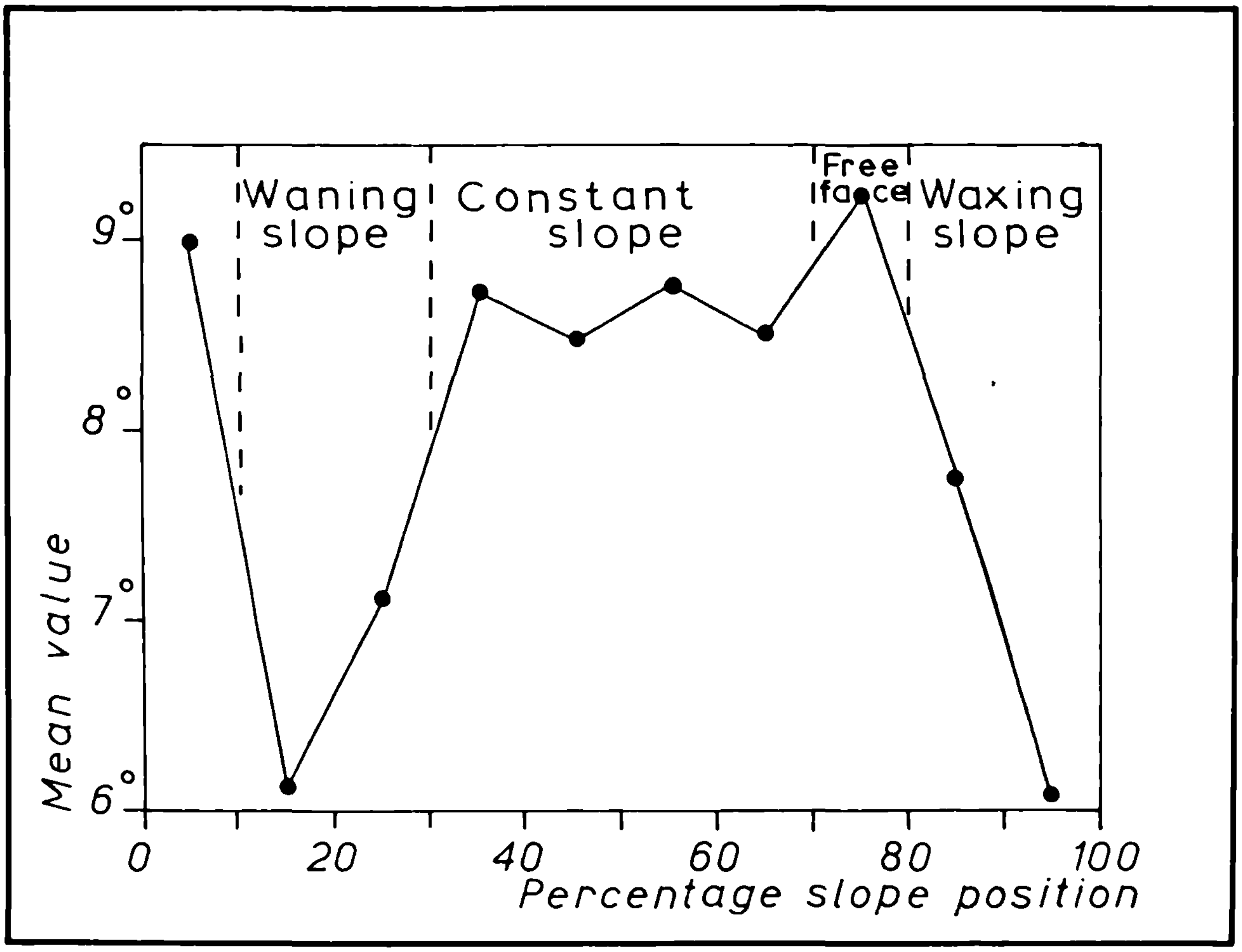


Fig 32. Mean values of slope angles for slope facets.

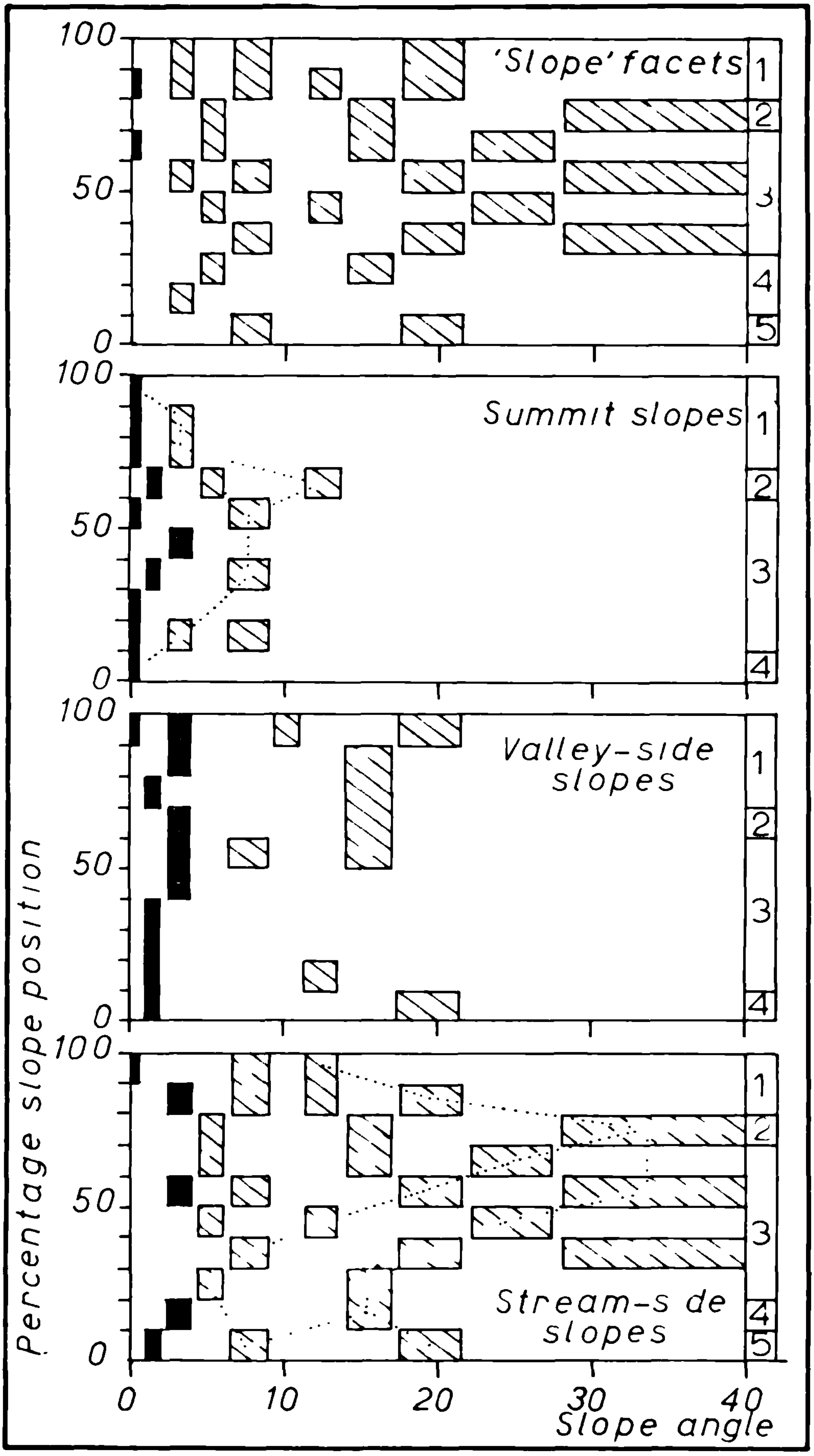


Fig 33. Characteristic angles for different slope types.

for the five le ents in the slo e profile ap ear to de end upon the pres nce or absence of a free face or a si ilar steep le ent in the profile (Fig.33). Wh re a steep el ment occurs in th slope profil the constant slope is characterised by an les greater than $17\frac{1}{2}$ de rees out wher the steep facets are not resent the constant slope angle has a value b tween $4\frac{1}{2}$ and 9 degrees

ii) (b)

T e use of t per ntage position of 'slope' facets (ii.a above and Fig.31) is difficult to interpret. Angle - area correlations (App ndix 3; 5) were drawn for the three types of slope recognised in Eskdale (Fig.31) The percentage area occupi by each of these slo e types in the sam le area is:

Summit slopes	5.00%
Valley side slopes	45.75%
Stream side slo es	49.25% of the sample area

In this section of the analysis discrimination is made between slope types but not between flat and slope facets. The distributions for each type show maximum values repr senting characteristic angular groups for specific types of facets.

The angle - area distributions for summit slopes are limited by a number of an les which vary according to the position of the facet in the slope (T ble 7).

Table 7. Limiting angles on summit slopes

Percentage osition of facet	Number of facets in analysis	Limiting ang
0 - 10%	72	9
10 - 20%	13	9
20 - 30%	30	9
30 - 40%	17	9

Percentage position of facet	Number of facets in analysis	Limiting angl
40 - 50%	12	6
50 - 60%	22	9
60 - 70%	23	13½
70 - 80%	14	4
80 - 90%	16	9
90 - 100%	7	½

Therefore summit slopes in Eskdale never possess angles of slope greater than 13½ degrees and these occur between 60 and 70% above the base of the slope; this is largely the effect of the Cornbrash and the Grey Limestone - Moor Grit outcrops which promote high angles of slope similar to a free face in some cases. There is a general decrease of limiting angle above slope base and the percentage of higher angles decreases appreciably above 60%. The 10% height groupings usually show two maxima corresponding to the flats and slopes in each relative position (Fig.31, summit slopes). Between 10 and 20% and also between 60 and 70% a third peak occurs representing the incidence of a group of higher - angled slopes. The distributions (Fig.31) and the weighted mean values for these 10 relative height groupings (Fig.34) indicate that four elements are present in the profile of the summit slopes and these are:

waxing slope	above 70%
free face or steep element	60 to 70%
constant slope	10 - 60%
waning slope	below 10% slope positio

The modal values of the distributions, plotted as characteristic angles (Fig.33), indicate that the constant slope is characterised by slope angles between 6½ and 9 degrees and the steep element in the profile (equivalent to

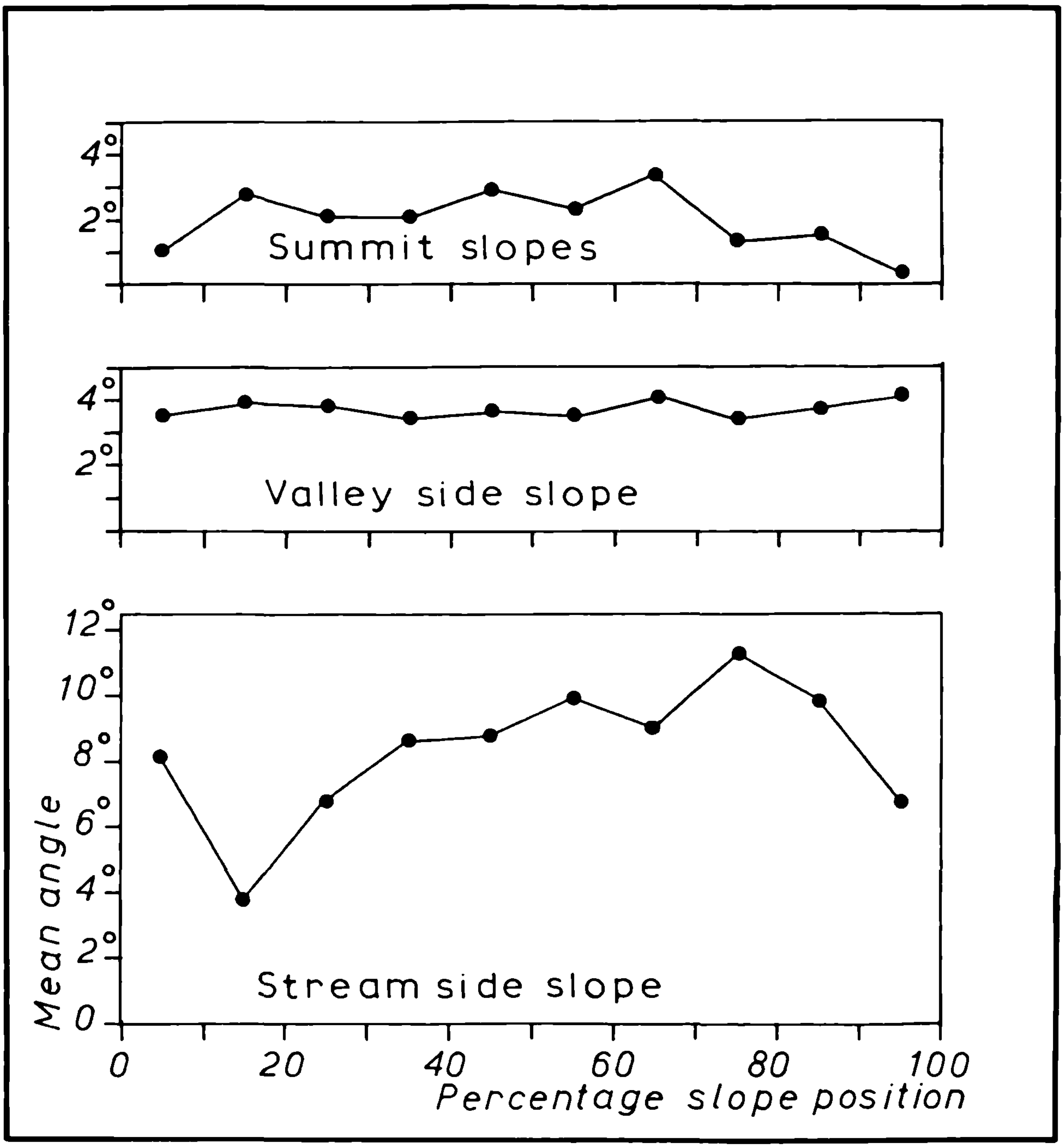


Fig 34. Mean values of slope angles for different slope combinations.

th free face) by angles b tw^e^en 11½ and 13½ degre.s. The waxing slope element is charact ris d by angles of 2½ to 4 d gre s whe the steep element is present in the profile and of 2½ to 6 degrees when this is absent (Fig.33)

Angles of slope gr ^e^t r than 28 de_grees never occur in the vall y ide slo es (Fig.31) and the limiting angles for percentage positions above the slope base are r corded in Table 8.

T ble 8. Limiting angles for valley side slo es.

Percentage position	Limiting angle
0 - 10	28
10 - 20	22
20 - 30	17
30 - 40	14
40 - 50	17
50 - 60	17
60 - 70	22
70 - 80	17
80 - 90	22
90 - 100	22

The angle area distributions for the valley side slopes (Fig.31) contrast with those for both summit slopes and stream side slopes in that the second or third maxima are far less pronounced and the curves approximate to a 'normal' distribution. The two maxima which occur thr ughout the distributions correspond to the flat and slo e f cets in similar relative environment but it is ignificant that below 0% slo e posi ion the s c nd pe k on the distribution is al ays very small, if it occurs at all. The mean values for each of the distributions (Fig.34) illustrate the small amount of variation and it is not possible to discriminate between ele ents in the rofile or to note any characteristic angles. The maxima w'ich do occur are lotted in Fig.33 but the distribution of the c'aracteristic angular grouping and their size does not indicate any definite type of preferred profile (Fig. 33).

Stream side slopes afford a number of angle - area distributions (Fig.31) with definite ma imum values which represent the characteristic angular groups of specific types of facets. The complete range of angular values occur on these slopes except between 10 and 30%, 40 - 50%, 60 - 70%, 80 - 90% (limiting angle 28 degrees in each case) and also between 90 and 100% (limiting angle 13½ degrees). The modal values, plotted as characteristic angles (Fig.33) show a considerable range and may be incorporated into several types of profile. There are two types of stream side slope; one where the base of the slope is composed of a steep facet (or facets) immediately adjacent to the stream and with a characteristic angle between 17½ and 21½ degrees (element 5 in Fig.33) and one where the base of the slope is composed of a slope f cet which characteristically has an angle of slope between 6½ and 9 degrees. This type may be based at the level of the stream or alternatively as a second stream side slope.

3) Implications for slope development.

The methods of morphological analysis used above afford quantitative confirmation of the presence of the four elements previously noted in the typical slope rofile (Wood, 1942). The position and extent of the constituent elements varies according to the metho used. Using the height of facets above stream base the average position of the free face ele ent is between 240 and 300 feet above the stream, the waxing slope above 300 feet, the constant slope between 120 and 240 feet an the waning slo below this. Close to the stream a fifth element is introduced; this comprises a number of facets which reflect recent stream i cision at the foot of the slope. The absolute and relative positions of the slope elements according to the different methods of analysis are indicated in Table 9.

Table 9. Position of slope elements in different types of slope.

Slope element	Summit slope	Valley side slope	Stream side slope	Slope facets
Waxing slope	over 70%	over 70%	over 80%	over 80%
Free face or equivalent	60 - 70%	60 - 70%	70 - 80%	70 - 80%
Constant slope	10 - 60%	10 - 60%	20 - 70%	30 - 70%
Waning slope	below 10%	below 10%	10 - 20%	10 - 30%
Stream side element			below 10%	below 10%

The characteristic angles which are pronounced on all the distributions except those for the valley side slo es vary in value from one environment to another (Figs.29 and 33).

The fact that certain groups of slope angles occur as angles characteristic of specific types of environment suggests parallel retreat of slope facets rather than central rectilinear recession.[1] Stream side slopes possess characteristic angles for most of the range of percentage position (Fig.33) but these distributions and those for the summit slope facets contrast strikingly with those for the valley side facets; characteristic angles are more romin nt and more numerous in the former cas s than in the

1. See Bakker and Le Heux, 1947.

latter situation (Fig.33). This introduces the possibility that parallel retreat occurs on the summit facets and on the stream side facets maintaining characteristic angular groups whereas the intervening valley side slopes which have only a slight tendency to develop characteristic angles may be undergoing central rectilinear recession. The hillside slope has previously been subdivided into four elements (Wood, 1942) but few demonstrations or remarks have previously been made concerning the degree of repetition of these four elements in the composite profile of a major slope in a drainage basin. In Eskdale it is suggested that the three types of slope; summit, valley side and stream side; are all distinct although in many cases each includes the four slope elements.

Although the effects of slope recession on summit slopes and on stream side slopes are basically similar the rate and mechanism of recession must vary appreciably between the two types. Where these different rates and modes of retreat coalesce, in the valley side slopes there is a dominance of central rectilinear recession. Recession of a slope profile is basically a function of weathering and mass movement while climatic factors influence the rate of development. The climatic factors (enumerated by Langbein, 1947) are fairly constant over small areas in Eskdale although appreciable microclimatic differences must occur, particularly with regard to orientation of facets. The results and significance of micro - climatic environments as affecting slope processes has been stressed in the case of Spitsbergen (Jahn, 1960).

On the stream side slopes development is geared to the base of the slope. The base of the slope may be experiencing vertical or lateral erosion and each of these will affect slope processes both directly and indirectly. The slope base may be marked by one of three types of facet combination:

i) steep incision; characteristic angles $17\frac{1}{2}$ - $21\frac{1}{2}$ degrees (rapid removal of material).

ii) slope facets; characteristic angles $6\frac{1}{2}$ - 9 degrees (more gentle removal of material).

iii) flat facets; characteristic angles 1 - 2 degrees (the extent of mass movement on such a low angled slope depends upon the lateral extent of the low angle facet, the composition of the material and the water balance. Because of the low angle the rate of movement of material on the facet may be slow although to some extent this will be counteracted by the presence of the stream.

Material weathered from the free face of a stream side slope combines with material derived from above and moves down the constant slope by one of several flowage types (Sharpe, 1938) of mass movement. This mechanism is influenced by rainwash, the depth of infiltration of precipitation, the slope angle and the composition of the material involved. On a stream side slope the character of a facet is determined by the relationship between angle of slope, lithology and character of the detrital material. There will be a range of values for each of the determining factors but if controlling conditions, such as climate, are suddenly changed this relationship may be modified. Such modifications are often reflected in the sliding types of mass movement phenomena (Sharpe, 1938).

During the winter 1960/1961 the rainfall during the months October to March was appreciably higher than in preceeding years and this was reflected in the incidence of debris slides and earthflows - features which were largely the result of the greater than average rainfall (Chapter 7, Section 3). The facets on summit slopes are probably very stable whereas on certain critical portions of the stream side slopes slight variations in the controlling conditions may give rise to unstable facets and particular types of mass movement phenomena will occur to restore stability. A further process which operates on stream side slopes is effected by streams of lower order than the main one. These streams flow directly downslope in channels, effect erosion of the slope and concentrate mass movement material into the channels.

On the summit slopes there are few channels, even of first order, and so development is directly geared to the top of the valley side slope and only indirectly, if at all, to the foot of the stream side slope where the major eroding and transporting agent is available. Rainwash is the chief source of supply of moisture on the summit slopes and the low angles of slope frequently give rise to minimal movement. Gullying of blanket peat occurs on some parts of the summit slopes, particularly where the vegetation cover has been reduced by burning the calluna. If this process affects slope angles over wide areas the tendency will be to increase slope angles, or to maintain them, rather than to effect decline Spring sapping by small streams which are thrown out by particular lithologies also leads to the production of minor features but from field observation in Eskdale this appears to be of small significance compared with the effects of creep and overland flow by rainwash.

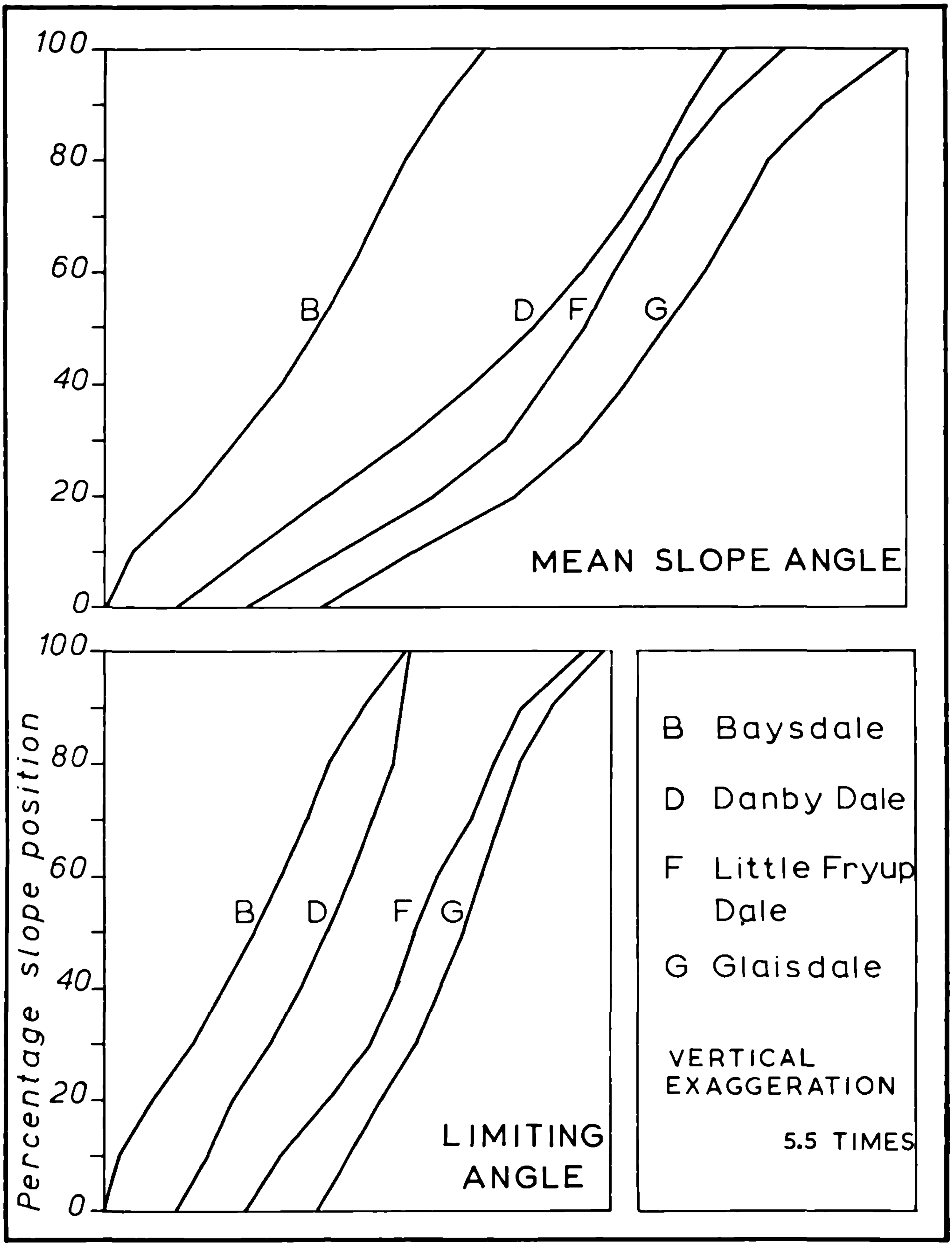
The valley side slopes which occur in an intermediate location, between the summit slopes and the stream side slopes, are subject to a gradation of processes. The rate of erosion and removal of material on valley side slopes must vary considerably laterally as well as vertically and so slope angles in this location tend to be drawn from a considerable range of values suggesting that central rectilinear recession may occur.

The type of retreat suggested, varying with the location of the particular slope type, is supported by studies of slope angles in profile, especially where outliers occur. The contention that "residuals when made of the same rock have the same angle of slope regardless of size" (Bryan, 1940) is supported by studies of outliers in Eskdale. Simon Howe (SE 83298 is an outlier of Kellaways - Cornbrash which supports angles of slope betwee 6 and 7½ degrees according to aspect. The Cornbrash of Stone Rigg (SE 836978) also supports similar angles of slope between 6 and 7½ degrees. These two features occur on a summit slope and are ¼ mile apart. An outlie of Cornbrash south of Rutmoor Beck (SE 794959) supports angles of slope between 8½ and 10½ degrees but the corresponding main line of the Cornbrash outcrop maintains angles of slope less than this - between 6½ and 7½ degrees. This outlier and the main outcrop occur on a valley side slope and constant angles are not maintained in similar environments with corresponding values of orientation. The Howe at Danby (NZ 693075) is fringed by angles of slop of 13½ and 14 degrees while the equivalent slopes on the opposite stream side slope also supports angles between 12½ and 14 degrees. The constancy of angles on the summit slopes and stream side slopes suggests that slopes develop by parallel recession whereas on the intervening valley side slopes constancy of angles is not maintained so rigorously.

The detail of slope recession may be ascribed to one of several types. Savigear (1960) has discriminated between decline, replacement and parallel retreat. The evidence adduced above, on the basis of characteristic angles, favours the hypothesis of slope replacement rather than the type noted by Bryan (1940) and King (1953) which is essentially parallel retreat. The differences between parallel retreat and slope replacement arise as a result of variations, in the amount of material removed from the constituent facets comprising the slope. If parallel recession occurs to a greater extent on the 'slope' facets of a slope profile, then the net effect on the general angle of the hillside may be one of decline although the mechanism involves parallel recession of certain facets. This complication arises from the fact that most, if not all, hillside slopes in Eskdale are polycyclic in form. The simple pattern of waxing slope, free face, constant slope and waning slope is frequently punctuated by flats of various types. The angle - area distributions for different slope types (Fig.31) indicate that flats are areally more extensive at some heights than at others. The occurrence of such 'cyclic stages' is further emphasised by the mean values diagram (Fig.34). Although the mean values of summit slope and stream side slopes indicate a general division into four or five elements respectively there is slight variation within these elements reflecting the incidence of cyclic stages. On the constant slope of the stream side slope the weighted mean value for the 60 - 70% slope position is lower than that for the 50 - 60% slope position (Fig.34). The occurrence of cyclic stages in the slope profile seriously complicates the interpretation of slope morphology and the processes of slope evolution. On the slope facets of summit and stream side slopes the presence of characteristic angles suggests parallel recession. The rate of lowering of the surface of the intervening flats must be appreciably less than that on the slope facets. This general pattern is illustrated in Fig.35. The incidence of flats in slope profiles renders the quantitative analysis of slope morphology rather more complex than that encountered by Koons (1955) although the methods used are basically similar. An important factor influencing the development of a slope is the relative rate of development of the constituent facets. In the case of a stream side slope angle of slope is one factor influencing the rate of development and so it is probable that the higher facets in the slope profile will be destroyed at a greater rate than the lower ones which will be extended.

4) Profile Analysis.

Two types of profile may be constructed from a geomorphological map. A series of absolute profiles may be constructed directly and compared, or alternatively relative profiles may be employed where the percentage position of each facet above the slope base is used rather than the absolute position. An example of the relative method was obtained by using number rather than area of facets. All of the slope facets on the stream side slopes of four of the tributary dales of Eskdale (Baysdale, Danby Dale, Little Fryup Dale and Glaisdale) were referred to one of 10 percentage slope positions above slope base. The mean value was calculated



MEAN SLOPE ANGLE
LIMITING ANGLE
Percentage slope position
0
20
40
60
80
100
B
D
F
G
B Baysdale
D Danby Dale
F Little Fryup Dale
G Glaisdale
VERTICAL EXAGGERATION
5.5 TIMES

Fig 35.

for each percentage slope position and then four mean value profiles plotted (Fig.35). The mean (of opposite sides of the valley) maximum angle for each percentage slope position was also plotted (Fig.35) and this represents the limiting angle for specific environments. In each diagram the profiles were arranged in order of decreasing distance from the mouth of the Esk. The presence of four or five slope elements in each profile may be noted (Fig.35). The waning slope tends to increase at the expense of the constant slope when the four profiles are considered in sequence but the profiles remain approximately parallel. The detailed variations which occur on the individual profiles must be a reflection of lithology. Although the effect of lithology varies with height and characteristic angles have been shown to occur for particular slope positions, the variation within the characteristic angular groups is largely a function of lithology.

The difficulties which arise if different slope profiles are employed to suggest the mode of development of slopes are largely a result of varying lithology. Profiles may be compared within a dale or alternatively generalised profiles of different dales may be compared (Fig.35). If these profiles are required to suggest the mode of development of slopes they should be analysed according to the geological type. An example of the use of absolute profiles, constructed from the geomorphological map, is illustrated in Fig.36 which includes cross sections constructed across Glaisdale. These profiles all show the presence of the four elements in the profile of the stream side slope but the succession of profiles does not represent the sequence of development. This is partly a reflection of the occurrence of a major terminal moraine at the end of Glaisdale. This moraine

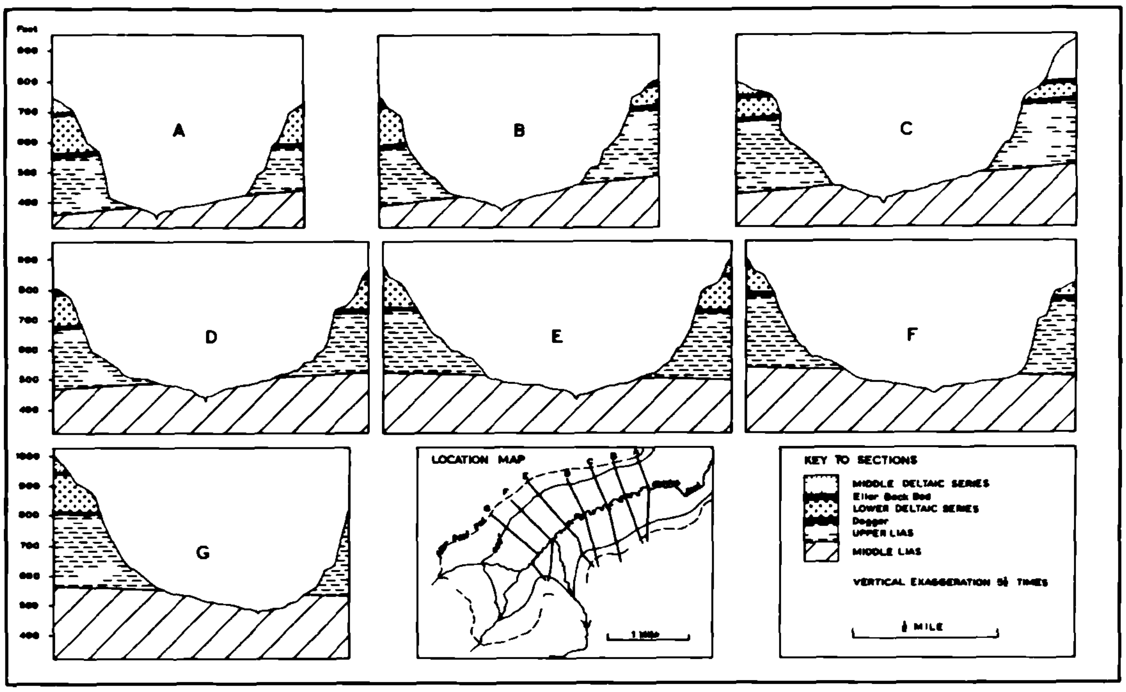


Fig 36. Transverse profiles across Glaisdale.

Constructed from the geomorphological map.

has obstructed the outlet of the dale and so complicating factors have been introduced into the evolution of the Glaisdale stream side slopes.

5) Conclusion.

Slope development is essentially a function of the relationship between the production of material and the removal of material (King, 1957). Runoff and/or infiltration, as controlled by soil and vegetation cover, influence both of these processes. The exposure of facets and their underlying lithology are additional factors affecting the production of material. The characteristics of a facet in any slope profile are confined within certain limits and if the equilibrium condition is exceeded compensation will occur (Chapter 7, Section 3).

Quantitative analysis confirms the existence of four main elements in the profile of a hillside slope and also indicates the presence of groups of angular slope values characteristic of specific rock types, slope position (relative and absolute) and orientation values. The presence of such characteristic angles suggests that parallel retreat is dominant on slope facets but this may be effected in different ways according to position. There may be a considerable difference in the amount of recession at the top of the slope compared with that at the base. Although slope facets in the profile of the summit and stream side slopes undergo parallel retreat, the net effect on the macro - profile (Savigear, 1960) is a reduction in the general angle of slope. In Eskdale climatic variation within the framework of the drainage basin is slight. Comparison with other areas, possessing different climatic conditions, could be realised if a mechanical and/or chemical means of comparing the resistance of various geological formations was devised. The relative resistance, established by laboratory methods, could then be compared with the landscape effects as illustrated by the methods of quantitative analysis. Such analysis on a large scale, for several different but widely - spaced areas, might go at least part of the way towards providing the answer to the problem of process and topographic expression according to the climatic variable.

CHAPTER 6.

THE MAJOR PLANATION SURFACES - FLATS.

Landscape consists of a mosaic of flats and slopes (Linton, 1951a); these two constituents are equally important and one can only be interpreted in the light of the other. Recent years have seen the emergence of interest in slopes as well as in flats and this has led to attempts to coordinate the study of the two and to discuss the implications (Cotton, 1961). Slopes occurring between terraces and between erosion surfaces have been termed cyclic slopes by Sissons (1960a).

The morphology of planation surfaces (Baulig, 1952; Brown, 1961) may be studied by the use of morphological mapping. A major planation surface will be represented by several constituent facets on the geomorphological map and so the use of facets in landscape analysis necessitates the use of a fine, exacting technique in the correlation of these facets throughout an area. The detail available on morphology, in addition to providing a source for the study of planation surfaces and landscape development, allows some consideration of the factors which have affected the morphology of the remnant since its development.

Flats are bounded by breaks or changes of slope and these may have been initiated by processes which have not been of direct significance in the subsequent development of the flat. Since the inception of the flat as a planation surface, the bounding breaks and changes may have been modified in one of three ways:

i) the change or break of slope may be substantially unmodified since it was initiated and only the angles of slope above and below the change are altered. This type may be preserved at the back of a river terrace.

ii) a <u>derived facet</u> may develop where the break or change persists but is developed and its absolute position is changed. This type occurs where breaks or changes demarcate remnants of planation surfaces which have undergone replacement as a result of slope recession.

iii) a <u>secondary facet</u> will occur where a new facet is introduced into the framework of an existing one. This will obtain, for example, during deglaciation, when ice - marginal drainage tended to follow pre - existing flats. The morphology of the existing flat is modified by the introduction of further secondary facets.

The landscape of Eskdale includes several types of flats. Some are erosional, including valley benches, high level planation surfaces, periglacial terraces and ice - marginal benches, some are depositional, including flood plains and the surfaces of kame terraces and eskers. The deposition of a mantle of drift from the last glaciation modifies the pre - existing pattern of facets but the mantle is seldom thick enough to oblitera the pattern completely. The changes of slope are often preserved but the intervening angles of slope have been reduced as a result of the superimposi tion of glacial deposits. This is effectively a special case of the secondary facet noted in iii) above. In addition to the information avail from the geomorphological maps produced in the field and from the derived analysis, height readings were taken, using a surveying aneroid, of all the major planation surfaces above 700 feet and also of the major valley benches in the Esk valley.

1. <u>Major Planation Surfaces.</u>

1a) <u>Preliminary Analysis.</u>

Several methods of preliminary cartographic analysis were undertaken to suggest the surfaces and planation levels which may be significant and also to compare the results with those from the analysis of geomorphological maps. The spot heights which are marked on the 6 inch maps for Eskdale were noted and a histogram drawn by plotting the number of spot heights in frequency groupings (Fig.37). The heights derived using this method are effectively a controlled sample rather than a random one, and so the second method used a series of sample heights, one derived for each grid square in the Eskdale basin. The measurement of the area between each 50 feet contour and the mouth of the drainage basin allows the calculation of the area between successive 50 feet contours and so a histogram may be plotted using these areas. The peaks on this distribution should indicate heights at which possible planation surfaces occur (Fig.37). A development of the method using contour areas was made by plotting the mean slope angle for 50 feet height groups. This mean slope angle was calculated by measuring the length of two adjacent 50 feet contours, computing the average length and dividing this into the areal value. This gives the average width between the contours and may be used to calculate the tangent of the mean slope angle (Strahler, 1956). The distance between successive 25 feet contours was measured on the watershed profile and this was used to plot length against height. This method is particularly suitable to the higher

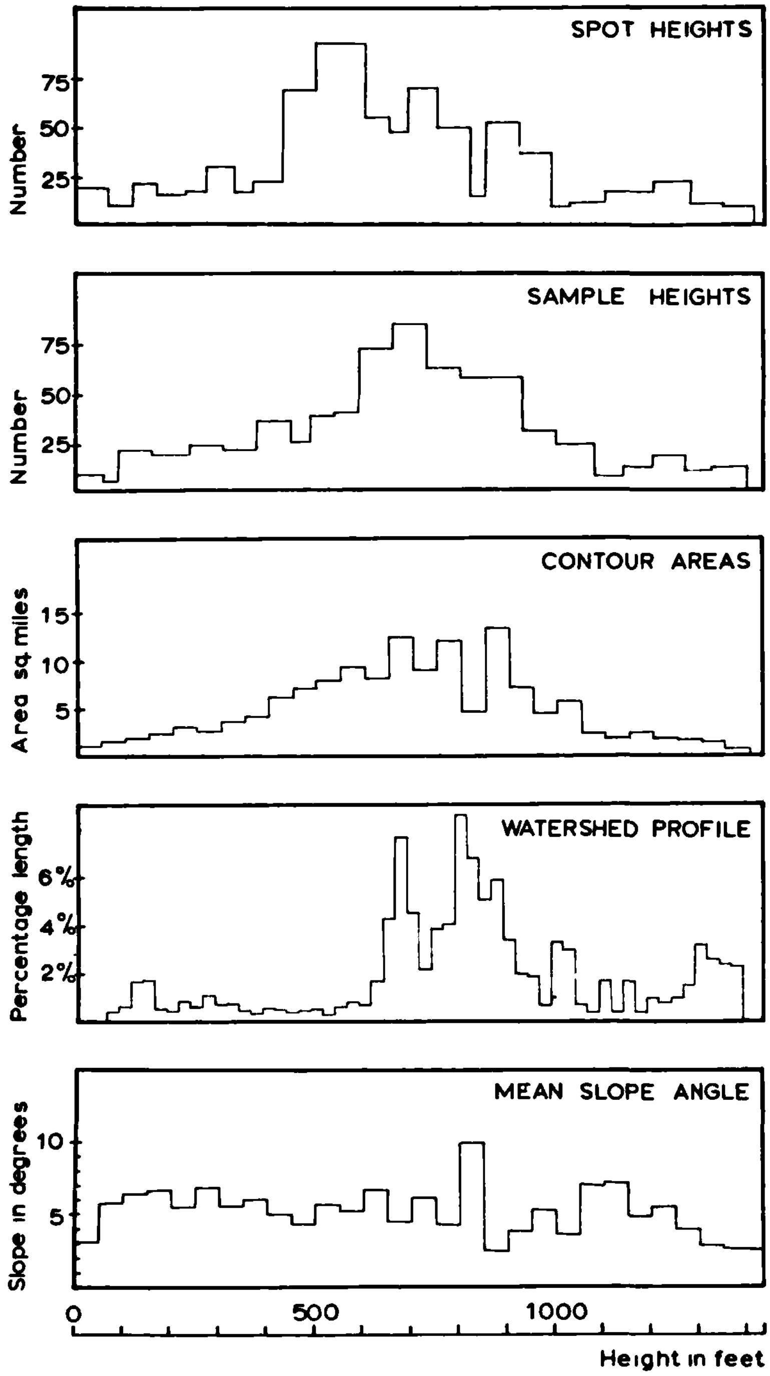


Fig 37. Cartographic analysis.

levels, above 700 feet, as most of the watershed occurs in this height range

The results of these several methods are plotted in Fig.37 and most of the histograms show pronounced maxima and minima. The break down o these diagrams suggests that relatively extensive areas tend to occur below 50 feet, between 100 and 325 feet, 350 - 450, 500 - 750, 800 - 925, 950 - 1050, 1100 - 1250 and above 1325 feet. These quoted heights are based upon the combined results of all five diagrams (Fig.37) and in fact the most reliable is the method of contour areas. The watershed profile affords abundant data but may not be as reliable, in that the watershed does not necessarily preserve surfaces typical of the area as a whole (Rich, 1938).

The use of a punch card for each facet would allow a comprehensive analysis of the occurrence and morphology of flats if the total area analys was sufficient to allow the program to be undertaken. Three methods of analysis could be used and these are:

i) analysis of flat facets with absolute height. This would give more accurate and refined detail of the type obtained (Fig.37) from cartographical analysis.

ii) for surfaces which have a regional slope a method of comparison must be devised, particularly in the case of valley benches where absolute height is not significant throughout the drainag basin. One possibility is to calculate the position of the facet above a local base level and then to compare facets on this basis.

iii) a third alternative is based upon calculating the percentage position of a facet in a particular slope type and then by considering mean values for the angle - area distributions, the significance of particular relative heights could be ascertained (see cyclic stages referred to in Chapter 5).

The application of automatic plotters to the analysis of this type of data would be particularly valuable. If the cards are punched according to some form of grid reference the distribution of the flats of any one type may be plotted automatically by the tabulator.

Mechanical analysis was used to indicate the overall pattern of flats in relation to height but the program was strictly limited by the size of the sample and the corresponding numbers of punch cards available. The angle - area analysis according to height groups (Fig.17) suggests that with: the sample area flats are areally very significant between 800 and 900 feet and also between 1200 and 1300 feet (Fig.17: 13). The mean slope values diagram (Fig.17: 16) suggests that there is a distinct break between 1100 and 1200 feet and that areas above and below this level are significantly lower in angle of slope. On the basis of this diagram flats appear to occur above 1200 feet, 800 - 1100 feet and 400 - 500 feet.

1b) <u>Fieldwork.</u>

The landscape of the moorlands of Eskdale, viewed from a distance, is frequently observed to consist of two major flats. The use of geomorpho- logical mapping technique results in the subdivision of each of the major flats into a series of constituent parts. Therefore in some cases two flat facets will be represented, separated by a slope facet, although the three together effectively constitute a larger 'flat' facet. The distribution of the planation surfaces was derived from a geomorphological map but only those flats which are independent of a river valley were selected. The flats which occur as valley benches along the tributary valleys are considered separately, together with the long profile of the river Esk (Fig.44). The heights of the remnants of planation surfaces preserved on the interfluves, spurs and summits, were determined using a compensated surveying aneroid.

The distribution of planation surfaces above 700 feet is shown in Fig.39. The accompanying height range diagram was constructed by projecting the height range of each facet on to an east - west grid line. This method does not allow for any irregularities on either the present rive course or in the present valley but as the surface remnants, if related to a former river, would be associated with a generally west - east flowing stre this method is considered to be valid. The distinction between remnants occurring south and north of the river indicates that most of the higher lev planation surfaces occur on the south side. There are no surfaces above 1 feet to the north of the river Esk and very few above 950 feet. This shows that there is a broad correspondence between the occurrence of surfaces and geological structure. The surfaces fall in height as the rocks dip away from the crest of the anticline. As early as 1901 it was suggested that th river Esk was a remnant of a formerly longer proto - Esk (Reed, 1901) and this theory of a major eastward - flowing consequent has been followed by other workers (e.g. Linton,1951b). The possibility of such a major easterl - flowing consequent justifies the method of producing the height range diagram (Fig.39). A possible disadvantage may occur in the case of Wheeldale. According to Reed (1901) the present stream formerly was part of a more extensive stream system, independent of the Esk, and so the surfaces

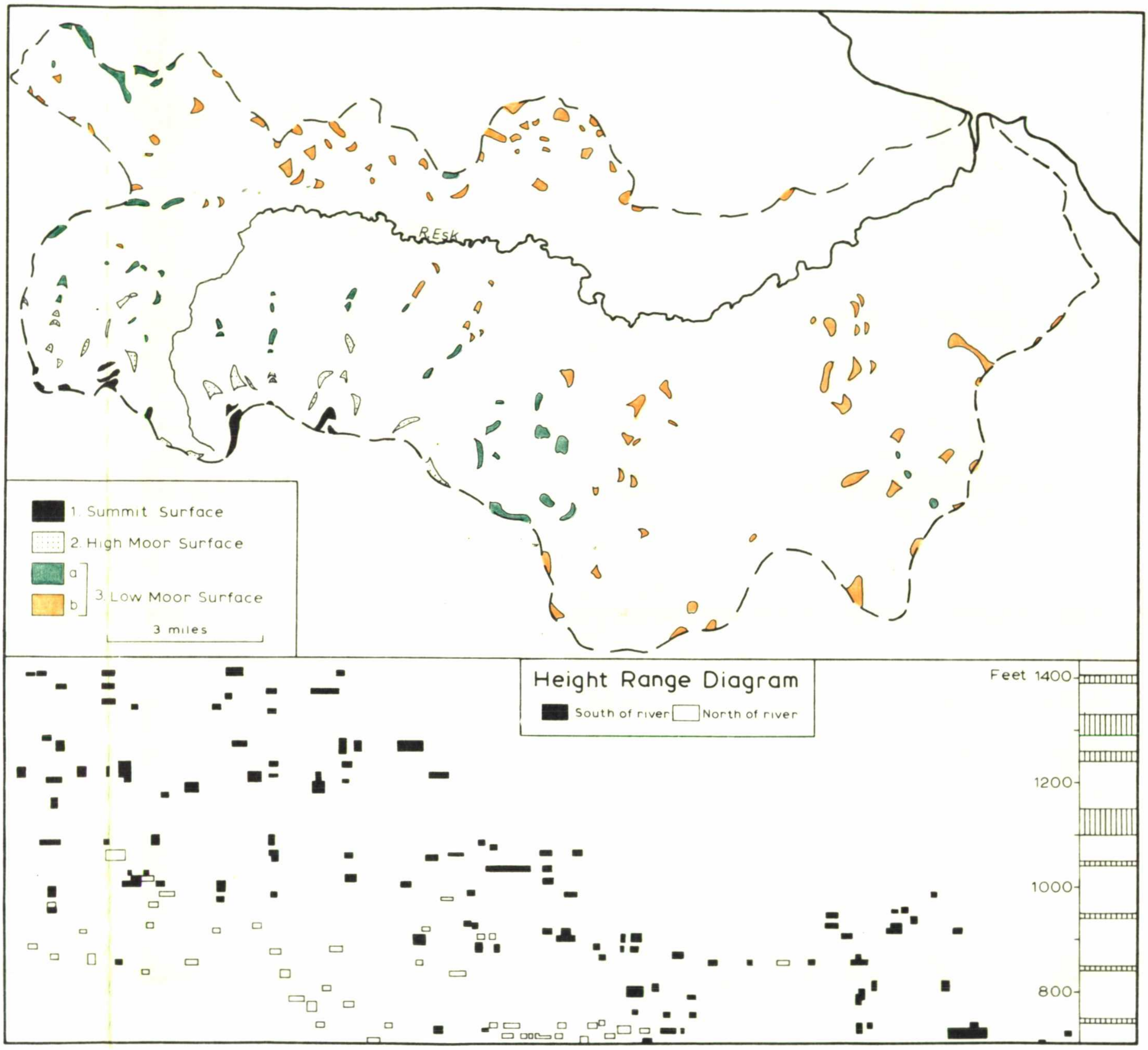


Fig 39. The distribution of high - level planation surfaces.

Note The easterly fall of the Low Moor Surface, apparent in the field, explains the narrow shaded bands below 1100 feet in the key.

the Wheeldale drainage basin should be examined carefully when they are projected on to the same east - west line.

The height range diagram (Fig.39) shows three major groups of surfaces; one above 1330 feet, one between 1150 and 1290 feet and one below 1100 feet. The key column at the margin of the height range diagram (Fig.39 indicates these major breaks, and other minor ones as well. This column is obtained by shading the height intervals in which flats do not occur. The fact that several height groups do occur without any flats suggests that the surfaces are substantially preserved in an unwarped form. The breaks indicated in the column are:

1390 - 1405 feet
1290 - 1330
1240 - 1250
1100 - 1150
1030 - 1050
930 - 950
840 - 850
740 - 750 feet

The major breaks of this height range occur between 1290 and 1330, 1100 and 1150 feet and this gives three surfaces which occur over 1330 feet,
between 1150 and 1290 fee
below 1100 feet.

These three planation surfaces may be subdivided further on the basis of the analysis of the height range diagram (Fig.39) and this would give the following series of flat facet groups:

over 1405 feet

1330 - 1390 feet

1250 - 1290 feet

1150 - 1240

1050 - 1100 feet

950 - 1030

850 - 930 feet

770 - 840

The analysis from which these height groups of surfaces are derived is based upon facets; each major planation surface is therefore broken down into its constituent elements. In order to ascertain that the groups given above are valid a further height range diagram was constructed showing the breaks between the surfaces (Fig.40) and this was also projected on to an east - west grid line. During the course of field mapping it is relatively easy to recognise major planation surfaces in profile from a distance but actually on the ground the breaks between the surfaces are the most easily distinguished. A planation surface ranging from 1150 to 1250 feet will include a number of facets with angles varying between 0 and 4 degrees and in some cases it is difficult to ascertain exactly where the surface ends. The breaks between the surfaces also contain a number of facets but the slope angles of these are significantly higher, usually above 5 degrees and in some cases up to 13 degrees. The breaks between the major surface remnants preserved on interfluves, spurs and summits are plotted in Fig.40 and the key indicates, by shading, the breaks between the surfaces. The intervening areas, left unshaded, represent the planation surfaces and the heights of

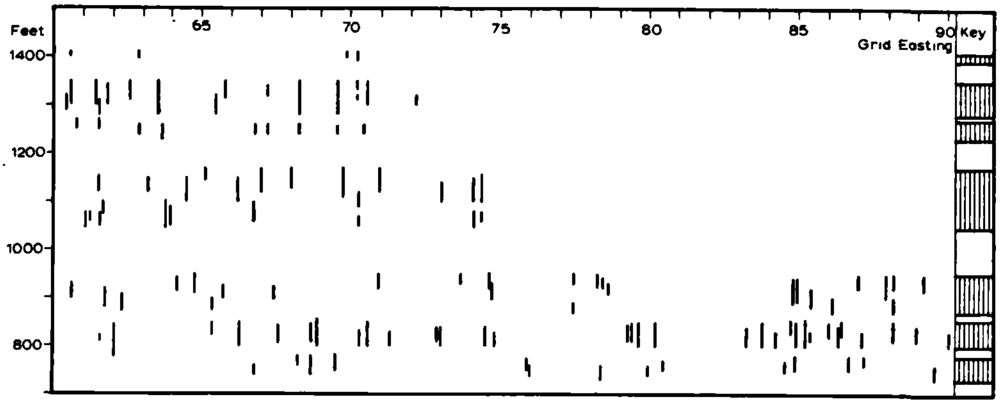


Fig 40. Breaks between planation surfaces.

these are as follows:

1350 - 1365 feet

1270 - 1280 feet

1170 - 1230 feet

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950 - 1040 feet

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855 - 870 feet

780 - 800 feet

below 730 feet.

There is a very close agreement between the results of this method (Fig.40) and those derived from the height range diagram (Fig.39). Above 1150 feet the agreement is very pronounced but the method of using breaks between surfaces does not separate two surfaces in the range from 950 to 1100 feet.

The results of both methods show that there are two major breaks between planation surfaces and the three surfaces occur above 1330 feet, between 1150 and 1290 feet and below 1100 feet. The latter surface, below 1100 feet, occurs more frequently than the others and Fig.40 shows that there is a distinct break somewhere between 870 and 950 feet. The lowest surface may therefore be further separated into two parts with corresponding height ranges from 950 to 1050 and from 770 to 930 feet. These three surfaces may be referred to as:

Summit surface - over 1330 feet.

High Moor Surface - between 1150 and 1290 feet.

Low Moor Surface a. - between 950 and 1100 feet.

Low Moor Surface b. - between 770 and 930 feet.

1c) Planation surfaces.

The Summit surface (above 1330 feet) consists of a group of flats which bevel the crest of the Yorkshire Moors and are confined to the extreme south western part of the drainage basin. It occurs on the Middle Deltaic Series south of Baysdale, is very well - developed on the outcrop of the Grey Limestone at Stony Ridge and Howdale Hill, and may be traced to the head of Castleton Rigg at Ralph Cross. In only one case does the surface have a back and this is where the small Burton Head rises gently to a level about 20 feet above the main surface. This summit surface maintains a constant height and is responsible for the even crestline of the south western part of Eskdale.

The High Moor Surface (1150 to 1290 feet) is composed of remnants which are separated from those of the summit surface by groups of facets which have angles of slope generally between 5 and 7½ degrees. These remnants are also confined to the south western portion of the drainage basin (Fig.39) fringing the area of occurrence of the Summit Surface. Largely restricted to the outcrop of the Middle Deltaic Series the remnants are very well - developed immediately west of Westerdale Head, but also extend on to the Grey Limestone outcrop of Glaisdale Moor.

The Low Moor Surface a. (between 950 and 1100 feet). The existence of a major break in the landscape of the North York Moors between 1100 and 1150 feet is shown by the results of punch card analysis (Fig.17), preliminary cartographical analysis (Fig.37) and the distribution of surfaces (Fig.39). This break has also been noted as a salient morphological feature by Versey (1937) and taken to represent the division between a major peneplain surface below this level from a monadnock group above. The remnants of the surface occur on the southern side of the drainage basin fringing the higher surfaces and also near the watershed in the north western part of the drainage basin (Fig.39). It occurs on a variety of geological types including the Upper Deltaic, Moor Grit, Grey Limestone, Middle Deltaic and Lower Deltaic formations. The even skyline in the north west of the drainage basin, on Guisborough Moor, shows remnants of this surface and a large remnant occurs on North Ings Moor. The spurs separatin Baysdale, Westerdale, Danby Dale, Little Fryup Dale, Fryup Dale and Glaisdal all have representatives of this surface and extensive remnants also occur on Egton High Moor and Wheeldale Moor at the head of Wheeldale Gill. These remnants are cut across various geological formations regardless of structure and must represent the remains of a formerly very extensive, gently undulating surface developed at circa 1000 feet. The flat - topped Danby Beacon, occurring on the Kellaways Rock, also belongs to this group and rises above remnants of the lower part of the Low Moor Surface. This surface shows a gentle fall to the east and is preserved on the summit of Stony Leas and Sneaton High Moor in the eastern part of the drainage basin.

The Low Moor Surface b. (770 - 930 feet) includes the most extensi planation surface remnants of Eskdale and is well - developed throughout the area (Fig.39). In the north west remnants occur on the watershed west of Sleddale, relics are particularly abundant on Skelderskew Moor, near Brown Hill, on Haw Rigg and on Danby Low Moor to the north of the river Esk. In this area, north of the Esk, between Castleton and Lealholm, the surface extends across a number of outcrops including the Kellaways, Cornbrash, Upper and Middle Deltaic Series, the Moor Grit and the Grey Limestone. Remnants were found on Commondale Moor but there is little trace of this surface in the drainage basin south west of Castleton. Further remnants occur west of the Murk Esk and the surface is well - developed between Collier Gill and Wheeldale Gill. The surface may be traced round the southern and eastern part of the Murk Esk valley where it is well - developed on Sleights Moor. The upper part of the Low Moor Surface shows an overall fa from west to east whereas the lower part of the Low Moor Surface also falls in height from south to north. The remnants of the lower part of the Low Moor Surface appear to be more significantly related to the river and the constituent flat facets are distributed in the manner of high level valley benches. Unfortunately any attempt to relate these on the long profile of the river (Fig.44) would be frustrated because the constituent remnants are not very numerous and the interposition of the Murk Esk valley gives a considerable break in the sequence across which correlation would be very tentative. The height range diagrams (Figs.39 & 40) indicate a break be two surfaces at approximately 750 feet and extensive remnants of the lower element (i.e. below 750 feet) occur near the northern part of the Stonegate valley. These flats represent the remnants of a formerly very extensive surface at the head of Stonegate at a height of approximately 725 feet; this surface is probably related to the Calabrian sea levels as will be demonstrated later.

1d) Previous studies.

A masterly essay on the development of the rivers of East Yorkshir was written in 1901 (Reed, 1901). In this work six cycles were recognised and it was considered that the drainage was initiated on the emergent Cretaceous sea floor. The first cycle culminated in the production of a peneplain extending from the Pennine area to the North York Moors and was terminated by the onset of the mid - Tertiary earth movements. Uplift initiated the second cycle which continued until the late Pliocene when subsidence produced the North Sea and initiated the third cycle at a stage which may possibly be equated with the stage of landscape development now designated as the Calabrian shoreline in southern Britain (Brown, 1960b). The fourth cycle was described as post - glacial and the fifth represented by a relative uplift of the land which is reflected by the 30 feet raised beach. Finally the present cycle was described as a sixth cycle of erosion Following Davis (1895) Reed envisaged four major eastward - flowing consequent streams which incorporated remnants or extensions of parts of the present Tees - Esk, Swale, Ure and Humber (Fig.41). During the first cycle a peneplain was produced and the rivers gradually became adapted to structur This was reflected most significantly in the capture of the upper Swale and Ure by the subsequent developing along the present Vale of York and also by the capture of the headwaters of the proto - Esk by the Tees (Reed, 1901).

More recent work has elaborated and modified Reed's original ideas. Versey has suggested that a peneplain surface exists in Cleveland, developed in the west up to 1100 feet and warped down to approximately 600 feet in the east near Whitby (Versey, 1937). This surface was described as being backed by a marked break above 1100 feet and above 1150 feet a monadnock group occurred. The results of cartographical analysis in the Pennines suggested the occurrence of two peneplains and the lowest of these

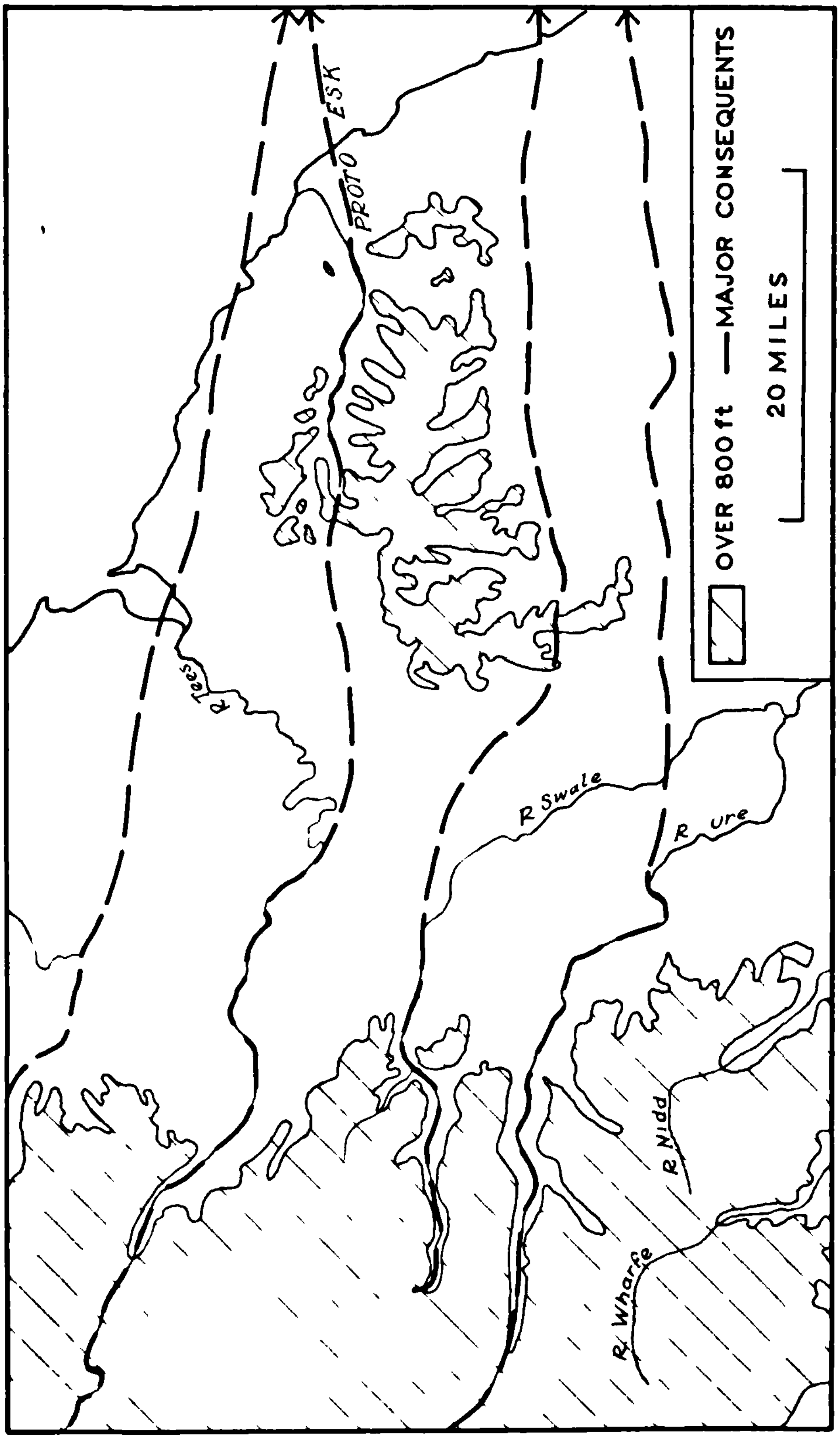

Fig 41. The initial drainage pattern (mainly after Reed, 1901).

is equated with the Cleveland peneplain (Versey, 1937). A surface at about 800 feet has also been noted in the Yorkshire Wolds and correlated with the other two areas. Deposits which occur on the Wolds may be Tertiary in age and related to this surface (Versey, 1937). The overall picture presented b Versey is of a warped peneplain sloping from the Pennines down to the North York Moors and the Yorkshire Wolds (Versey, 1937, 1947). Reed (1901) suggested that the proto - Esk included part of the upper Tees and this was adopted by Fawcett (1916) but Versey (1942) has related the upper Swale with the Esk. The surface which has been described in Cleveland has been equated with the Miocene - Pliocene surface of south eastern England (Peel and Palmer 1955).

The Mesozoic and Tertiary record of east Yorkshire and north Lincolnshire has been very different from that of the south of England (Verse 1947). In Cleveland the absence of post - Jurassic deposits has made interpretation of the effect of the Alpine movements difficult. The recognition of a similarity between North East Yorkshire and the Teutoburger Wald was used as a means of giving the basis of a study of.. Tertiary events in Cleveland and the Saxonian folding of Germany (Versey, 1947). The warping of the peneplain in Cleveland was suggested to be Attic in age (middle - late Miocene).

1e) A re - examination.

The structure of Eskdale was deduced by drawing structure contours at the base of the Dogger and supplemented, where necessary, by interpolatio from the Grey Limestone outcrop (Fig.42). The main Cleveland anticline (Fig.42) is composed of a series of small structures as noted by Versey (1947

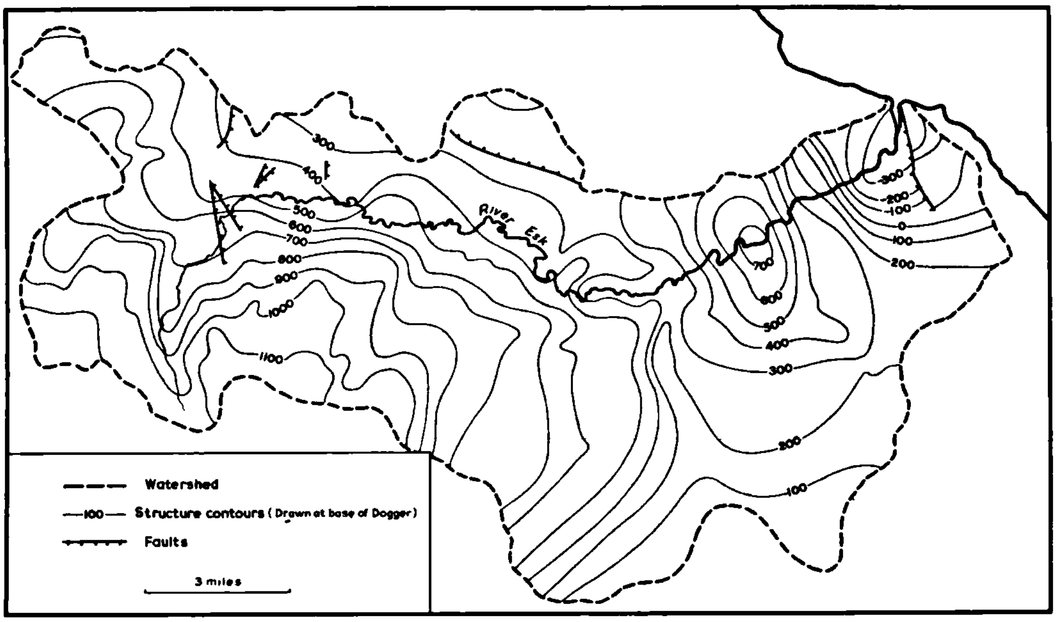

Fig 42. Structure contours for Eskdale.

A series of elongate domes occur superimposed on the major structure. The crest of the anticline occurs in the south western part of the drainage basin A major anticline, the Sleights anticline, occurs between Sleights and Grosmont and immediately to the west of this fold is a syncline extending south of Goathland. A further syncline occurs to the east, between the Sleights anticline and the Robin Hood's Bay anticline, and this is continued north to Whitby.

The drainage pattern is largely independent of structure. West of Lealholm the Esk flows on the northern flank of the anticline but east of this it runs eastward directly across the Sleights anticline and the Whitby syncline regardless of the incidence of these structures. The south bank tributaries, west of Glaisdale, flow with the dip, but the Murk Esk occupies the Goathland syncline and Little Beck has a course along the margin of the margin of the Sleights anticline. The north bank tributaries are appreciably shorter than those to the south and flow against the dip. This stream pattern is developed independently of structure suggesting superimposition of the drainage pattern.

There is some doubt concerning the exact age of the structure in Cleveland. Although the folds are not strictly posthumous, a structure contour map drawn at the base of the Permian (Kent, 1949) suggests an anticline underlying the watershed of southern Eskdale and this is of similar trend to the Charnian of the West Midlands (Arkell, 1933). The drainage pattern, independent of the underlying structures, suggests superimposition and it is unlikely that any extensive Tertiary deposits extended over Cleveland. The presence of the chalk in the adjacent Yorkshire Wolds admits the possibility of a former chalk cover (or a formation equivalent in time, to the chalk). This former Cretaceous cover would be the most plausible basis for the superimposition of drainage. The structures of Cleveland should therefore antedate the upper Cretaceous, at least, and Versey (1947, p.189) has ascribed the age of these structures to the Kimmerian. The culmination of the Alpine movements (Savian, Styrian and Attic) must have affected Cleveland to some extent and Versey (1937) has assigned the warping of the early Tertiary peneplain to the Attic phase.

The three planation surfaces now recognised in Eskdale do not show any trace of warping (Fig.39) and so these must post - date the mid - Tertiary movements. The early Tertiary uplift (Laramide) would produce an easterly - dipping surface on which Cretaceous rocks covered earlier ones deformed by Kimmerian structures. Landscape development would commence upon this surface. The evidence for an easterly - dipping early Tertiary surface in Britain has been described and a map produced showing the generalised easterly fall of summit levels (Linton, 1951b). The period between the Laramide and Attic movements must have seen the realisation of a surface of low relief. The initial drainage pattern, of easterly - flowing consequent would be disrupted before the end of the mid - Tertiary uplift and the headwaters of the Esk captured by the Tees. After the Attic movements, Cleveland was dissected, giving several planation surfaces, before the onset of the Pleistocene.

This interpretation agrees with the evidence now collected and at first apparently conflicts with the idea of a warped surface between 1100 and 600 feet proposed by Versey (1937). In the field late Tertiary flats are the most significant and yet it may be possible to appreciate an envelo passing through the summits of the North York Moors which approximately corresponds to the deformed early Tertiary surface. This will be particularly apparent if analysis is based upon profiles constructed from topographical maps, especially on a north to south basis.

1f) Types of planation surfaces

The term planation surface, adopted in this country by Brown (1961 was fully discussed as surfaces d'applanissement by Baulig (1952). The mode of origin of the surfaces does not affect the pattern of development suggested above. The main outstanding problem is associated with the development of the river Esk despite the mid - Tertiary uplift of Cleveland. This uplift must have been greatest along the southern watershed of Eskdale and to the south of this a series of streams were initiated flowing down the gradient of the uplifted surface (Versey, 1937). Any trace of a former proto - Swale (Fig.41) has been eliminated by the institution of a radial pattern of drainage. The river Esk, however, persisted in its easterly course despite the uplift. The upper part of the stream thus followed a course on the northern flank of the uplift and was not replaced by a simple radial pattern of drainage such as the one introduced to the south of Eskdal Reed (1901) and Versey (1937) have both interpreted the development of the North York Moors as effected by peneplanation.

Studies of the morphology of planation surfaces are restricted by the limited number and the small area of the present remnants. Several general characteristics of the surfaces may be noted however:

(i) the lower part of the Low Moor Surface (b) is consistent in form with an origin as a partial peneplain. The various remnants have a down - valley gradient and they also fall in level towards the centre of the present valley. This planatic surface may be related to a group of high level valley benches in the upper Esk valley and the reconstructed profile of these benches has a considerable gradient indicating that developmen was related to a sea level in the position of the present one or even further from the crest of the North York Moors.

(ii) the upper part of the Low Moor Surface (a) also shows a gradual eastward fall in height. Valley benches occur in the upper Esk valley corresponding to this surface and again have a considerable gradient suggesting development of the surface as a partial peneplain at an appreciable distance from base level

(iii) the High and Low Moor surfaces are separated by a distinct break between 1100 and 1150 feet which may be traced throughout the south western part of Eskdale. The regularity of thi feature and its morphology, including angles of slope of 11 degrees (on Danby High Moor), suggests some form of slope recession instrumental in the development of the break between the two surfaces.

The High Moor surface has little downstream gradient and the corresponding valley benches of the upper Esk valley also have only a very slight gradient. The Summit surface has a back in only one case but the constituent flats maintain a constant height and show little lateral gradien

Both the summit surface and the High Moor surface have relative slope values appreciably lower than those typical of the Low Moor surface (see Section 4 below). Residuals bounded by distinctly concave slopes occur on the High Moor Surface. On the rigg between Danby Dale and Fryup Dale an isolated hill is topped by a flat, occurs between 1250 and 1290 feet and is separated by concave slopes from remnants of the lower part of the same surface. The top of Brown Hill, on Castleton Rigg, conforms with the height of the upper part of the Low Moor Surface (a) and is surrounded by remnants of the lower part of the same surface. These residuals have developed as a result of slope recession but the amount of slope recession occurring at present is probably very slight because the residuals are all on summit slopes. They may have been instigated under climatic conditions rather different from the present, possibly with a higher rainfall.

The Low Moor Surface was therefore developed as two partial peneplains. The High Moor Surface and the Summit Surface differ morphologically from the Low Moor surface and their form suggests an appreciable measure of slope recession in either their formation or in their subsequent modification. The absence of a marked lateral gradient could reflect an origin proximate to base level, as a marine - trimmed surface, which has subsequently been developed by cyclic slopes (Sissons, 1960a). If a relatively high sea level had been characteristic of the High Moor stage this would satisfactorily explain the present anomalous course of the Esk in relation to the mid - Tertiary uplift. A relatively high sea level would necessarily lead to the development of the Esk by superimposition between the High and Low Moor Surface stages.

Alternatively, the climate of the late Tertiary was probably warmer than that of today and the rainfall was also higher (Brown, 1960b, p.170) and this may have been represented in different or more extreme types of processes operating. Runoff may therefore have been greater and a more significant role would be played by slope recession. The two high leve surfaces would therefore have developed to a certain extent under modified peneplanation conditions - i.e. conditions which incorporated some of the characteristics of pediplanation.

There are few areas adjacent to the North York Moors where planatic surfaces similar to those of Eskdale may be sought. Two surfaces in the appropriate height range have been noted in the limestone areas of the Pennines, between 1250 and 1400 and also between 1000 and 1150 feet (Sweeting 1950) and in south west Yorkshire marine stages have been recognised at 1300 1350 and at 1070 feet (Sissons, 1954). In the Lake District Parry (1961) has recognised surfaces at 1300 - 1500, 1000 - 1300 and 700 - 950 feet and these agree with those found in Eskdale. Correlation on the basis of height is extremely tentative at this level but these results are shown, with others, in Fig.43. The drainage diversions may be examined in the light of the proposed sequence of development after considering the Pleistocene valley cutting.

2a) <u>Valley benches and the river long profile.</u>

The long profile of the river Esk has been studied (Henry, 1956) and exponential equations derived to express the form of various parts of the curve (Henry, 1956, p.191). In order to study the valley benches the heights of all the bench levels in the Whitby area were determined using a

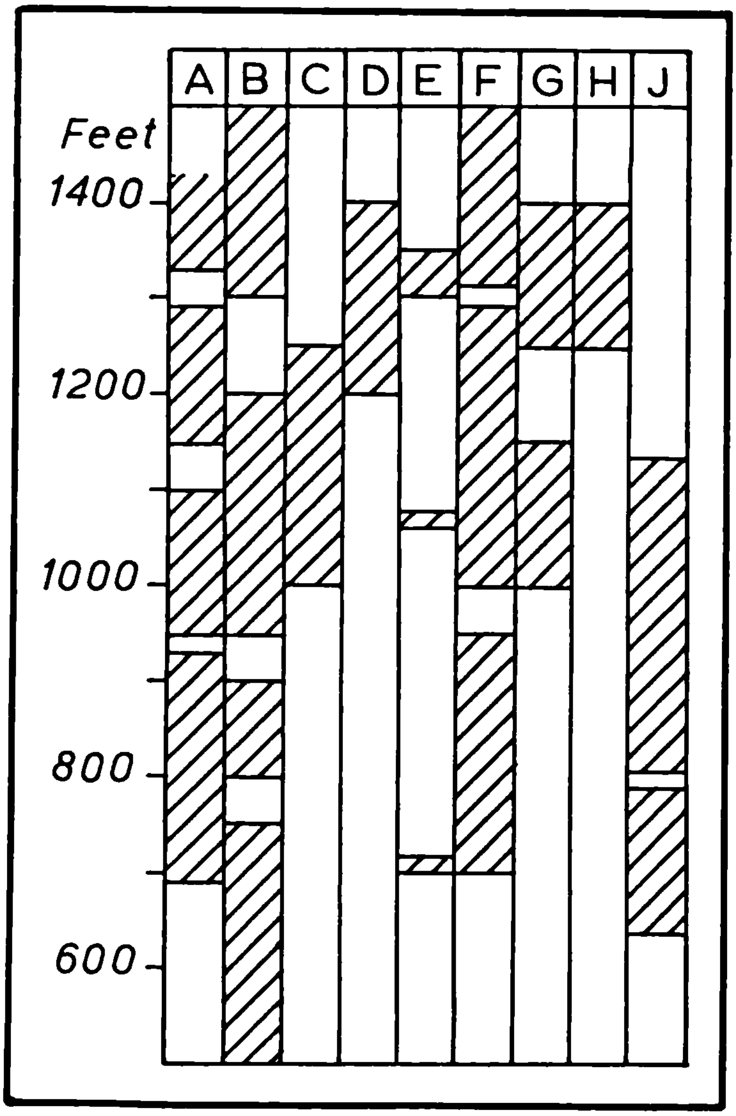

Fig 43. Planation surfaces in Northern England.

Key

A. Eskdale
B. Eastern Cheviots (Common, 1954)
C. Southern Pennines (Linton, 1956)
D. South West Pennines (Johnson & Rice, 1961)
E. South West Yorkshire (Sissons, 1954)
F. Lake District (Parry, 1960)
G. Pennines (Sweeting, 1950)
H. Howgill Fells (McConnell, 1939)
J. Manifold Valley (Warwick, 1953)

surveying aneroid and the heights of the major levels along the main valley were also determined in a similar way. The additional evidence of flats indicated on the geomorphological map was inserted afterwards and the heights of these determined from the surveyed contours and slope angle measurements indicated on the survey maps. The long profile was drawn from the 1:10,560 maps and the details inserted after considering the surveyed long profile[1]. The long profile used by Henry (1956) is that of the water surface of the river, whereas for the purpose of plotting the height range occurrence of flat facets along the length of the valley, the valley floor profile has been used. If the river profile had been used, the length of the profile would have been far greater than that of the valley profile. The method adopted was to draw in the flats which occur near the coast and then to plot the valley benches further westwards along the valley using the geomorphological map and notes made in the field as a constant guide.

The long profile is presented in Fig.44 and the various stages which occur along the Esk valley are noted. The heights included on the height range diagram (Fig.44) refer to the height of the profile at present sea level and no attempt has been made on this diagram (Fig.44) to suggest the position of former base levels. In Eskdale, the valley benches must be considered in the light of four complicating factors; glaciation, the indirect effects of glaciation, slope recession and possible post - Pleistocene warping. During the last phase of deglaciation there was a considerabl amount of marginal drainage and in many cases this must have been controlled

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[1] The author is grateful to Dr D.F.C.Henry for allowing him to consult the results of the survey of the long profile of the Esk and to draw upon this.

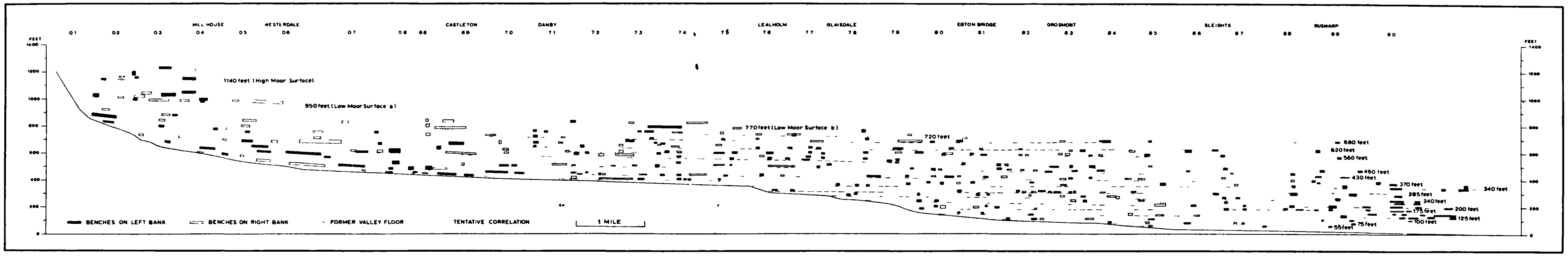


Fig 44. The valley floor long profile and valley benches.
Heights are given for the lowest part of the valley in which each particular stage is traceable.

by the detailed form of the valley sides so that a well - marked valley bench would, in some cases, be developed as an ice - marginal bench hence leading to a considerable modification in the height of the back of the flat. Glacial deposition, particularly near Whitby, has been responsible for the mantle of drift which covers the series of stage remnants developed before the last glaciation. This mantle is seldom greater than 10 feet thick and there are no substantial variations in the pattern of the landscape. In central Eskdale, above Lealholm, deposition has led to infilling of the floor of the original valley and although the river has now cut down to bedrock in some cases the valley floor contains up to 60 feet of drift (Fox - Strangways 1885, p.52). The indirect effects of glaciation are reflected in the oscillations of sea level which complicates the interpretation of the lower stages of valley development, especially as the Esk (between Sleights and Lealholm) is underlain by a buried channel (records from the construction of the rail bridge at Ruswarp). Slope recession must have been considerable during the Pleistocene because rapid incision in an upland area must lead to some measure of slope recession as the valley is widened. A possible method of counteracting this complication is to use the angle of slope of the facet to project the present height of the flat to a position above the present stream. This method is open to criticism however, because angle of slope varies with lithological type and so the technique would not achieve any increased accuracy unless all flats occurred on the same outcrop. A final complication was introduced by Valentin (1953) who showed the amount of possible post - Pleistocene warping. The situation of Eskdale means that, assuming Valentin's map to be valid, such warping has been very slight and of the order of not more than 10 feet. These four factors were considered too significant to contemplate the extrapolation of reconstructed valley floors.

2b) Valley Benches.

In many cases valley benches are narrow (see Fig.19) and they become more extensive upstream as dissection decreases. Four groups may be recognised on Fig.44:

i) high level benches.

ii) the 600 feet group.

iii) lower stages.

iv) post - glacial stages.

i) High level benches.

Three groups of valley benches occur at levels well above 700 feet. The first of these comprises a group which occur in the Esk valley above Westerdale village. They all occur above 1140 feet and there is little slope in the down - valley direction. These flats are cut across the Lower and Middle Deltaic rocks and the absence of a definite slope agrees with remarks previously made about the High Moor Surface (Sections 1c and 1e above) with which the heights of this valley stage correspond. A second group of valley benches, also confined to the Esk valley above Westerdale village, shows a more considerable down - valley gradient. This group is cut across the Lower Deltaic succession and grades down to a height of 950 feet at Westerdale village, corresponding in height with the base of the upper part of the Low Moor Surface. This affirms the suggestion that the upper part of the Low Moor Surface was initiated as a partial peneplain and that this group of valley benches is the equivalent of the surface trace up the Esk valley.

The third group of benches on the valley sides is areally more extensive and stretches down the valley almost as far as Lealholm. This group is cut across a variety of rock types and has a considerable gradient. It stands at a height of 770 feet at Lealholm and so must be equivalent to the lower part of the Low Moor Surface. In the valley above Egton Bridge there is a fourth group of valley benches which grade down to about 720 feet. There are no further relics of this stage lower down the valley but the gradient of the reconstructed profile suggests that this is a terrace stage which is probably related to the planation surface between 725 and 735 feet at the head of Stonegate.

ii) The 600 feet group.

The remnants in this group are often difficult to trace and the record is very incomplete for two reasons; in many cases the steep valley side slope occurs between 500 and 700 feet and so the absolute height values have been modified even if the facets remain and in other cases the work of glacial meltwater has exerted a modifying influence. There are at least three stages near Whitby which correspond in height to the Calabrian shoreline(s) noted in southern Britain (Brown, 1960b). The 720 feet stage may also belong to this group but this cannot be tested because of the absence of any relevant flats in the lower Esk valley. The upper stage, reaching 680 feet at Whitby, has a slight gradient above Grosmont but it is preserved in only four remnants in the lower valley and so it is difficult to decide whether this is a shoreline stage or not. The succeeding 620 feet stage is easier to interpret. It falls gently from a knickpoint on the river below Piethorn (NZ 655025) and below Grosmont the valley has a number of flats all of which have backs at a height of approximately 620 feet. The constancy of height of these flats and their position suggests that they represent a forme shoreline and the evidence is illustrated in Fig.45. On the basis of height correlation this may be Calabrian in age (Brown, 1960b). The extent of the shoreline, inland almost to Egton Bridge, explains the anomalous course of the lower Esk; at Egton Bridge it suddenly assumes a north easterly directio although the average direction along the rest of its course is due east. Th distribution of the Calabrian shoreline suggests that the sea retreated to th north east and so the Esk was extended across the emergent sea floor, forsaking its previous course which probably continued east and crossed the present coastline between Whitby and Robin Hood's Bay[1].

The 560 feet level falls gently between Grosmont and Whitby and upstream has not been traced beyond Castleton in the Esk valley. The gentle gradient of this stage suggests that the position of the associated sea level was not far from the present one.

iii) Post - Calabrian stages.

A series of stages have been detected along the valley (Fig.44) below the 560 feet stage. The first of these occurs at 460 feet at Whitby and is traceable to a knickpoint below High House (NZ 653031) and there is no trace of constancy of height in the case of the flats near Whitby which are related to this stage. The 430 feet stage is traceable to a change of

[1]At a very early stage the Esk may have flowed due eastwards to Robin Hood's Bay. The position of the breached anticline is directly in line with the middle and upper course of the Esk. Erosional 'stage' evidence for or against this possibility does not occur however. **Near Egton Bridge the Esk is now up to 1 mile south of its preglacial course and this, in addition to the junction of two valleys, explains the embayment indicated by the Calabrian shoreline (Fig 45).** **See also page 162.**

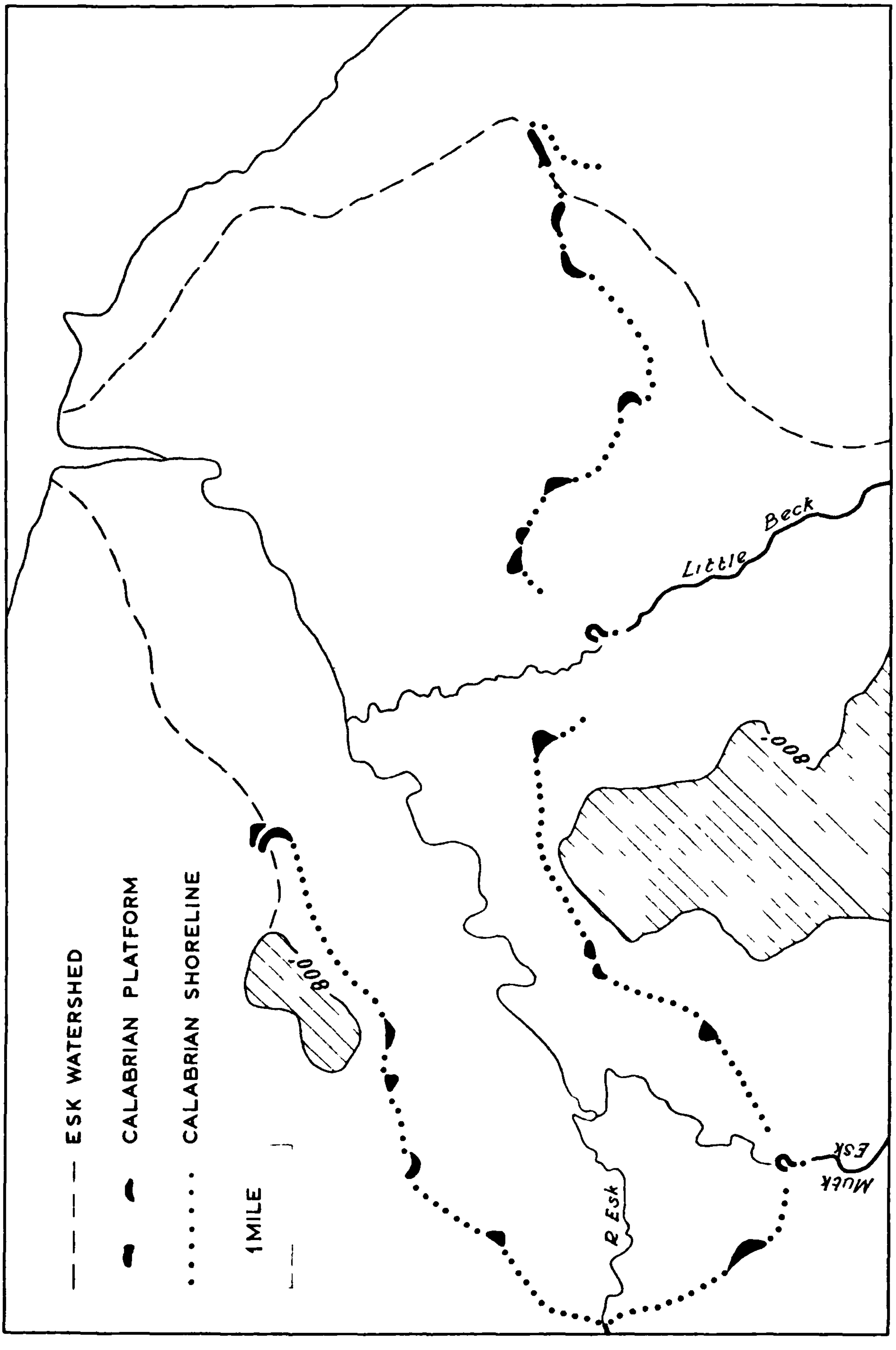


Fig 45. Remnants of the Calabrian shoreline in eastern Eskdale.

slope on the long profile (Fig.44) and near Whitby the flats maintain a constant height, with backs at 430 feet, and so these flats in the lower par of the valley may represent a shoreline at this level. The 370 feet reconstructed valley floor is traceable inland to Westerdale village. The record of flats is continuous down the valley and there is no trace of a shoreline. Between the 370 and 340 feet stages there is a well - marked level developed in the upper part of the Esk valley above Lealholm. This represents a former flat floor which has been dissected by subsequent erosio and is part of the floor of the pro - glacial lake described by Kendall in 1902. This stage is not traceable below Lealholm but is particularly well developed near Houlsyke on the north bank of the river (Fig.44).

The 340 feet stage rises up to 360 feet at Lealholm where it corresponds to a knickpoint on the long profile which is preserved on the Dogger immediately upstream from Crunkly Gill. The number of flats corresponding to this stage suggests that this is a major stage in valley development. The very gentle gradient of the reconstructed profile and the occurrence of flats at a constant height near Whitby suggests that this may be a shoreline stage.

The 285 feet stage rises to Crunkly Gill at Lealholm but correlatic cannot be made with an irregularity on the long profile in the gorge because this gorge is a glacial and post - glacial feature. However the difference between the height of the valley floor above and below the Lealholm moraine indicates that a knickpoint is probably buried beneath the moraine. The reconstructed floor falls gently and the corresponding shoreline must have been close to the position of the present one.

The succeeding 240 feet stage corresponds to a knickpoint on the river at Glaisdale, preserved on the Eller Beck Bed. The steep gradient of the reconstruction (Fig.44) suggests that this stage corresponds to a low sea level.

A discontinuous record of benches reaching Whitby at 225 feet is traceable inland to between Sleights and Grosmont but the record is then obliterated and the gradient suggests a low sea level. The 200 feet stage may be followed inland to a point just east of Glaisdale where the benches reach a height of 250 feet. Near Whitby there are a number of flats with backs at 200 feet and so this level may represent a former shoreline. The 175 feet stage is represented by a discontinuous record between Sleights and Grosmont and the gentle gradient suggests that the appropriate sea level was in a position very close to the present one. The 125 feet stage has a significant gradient, rising to 150 feet at Egton Bridge, and so may have been associated with a low sea level. The 100 feet stage is indicated by very few flats and the gently sloping gradient suggests a relatively low sea level.

iv) Post - glacial stages.

The latest stages of valley development are represented by stages which reach Whitby at 75 feet (with a knickpoint between Sleights and Grosmont), at 55 feet and by a 25 feet terrace which occurs at Whitby (a similar level was noted by Agar - 1953 - in the Tees valley). In addition to these levels a buried channel occurs below the present valley floor at a depth of 35 feet at Ruswarp (Civil Engineer, York). The buried channel is filled with gravel (1882 records) and is only 3 to 4 feet below the present one at Sleights. There must be a very appreciable gradient on this channel floor and if maintained to Whitby the floor of the buried channel should be approximately 40 feet below the present one and so the stage of development should correspond to a low glacial sea level.

2c) The chronology of the valley benches.

Attempts to establish an absolute chronology on the basis of heigh must be tentative but this is attempted in the following table:

Valley Benches of the Esk Valley.

Lowest height of stage	Lowest record at	Gradient	Shoreline or valley stage	Possible Correlatio
1140	Westerdale	Small	———	
950	Westerdale	Considerable	valley stage	
770	Westerdale	Considerable	valley stage	LATE
720	Egton Bridge	Very small	valley stage	TERTIARY
680	Whitby	Very small	possible shoreline	
620	Whitby	Very small	shoreline stage	CALABRIAN
560	Whitby	Moderate	valley stage	
460	Whitby	Considerable	valley stage	
430	Whitby	Moderate	shoreline stage	
370	Whitby	Considerable	valley stage	
340	Whitby	Very small	possible shoreline	SICILIAN
285	Whitby	Moderate	valley stage	
240	Whitby	Considerable	valley stage	
225	Whitby	Considerable	valley stage	
200	Whitby	Very small	possible shoreline	MILAZZIAN
175	Whitby	Moderate	possible shoreline	
125	Whitby	Considerable	valley stage	

Lowest height of stage	Lowest record at	Gradient	Shoreline or valley stage	Possible Correlation
100	Whitby	Considerable	valley stage	TYRHENNIAN?
75	Whitby		valley stage	
55	Whitby	Poor terrace record	valley stage	MAIN MONAST
25	Whitby		valley stage	
-40	Whitby	Considerable	valley stage	

The four factors mentioned above (2a) which should affect the interpretation of the valley benches appear to have had little or uniform effect and the degree of agreement in this glaciated area is surprising. The drainage diversions and developments may now be considered against the chronological background established by the study of the high level planation surfaces and the valley benches.

3) Drainage development.

The drainage diversions of Eskdale are of two particular types; those which occurred during the Pliocene and early Pleistocene and those whi were enforced upon the drainage system as a result of the last glaciation.

3a) Wheeldale.

The possibility of an early diversion was referred to by Reed (1901 who suggested that the present Wheeldale Gill was a tributary of the proto - Swale in the initial drainage pattern (Fig.41). The anomalous course of Wheeldale Gill is apparent but the course of Rutmoor Beck is even more striking; at first it flows south east but then turns north to flow into the Murk Esk. The tributaries of these two major streams also tend to be aligned to the south east in a way that favours the possibility of the cours of early drainage to the south east (Fig.3). These anomalous streams probably developed after the mid - Tertiary movements when the radial pattern of streams south of Eskdale was instituted. Fieldwork shows that there are several features relevant to this problem. A col on White Moor, near Blue Man - i' - the Moss is broad but shallow and has a floor at 1020 feet O.D. This col intervenes between the course of the upper Bluewath Beck and the upper part of Rutmoor Beck and it is easy to visualise a major stream connecting these three elements (Fig.46, col A). The long profile of Bluewath Beck (Fig.46) shows several valley benches in the upper part of the valley which grade down to this col. There are no further remnants at this height in the upper part of the Rutmoor Beck valley. Subsequent to the stage when upper Bluewath Beck was continuous with Rutmoor Beck and passed through the 1020 feet col (Fig.46, col A), the upper part of Bluewath Gill must have been captured by the headwaters of Bluewath Gill. In the Wheeldale Gill valley there is a well - marked valley bench which is at a height of 1000 feet in the upper part of the valley and may be traced round the present stream course.

Meanwhile the beheaded Rutmoor Beck continued to drain to the south east. A well - defined stage may be traced down Rutmoor Beck beginning at 890 feet and corresponding in height and orientation to a col on the crest of Pickering Moor at a height of 820 feet (Fig.46, Col C). Subsequently this south easterly - flowing stream must have been captured by a stream flowing north; a tributary of Wheeldale Gill. The sides of the Wheeldale Gill valley are broken by a well - marked, broad bench which is traceable down most of the south side of the valley. This occurs immediately above

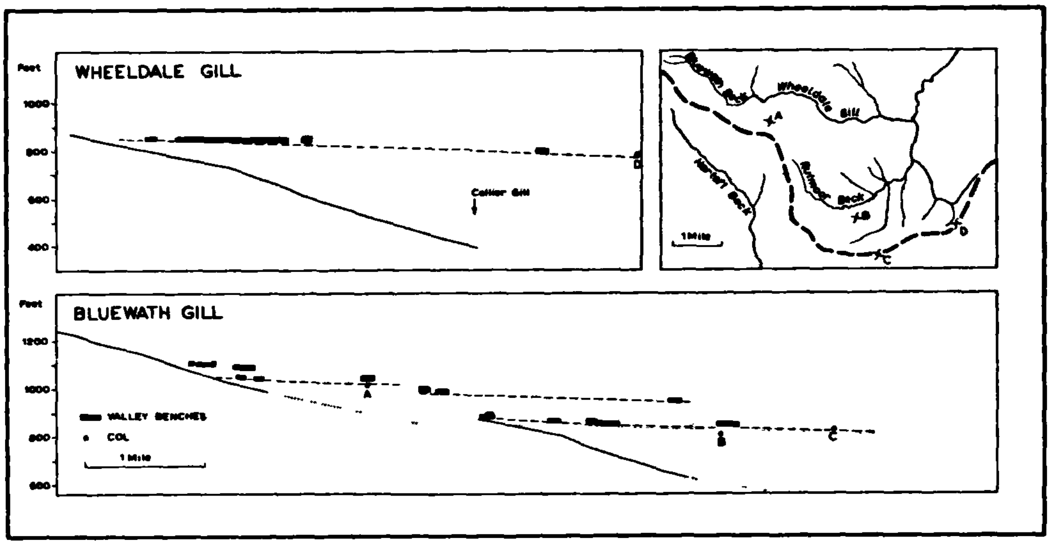


Fig 46. Valley stages and diversions in the Wheeldale Basin.

Valley floor long profiles constructed from 1:10,560 maps.

the steep incision which flanks the present river and so represents a valley floor cut prior to marked downcutting. The profile of this reconstructed valley floor agrees in height with the col on Wilden Moor at 780 feet (Fig.46 Col D). This col (D) is flanked by fairly steep slopes developed on the Cornbrash and so may have suffered lowering since the inception of the feature. In this case the break up and capture of Wheeldale Gill by a tributary of the Esk may have been contemporaneous with, or may have preceede the capture of Rutmoor Beck by the tributary of Wheeldale Gill. The sequenc of events corresponds to the heights of the planation surfaces considered above (Section 1c). The two major south - easterly flowing streams initiall would be Bluewath Beck - Rutmoor Beck and Wheeldale Gill and this situation persisted until the end of the upper part of the Low Moor Surface stage. Th first capture, by Wheeldale Gill, was effected at the end of this stage and resulted in the capture of the upper part of Bluewath Beck. The remainder o Rutmoor Beck continued to flow south eastwards and the enlarged Wheeldale Gil developed further until the end of the lower part of the Low Moor Surface stage when the middle part of Rutmoor Beck was captured. Wheeldale Gill itself was also captured, at a height of 800 feet, at this time.

The first capture occurred between two stages of landscape development and so possibly the greater gradient of Wheeldale was the motivating factor. A contributing cause must have been the resistance to erosion of the Moor Grit - Grey Limestone outcrop, across which the Rutmoor Beck - Bluewath Beck stream flowed while the Wheeldale Gill valley had reached the more easily eroded shales of the upper part of the Middle Deltaic Series. The capture of Wheeldale Gill by a tributary of the Esk may be ascribed to several factors. The capture occurred towards the end of the Low Moor Surface stage and just prior to incision in the Wheeldale Gill valley. The Sleights anticline (Fig.42) would have been breached at this time and the easily eroded Upper Lias shales revealed, replacing the comparatively resistant Dogger and Lower Deltaic Series. Thirdly the distance to the coast would have been less via the Esk thus giving the steeper gradient required to contribute towards the capture. The proposed sequence of events in Wheeldal is illustrated in Fig.46.

3b) Vale of Goathland.

The eastern side of the Vale of Goathland includes several anomalou drainage diversions on a smaller scale. These include the south western - flowing streams of Brocka Beck, Sliving Sike and Little Eller Beck. The directional trend of these streams suggests, like Wheeldale, that the Esk watershed was formerly further north than it is today. Brocka Beck must have been captured first, probably at the 800 feet stage, paralleled by the capture of the middle of Rutmoor Beck by Wheeldale Gill further west (Cols B and C abandoned in Fig.46). The other two drainage elements (i.e. Sliving Sike and Little Eller Beck) appear to have drained to the south until the las glaciation when meltwater cut Newton Dale and drainage was extended towards and across the ice during the later stages of deglaciation. Newton Dale occurs in a broad, former valley floor at Fen Bogs Houses and this must represent the floor which Little Eller Beck and Sliving Sike occupied until the incidence of the last glaciation.

3c) Danby Dale.

The upper portion of Danby Dale is narrow in width but, at the northern end, towards Castleton, the dale broadens and the 'Howe' occurs as an outlier at the end of the dale, interposed between the true floor of the dale to the west and the higher drift - covered area to the east. Henry (1956) suggested that the Howe originally separated Danby Dale from a second, smaller dale to the east. He contends that capture is not involved. The long profile and valley benches are indicated in Fig.47 and each of the stages shown corresponds to an appropriate stage in the Esk valley just below Castleton. The occurrence of valley benches in the two areas suggests that stage D (Fig.47) is the relevant one. Reconstruction of the Dogger outcrop at this stage indicates that Danby Dale was then being developed over a breached inlier of Liassic rocks eroded more easily than the Deltaic rocks above. The stream which existed to the east of Danby Beck, although smaller was able to breach the valley side of Danby Dale, partly as a result of stream incision and partly reflecting the broadening of the Dogger outcrop as the extent of the outcrop of the Lias increased with the development of Danby Dale. The breach in the valley side slope on the eastern side of Danby Dale ultimately realised the isolation of the Howe as an outlier. If the process had continued the smaller stream may have extended headwards, to capture Danby Beck, but this was precluded by the incidence of glaciation which placed a dam of 60 feet of sand and gravel at Ainthorp, thus obstructing the former valley and fossilising Danby Howe.

3d) <u>Western Eskdale.</u>

A further series of drainage diversions is suggested by the courses of Baysdale Beck, the upper Esk, Tower Beck, Sleddale Beck, the river Leven and Lounsdale (Fig.3). In the present pattern Lounsdale is a tributary to a

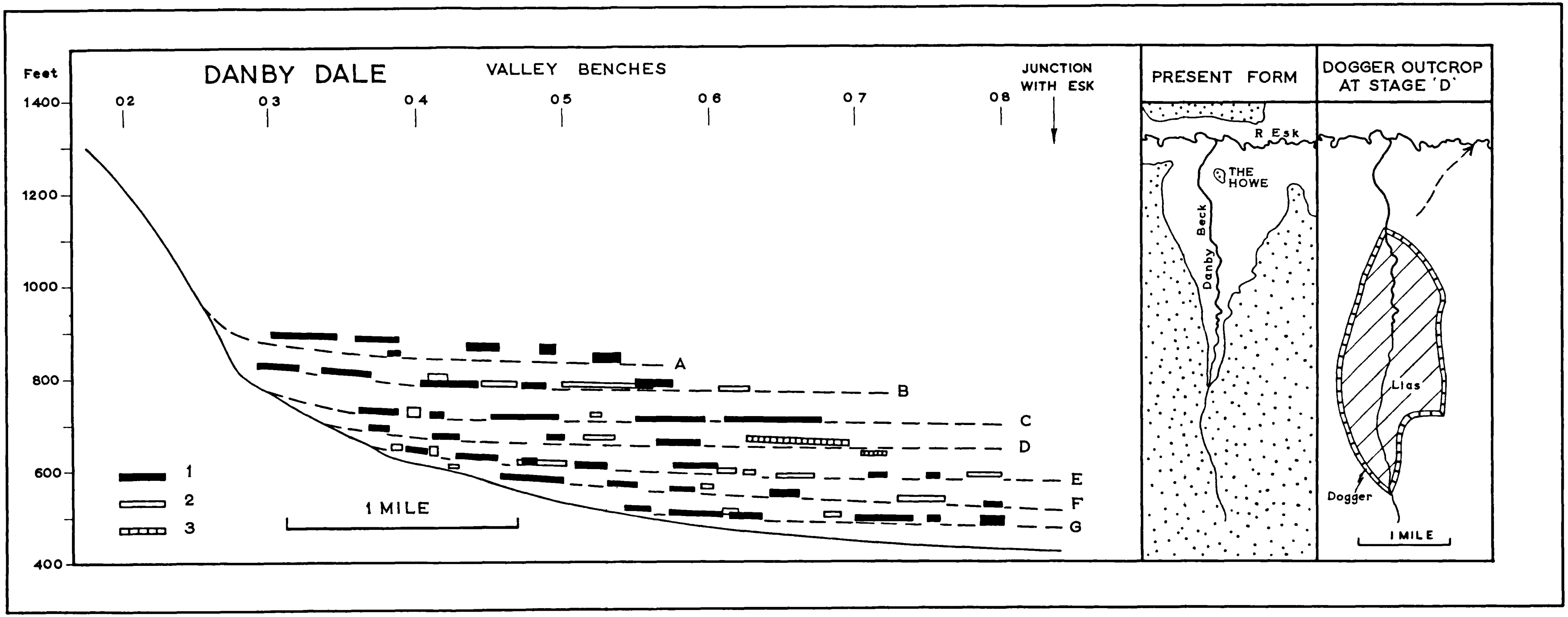


Fig 47. Valley stages in Danby Dale.

the Leven and this latter river flows north east in its upper course before turning west to Kildale. The orientation of streams suggests that the upper Leven and Lounsdale must originally have flowed into the Esk drainage system. Kendall (1902) attributed the diversion of the Leven to the production of a "bridge delta or 'corrom" across the intervening area but the diversion of Lounsdale, although referred to (Henry, 1956), has not been analysed in detail.

Reconstruction of the former drainage pattern must be based largely upon drainage alignment because the col on Kildale Moor, at 945 feet, is well above any valley benches which occur in Sleddale Beck valley and so the exact time of drainage diversion cannot be determined. The inherited proto - Esk probably flowed approximately along the line of the present west - east section of Baysdale Beck. The head of this major stream was composed of the upper Tees and the central portion was represented by the present middle course of the Leven. The col on Warren Moor at 1020 feet would afford a suitable point of entry into the present Eskdale system but possible lowering of the col as a result of the recession of the main Cleveland escarpment must be borne in mind during examination of the development of this part of the drainage system. Even if the upper part of the Swale represented the headwaters of the proto - Esk (Versey, 1942), the main stream would presumabl have followed the Baysdale course rather than a more tortuous one along the present course of Sleddale and Commondale Becks.

The early course of the Esk, thought to have been through the col on Warren Moor, followed a due easterly direction. It was joined by Sleddal Beck through the col on Kempswithen and Commondale Beck was quite distinct at this stage. The long profiles of the relevant streams were constructed using the 6 inch maps and the valley benches in each of the valleys shown (Fig.48). Each of the long profiles is drawn, or extended, to the position of Stitch Hill (NZ 636097); the point at which Sleddale changes from a south easterly to an easterly course. The valley benches of Sleddale occur in three groups (A,B,C, in Fig.48). The height range diagram for the Lounsdale valley shows that the valley developed in at least four major stag and the first two of these (A1 and B1 in Fig.48) correspond to appropriate stages (A and B) on the long profile of Sleddale Beck. The col, interposed between Lounsdale and Sleddale drainage, has a floor at 720 feet and marks the stage of capture of Lounsdale by a westward - flowing stream. Stages D and E in the development of Lounsdale show a more gentle gradient and these must represent development after capture. The Leven has three lines of reconstructed valley floors (A2, B2, C2 in Fig.48) and each of these corresponds to stages (A,B,C) of the Sleddale Beck valley at Stitch Hill. The Baysdale long profile (Fig.48) shows the complete succession of valley stage along the length of the river as far as the junction with the Esk. The upper two levels (F and G) each have a col on the reconstructed profile; the higher one (F in Fig.48) has a col at 1020 feet representing the last stage at which the Esk rose further westwards and the lower one (G in Fig.48 represents the col through which Sleddale Beck was formerly confluent with the Esk over Warren Moor.

The succeeding valley stages are well - documented in Baysdale (Fig.48) and are all related to valley stages in the main Esk valley as follows:

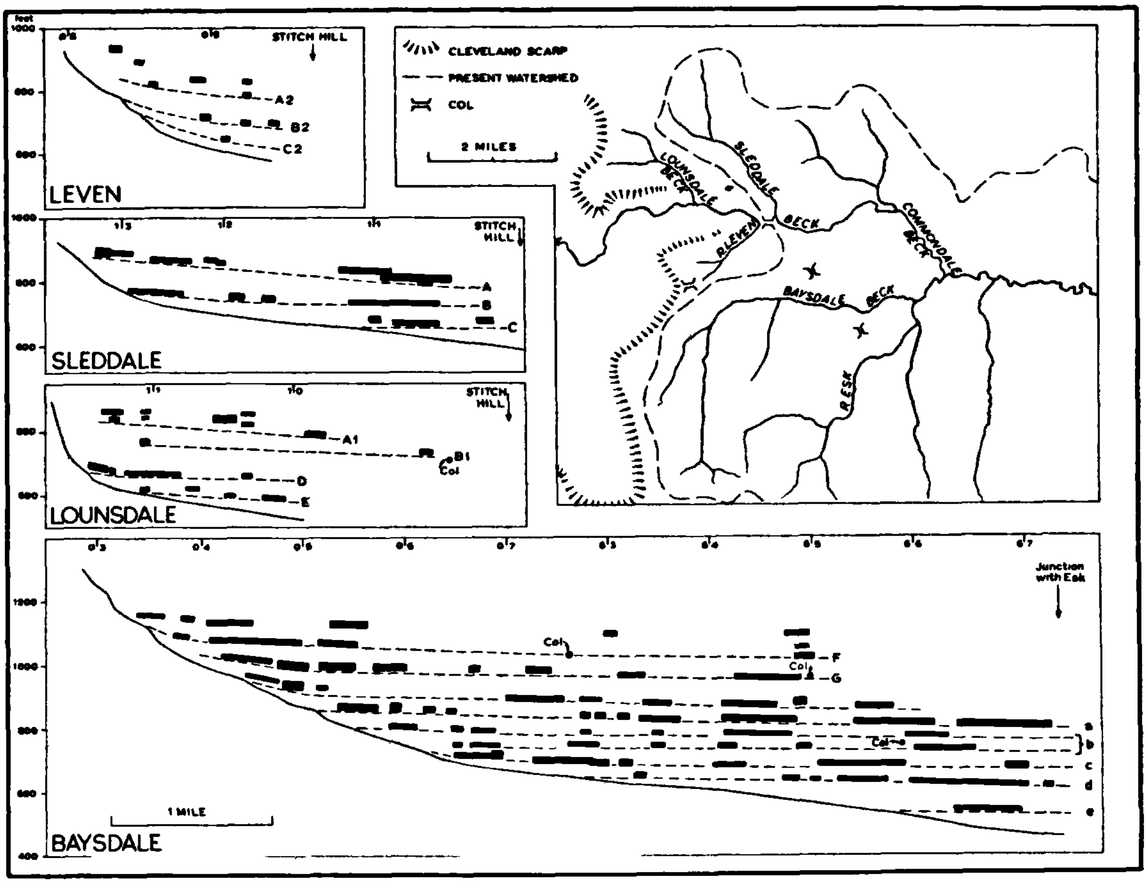


Fig 48. Valley stages and diversions in western Eskdale.

Valley floor long profiles constructed from 1:10,560 maps.

Stage a	corresponds with the	720 feet at Whitby
b		680 feet
c		620 feet
d		560 feet
e		430 feet

Along the Baysdale Beck valley there are two stages corresponding with one which represents the 680 feet stage in the main Esk valley (stage b in Fig. 48). Intervening between these two stages is a col on Kempswithen through which the Esk formerly flowed.

There are three main phases of drainage modification in the western part of Eskdale. The first occurred at the end of the upper part of the Low Moor Surface stage, the second at the end of the Low Moor Surface stage (770 feet) and then a series of readjustments occurred during the cutting of valley stages related to the Calabrian sea levels. A final, fourth, stage of evolution was represented by the diversion of the Leven and the minor diversion of Commondale Beck round the Scale Foot moraine (Chapter 7). The reasons for this series of captures appear to stem mainly from the changes of base level imposed at the end of each planation surface stage but the detailed explanation in each case must reflect the pattern of geological outcrops exposed by the downcutting of various streams. The early course of Sleddale Beck, during the Low Moor Surface stage and earlier, would have followed a course across the resistant Moor Grit - Grey Limestone. At the end of the upper part of the Low Moor Surface stage Commondale Beck would have cut down to the upper part of the Middle Deltaic Series and so the decreased resistance to erosion would facilitate the capture of the upper part of Sleddale Beck by Commondale Beck. The course of Lounsdale was into the Esk until stage B1 (Fig.48). The successive portions of valley development all have a gentle gradient and this may be due to the fact that a more proximate shoreline allowed the westward - flowing stream to capture the headwaters of Lounsdale Beck. In this context it is notable that the Vale o York must have been developed, in some form, prior to the Calabrian transgres sion and a shoreline may exist round the margin of the North York Moors. It influence upon the course of the lower Esk near Whitby has already been noted (Fig.45) and if it also occurs on the southern side of the North York Moors i would explain the rather anomalous courses of the southward - flowing streams over the Corallian, including the Severn. If the Calabrian transgression extended even part of the way up the Vale of York the streams draining to it would facilitate the capture of Lounsdale Beck. This problem is linked with that of the recession of the Cleveland escarpment and the col at 1020 feet, plotted on the Baysdale long profile (Fig.48), shows that the Esk did not ris very far to the west of Baysdale Abbey after the end of the upper part of the Low Moor Surface stage.

3e) Conclusion.

The series of drainage diversions in Eskdale has led to a considerable modification of the outline of the drainage basin. In all cases the drainage changes are referable to the end of a major planation stage and so tentative maps showing the evolution of the drainage basin framework may be produced (Fig.49). The end of the first part of the Low Moor Surface stage (a) showed the Esk flowing well to the south of its present course in Eastern Eskdale and it was supported by a series of tributaries flowing down the dip

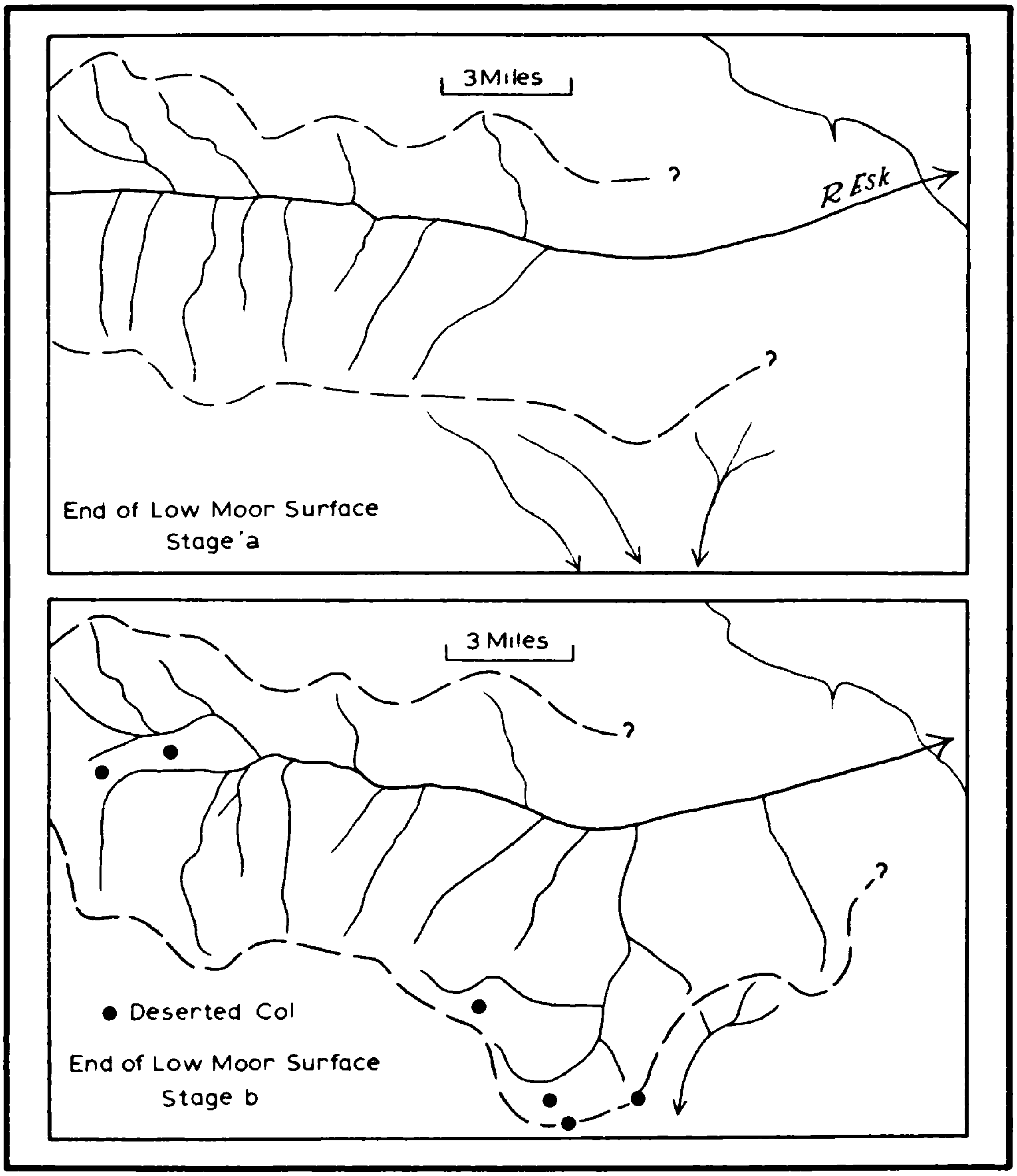


Fig 49. The evolution of the drainage pattern.

to the south bank of the river and fewer streams flowing south east to join the north bank of the river. Rutmoor Beck, Wheeldale Gill and Little Eller Beck all followed courses generally south eastwards. The end of the Low Moor Surface stage at 750 feet saw the development of Sleddale Beck, captured by Commondale Beck, and the development of Rutmoor Beck and Wheeldale Gill as tributaries of the Murk Esk. Subsequently the north easterly - orientated course of the Esk between Grosmont and Whitby occurred as a result of the Calabrian transgression. The final chapter in the story of drainage develop ment was introduced by glaciation which led to the capture of the Leven, the capture of Little Eller Beck and also modified the valley pattern by the introduction of steep - sided gorges and drift - filled valleys.

4) Relative slope.

The criterion of relative slope was devised to give an index of the flatness of a facet. Angle of slope is determined by a variety of factors a illustrated in Chapters 4, 5 and 7 but it is possible that broad, general groups of slope angles exist representing different types of flat. When dealing with stage evidence some other workers have used particular slope angles as criteria for the definition of flats and others have used a relatio ship between the angle of slope of a particular facet and those of the bounding slopes. Macar (1955, p.255) accepted flats with a slope angle (calculate from contour maps) equal to or less than ½ of the angle of slope of the bounding slopes. If variation does occur between flats of different types the variations in the index of relative slope will be determined by the slope of the bounding facets rather than merely that of the slope itself (see Fig.6 An altiplanation terrace may have the same angle of slope on the flat as a high level planation surface but the bounding angles will be significantly higher in the former case and so the degree of definition of the flats (i.e. their relative slope) will differ.

Satisfactory conclusions regarding the criterion of relative slope will only be possible after a thorough analysis but a preliminary examination was effected in Section 6a of the main program (Appendix 3). This gives the areal extent of flats with specific values of relative slope in particular height ranges. An obvious disadvantage of the method is that, as a result of the restrictive number of punch cards used, only five groups of relative slope could be recognised. The five groups considered were relative slope values of 0 to 0.09, 0.1 to 0.19, 0.2 to 0.29, 0.3 to 0.39 and 0.4 and above. Significant groups of relative slope may be disguised by these five categorie and the use of 100 feet height groupings (in Fig.50) adds a further generalisation. However, the size of the sample dictates the manipulations which may be achieved and the present analysis is considered to be valid as a preliminary test. The percentage of flats contained in the sample area according to relative slope is shown in Table 10.

Table 10. The percentage area of flats according to relative slope categories.

Relative slope	Percentage of flats included
less than 0.1	5.7%
0.1 to 0.19	26.7%
0.2 to 0.29	32.5%
0.3 to 0.39	23.4%
0.4 and above	13.1%

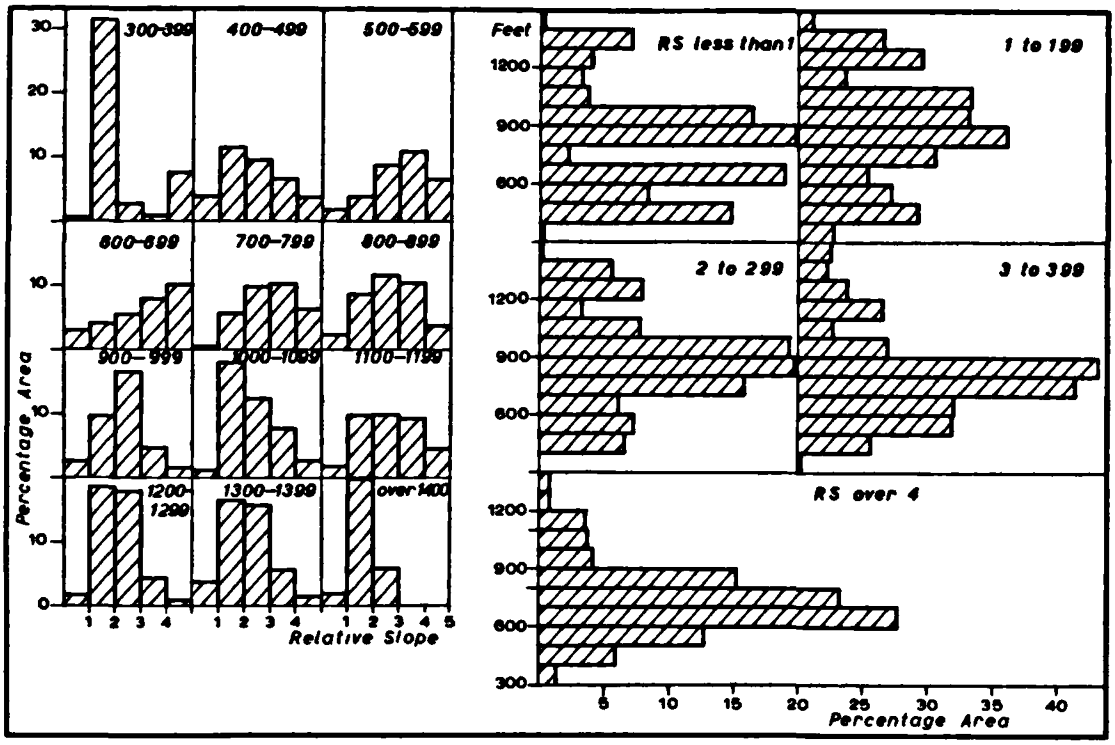


Fig 50. Relative slope.

A more detailed and extensive scheme of analysis would allow a program to be devised in which sorting was first effected according to origin (planation surface, valley bench, altiplanation terrace etc.) and then relative slope could be examined for each of these types to consider the variation between each one and also to examine the variation with height. The percentage number of flats in each of the relative slope groups was calculated for four types of flats which occur frequently in the sample area and the results are expressed in Table 11.

Table 11. Relative slope populations for different types of flat facets.

Relative slope	High Level Planation surfaces	Altiplanation Terraces	Flood Plain	Valley Benches
Less than 0.1	10.7%	4.6%	44.4%	9.9%
0.1 to 0.19	34.0%	11.4%	22.2%	31.8%
0.2 to 0.29	39.8%	36.4%	14.8%	37.1%
0.3 to 0.39	13.6%	25.0%	14.8%	14.4%
0.4 and above	1.9%	22.7%	3.7%	6.8%
Mean value	.197	.300	.153	.221

The values for each of the four types of flats (Table 11) arrange themselves in a normal distribution suggesting that there is a gradation of relative slope with various factors. Relative slope values between .2 and .3 are most common on planation surfaces, altiplanation terraces and valley benches but the flood plain type of flat is characteristically represented by a group with a relative slope value less than .1. There is a high percentage of relative slope values of less than .3 on the planation surfaces (84.5%) and many of the higher relative slope values are found on planation surface remnants below 850 feet. Altiplanation terraces have a significant proportion of relative slope values above .3 (47.7%) reflecting the higher angles of slope developed on these flat facets. The relative slope values for the valley benches are similar to those of the planation surfaces and the flood plain facets are mainly characterised by very low relative slope values (81.4% less than .3) suggesting a marked degree of definition.

The information derived from mechanical analysis may be expressed in two ways (Fig.50). The different values for relative slope, plotted for 12 height groups show a series of distributions, all of which are unimodal except the first group representing the area between 300 and 400 feet. The form of the distributions varies considerably with height as a result of the reasons noted above (Chapter 4, Section 3). Between 300 and 400 feet the distribution is characterised by two peaks, the lower one representing well - defined erosion stages in the lower part of Glaisdale and the higher group reflecting a number of less well - defined flats on the surface of the Glaisdale moraine. Between 500 and 900 feet, higher values of relative slop are common whereas above 900 feet, where the form of the facets is primarily determined by the distribution of planation surfaces, the lower relative slop values predominate. The poorly - defined facets, particularly between 500 and 800 feet (R.S. values characteristically between .3 and .4 or greater than .4) reflects the large number of high angle flats and the effect of glacial interference. Above 800 feet and below 1100 feet the number of well - defined flats corresponds to the Low Moor Surface but between 1100 and 1200 feet the facets which do occur as flats have significantly higher relative slope values as a result of the major break between the High and Low

Moor Surfaces. The distributions corresponding to the High Moor Surface (1200 to 1400 feet) are rather different from those representing the Low Moor Surface. This salient difference may be a morphological reflection of the differing origin and development of the two surfaces (Chapter 6, Section 1). Relative slope values above 1400 feet are all very low and this reflec the pronounced definition of the summit surface to which almost all the flat at this height belong.

The information may also be plotted according to relative slope values (Fig.50). This also illustrates the points noted above and emphasis the distinction between the High and Low Moor Surfaces. Relative slope values greater than .4 are particularly common between 600 and 900 feet and to a certain extent this must reflect the effects of glaciation and periglaciation upon an existing framework of flats and slopes. In many cases the cold phases of the Pleistocene were responsible for increasing the angles of slope on the flat and slope facets between 600 and 900 feet (Chapter 7, Sections 2a and 2b). At higher levels (above 1200 feet especially) the existing pattern of facets may have been initially rather different and the planation surfaces more extensive but it is probable that the periglacial modifying processes were not so active at this height and removal of weathered material would not be accomplished so easily.as angles of slope are small.

5) Conclusion. The emergence of the landscape anatomy and the development of flats.

The methods used in the interpretation of flats in Eskdale include morphological mapping, cartographic analysis and height determination and to a certain extent these are complimentary. The efficacy of the methods of cartographic analysis (Fig.37) is surprising but the possibilities of the use of morphological mapping in the interpretation of 'stage' evidence are numerous. Flats on valley sides may be interpreted as relics of former valley floors and in many cases traced along the entire length of the valley using changes and breaks of slope between the definite flats. This is possible because breaks and changes of slope are seldom eliminated completely but merely modified. The use of these methods allows the emergence of the topographic and geological 'island' of the North York Moors to be traced. The initial drainage was developed on an easterly - dipping Cretaceous surface and ultimately an early Tertiary planation surface must have been produced. This surface was warped and in late Tertiary times, after the mid - Tertiary movements, three distinct planation surfaces were produced and of these, the upper two may be distinguished from the lower one on morphological grounds using the criterion of relative slope. The Esk must have been captured by the present Tees - Leven at least during the High Moor Surface stage, if not earlier; the evidence in Eskdale does not allow more precise dating than this. After the capture of the upper part of the proto - Esk the North York Moors developed as an island and during the Calabrian stage a shoreline extended up the lower Esk valley to Grosmont and led to the north easterly diversion of the river at Grosmont. The Calabrian shoreline may also have extended up the Vale of York, as this would be the most plausible reason to explain the capture of Lounsdale by the Leven from the Eskdale system of drainage. The early and mid - Tertiary landscape development of of Eskdale was as the lower or middle section of a major eastward - flowing river but subsequent development has given a landscape of much greater relief as a result of the beheading of the proto - Esk and the Pleistocene sea level variations. During these sea level changes other modifications were being made to the Eskdale landscape and these will be considered in the next chapter.

CHAPTER 7.

CHANGES OF CLIMATE AND THE ESKDALE SCENE.

The late Tertiary may have seen a substantial change in climate as conditions became cooler during the Pliocene but the Quaternary period, punctuated by the incidence of glaciations, led to far more significant variations in climate. These are firmly imprinted upon the Eskdale landscape by the direct effects of glaciation with associated landforms and also by the indirect effects which led to increased valley cutting and development. The changes of climate will be considered under the headings of glaciation, periglaciation, post - glacial processes and finally an analysis of the result of a micro - climatic difference which resulted in an intensification of mass movement phenomena between 1960 and 1961 will be made.

1) Glaciation

The glacial deposits of Cleveland have been studied by several authors but no generally accepted explanation exists regarding their correlation and dating. Radge (1939) contended that a sequence of five elements could be recognised in the glacial succession; a high level blue clay (weathered with occasional boulders), a low level blue clay (more recent than the high level type), a red boulder clay which may be correlated with the Hessle of south east Yorkshire, sands and gravels with intercalated laminated clay and occasionally red boulder clay, and finally the lower brown boulder clay and gravels shown only in borings. Bisat (1939) suggested a two - fold division of the deposits into the upper Purple Series and a lower Drab Series and he concluded that the break between the two was not sufficient for an interglacial and that the Basement Clay is part of the 'Newer Drift'. Penny (1958), dealing with an area to the south of the North York Moors, assigns all the deposits to the last glaciation with the exception of scattered deposits found at high levels on the Wolds and on the Pennines. Occasional deposits have been noted on the summits of the North York Moors (Elgee, 1912; Hemingway, 1958) and these may represent the relics of an older glaciation. A final assessment of the glacial sequence in North East Yorkshire must await studies of the succession of drifts, their constitution and extent when a correlation may be made with the sequence established further south. The deposits in fossil ice wedges in the North York Moors to the south of Eskdale may indicate an earlier glaciation (Dimbleby, 1952).

The glacial features of eastern Eskdale are all related and freshly preserved and so may be assigned to the last glaciation in this area. A masterly exposition of the 'Glacial Lakes of the Cleveland Hills' by P.F.Kendall in 1902 placed the interpretation of the sequence of glaciation and deglaciation in the North York Moors on a firm basis. Kendall showed that the glacial deposits include erratics of western (Pennine and Shap), northern (Cheviot) and eastern (Scandinavian) origin (Kendall, 1903a, p.2). Using the criteria of glacial lake strandlines, deltas, glacial lake deposits and overflow channels, a sequence of glacial retreat was established which distinguished up to five stages of ice - margin recession with a minor readvance in some cases. This method of interpretation was adopted to elucidate the sequence of glacial retreat in other parts of Britain and remained unchallenged until after 1945. Recent work, both in areas of contemporary glaciation and in regions which were glaciated during the

Pleistocene, has shown that not all glacial drainage channels were initiated as marginal features. Furthermore, the comparative rarity of shoreline features and the alternative interpretation of the laminated clays have been advanced as criticisms of the original explanation (Sissons, 1960b, 1961). To consider the deglaciation of Eskdale the area will be subdivided into three parts; Eastern, Central and Western. Eastern Eskdale contains considerable amounts of drift and a large number of glacial features, central Eskdale was described by Kendall (1902) as the area formerly covered by a pro glacial lake and western Eskdale included part of the glacial lake but the present work has shown the situation there to have been rather more complex.

1a) Eastern Eskdale.

To elucidate the probable nature of deglaciation all ice - marginal features have been mapped and related to other glacial features (Fig.55). Erosional features include glacial drainage channels, ice - marginal benches, twin parallel streams and gorges; depositional features include moraines, kame terraces and lobe edge embankments.

(i) Glacial drainage channels. Those features first described as 'furrows on an aged cheek where tears have ceased to flow' (Belcher, 1836) were called overflow channels by Kendall (1902, p.480). This term implies overflow from a lake but in this part of the North York Moors it has been found that very few channels were cut by water immediately after leaving a lake. In most, if not all, cases the water flowed at the ice margin where it was supplemented by meltwater and acquired a load of superglacial and englacial material derived from ablation of the ice. Alternative terms for overflow channel include the American term spillway which was adopted by

Drehwald (1955, p.2) but this suggests water derived exclusively from a lake Meltwater channel suggests water derived solely from ice melt (Common, 1957) The broader term, glacial drainage channel, will be adopted as the most satisfactory (Sissons, 1958a). Glacial drainage channels are usually broad dry depressions which may have an infilling of peat and an anomalous course (Fig.56a).

Kendall (1902, p.481) divided glacial drainage channels into two main types; marginal and direct. Marginal channels were thought to have originated parallel, and usually adjacent to the ice margin. Direct channels, such as Newton Dale, were cut across a watershed independently of the line of the ice margin, to drain water away from a pro - glacial lake. Inspection shows that the direct channels are of greater complexity than the marginal ones and so a detailed study of eight of the Eskdale channels includes seven of the direct type.

Transverse sections were taken across each of the selected channels (Fig.55, Channels, 1 - 6, 15, 24) at intervals of 110 yards. For each cross section the height of the centre of the channel and the top of each side was measured using a compensated surveying aneroid. Where irregularities on either the floor of the sides of the channel occurred the heights of these were also determined. For each channel all heights were measured at least twice. The slope angle of the channel sides was measured with a tape and three or more borings made through the peat to ascertain the depth of the solid rock and the extent and character of superficial deposits. Previous studies of the morphology of glacial drainage channels have involved the use of more precise levelling methods

(Peel, 1949; Twidale, 1956) but an aneroid, combined with angular measureme was chosen to enable more channels to be studied.

The transverse profiles plotted for each channel illustrate the depth and nature of the infill, the form of the channel floor and also the benches which occur on the sides of some of the channels (Fig.52). Almost all the transverse sections show an infilling of peat. This reaches a maximum depth of 18 feet in Ewe Crag Slack where the peat covers a thin veneer of clay resting on the solid bedrock. The sand and gravel deposits are well - rounded and are confined to the floor of the channel and so they must have been deposited during the latest stage of channel development (Fig.52, Sections 2 & 3). Clay infill is white - grey in colour, very tenacious and more common in occurrence than either the sand or the gravel. It contains small boulders but there is no trace of stratification. This clay occurs frequently in Ewe Crag Slack and also in Moss Slack (Fig.53). In other channels the clay occurs below the steepest slopes, particularly at the junction of two channels. At the junction of Hardale Slack and Hardale Beck it is sufficiently thick to produce a distinct terrace (Fig.52, Section K). The clay always occurs below the peat indicating that it accumulated prior to peat formation. The absence of stratification in the deposit favours a solifluction origin and this is supported by its occurrence below the steepest slopes and particularly below those facing north and nort east.

The lower parts of the transverse sections of the channels vary in form. In some cases the floor is flat and attains a considerable width (Fig.52, Section 2; Fig.53, Sections 1 & 2), but in others the profile is

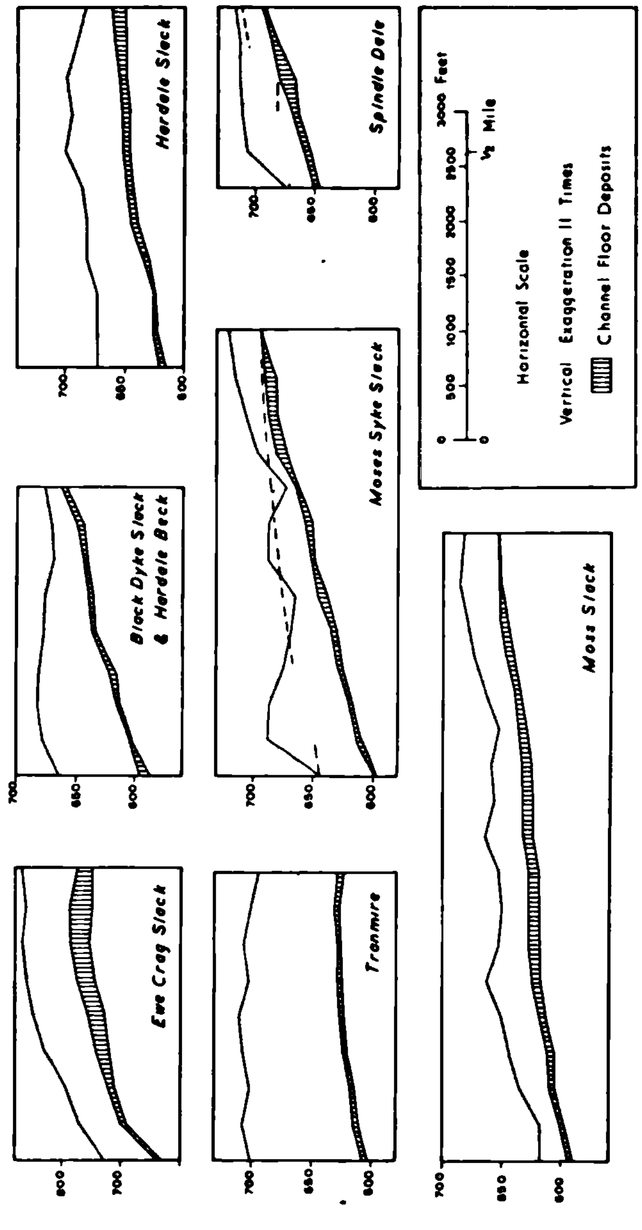


Fig 51. Long profiles of glacial drainage channels.

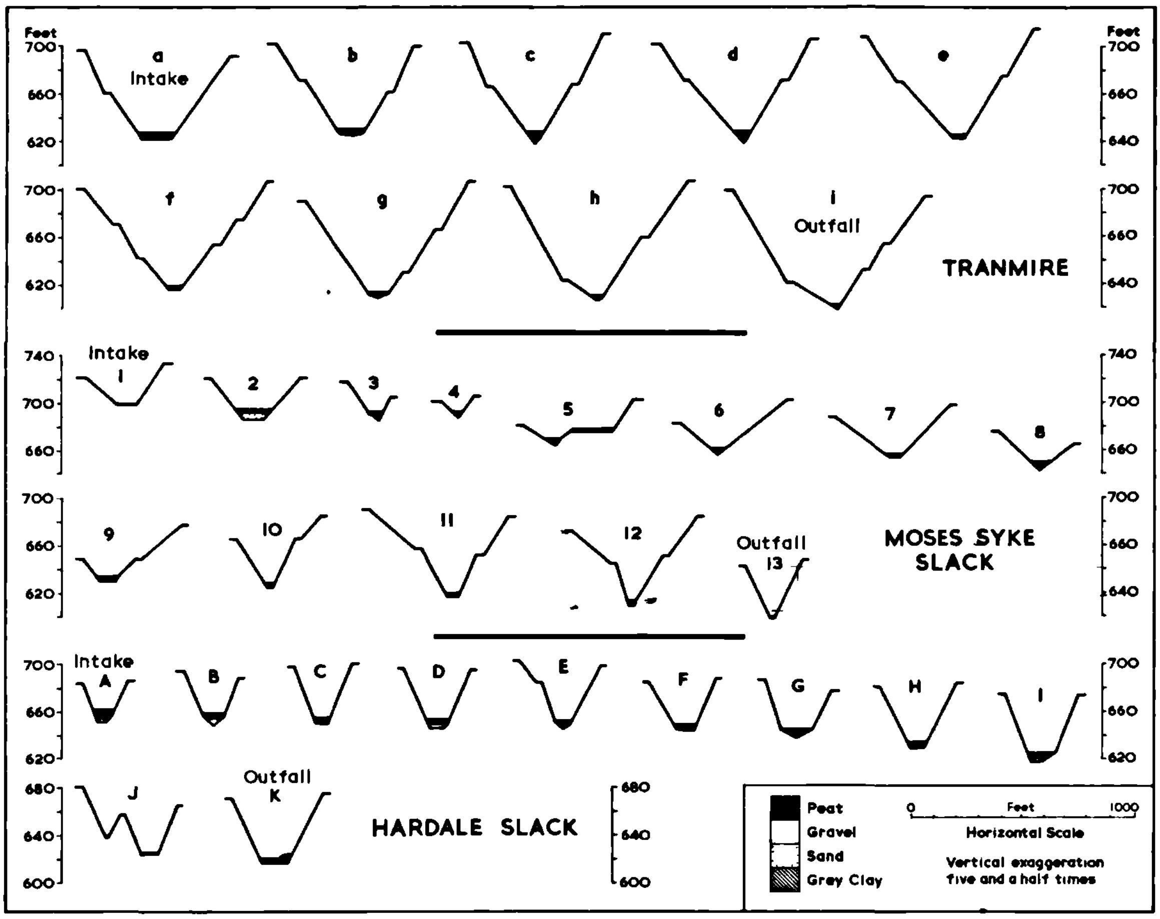


Fig 52. Transverse profiles for three Eskdale glacial drainage channels.

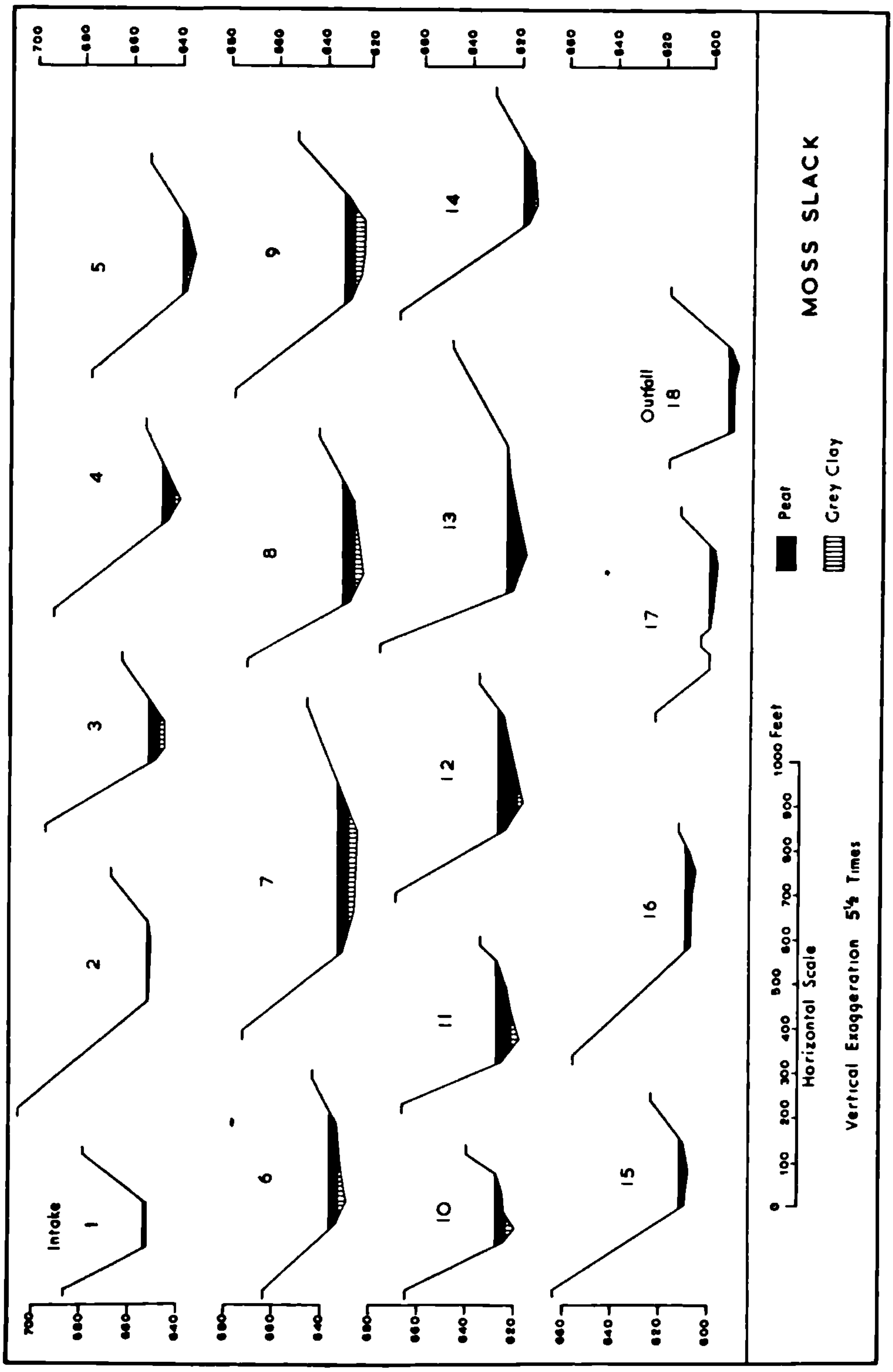

MOSS SLACK
Intake
Outfall
Peat
Grey Clay
Horizontal Scale
1000 Feet
Vertical Exaggeration 5¼ Times

Fig 53

V - shaped. These two types have previously been described in different parts of the Beldon Channel, Northumberland (Peel, 1949). In Eskdale a further type also occurs where a flat channel floor has been dissected by a smaller, V - shaped channel (Fig.52, Section 3; Fig.53, Section 16). In Moses Syke Slack the V - shaped portion must have been eroded prior to the deposition of the sand which rests in it. In cross sections of other Eskdale channels solifluction clay occupies the V - shaped portion and so the latter is thought to represent the last stage in the development of the channel when a very small stream persisted for a short time as a result of a decreasing supply of drainage to the main channel.

Prominent on the cross sections of Tranmire, Moses Syke Slack, Spindle Dale and Hardale Beck are narrow, channel - side benches (Fig.52). Only in the case of Tranmire is there any possibility of structural control in the channel sides, but even there the boundaries of the benches do not coincide with those of the Cornbrash as mapped by the Geological Survey. Moses Syke Slack has a series of benches which, when joined together, form a profile similar to that of the present floor. This reconstructed profile extrapolates to the outfall of the present channel at approximately 650 feet O.D. A more fragmented series of benches occurs at a slightly lower level in the same channel and, if extrapolated, would grade down to a height of 625 feet O.D. (Fig.51). Tranmire contains two groups of benches; the lowest grades down to 625 feet O.D. and the higher one would reach the vicinity of the present outfall at 655 feet O.D. The upper profile has a hump in it much further downstream than that on the present channel floor. These channel side benches are thought to be remnants of former channel floors.

The longitudinal profile of each channel was plotted (Fig.51) and they show a general upward convexity. Two of them have a 'hump profile' (Peel, 1949) and in both cases the hump section occurs very near to the intake end. A subdivision of each bedrock long profile into a series of steeper segments separated by portions with a much gentler slope is evident, although many of these irregularities are masked by the later floor infillin The bedrock long profile of Spindle Dale shows a marked flattening approximately half way along the length of the channel (Fig.51). When the flattenings on each of the long profiles of channels at the head of Stonegate are extrapolated to the present outfall there is a marked accordance of outfall heights and the different portions would grade down to heights of 650, 625 and 615 feet O.D. In the case of Moss Slack, there are two such flattening along the long profile.

Origin of the Stonegate Channels. The channel side benches are thought to be remnants of former channel floors and the irregularities on the long profiles also indicate that channel development occurred in stages. Immediately south of Tranmire (NZ 770107) three stages are indicated by the evidence from the channels and so water must have drained through the channels to the ice margin during three stages at outfall heights of 680, 650 and 625 feet O.D. At the head of the Stonegate valley there are two groups of ice - marginal features, including kame terraces, and these correspond to the lower two stages of channel development. Thus drainage through the channels must have been draining to and round the ice margin at the head of Stonegate during these two stages.

Two of the long profiles (Fig.51) show a hump profile. This profile is anomalous in that the highest point is not at the intake and but along the length of the profile. The hump profile was first noted by Kendall (1903b, p.40) and tentatively ascribed to reversal of flow. This hypothesis was later applied to two Northumberland channels (Peel, 1949) but in the Stonegate valley the two groups of ice - marginal features fall in one direction only. An alternative explanation is afforded by post - glaci erosion but this has been very slight in the channels studied and undisturb superficial deposits cover the floors of the channels. The two Northumberland channels have subsequently been explained on the basis of subglacial stream erosion (Sissons, 1958b) and contemporary glaciological study has shown that subglacial streams may flow uphill under hydrostatic pressure.

The two channels having a hump profile in Eskdale (Ewe Crag Slack and Tranmire - Fig.51; Fig.55, Channels 24 and 3) breach the same pre - glacial watershed and so a hump must have existed immediately before channel development. As a hump occurs in the present profiles the channels must have developed either completely or partly as subglacial features. The two later stages of the development of Tranmire correspond with ice- marginal features at the head of the Stonegate valley and hence this channel, at least, must have developed partly subglacially and partly sub - aerially. The channel was initiated by a subglacial stream and thinning of the ice sheet exposed the channel between two ice margins, and one of these - that o the Stonegate ice - retreated more rapidly than the other owing to separatio from the main mass of ice. This mode of origin of compound channels is illustrated in Fig.54. In the case of Tranmire the sequence of development was complete but in other cases (Fig.55, Channels, 17, 18) the channel

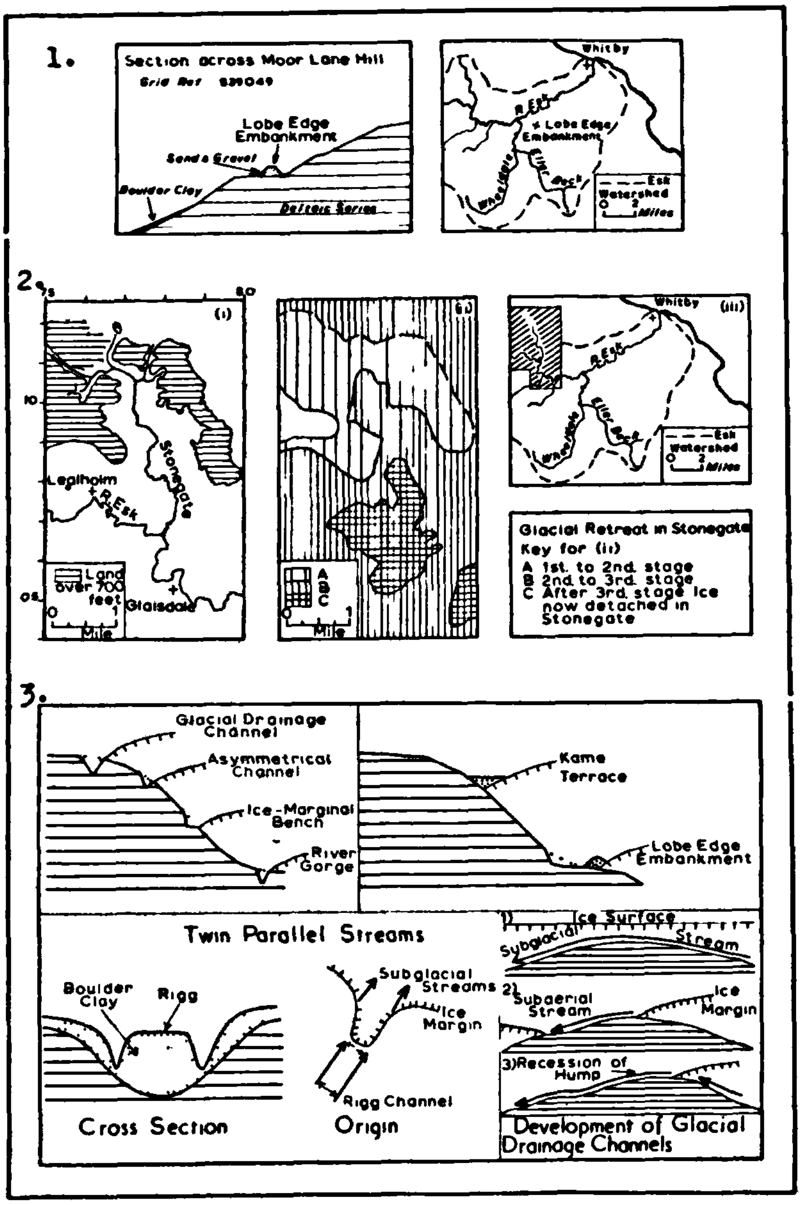


Fig 54. Glacial features in Eskdale:

1. Lobe edge embankment
2. The decay of ice in the Stonegate area
3. The origin of twin parallel streams, glacial drainage channels and ice - marginal benches.

initiated by subglacial stream erosion was abandoned very soon after it was exposed by downwasting of the ice.

<u>Other types of glacial drainage channels.</u> There is a fundamental distinction between those channels developed independently of the line of the ice margin and those developed parallel to it. Marginal drainage channels often occur interspersed with ice - marginal benches, both of which are observed to pass into kame terraces and other marginal features. Throughout eastern Eskdale the occurrence of glacial drainage channels or ice - marginal benches was determined by the slope of the ground before each retreat stage. From the geomorphological map it is apparent that ice - marginal benches were cut where the slope was greater than 2½ degrees. Where the angle was less than this glacial drainage channels developed. This explains the occurrence of glacial drainage channels above the main valley side slope (Fig.54), illustrated by Moss Swang and Randay Mire at Goathland. The present river gorges of Eskdale were, in some cases, initiated marginal to the ice and in these cases, including Crunkly Gill north of the Lealholm moraine, the slope near the top of the gorge never exceeds 4 degrees. On a slope with an angle between 3 and 5 degrees an ice - marginal bench would be formed first and this could later be developed into an asymmetrical channel (Fig.54).

Glacial drainage channels sometimes show abandoned ox - bow features and to these Kendall gave the name in and out channel. He suggested that they could be attributed either to erosion round a projecting lobe of ice or to a local readvance which caused a diversion of the marginal drainage (1903a p.11). The abandoned channel frequently hangs above the floor of the main channel. The three Eskdale examples which occur along Hardale Slack (Fig.52

Section J), along Moss Slack (Fig.53, Section 17) and along Moss Swang (Fig.5 Channel 13) have one common characteristic; they occur on the right bank of the channel near, or at, the outfall. Castle Hill, which separates the in and out channel from Moss Swang, has a bench round it at a height of 630 feet O.D. and this is continuous with the floor of the in and out channel. This suggests that the main channel and the abandoned feature were developed simultaneously until a floor level common to both was attained during a peri of ice - marginal stability. The heights of the floor of the Hardale in and out channel and the top of the isolated hill coincide with periods of stability in the development of the Hardale Slack channel. On the basis of this evidence it is suggested that the abondoned channels developed near the outfall between two phases of ice - marginal stability. During the latest stage of channel erosion, when the amount of water flowing through the channel was diminished, the in and out channel was deserted.

In many cases glacial drainage channels operated through more than one period of ice - marginal stability. A strictly marginal channel developed adjacent to the ice margin but a slight retreat of the margin caused a decrease in the amount of water flowing through the channel. In the cases of Moss Swang and Randay Mire (Fig.55, Channels 13, 14) an ice - marginal bench occurs parallel to the channel but at a lower level on the si of the Murk Esk valley. During the early stages of channel cutting all marginal drainage was flowing through the channel but subsequently the channe was deepened contemporaneously with the formation of an ice - marginal bench. The gradual fall of the ice margin accounts for the multicyclic long profile of Moss Slack (Fig.51). The ultimate stage in the development of the channe

Key to Fig 55 (continued)

5. Spindle Dale
6. Hardale Slack
7. Sunny Brake Slack
8. Glaisdale Rigg
9. Butter Park
10. Lady Bridge Slack
11. Purse Dyke Slack
12. Hollins Channel
13. Moss Swang
14. Randay Mere
15. Moss Slack
15a. Goathland Church Channel
16. Newton Dale
17. Barton Howl
   Middle Carr Slack
   Nigh Middle Slack
18. Aislaby Channels
19. May Becks Channels
20. Biller Howe Channel
21. Highcliff Gate
22. Bold Venture
23. Cribdale Gate
24. Ewe Crag Slack
25. Chimo Channel

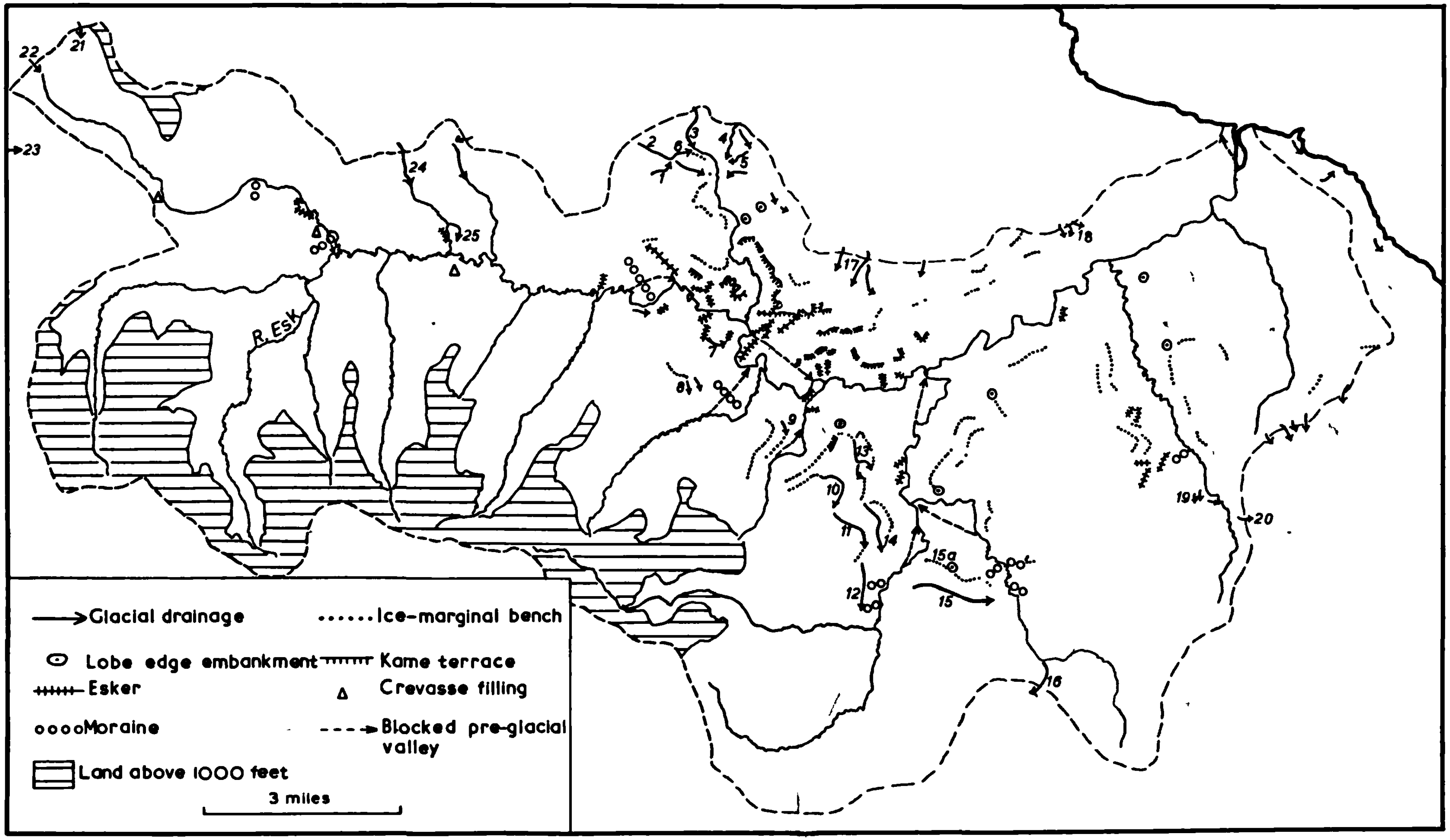


Fig 55. The glacial features of Eskdale.

The major line of glacial drainage, marked by channels, are numbered.

1. Black Dyke Slack
2. Hardale Slack
3. Tranmire
4. Moses Syke Slack (key opposite)

was the incision of a small channel into the major one as noted above.

There are two other types of channel which have been noted in eastern Eskdale. The lowest series of ice - marginal benches and glacial drainage channels are short and intermittent. They do not correspond in height and are related to small channels leading downslope, interpreted as subglacial chutes (Mannerfelt, 1945). This type of channel or ice - margina bench was sub - marginal in origin; drainage flowed along the ice margin for a short distance and then flowed into the ice. Examples of this type occur along the south side of the Esk valley between Grosmont and Sleights and also on the western side of Little Beck valley (Fig.55).

Sunny Brake Slack (Fig.55, Channel 7) was described as an in and out channel by Kendall (1902, p.483). This channel, although short in length, has a hump profile and so could not be ice - marginal, especially as the hump occurs almost exactly half - way along the channel floor. As shown below (Section ix), ice thinned in the Stonegate valley and became detached from the ice north of the Eskdale watershed and in the lower Esk valley. Thus if Sunny Brake Slack was developed as a marginal feature it would have been developed by a marginal stream flowing round a mass of ice no more than 100 feet thick. Flint has suggested that in North America 150 feet may be a limiting thickness for stagnant ice formation (Flint, 1942). The incidence of eskers in this part of Eskdale shows that the residual mass of ice was passive and so marginal channels of the magnitude of Sunny Brake Slack could not be formed. Eskers occur near both the intake and outfall ends of this channel and the relationship to two gorges lower down Eskdale suggests that Sunny Brake Slack was part of a major subglacial stream system.

This system may first have been confined in a tunnel but as the ice was detached and thinning rapidly the stream probably later flowed in an ice - walled channel (Gravenor and Kupsch, 1959).

(ii) Ice - Marginal Benches. Where the slope of the ground exceeded 3 degrees prior to a retreat stage an ice - marginal bench may have been eroded at the ice margin. These features are one - sided channels and may be recognised on the basis of their pronounced definition, lateral slope and relationship to other marginal features. The magnitude of an ice - marginal bench reflects three major factors; the duration of the particular ice - marginal position, the volume of meltwater flowing near the ice margin and also the detailed nature of the slope of the ground before each retreat stage. These features are seldom continuous and become intermittent at lower levels as a result of increasing subglacial drainage with continued deglaciation.

(iii) River gorges. Kendall (1902, p.481) ascribed many of the gorges of Eskdale to diversion by ice, of drainage from an existing course. Where the slope of the ground was less than 4 degrees a channel would be cut at the ice margin and this could be deepened post - glacially into a river gorge. Crunkly Gill, which occurs on the south side of the Lealholm moraine is an excellent example. East Arnecliff Gorge (NZ 786050) is a much broader feature and the morphology suggests a more complex history. At each end of the East Arnecliff gorge is an esker, tributary to the line of the gorge. If the gorge had been initiated ice - marginally the eskers would have been destroyed as the active ice margin retreated. Ice downwasted in Stonegate, as shown below (Section ix), and when the margin reached the line of this gorge the ice would not have been of sufficient thickness to control a line of ice - marginal development. Therefore the gorge must have been initiated subglacially; the depth alone, up to 350 feet, indicates that a substantial part must have been eroded before, or during, the last glacial retreat. The subglacial element in the development of certain gorges has been discussed by Tricart (1960).

(iv) Twin parallel streams. Twin parallel streams are a unique feature of this part of the Yorkshire coast; a plug of drift occupies the centre of a pre - glacial valley and two streams at present flow on each side of this 'rigg'. Fox - Strangways first referred to these features and ascribed them to post - glacial erosion at the junction of the solid rock and boulder clay (1892). In many cases boulder clay is not confined to the central rigg (Fig.54). A later worker (Henry, 1956) has suggested that the twin parallel stream courses developed as ice - marginal drainage channels and some were adopted and deepened post - glacially. It can now be demonstrated that recession of the ice margin occurred at right angles to the direction of flow of the streams whereas this theory (Henry, 1956) would require them to flow parallel to the ice margin.

The rigg is always lower in height than the sides of the main valle and often has a small channel, a rigg channel, cut across it. An example occurs east of Rigg Mill Beck (NZ 913072). Occasionally a kame terrace occurs on the rigg instead of the rigg channel (e.g. NZ 818058) and this suggests that the ice margin must have crossed the rigg during the development of the twin parallel stream system. Ice - marginal features, although intermittent, may be traced round the sides of the valley and correlated with the rigg channel. The twin parallel streams would therefore develop marginal to a lobe of ice extending up a pre - glacial valley and, as the ice was fragmented, they would be continued into or onto the ice sheet (Fig.54).

(v) Kame Terraces. A kame terrace (Fig.54) is a constructional feature formed between the ice and a hillside slope by deposition of sand and gravel in a marginal position (Flint, 1957, p.149). There is great variation in the size of these features in Eskdale. The largest examples occur near the junction of Stonegate and the Esk valley, in Egton Banks (Fig.56c) and also on the opposite (western) side of Stonegate. Downstream from the outfall of the Stonegate channels (Fig.55, Channels 1 - 6) the marginal drainage was erosive for about ½ mile but this was followed by deposition giving kame terraces. The ice - contact faces of the kame terraces have angles of slope up to 30 degrees and this slope is characterised by great irregularity; partly a reflection of the form of an ice - contact slope and partly the result of more recent slipping of unconsolidated material on a high angle slope.

One of the most striking features of the kame terraces is that they are dissected by **coombe** - like features; dry valleys with steep sides (up to 20 degrees) and a steep headwall. Similar crenulate margins have been recorded in New England (Flint, 1929) and described as a direct reflection of the original form of the ice margin. The Eskdale examples have all the features of a water - worn valley and yet are generally independent of the present drainage system. This latter characteristic seems to preclude the possibility of post - glacial dissection. Towards the end of the retreat stage during which the kame terrace developed the ice was more susceptible to the development of englacial and superglacial streams and so marginal melt-water was subtracted in subglacial channels, dissecting the kame terrace. West of Glaisdale, eskers occur in association with the kame terraces.

(vi) Lobe edge embankments. A lobe edge embankment was described by Logan (1945) as a depositional feature of the ice margin. The feature is a mound of semi - stratified sand and gravel deposited adjacent to the margin of a lobe of the ice sheet (Fig.56b). In Eskdale there are two types of feature which may be described by this term. The first, as originally described, results from deposition at the ice margin and may be distinguished from a kame terrace as the marginal channel still persists (Fig.54). On the eastern side of Stonegate, at the head of the valley, there is an example of this type (Fig.55). The second type, of more common occurrence, is partly erosional and partly depositional. Erosion occurred first at the ice margin and was later replaced by deposition and so a lobe edge embankment occurs in conjunction with an ice - marginal bench. This is illustrated by the exampl at Fairhead, near Grosmont (Fig.54 and Fig.56b).

(vii) Moraines. There are three types of moraine in Eskdale which indicate stable positions of the ice margin. The largest, illustrated by the major terminal moraines of Glaisdale and Lealholm, are associated with stages in deglaciation in the main valleys. The counterparts of these on the steeper hillside slopes comprise a second group and are much smaller features occurring only where there was no appreciable marginal drainage. They often occur in groups and since they were deposited have been dissected by water flowing downslope towards the retreating ice margin. Examples of this type occur between Goathland and Moss Slack (NZ 824005) and also near

Fig 56a. Black Dyke Slack glacial drainage channel

Fig 56b. Lobe Edge embankment (NZ 839048)

Fig 56c. Kame Terrace at southern end of Stonegate

(NZ 785069)

Good Goose Thorn (NZ 747112). The latter example is multiple; between eacl dissected morainic ridge there is a marginal channel. The third type of moraine isaalso terminal in origin, in a valley, but as a result of either the duration of the retreat stage or the constricted form of the existing valley, no river course could be developed round the edge of the moraine and sustained post - glacially, as in the case at the head of the Little Beck valley (Fig.55). These moraines are small in size and do not possess the regular form characteristic of the other two types.

(viii) Eskers. Throughout eastern Eskdale there are several examples of ridges of sand and gravel which have a freshly preserved form, are flat - topped and steep - sided, sometimes with slope angles up to 30 degrees. The trends of the ridges varies; some run directly across the valley as at Glaisdale, some trend obliquely down the valley side slope as between Glaisdale and Lealholm on the north side of the Esk valley, while others have a course directly downslope as in the two examples on the west side of Iburndale (Fig.55). These features could not have been formed in active ice or at an active ice margin because the trend of the features varies so much that they could not all be consistently in line with the direction of ice movement. Furthermore the freshly preserved form, with slope angles up to 30 degrees, could not have been maintained. These features are interpreted as subglacially engorged eskers which were formed by deposition of material in tunnels in the stagnant ice. The largest example, which crosses the Esk valley at Glaisdale, has recently been noted by Sissons (1961).

(ix) Deglaciation. The maximum extension of the ice in Eskdale may have been beyond the line of the outermost marginal features. This possibility has been discussed with special reference to North East Yorkshire by Hollingworth (1952) who suggested that at the climax of the last glaciation snow may have accumulated at the ice margin, presenting a surface concave upwards. The ice - marginal features would then begin to develop only with climatic amelioration. Alternatively it has been suggested that the snow line would not reach down to the maximum position of the ice in the area and so the outermost marginal features could reflect the maximum extension of the ice (Linton, 1952). In the Goathland area, no drift has been discovered on the moor above Lady Bridge Slack (Fig.55, Channel 10) and above the highest channels small altiplanation terraces, the product of intense periglacial activity occur (Fig.59). If the ice did extend beyond the outermost features it was probably very thin.

Throughout eastern Eskdale ice - marginal features are well - preserved at higher levels but become more intermittent and are difficult to relate at lower levels. Eskers occur in the valleys and are related to the lowest ice - marginal features. This general pattern shows that ice downwasted throughout the area with marginal drainage producing ice - marginal features during the early stages but continued downwasting led to the complete stagnation of the ice. This increasing stagnation is reflected in the incidence of eskers (Fig.55).

In the upper part of the Stonegate valley the evidence from the glacial drainage channels and from the marginal features indicates a series of minor stages in the downwasting with marginal drainage grading down to heights of 680, 650 and 625 feet O.D. near Red Mires Farm (NZ 770107). At the latest of these three stages the ice margin had reached Stonegate gill. This gorge was established prior to the complete stagnation of the ice which would occur when the mass of ice was detached from that in the Esk valley (Fig.54). Black Dyke Slack (Fig.55, Channel 1 and Fig.56a) was initiated by meltwaters at the beginning of downwasting and Hardale Slack and Trannire (Fig.55, Channels 2,3,6) were initiated subglacially. As the thinning of the ice progressed Black Dyke Slack would lose the supply of meltwater and would cease to function whilst the other two channels continued to drain the area between the two ice masses; i.e. one mass to the north of the Eskdale watershed and one in Stonegate and Eskdale. This explains the nature of Black Dyke Slack 'hanging' above the main channel. Moses Syke Slack and Spindle Dale (Fig.55, Channels 4,5) were also initiated subglacially and continued as sub - aerial features. Trannire is the best developed channel; it shows evidence of development during three stages and so must have operated for the longest period of time.

In the lower Stonegate valley and the Esk valley between Glaisdale and Lealholm ice - marginal benches and kame terraces occur at higher levels and small esker ridges occur on the lower slopes. Some of the eskers stem from the lower group of kame terraces suggesting that marginal drainage may occur, if only intermittently, with stagnant ice conditions. Eskers are not always indicative of stagnant ice conditions (Flint, 1942) but these examples are all orientated in such a way that they could not have developed if the ice was still in motion. After two stages of dominantly ice - marginal drainage, the ice in this area was detached from the main mass and so must have become stagnant (Fig.54). Drainage was now dominantly subglacial and a major subglacial stream system developed with a main artery initiating Sunny Brake Slack and Oak Scar gorge (NZ 778056) and developing East Arneclif gorge. The series of small eskers were developed in tunnels tributary to this major line of drainage.

The Vale of Goathland contains two lines of marginal features and the first of these includes Lady Bridge Slack, Purse Dyke Slack and Hollins channel (Fig.55, Channels 10, 11, 12). The intake and outfall heights of these channels show a progressive fall to the south. The channels have gradients ranging from .7 to 1.5 per 100 and this accords with gradients noted for strictly marginal channels in Scandinavia (Mannerfelt, 1949). The Hollins channel must have been abandoned before Purse Dyke Slack and Lady Bridge Slack continued to function when both of the others had been deserted. A subglacial chute occurs between Lady Bridge Slack and Purse Dyke Slack and there is a second example between Purse Dyke Slack and Hollins channel. These features are channels at right angles to the line of marginal drainage. The successive abandonment of the marginal channels was a result of the opening of these subglacial chutes rather than a reflection of major recessions of the ice margin. The succeeding position of the ice margin is well documented by Moss Swang and Randay Mire (Fig.55, Channels 13,14). During the first stage of their development Moss Swang, Castle Hill channel and Randay Mire were eroded simultaneously and ice - marginal benches continue between the channels. Moss Swang was the last channel to operate. There are considerable accumulations of gravel at the outfall ends of both Moss Swang and Randay Mire which represent material derived from the channel and deposited on the surface of the ice.

A small lake occupied the Wheeldale valley during the early stages of deglaciation as Kendall suggested, and this is reflected by narrow flats at heights of 600 and 650 feet O.D. From the details of the operating heigh of the channels (Table 11a) it is apparent that Lady Bridge Slack, Purse Dyke Slack and Hollins channel formed the first line of marginal drainage grading down to 655 feet O.D. and this drainage was carried through Moss Slack (Fig.55, Channel 15) from Lake Wheeldale towards Newton Dale. The highest lake bench of Wheeldale would be formed at this time and the lower example would be formed during the next stage of marginal drainage through Moss Swang and Randay Mire. During the second stage of drainage the outlet of Lake Wheeldale was through the Goathland Church channel (Fig.55, Channel 15a) towards Newton Dale. These two positions of the ice margin can be correlated with moraines in each of the Wheeldale and Eller Beck valleys. Subglacially engorged eskers occur in the northern part of the area representing the final disintegration of the ice. Subsequent to the second stage of marginal drainage Newton Dale was abandoned; the ice was now fragmented and so alternative outlets were available.

In the Egton Grange valley drained by Butter Beck, ice - marginal features are traceable round the sides of the valley (Fig.55). The ice downwasted until approximately half of the valley was occupied by ice but subsequently subglacial drainage became dominant and this is reflected by two small subglacially engorged eskers which occur near the outlet of the valley.

Table 11a. Operating heights of glacial drainage channels in Eskdale.

Channel	Number on Fig.55	Intake		Outfall	
		Initial	Present	Initial	Present
Lady Bridge Slack	10	750 feet	720 feet	715 feet	680 feet O.D.
Purse Dyke Slack	11	735	705	675	650
Hollins	12	725	700	685	655
Moss Swang	13	630	570	615	540
Castle Hill		700	620	685	625
Randay Mire	14	650	570	620	540
Moss Slack	15	690	660	615	575
Goathland Church channel	15a	540	520	535	510
Newton Dale	16	610	500		

At the head of Iburndale (Little Beck) there is a series of channels and moraines indicating the first stage of marginal drainage from two small lakes at the head of the Dale (Fig.55, Channels, 19,20). Biller Howe channel (20) was abandoned when the intake height reached 665 feet O.D. and subsequent drainage must have flowed northwards. The channels crossing the watershed east of Iburndale into Robin Hood's Bay were initiated subglacially and carrie meltwater during the disintegration of the ice. Three groups of marginal features occur in the Little Beck valley, but it is significant that small eskers occur in the upper and middle sections of the dale suggesting that complete stagnation occurred relatively earlier than in the other areas considered.

The main Esk valley between Egton Bridge and Whitby shows two lines of marginal drainage marked on the valley side slopes. The first of these two stages includes the small channels crossing the watershed above Aislaby (Fig.55, Channel 18). On the south side of the Esk valley the outlet of the marginal drainage during the later stages of ice dissipation must have been to the south and a series of marginal features, some truncated by the present cliff line, can be found between the watershed and the coast.

(x) Deglaciation in Eastern Eskdale. A recent general study of glacial drainage channels (Sissons, 1961) referred to glacial features near Glaisdale and concluded that ice downwasted in that area. However, as shown above, ice in Stonegate ultimately became detached from the main mass in the lower Esk valley and so this cannot necessarily be taken as typical of the whole of eastern Eskdale. Kendall (1903a, p.24) suggested that the ice margin retreated actively towards the north and east but from the distribution and relationship of glacial drainage channels, other ice - marginal features and subglacially engorged eskers it is now concluded that there were two major stages of deglaciation followed by stagnation of the ice mass. The two major stages recognised in the Goathland area do not necessarily correspond to the three stages recognised at the head of Stonegate and any reconstruction of former ice gradients (Mannerfelt, 1949) can only be tentative because the Goathland channels are not strictly parallel to the major line of ice advance. There are no strictly marginal channels at the head of Stonegate which might also be used to relate the Goathland and Stonegate sequences. Using the gradient of the outermost line of marginal features at Goathland as an indication it seems likely that the second of the major stages at Goathland corresponds to the three minor stages recognised at the head of Stonegate. This is confirmed by the fact that Moss Swang, Castle Hill channel and Randay Mire developed in three minor stages as noted above (Section (i)). The intermittent marginal features and the incidence of eskers indicates that ice was stagnant throughout eastern Eskdale after this stage of drainage at Goathland.

The continuous mass of North Sea ice which covered eastern Eskdale, at the maximum of the last glaciation separated, as a result of thinning, into three lobes branching from the main sheet; one in Newton Mulgrave to the north, one in the Robin Hood's Bay area to the south and one in Eskdale. After the two stages of marginal drainage glacial drainage became predominantl subglacial and the major subglacial stream system of Lealholm to Glaisdale was probably continued down the Esk valley from East Arnecliff gorge and initiated the minor gorge sections, including the striking gorge near Whitby Harbour. The ice would become progressively more fragmented during dissipation and so the antecedents of the post - glacial drainage system would be established before the ice finally disappeared. The significance of relief and 'the form of the ground' emerges from this study as a major factor in deglaciation; controlling the morphology and distribution of the glacial features and also explaining the thinning of the ice into three lobes stemming from the main sheet.

1b) Central Eskdale.

Central Eskdale extends from the Lealholm moraine to Castleton and includes broad, flat - floored valleys possessing few glacial features.

Kendall thought that glacial lake Eskdale occurred in this area but several problems arise from this interpretation. The evidence for the existence of a pro - glacial lake included the occurrence of very fine laminated clay, deltas and standlines. Kendall also quoted the evidence of overflow channel but as shown above glacial drainage channels are not always marginal in origin.

There are comparatively few glacial features in this part of Eskdal and so the evidence upon which Kendall's interpretation rests will be discussed and then some new evidence offered.

(i) The laminated clay was cited by Kendall as a glacial lake deposit but in other areas similar clays have been interpreted as undermelt deposits arising from deposition of material contained between shear planes in stagnant ice (Carruthers, 1953). Observation of the laminated clay led Canon Atkinson to suggest the former existence of a lake in Eskdale (Atkinson 1891, p.395). The clay was noted at Danby brick and tile works and near Ainthorp bridge (Fox Strangways, 1888) but few other records of its occurrenc exist. At Danby the possible existence of 60 feet of clay has been recorded (Fox Strangways, 1888) and yet there is no trace of the deposit in Danby Dale Westerdale or Baysdale. If a lake, with a maximum level at approximately 750 feet O.D. had existed it is difficult to understand why a great thickness of sediment should occur in one area and little or none elsewhere. Immediately east of Danby Howe there is a mass of sand and fine gravel in a ridge - form which must be glacial in origin and yet is difficult to explain as the bottom deposit of a pro - glacial lake.

(ii) The delta quoted by Kendall for this area (1902, p.521) is the one which occurs at the end of Ewe Crag Slack but the irregular structure of this deposit and its distribution along the valley side is rather anomalou The distribution suggests that the deposition was controlled by a more definite barrier than the shoreline of a lake. Below Black Beck Swang and above Clither Beck (NZ 702100) there is a second 'deltaic' deposit of sand and gravel which is stratified but does not extend below 700 feet. This also extends round the valley side rather than down the valley side slope. At Hell Hole, Commondale, there is a ridge extending across the valley and this was described as a deltaic feature by Kendall (1903a, p.14) but there is a difference in level between the valley floor and the top of the ridge on both sides and the river has cut a gorge round the ridge. This ridge is more typical of a well - developed moraine than a delta.

(iii) Strandlines were described on the north side of the Esk valley between Castleton and Danby (Kendall, 1903a, p.15) but the two features described both correspond to stages in the development of the valley traced on the long profile. In this case the valley benches may have been further developed as lake strandlines but there are no other examples of such features in central Eskdale at the same height.

(iv) Other glacial features. Several features occur in central Eskdale which were not mentioned by Kendall and many of these are not consistent with the theory of a pro - glacial lake. Ewe Crag Slack (Fig.55, Channel 24), a major glacial drainage channel, trenching the northern watershed of Eskdale was described as a direct overflow channel by Kendall (1902, p.521). This channel has a hump profile (Fig.51) and so must have developed at least in part as a subglacial feature. The irregular distribution of the various glacial deposits in central Eskdale has already been noted and it is significant that these are restricted in area, very variable in thickness and the laminated clay may be confined to very small localised areas. The strean at present draining from Ewe Crag Slack joins the river Esk at Danby. Approximately half way along its course it changes from a south-easterly to a southerly direction although there is a deep abandoned channel directly in line with the upper course (Fig.55, Channel 25). This channel (NZ 709089) is a feature containing some drift on the sides and on the floor, is broadly V - shaped and approximately 60 feet deep. The floor of the channel is only 60 feet above the present level of the river Esk at Danby and so the feature could not be ice - marginal in origin even if the location rendered this possible. Furthermore the channel must be the result of glaciation in the area; it has a freshly preserved form and no reason other than glaciation could be invoked to explain why the present stream abandoned the channel to cut a narrow gorge. If the area was covered by a lake it is difficult, if not impossible, to envisage the development of this erosional feature under the surface of the lake.

On the opposite (western) side of this stream below Hollin Top (NZ 706089) there is a narrow - crested, steep - sided ridge of sand and gravel which follows a sinuous course towards the floor of Eskdale. This ridge is similar in form to the subglacially engorged eskers of eastern Eskdale and is directly in line with the outfall from Ewe Crag Slack. The freshly preserved form shows that it has not been substantially modified since it was formed. If, therefore, a glacial lake did exist it must have preceded the formation of this feature. Eskers do not always reflect the presence of stagnant ice (Flint, 1942) but this example is located at a very low level or the floor of the dale and could not have been formed at the ice margin during active retreat. Therefore the feature is considered to be a subglacially engorged esker which represents the subglacial deposition of material derived from Ewe Crag Slack. A second ridge, similar in form but smaller in size, occurs between Houlsyke and the Lealholm moraine. This feature, although small, is composed of stratified sand of varying coarseness and is similar in form to the eskers of eastern Eskdale. The comparative rarity of such subglacially engorged eskers in this part of the valley must arise from the fact that there were few large streams entering the area during the maximum and early stages of deglaciation. A further feature of glacial origin is Creak Hill; an isolated hill of sand and clay which occurs on the south side of the Esk at Ainthorp (NZ 708078). This feature is not more than 70 feet above the valley floor and so must be a subglacial feature - it is similar in form and situation to the crevasse filling noted in western Eskdale (Section 1c below).

The evidence collected above (Fig.55) is all contrary to the idea of a pro - glacial lake and suggests the former presence of stagnant ice. The floor of Central Eskdale, sometimes underlain by 50 feet of superficial material, must have been built up prior to the accumulation of stagnant ice. In fact the idea of a lake, as a result of impounded drainage, during glaciation is very tenable. The possibility that a large body of water would freeze under the climatic conditions obtaining at the height of glaciation has been discussed (Hollingworth, 1952). The occurrence of ice on the northern watershed up to a height of at least 850 feet, and in some cases up to higher levels, suggests that once the lake began to freeze it may have coalesced with ice to the north of the watershed and with the ice of eastern Eskdale to form a large sheet. With the onset of deglaciation the ice in central Eskdale would soon be detached from the main mass to the north as the high land near Danby Beacon, up to 980 feet O.D., would emerge as a nunatak and lead to the separation of the two masses. The relations of this mass of stagnant ice in central Eskdale to that in the other two areas will be considered below (Section 1d).

1c) Western Eskdale.

Kendall contended that the pro - glacial lake extended from Lealholm to Kildale at the maximum and subsequently separated into two sections; one from Castleton to Lealholm (Lake Eskdale) and one near Kildale (Lake Kildale) (Kendall, 1903a, p.14). The difficulties which arise in connection with the proposed lake in central Eskdale may be echoed against the existence of the same lake in western Eskdale. There is a contrast between the two areas in that the valleys are narrowed, more restricted and V - shaped in western Eskdale; characteristics which must have affected the pattern of deglaciation. The ice mass in the Vale of York, rising to 1000 feet on some parts of the western escarpment (Kendall, 1902, p.492) is generally considered to have extended down the vale, to York and Escrick, and yet did not extend into western Eskdale beyond the Kildale moraine! This anomaly is particularly striking when the various glacial features of western Eskdale, more numerous than those in the central part of the area, are considered.

A ridge extends across the Commondale Beck valley near Castleton and was described as a delta by Kendall (1903a, p.14). Although there are no exposures in this feature the morphology is not consistent with a deltaic origin. The ridge attains a height of 100 feet above the valley floor, is steep - sided on both sides and is avoided by the river which flows in a gorge round the edge of the feature. If this developed as a delta on the shore of a lake the feature should grade almost imperceptibly into the valley floor on the upstream (north - western) side of the valley. The feature is an almost exact reproduction of the moraines of eastern Eskdale and must represent the former extent of the ice margin.

Also in the Commondale Beck valley between Castleton and Commondale there is a freshly - preserved ridge (NZ 673091) with very steep sides (up to 20 degrees) which shows semi - stratified sand and gravel in the few available exposures. The trend of this ridge is obliquely across the valley and it could not have developed marginal to a mass of ice but must have developed as an esker or crevasse filling in the ice. An isolated hill of sand and gravel with steep sides also occurs in the same valley (NZ 675088) and as a result of the freshly preserved form and location must also be a subglacial feature; one which accumulated as a crevasse filling.

Stitch Hill (NZ 635096) is a circular hill composed of glacial gravel rising 40 feet above the valley floor near the former confluence of the Leven with Sleddale Beck. The morphology and location of this feature is not consistent with a sub - aerial origin but rather with a subglacial one. In the lower part of the Sleddale Beck valley a deserted channel, cut in solid rock, occurs on the eastern side of the present stream slightly above the present floor level. This feature, rather like an in and out channel, could not be cut subaerially as a result of the narrow valley and must have been abandoned by glacial interference - possibly as a result of the superimposition of a new course upon the old one. The glacial deposits mapped by the Geological Survey (Fig.26) extend almost to Commondale from the east but were not mapped between this point and Kildale. However, deposits do occur and near Wayworth (NZ 646097) there is a deposit of fine glacial sand occurring at approximately 770feet. The deposits are probably more extensive than originally suggested by the Geological Survey. The implication of these various features in western Eskdale, all freshly - preserved and indicative of stagnant ice, is that ice must have been intrude into western Eskdale from the Vale of Tees.

Glacial drainage channels have been studied in this area by Best (1956) who interpreted them as part of an aligned sequence (Kendall, 1902, p.482) of overflow channels. Adopting the Kildale moraine as the eastern limit of ice in this area, as Kendall originally suggested, this is probably the most satisfactory explanation. When the possibility of ice extending further inland is appreciated the origin of the channels must be reconsidere Best (1956) commented that the sequence was not completely satisfactory particularly in relation to the low level features of the Vale of York and s he suggested two glaciations. The relevant channels, typical of many other in north west Cleveland, are indicated in the following table:

Channel	Grid. Ref.	Probable Initial Height	Final Height
Cribdale Gate	NZ 592110	850 feet O.D.	755 feet O.D.
Bold Venture	NZ 606128	850 feet O.D.	770 feet O.D.
Highcliff Gate	NZ 616138	980 feet O.D.	960 feet O.D.

These features are not simple channels similar to those described in eastern

Eskdale but are cols in a watershed and at least one (Bold Venture) has a hump profile. The cols are not graded to the remainder of the valley and this cannot be the result of post - glacial stream erosion which must have been slight in these valleys which comprise the headwaters of the Esk drainag system (See Figs. 3 and 55).

Ice must have extended eastwards from the Vale of York to the Castleton moraine at the maximum and there seems to be no reason why the cover did not extend over most of north west Cleveland. If this cover was comparatively thin the associated deposits would remain largely undetected. The onset of deglaciation would reveal the summits of the area (remnants of the upper part of the Low Moor Surface) as nunataks between which ice drainag could occur. The emergence of nunataks on the northern watershed of Eskdale would lead to the stagnation of the mass of ice in western Eskdale and so the associated ice features would then be formed. The drainage channels in this area would develop as superimposed features or as col gullies (Mannerfelt, 1945). Once the ice in western Eskdale became detached from that in the Val of York a compound system of glacial drainage would be established in which streams under and in the ice would predominate producing the stagnant ice features noted in the area (Fig.55). The Castleton moraine may possibly be contemporaneous with the Escrick moraine in the Vale of York whereas recessio to the next stage, indicated by the York moraine, would lead to stagnation of the ice in western Eskdale.

1d) Pro - Glacial Lake Eskdale after 60 years.

Kendall envisaged ice in eastern Eskdale to the Lealholm moraine and a lake between this and the ice of the Vale of York. He interpreted the sequence of retreat as a reflection of the recession of an active ice margin but on the basis of data now collected (Fig.55) this is not thought to have been possible. In eastern Eskdale ice - marginal features occur on both sides of the Esk valley and not on the south side only as would be expected in the case of active ice - marginal retreat. Stagnant ice features occur throughout the area suggesting that the final stages in the ice decay were typified by passive ice. Assembling the evidence from the three parts of Eskdale the sequence may be summarised in the following way:

A. Glaciation

Advance of the ice from the north and east into eastern Eskdale from the north and west into western Eskdale. A lake was impounded between these two advancing margins and sedimentation in this lake was responsible for the development of the flat floor of central Eskdale (See long profile, Fig.44).

B. Maximum extent of the ice

Ice from the east extending to the Lealholm moraine and from the west as far as the Castleton moraine (terminal positions) with ice to the north coalescing with these masses to form a uniform sheet. Probable freezing of the impounded lake to form a mass of ice or ice underlain by water (Escrick moraine??).

C. Deglaciation

Recession of an active ice margin to a retreat position accompanied by thinning of the ice which revealed some of the higher areas as nunataks. As a result of this tendency ice became stagnant in western and central Eskdale. This stage was represented at Goathland by the Moss Swang - Randay

Mire line of drainage and in the Stonegate valley by the inception of the channels at the head of the valley.

D. Continued deglaciation

Stagnant ice between Glaisdale and Lealholm as a result of thinning and detachment and subsequently in the lower Esk valley. Superimposition of the major lineaments of the present drainage system from the thinning mass of ice.

The underlying theme which emerges from the study of glaciation and particularly deglaciation in Eskdale is the controlling influence of the underlying ground surface. On a large scale this explains the successive stagnation of masses of ice in Eskdale as the northern watershed emerged as a series of nunataks, severing ice in Eskdale from the main sheet. On a smaller scale the form of the ground controls the nature of the glacial features and determines whether deposition or erosion occurred. The last chapter in the glacial sequence is explained by the gradual transition from glacial to fluvial drainage - the antecedents of the present system must have been established before the ice finally disappeared.

2) Periglaciation.

In Eskdale two types of area were affected by Periglaciation during the Pleistocene. Areas not covered by ice during the last glaciation were subjected to intense periglacial processes even at the maximum of the glaciation and secondly areas covered by ice at one stage experienced similar conditions as they were exposed by recession of the ice margin. However, periglacial landforms are largely confined to the unglaciated (last glaciation area above 850 feet. There are essentially two scales of analysis. Small features or landforms which are repeated throughout the area are easily detected but the more widespread effects which characterise the actual shape of the region are more difficult to discern.

2a) Orientation.

Variations in slope angle according to different values of orientation and aspect were originally noted by Schostakowitsch (1927) although asymmetry was mentioned by Gilbert in 1909. Since 1927 different types of asymmetry have been observed by various authors in many areas. Periglacial activity should vary according to different values of orientation; facets orientated in one particular direction would suffer a greater degree of weathering, erosion and mass movement than others. To examine the possible occurrence of this variation, orientation was recorded to the nearest 10 degrees for each facet in the sample. Mechanical analysis was first devise to give an angle - area correlation for each of the 37 orientation groups and then to analyse the variation with different values of absolute height (Appendix 3; 2 & 8).

The results were first drawn in the form of an orientation diagram expressing the percentage area of each of the 11 slope categories (Chapter 3 in each orientation group. The rose diagram (Fig.57) affords a method of representing 36 cumulative frequency histograms in a directional way. Percentage areal groups were adopted so that direct comparison could be made although the 11 slope categories are not always represented for each 10 degree orientation groups. A possible criticism of this method would be that, as angle of slope depends upon so many factors, the analysis of 36 orientation groups in the sample area may not yield significant results.

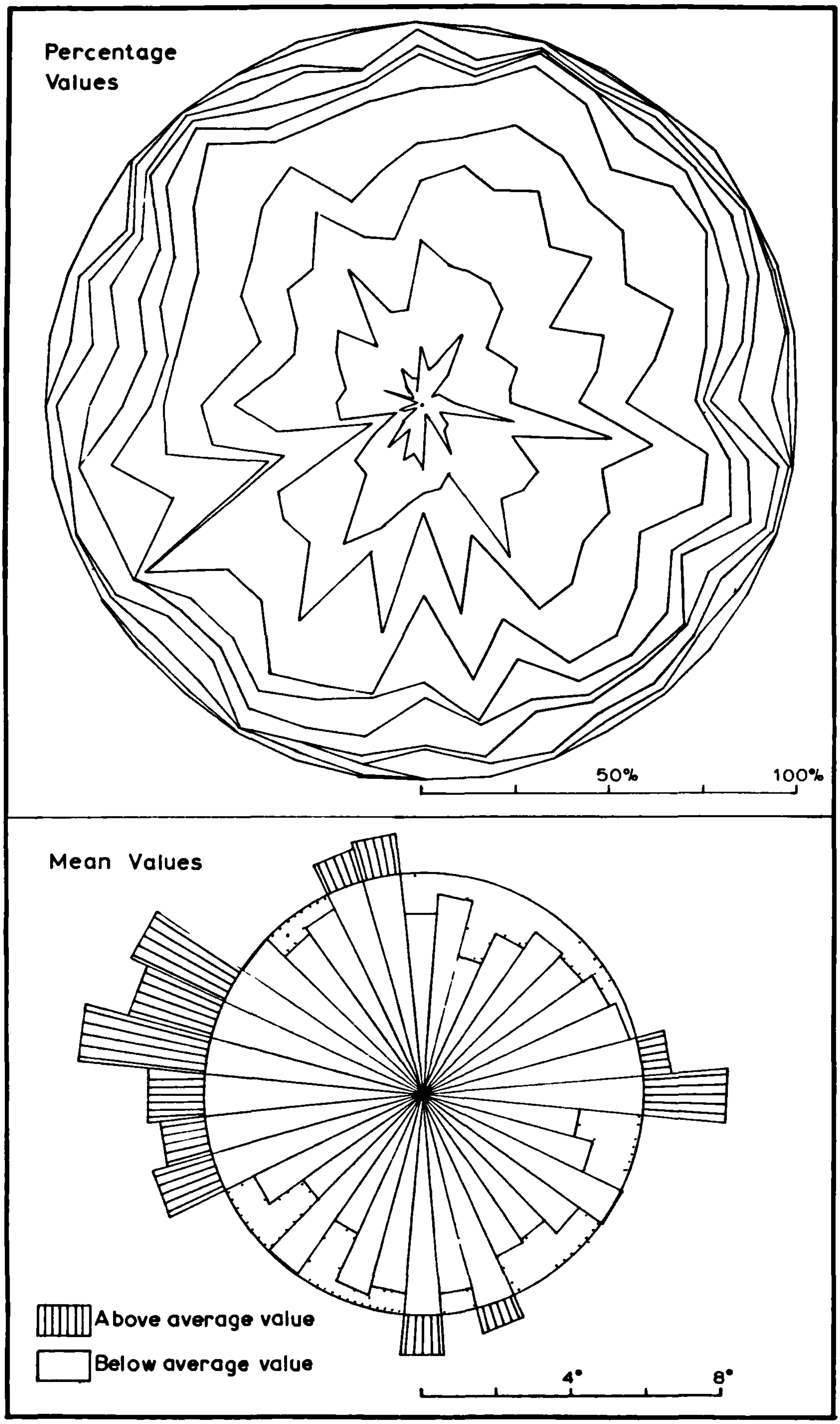


Fig 57. Orientation.

However, as the sample area consists of a series of drainage basins with a simple angle - area relationship the consideration of orientation alone is considered to be valid. The summit areas (i.e. areas not backed by a facet on any side) are grouped together and the percentage area representing the angles of this group are shown in Table 12.

Table 12. Summit Flats (i.e. flats without a value of orientation).

Slope angle category	Percentage area	Weighted mean value
0 - ½	82.2%	
1 - 2	2.4%	
2½ - 4 degrees	15.4%	0.74 degrees

The form of this distribution (Table 12) with two well - marked maxima occurs as a result of the presence of two types of summit facets. Those on the watershed and at high levels generally possess low angles of slope, less than ½ degree. Summit facets occasionally occur at lower levels, on a spur for example, and these have considerably greater angles of slope, between 2½ and 4 degrees.

The percentage values diagram (Fig.57) may be interpreted by considering the areal values of particular angular groups which are significantly higher than those with a different orientation. Small areal values of the lower slope categories indicate a greater percentage of higher slope angles with particular values or orientation. Following the breaks between successive slope categories round the diagram it may be noted that slopes facing 040 - 050, 080 - 090, 100 - 110, 140 - 150, 170 - 180, 240 - 250 and 340 - 350 degrees tend to have higher angles of slope than the intervening values. In addition to these values it is apparent that the range between

240 and 300 degrees shows generally minimal areal values for low angle slopes The amount of variation of percentage content of slope categories in differen orientation groups is quite substantial and contrary to the results of anal effected in other areas (Table 14) it is apparent that no one particular orientation value predominates over all others. A further method of approach is to consider the modal value for each orientation histogram. These values are not immediately apparent from the rose diagram (Fig.57) and so they are given in Table 13. The three modal values correspond to peaks on the angle area distribution for each of the respective orientation groups. Consideri the angular values of specific types of facets the orientation groups which have predominantly higher angles may be selected and these are:

190 - 200, 260 - 270, 240 - 250, 130 - 140, 080 - 090, 170 - 180,

120 - 130, 160 - 170, 330 - 340, 050 - 060, 090 - 100, 230 - 240.

These values are placed in approximate order of significance and it is apparent that the different values may be resolved into south - facing, west facing, east - facing and south east - facing components. The north east - facing group is comparatively small and insignificant.

The mean values diagram (Fig.57) offers a further method of analysing the data presented. The weighted mean values were calculated and indicated in the diagram according to whether they were above or below the average of all the mean values. This diagram shows four elements to be dominant (Fig.56); 240 - 310, 170 - 190, 330 - 000, 070 - 100 degrees.

There is a general correspondence between the results of the analysis using these different methods (Fig.57). Many workers (Table 14) have found only one dominant direction group prevailing in a particular area but most others studied have been based solely upon the generalised valley sides whereas the present data is derived from the detailed form of a group of drainage basins.

Table 13. Modal Values for Angle - Area distributions for specific orientation groups.

Orientation value	Percentage Area	Modal Values		
		Flat Facets	Slope Facets	Steep Face
0 - 10	1.76	1 - 2 (1)	6½ - 9 (2)	
10 - 20	3.68	1 - 2 (1)	6½ - 9 (2)	
20 - 30	3.14	1 - 2 (1)		17½ - 21½(2
30 - 40	2.59	0 - ½ (2)	2½ - 4 (1)	6½ - 9 (3)
40 - 50	2.95	1 - 2 (1)		9½ - 11 (2
50 - 60	3.86	2½ - 4 (1)	6½ - 9 (2)	17½ - 21½(3
60 - 70	3.56	1 - 2 (2)	6½ - 9 (1)	11½ - 13½(3
70 - 80	4.70	2½ - 4 (1)		
80 - 90	4.92	2½ - 4 (1)	11½ - 13½(3)	17½ - 21½(2
90 - 100	2.49	2½ - 4 (2)	6½ - 9 (1)	17½ - 21½(3
100 - 110	4.25	1 - 2 (1)	4½ - 6 (2)	11½ - 13½(3
110 - 120	3.21	2½ - 4 (1)		
120 - 130	2.72	1 - 2 (1)	11½ - 13½(2)	17½ - 21½(3
130 - 140	4.08	1 - 2 (1)	14 - 17 (3)	22 - 27½ (2
140 - 150	3.57	2½ - 4 (1)		14 - 17 (2)
150 - 160	3.97	1 - 2 (1)		14 - 17 (2)
160 - 170	2.84	4½ - 6 (1)	9½ - 11 (3)	14 - 17 (2)
170 - 180	2.61	2½ - 4 (1)	11½ - 13½(2)	17½ - 21½(3

Orientation value	Percentage Area	Modal Values		
		Flat Facets	Slope Facets	Steep Facet
180 - 190	0.67	0 - ½ (2)	4½ - 6 (1)	11½ - 13½(3)
190 - 200	1.32	2½ - 4 (1)	9½ - 11 (2)	over 28 (3)
200 - 210	1.21	1 - 2 (2)	4½ - 6 (1)	9½ - 11½ (
210 - 220	1.41	1 - 2 (1)	11½ - 13½(2)	17½ - 21½ (
220 - 230	1.00	0 - ½ (2)	2½ - 4 (1)	14 - 17 (3)
230 - 240	1.00	1 - 2 (1)	6½ - 9 (2)	22 - 27½ (3)
240 - 250	1.14	4½ - 6 (1)	11½ - 13½(2)	17½ - 21½ (
250 - 260	1.04	0 - ½ (3)	4½ - 6 (1)	11½ - 13½ (
260 - 270	1.31	4½ - 6 (1)	9½ - 11 (2)	over 28 (3)
270 - 280	1.97	2½ - 4 (1)	6½ - 9 (2)	14 - 17 (3)
280 - 290	3.24	2½ - 4 (1)	6½ - 9 (2)	14 - 17 (3)
290 - 300	3.40	1 - 2 (2)	6½ - 9 (2)	14 - 17 (3)
300 - 310	3.91	1 - 2 (1)	4½ - 6 (2)	over 28 (3)
310 - 320	3.04	1 - 2 (1)	6½ - 9 (2)	17½ - 21½ (3
320 - 330	2.97	2½ - 4 (1)	6½ - 9 (2)	14 - 17 (3)
330 - 340	3.02	1 - 2 (1)	11½ - 13½(2)	17½ - 21½ (3
340 - 350	3.56	2½ - 4 (2)	6½ - 9 (1)	14 - 17 (3)
350 - 360	3.30	1 - 2 (2)	4½ - 6 (1)	22 - 27½ (3)

NOTE: The numbers in brackets represent the order of the modal values by size.

Further analysis was effected (Appendix 3, 8) to see if any of these orientation groups with greater than average slope values were restricted to a particular height range. The three height groups selected were:

i) below 700 feet - mainly confined to the valley sides. The lower parts would not be modified appreciably by periglacial erosion but could have been modified as a result of the exigencies of periglacial deposition.

ii) between 700 and 1000 feet - the main zone of influence. The results in this height group would be expected to correspond with those of earlier workers.

iii) over 1000 feet - a zone which should be less well - developed than the previous one as a result of the generally lower angles of slope and the fewer variations of aspect.

The restrictive number of punch cards available did not enable the same 36 orientation groups to be used again and so 7 were used in order that there would be a significant population in each. The results (Fig.58) show that below 700 feet there is little variation and comparison with the areal occurrence diagram indicates that even the south west - facing group, with only a small population, is comparable with the other results. The south - facing and west - facing groups are the most significant. Between 700 and 1000 feet there is more variation and north west, west and north east - faci slopes are dominant. Above 1000 feet there is a similar pattern and west - facing and north east and east - facing slopes are dominant again.

Combining the results of the above analysis (Figs. 56, 57) it is apparent that four groups of orientation have facets with significantly higher angles of slope, and these are:

i) a west - facing group; 240 - 310 degrees

ii) a south - facing group; 170 - 190 degrees

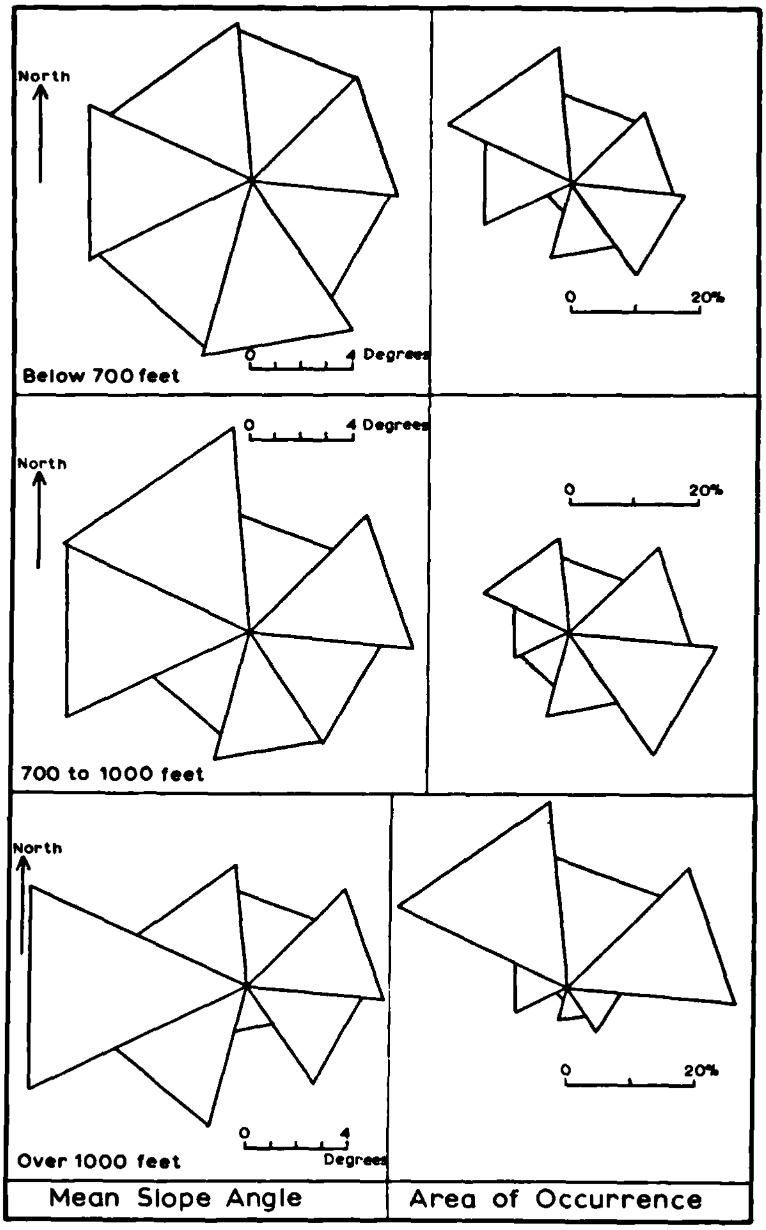

North
Below 700 feet
0 4 Degrees
0 20%
North
0 4 Degrees
0 20%
700 to 1000 feet
North
Over 1000 feet
0 4 Degrees
0 20%
Mean Slope Angle
Area of Occurrence

Fig 58.

iii) an east - facing group; 080 - 100 degrees

iv) a north north west - facing group; 340 - 360 degrees

There is also a further small group of slopes facing north east (between 040 and 050 and also between 060 and 070) which is slightly emphasised. The west - facing group is the dominant one and even in the height groups diagram (Fig.58) west - facing slopes appear to be steepest at all levels throughout the area. South - facing slopes are particularly significant below 700 feet but considerably less outstanding above 1000 feet. The two remaining groups orientated east and north north west respectively, show little variation and are never dominant although both are well - developed below 1000 feet (Fig.57

The problem of causes

The problem of asymmetrical valleys is one which may be found scattered throughout the European and American geomorphological literature. Most authors have suggested that one particular value of orientation is favoured by significantly steeper slopes and have explained the differences in slope angle accordingly.

Table 14. Asymmetrical valleys.

Author(s)	Date	Preference for:	Area	Explanation
Schostakowitsch	1927	North - facing	Siberia	Permanently frozen ground
Losche	1930	North east "	Germany	Stream erosion after insolation
Thorpe	1934	West "	Puerto Rico	Winds
Tuck	1935	South "	Alaska	Insolation
de Martonne	1938	West & south west	France	Winds

Author(s)	Date	Preference for:	Area	Explanation
Visher	1941	North "	Indiana	Differential erosion
von Engeln	1942	South "		Insolation
Taillefer	1944	West "	France	Snow and winds
Emery	1947	South & west "	California	Differences in vegetation and soil cover
Poser	1947	South & west "	Germany	Differential erosion
Walker	1948	North "	Wyoming	Differential erosion and vegetation
Smith	1949	South "	Europe	Insolation
Poser & Tricart	1950	North "	France	Snow melt on south facing
Strahler	1947	No preference	California	-
Taillefer	1950	West "	France	Snow and winds
Rockie	1951	North & north east	Idaho	Snow drift erosion
Gloriod & Tricart	1952	North east "	France	Differences of solifluction
Pierzchalko	1954	North & north east	Poland	Frozen ground
Pinchemel	1954	N.N.W. to S.W.	France	Differential erosion
Clayton	1957	West "	Essex	Tectonic down-warping

Author(s)	Date	Preference for:	Area	Explanation
Ollier & Thomasson	1957	West & south	Chilterns	Wind differences
Budel	1959	South & west	Central Europe	Wind action
Hack & Goodlett	1960	N.E. & S.E.	Appalachians	Differences in soil, vegetation and runoff
Beaty	1956	NW, N, NE, E.	California	Insolation
Beaty	1962	South facing	Montana	Insolation

Many reasons have been advanced to account for asymmetry and these are summarised in Table 14, which indicates the various workers, the areas studie the direction suggested to be significant and also, where possible, the reasons given for the variation.

There are three groups of reasons which have been proposed to explain the variations of asymmetry; structural, tectonic and climatic (von Engeln, 1942, p.142). Structural detail may produce asymmetrical forms as a result of the uniclinal shifting of streams which may occur if the strata are dipping in one direction only. The possibility of structure as the cause of asymmetrical valleys in France was considered by de Martonne (1938) but rejected in favour of a climatic explanation. The influence of the earth's rotation and the effect of downwarping have both been suggested as causes of asymmetry and Clayton (1957) ascribed asymmetrical valleys in Essex to downwarping towards the North Sea. In Eskdale, where the analysis of differing values of slope angle with orientation has been analysed by facets, it is considered unlikely that either of these explanations may be satisfactory especially as steeper angles have been found with several values of aspect, rather than one preferred direction as suggested by workers elsewhere.

Summaries of the various climatic theories which have been proposed have been given by Visher (1941), Ollier & Thomasson (1957) and Melton (1960) Most of the various authors concluded that asymmetry is an erosional feature initiated as a result of varying degrees of exposure under periglacial conditions. Previous studies of orientation differ from the present method in that they have assembled data on generalised slope angles, frequently constructed from contour maps (e.g. Ollier and Thomasson, 1957). The method of using such information have been discussed by Chapman (1952). All the mechanisms suggested are reflected by varying intensity of process operating on opposite slopes. The main ones include:

i) differences in insolation

ii) differences in exposure to winds

iii) differences in the depth and persistence of perm - frost.

These are essentially inter - related, primary mechanisms which may initiate asymmetry. However, once initiated, asymmetry may be perpetuated and furthe developed by secondary factors which include variations of soil type, vegetation cover and lateral stream erosion. Although present variations in asymmetry may correspond with variations in soil and vegetation, as noted in this country in Edale (Fawcett, 1917), and in North America in the Appalachians (Hack & Goodlett, 1960), the asymmetry was probably initiated under periglacial conditions. The secondary factor of lateral stream erosio is often resultant upon differences in the amount of solifluction which occurs on opposite slopes; a slope undergoing pronounced solifluction will tend to shift the stream at its base as a result of the accumulation of material at the foot of the slope (see Melton, 1960).

In North East Yorkshire the results from the sample area considered suggest that there are several directions which show slopes steeper than the average. West - facing slopes are always steeper, south - facing slopes are significantly steeper below 700 feet and east - facing and north north west - facing ones are appreciably steeper below 1000 feet. These variations could be the result of variations in the intensity of different processes at different heights or the result of different phases of periglaciation. The latter possibility has been suggested by Poser (1947) in Germany but could only be confirmed by detailed morphological studies in relation to deposits, if these are available. A more revealing examination could be made by considering the degree of shelter afforded by the opposite valley side as well as the aspect of the facet. This is particularly significant in a narrow, steep - sided valley where a facet on one side, although facing south or south east, will not receive as much insolation as would be expected as a result of the shadow imposed by the opposite slope.

Budel (1944) has noted that differences in exposure are not sufficiently great to explain the overall steepness of west - facing slopes and has suggested that a further factor must be responsible. The most likely explanation is the occurrence of predominantly westerly winds during the Pleistocene and these have been cited by Budel (1944) and Ollier and Thomasson (1957). Prevailing westerly winds would support snow cover on the east - facing (lee) slopes and so solifluction processes would be emphasised on the slopes exposed to the predominant wind direction.

A particular case of the development of slope angle under periglacial conditions is afforded by the development of altiplanation terraces (see 2b below). The backs of these features are generally associated with higher angles of slope than the backs delimiting other types of flats and furthermore the altiplanation terraces are associated with lower values of relative slope (Chapter 6). The development of altiplanation terraces (2b below) tends to be accompanied by an overall increase in angular slope value and so it is concluded that increase in intensity of freeze - thaw processes leads to an increase in the slope angles of facets. Slopes exposed to prevailing westerly winds would probably be subject to more frequent melting and freezing, weathering and solifluction would therefore increase, giving rise to higher slope angles.

South - facing, steep slopes are significant only below 700 feet and this is probably the result of deposition at the foot of the slopes and oversteepening as a result of the northward shift of streams consequent upon the intensity of solifluction on north north west - facing slopes.

North north west - facing and east - facing slopes are dominant to a certain extent below 1000 feet but these are only minor minima compared with the overall dominance of west - facing slopes throughout the area. Steeper angles on the slopes facing north north west and east probably developed as a result of the differential effects of insolation. Facets facing north and north east would receive the least amount of insolation and so permafrost would persist for the longest period of time. This has recently been confirmed by a contemporary study in Canada (Cook, 1961).

The south - facing slopes would receive the greatest amount of insolation and so accumulated snow would be melted more rapidly. On the intervening slopes however, those facing east, west and north north west, it is probable that the freeze - thaw cycle was developed to a greater extent and so altiplanation occurred more intensively and consequently slope angles were increased.

Contrary to previous work in other areas it is apparent that in Eskdale not one direction, but several, experienced oversteepening as a result of periglacial processes. The evidence from the altiplanation terraces suggests that freeze - thaw processes lead to a general increase of the angles of slope already available. The intensity and frequency of freeze - thaw processes will account for the greater angles on specific slopes but this may be caused by the effect, or dominance, of one of three factors. Prevailing westerly winds during the Pleistocene would lead to the melting of snow on west - facing slopes and so dominantly higher angles would be produced on these slopes. The effect of insolation is probably reflected in the significantly greater angles developed on east and north north west - facing slopes while the proportion of south - facing slopes which are significantly steeper may be attributed partly to deposition and partly to erosion as a result of the lateral shift of streams. Conclusions regarding the development of asymmetry must remain tentative, however, until more information is available on the relationship of duration of snow cover to intensity of process. The occurrence of several directions, each with significantly higher angles of slope suggests that more than one cause effected variations in the amount and extent of freeze - thaw. Therefore the duration of the last phase of periglaciation will probably give rise to the dominance of different orientation values according to the duration of periglacial activity experienced by the particular area. This may, in part, explain the various results which have been obtained by various workers (Table 14).

2b) Altiplanation terraces.

In the field altiplanation terraces were distinguished as flats which are laterally discontinuous, possess high - angled backs and cannot be related on the basis of height. The flat is usually narrow (often between 10 and 30 yards wide) and often boulder - strewn. Eakin (1916) first described these features as 'essentially accumulations of loose rock material (1916, p.78) but altiplanation terrace has usually been accepted, in the literature, as a feature cut in bedrock with only a thin veneer of waste on the feature (Te Punga, 1956; - Guilcher, 1950). The term nivation hollow has been applied to similar features in Quebec (Henderson, 1956). Depositional terraces have recently been described as block terraces in Antarctica (Nichols, 1960). The distribution of altiplanation terraces in Eskdale (Fig.58) shows that they occur mainly between 800 and 1100 feet and are generally restricted to the area beyond the heavily glaciated, eastern part of Eskdale. The flats are orientated in several directions but east, north east and west - facing ones are the most numerous. The fundamental control exerted on the distribution of the features is geological; most of the terraces occur on the Moor Grit - Grey Limestone outcrop where they are preserved more definitely and can be recognised easily. The processes which developed the terraces must have operated throughout the area but they

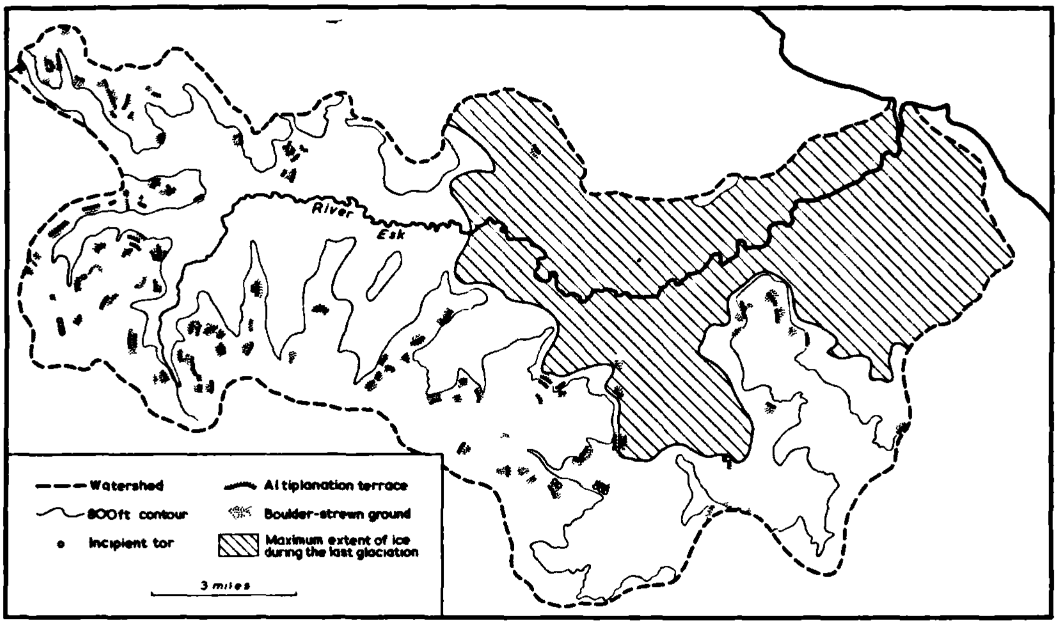


Fig 59.

(Note: the maximum extent of ice during the last glaciation is given for eastern Eskdale only).

were particularly effective and pronounced on these particular lithologies. Similar terraces have been noted in southern England (Te Punga, 1956).

The profile of the terraces was studied by constructing a section across one of them (Fig.60). Borings were made with a soil auger at horizontal intervals of 10 feet and the depth of the various soil horizons recorded. The borings are indicated (Fig.60) by numbers 1 to 19. The ang: of slope between bore 5 and bore 10 is 4½ degrees over a distance of 42 feet whereas the distance between bores 9 and 15 is 52 feet and the angle of slop of the facet is 3½ degrees. These slope angles are appreciably higher than corresponding angles on other types of flat. The edge of the flat of the terrace (Fig.60) is marked by a 'sill' and if this is a boulder it must be very substantial in size because three borings failed to reach a greater depth at this point (Bore 1, Fig.60). The greatest depth of superficial material occurs on the flat of the terrace and the soil profile includes:

A. black humus layer

B. & B1. fawn brown sand; very siliceous

C. fawn clayey sand; variable occurrence
intermittent iron pan

D. yellow sand

E. yellow clay; sometimes yellowish green in colour

F. yellow sand

G. blue clay

(Index letters refer to Fig.60).

The lowest part of the soil profile comprises fine sandy clay deposits which vary in colour from greenish - yellow to bluish - grey. The boulders

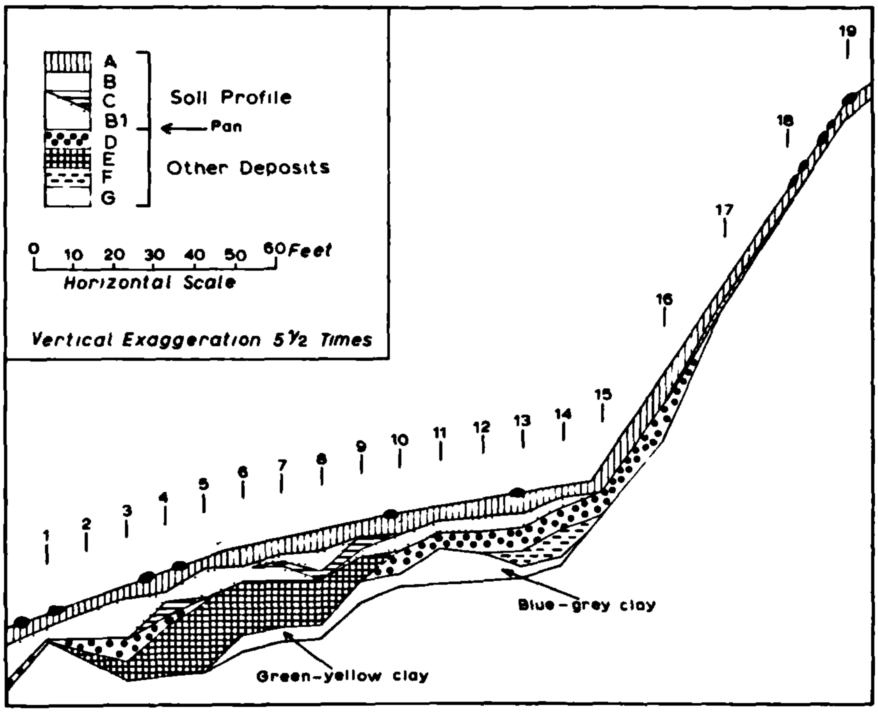


Fig 60. Section across an altiplanation terrace.

Grid. Ref. NZ 696097

The position of boulders is indicated.

are generally located below and above the flat facet and there are few on the flat itself. A second section was surveyed and although in a different part of Eskdale it presented exactly the same characteristics as Fig.60. The size of the boulders varies slightly and the large ones tend to occur near the lower edge of the flat. Vegetation on the terrace includes caluna and erica and bracken is colonising the slope below the terrace flat indicating that movement on the terrace is now comparatively slight if it occurs at all. No trace of specific modes of arrangement of the boulders could be detected either on the ground or on aerial photographs. The surface form of an altiplanation terrace is shown in Fig.61a.

The morphology and distribution of the terraces indicates that they were probably developed by snow patch erosion (Lewis, 1939; Henderson, 1956) Finely comminuted material found beneath snow patches in Spitsbergen and resulting from frost action probably corresponds to the sandy clay found resting on the bedrock surface in Eskdale. The occurrence of altiplanation terraces on the Moor Grit - Grey Limestone outcrop suggests that these lithologies are the most suitable for the maximum development and preservatio of the landform. The two outcrops are well - bedded and deep weathering along joints (and bedding planes) would greatly facilitate the process of altiplanation. The relevance of specific lithologies, controlling the present distribution of altiplanation terraces, has been noted in southern England by Guilcher (1950) and Te Punga (1950).

The development of an altiplanation terrace depended upon the previous existence of a flat in which a snow patch accumulated. The size of the snow patch, the duration of its presence and the extent of freeze-thaw processes (particularly as affected by orientation) would largely expla

Fig 61a. Altiplanation terrace (NZ 848049)

Fig 61b. Rotational landslips at the head of Great Fryup Dale (NZ 711034)

the extent of terrace development. The features noted in Eskdale are considerably smaller than those noted in southern England (Te Punga, 1956). This may reflect proximity to the ice sheet during the last glaciation when the opportunity for prolonged freeze - thaw processes was more restricted in northern than in southern England as a result of the mantle of ice. The angles of slope of the flat and slope facets constituting the terraces are always greater than those of the flats at comparable heights. This implies that altiplanation, between 800 and 1100 feet, leads to an increase in slope angle values. The size of the altiplanation terraces and the fact that they developed upon a pre - existing facet mediates against the consideration of this process as one which initiated or effected major changes in the landscape of Eskdale. On all geological outcrops, including the two particularly resistant ones,angles of slope were modified as a result of this process but there is no evidence to suggest widespread cryoplanation.

2c) Tors.

Three examples of tors occur in Eskdale (Fig.59) and unlike the Bridestones further south (Palmer, 1956) each of these is in an early stage of development. South of Wheeldale Gill (SE 798987) a free face occurs at the top of the valley side, developed on the Moor Grit outcrop and at a height of approximately 730 feet. The siliceous Moor Grit is well - jointed and heavily bedded and the joints have been deeply weathered and widened and large blocks of the formation have therefore been isolated (see Fig.24). The Raven Stones (SE 786986), again on the Moor Grit outcrop, occur on an altiplanation terrace and may have developed as a result of lowering of the surface of the terrace.

The third example, on the west side of Grain Beck (NZ 616043) includes the Cheese Stones which are also developing from a free face composed in this case of the Eller Beck Bed. The joints of this bed have been deeply weathered and the blocks isolated above, but resting upon, the free face.

The occurrence of three types of tor has been noted in Britain by Pullan (1959). The large massive type has been described by Linton (1955), small tors possibly occurring on altiplanation terraces comprise the second type and a further group has developed from valley sides and only occurs on slopes greater than ten degrees (Pullan, 1959). In Eskdale the Raven Stones belong to the second type, the others are typical of the third type. Lithology appears to have been the main determinant controlling the weathering and preservation of the incipient tors. Two of the Eskdale examples are related to the free face at the top of the valley sides and so it is concluded that the tor develops as the free face retreats. The present stage of development agrees with the sequence proposed by Palmer (1956) and the present condition in Eskdale corresponds to the early part of the sequence of development which he proposed (Palmer, 1956, p.67, Fig.8; Stages 2 & 3). This also substantiates conclusions regarding the presence of tors as indicative of the absence of glaciation. The incipient development in Eskdale, a glaciated area, contrasts with the more advanced development of tors in the Dove valley which was ice - free during the last glaciation. This is also supported by an incipient feature which has developed on the western side of Newton Dale, the largest glacial drainage channel in the North York Moors. The Needle's Eye (SE 843953) has persisted during the recession of the free face and must have been isolated since the last glaciation. This is also an early stage in the development of the valley side tors, similar to that proposed by Palmer and Radley (1961) in the Pennines.

A further factor which may affect the preservation of tors is the angle of slope of the valley sides. There is a marked contrast in Eskdale between the valley side below the Cheese Stones and that on the south side of Wheeldale Gill. South of Wheeldale the slope angle of the valley sides below the tors never exceeds 21 degrees and this angle occurs only near the stream. Below the Cheese Stones however, there is a slope angle of 33½ degrees. Eskdale usually shows slope angles between 28 and 32 degrees immediately below the free face of a valley side. If these slope angles are maintained with slope recession on the stream side slope (Chapter 5) then values above or below the average would tend to favour the preservation of tors for a longer period than on most other slopes. The morphology of the incipient tors indicates that they occur as developments from a free face as a result of slope recession and their preservation is effected by litholog and the slope angle of the valley sides.

2d) Landslipping.

Three types of major mass movement phenomena may be recognised in Eskdale. Rotational slips are represented by large slumped masses which form very irregular topography at the head of many of the southern tributary dales of the Esk (Fig.63). These features are now vegetated and stabilised. Their occurrence is largely dictated by the outcrop of the upper lias, particularly the Alum Shale (Fig.63) and they are dominant on north, north

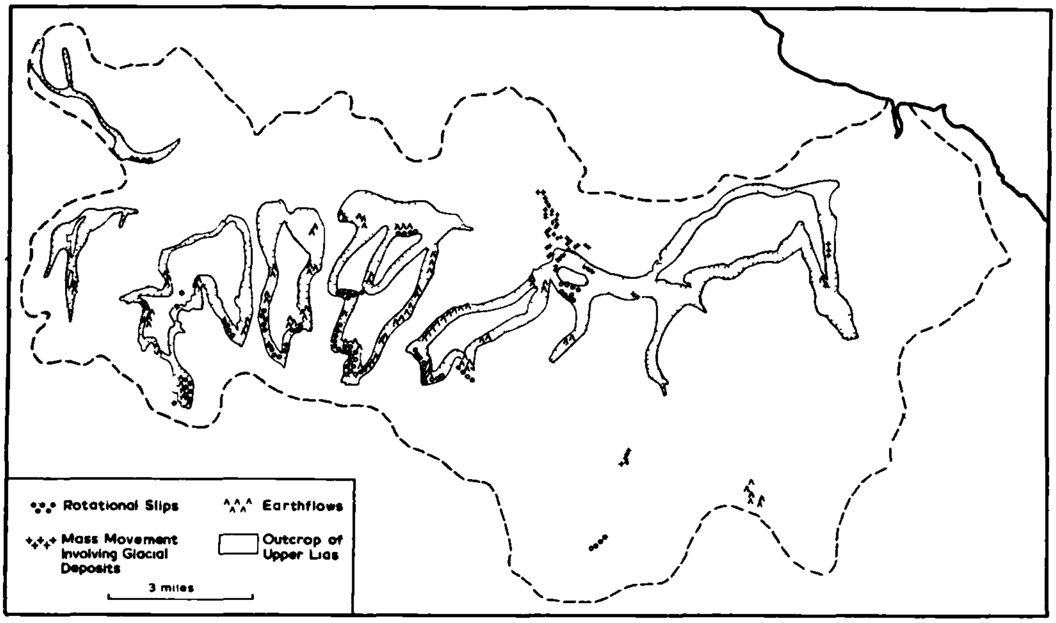


Fig 63. The distribution of major mass movement features in Eskdale.

east and east - facing slopes. Earthflows are predominant on slopes with other aspects. Beaty (1956) noted that 70% of the landslides in the Berkeley Hills occurred on slopes facing north west, north, north east or west. The slump features are largely confined to the head of the dales where erosion is more rapid and undercutting at the base of the slope is substantial. In some cases, as at the head of Fryup Dale, there are three lines of slipped masses on the slope below the free face suggesting the possibility of three generations of landslipping (Fig. 61b). The slipped masses are invariably composed of finely - laminated alum shale and in some exposures the stratigraphy is preserved indicating that the masses are slumps (Sharpe, 1938). Large boulders of Dogger or Lower Deltaic sandstones, derived from the free face, are occasionally incorporated into the margins of the isolated hills. The presence of these boulders indicates that the features developed as slumps with a shear plane which must have developed behind the free face. The slipped mass therefore included Alum Shale and also part of the free face as well.

The size of these features and their position suggests that they developed during more intense phases of mass movement than those which occur today. Several factors must have contributed to their formation including:

i) the lithology of the finely - laminated shales of the upper Lias which facilitate movement.

ii) the presence of a resistant band (Dogger or Lower Deltaic sandstones) as a free face occurring immediately above the Alum Shale. This protects the underlying Alum Shale and so promotes high angle slopes.

iii) steepening of the slopes at the head of the dale as a result of lateral stream erosion (headwards) and rapid runoff.

iv) the possibility of freeze - thaw processes isolating large blocks of free face material and so initiating a shear plane. This would be aided by cambering which occurs in the present landscape on the western side of Danby Dale.

A very well - developed case of slumping occurs in Round Hill, between Great and Little Fryup Dales (Fig.64a). The small, isolated hill, capped by Jet Rock, occurs in a broad col. Explanation of the origin of this feature is difficult until the existence of a large amount of material c the western side of Great Fryup Dale, immediately below the col, is appreciat ed. This mass of material, obviously derived from the col, must have been derived from slumping on the sides of the narrow interfluve between the two dales. This would ultimately lead to the complete breaching of the Dogger which formed the free face, so giving a large col between the two dales. Round Hill is a remnant of the original valley side, probably between two major movements, and persists as a result of the preservative capping of the more resistant Jet Rock.

<u>Earthflows</u> may be recognised as tongues of material which trend down the line of steepest slope and are often separated or bounded by shallow depressions. They occur below the free face on the major stream side slopes and are usually confined to the outcrop of the Alum Shale (Fig.63). They are very common on west - facing slopes and on other slopes they often occur below a series of rotational slumps. Earthflows are essentially flowage features (Sharpe, 1938) and probably developed as a result of the increased

Fig 64a. Broad col between Great Fryup and Little Fryup Dales. Round Hill (NZ 717048) occurs in the col.

Fig 64b. Scar produced as a result of a debris slide (NZ 698038)

lubrication of the Alum Shale as flowage would be facilitated by the fine laminations. The factors which contributed to their development include:

i) lithological control of the finely - laminated Alum Shale.

ii) abundant moisture and freeze - thaw processes, especially on west - facing slopes.

iii) in certain cases the introduction of material from slumps led to unstable slope conditions and so earthflows were generated to restore the equilibrium of the slope.

Mass movement features involving glacial deposits are of two types (Fig.63). The first type is represented on depositional slopes, when the angle of slope resulting from an origin in an ice - contact position was too great for the erosional environment on the side of the valley. Therefore adjustment occurred in the form of small slips of unconsolidated material. The original ice - contact faces of kame terraces on each side of the lower Stonegate valley display irregularity as a result of this type of movement. A second type of movement has developed where glacial clays were deposited on a surface of Alum Shale. This movement is slope flowage which has probably been arrested in the course of development as a result of the tenacious glacial clay overlying the Alum Shale. Such features are prominen along the east side of the Little Beck valley between Sleights and Little Beck.

These three types of mass movement formerly operated on a much larger scale than at present. The rotational slumps are now fossil features and in some cases peat has accumulated between the slumps and the free face. Earthflows and mass movement phenomena involving glacial deposits still occu throughout the area but on a very reduced scale.

2e) Dry valleys.

Dry valleys and depressions occur throughout Eskdale as one of three types. Glacial drainage channels of various types have been described above (Section 1). Broad, shallow depressions which were formerly part of the drainage network are also prominent, but as a result of either decreasing precipitation or a falling water table they have ceased to function. The third type includes broad depressions of much less relief and which are independent of the present drainage pattern. These probably developed when the ground surface was more permanently frozen, infiltration prohibited and solifluction more common. These dry depressions are probably equivalent to the corrasional troughs described by Dylik (1953). The occurrence of two types of dry valleys in Glaisdale is indicated in Fig.65. Wind gaps occur throughout Eskdale and result from a variety of causes as noted by Brown (1960a, p.123).

3) Mass Movement Phenomena 1960/1961.

The winter elapsing between two season's field work witnessed the instigation of several new mass movement features in Eskdale (Fig.66). These included 8 earthflows and one debris slide (Sharpe, 1938). They were all confined to the southern tributary dales, occurred near the head of the dale or on the east - facing slope and were associated with the outcrop of the Upper Lias, especially the Alum Shale. The resulting features are distributed within the area included by the 35 inch isohyet (Fig.66, inset) but the main reason for the occurrence of the features was the increased winter rainfall. The monthly averages (50 year average) and the 1960/1961

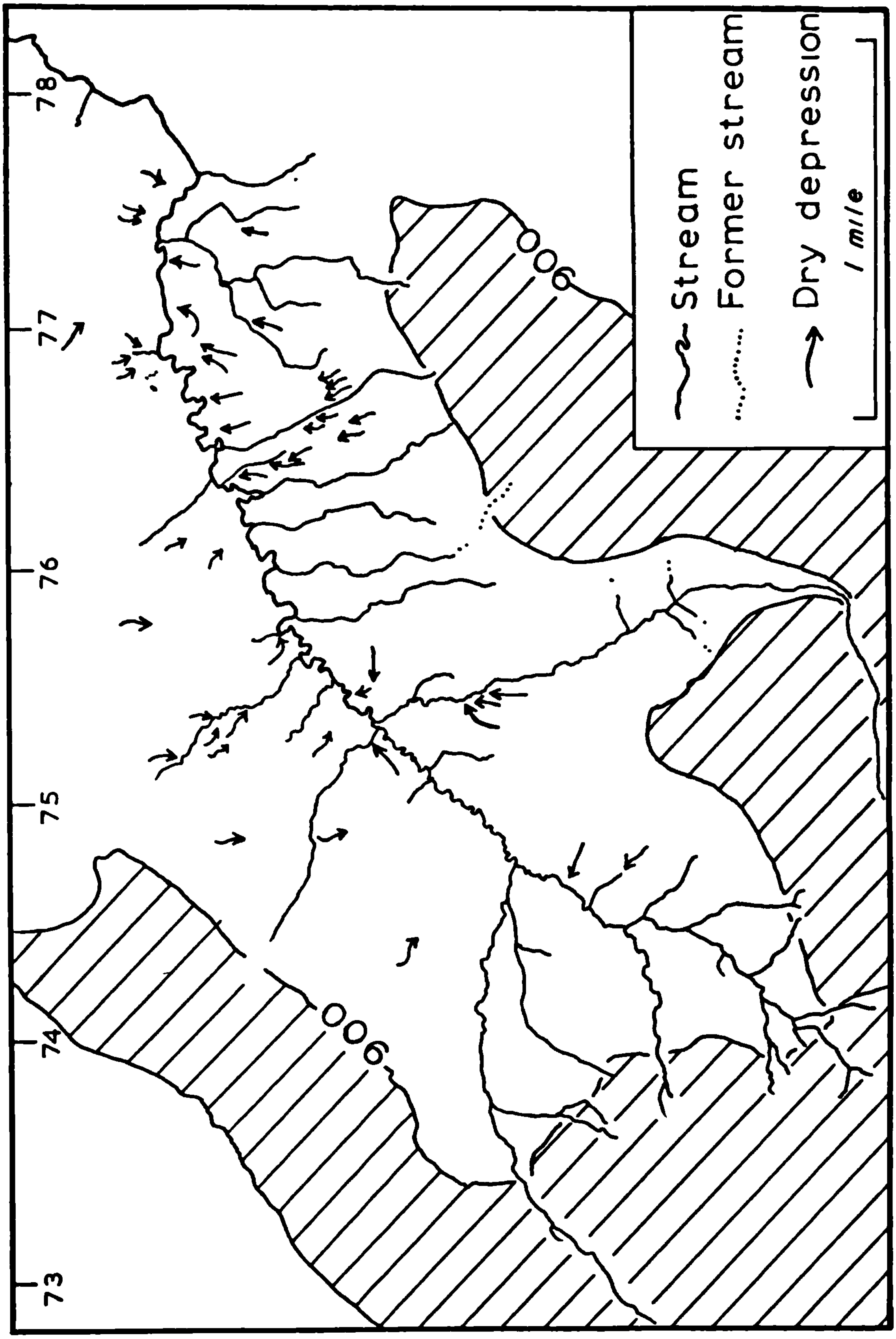


Fig 65. Glaisdale: dry valleys and depressions.

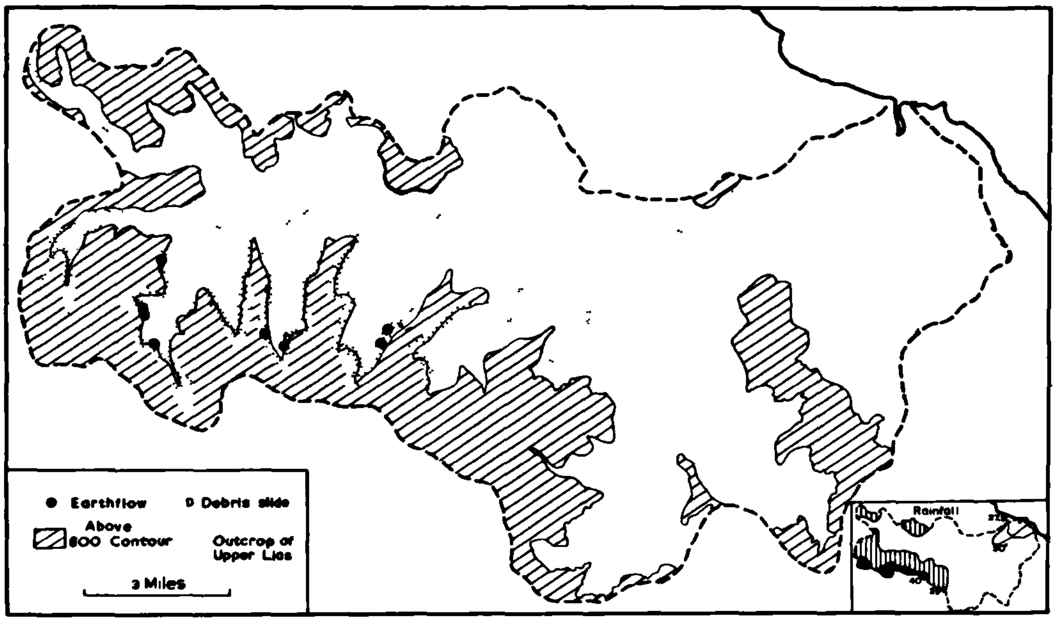


Fig 66. Mass movement features in Eskdale, 1960 - 1961.

figures are given for rainfall at Kildale Hall and the monthly average rainfall given for Kirkby Moorside may be contrasted with the 1960/1961 figures for Pickering (Table 15). The figures for Kildale Hall illustrate the greatly increased rainfall in late 1960 and January 1961 and this is also supported by the figures from the edge of the Vale of Pickering, to the south of Eskdale.

Table 15. Mean Monthly rainfall.

Station	October	November	December	January	February	March	Total (6 months
Kildale Hall NZ 612094 600 feet							
Average	3.34	3.85	3.21	3.29	2.53	2.37	18.59
1960/61	10.65	4.65	4.28	5.51	1.48	1.07	27.64
Kirkby Moorside SE 706873 270 feet							
Average	2.80	3.03	2.69	2.99	2.13	1.78	15.62
Pickering SE 795843 143 feet							
1960/61	6.97	3.59	3.37	3.11	1.46	0.70	19.20

The debris slide is a rapidly formed feature and sections show that it developed by movement of superficial material and Alum Shale on a slip plane in a gully. The material caused the destruction of the wall at the moorland edge and extended for a distance of approximately 15 yards into the field below (Fig 64b). The earthflows were much more slowly developing features and one, near Ajalon Houses (NZ 729039), began to move in late October and continued until March 1961. The slow movement of this feature led to a stone wall being moved approximately 8 feet without any substantial harm. The earthflows occurred in all cases below, or near the foot of, older stabilised earthflows.

The factors which contributed to the development of these features between 1960 and 1961 include:

i) the significantly greater than average rainfall of late 1960 and early 1961.

ii) the lithology of the upper lias.

iii) saturation of the Alum Shale so that flowage features could develop.

iv) the effect of the pressure of superficial material from above

v) inadequate land drainage - especially as a result of the inadequate ditching and drainage above the moorland edge.

vi) the orientation of the facets; movement was particularly pronounced on east - facing slopes.

Two similar types of feature were noted in South West England in 1953 rainfall was greater than usual (Gifford, 1953).

4) <u>Conclusion.</u>

Glaciation introduced new landforms into the Eskdale landscape as a result of the direct and indirect effects of the Pleistocene period whereas periglaciation has largely modified an existing framework. Periglacial processes were originally much more active, but even today, vestiges of the same processes, but on a smaller scale, may be detected in the landscape. The hand of man has also played a small part in shaping the form of the physical landscape and particularly in the regulation of drainage, the institution of tile drainage, subtraction of water at the head of Eskdale (Whitby Water Board), in ploughing steep slopes which promote soil creep and explain the differential surface heights at field boundaries and in the burning of the moorland vegetation which in many cases has led to rapid runof and peat erosion. These changes are slight, however, compared with the glacial contribution and the periglacial and post - glacial processes which have continued to adapt the glacial imprint to present conditions. The skeleton of the present physical landscape of Eskdale was established in Tertiary times but the detailed anatomy is the result of changes in the Quaternary period.

CHAPTER 8.

ESKDALE IN RETROSPECT.

There is a general paucity of research work in geomorphology on slope angles, although an early summary of ideas (de la Noe & Margerie, 1888) was cited by Young (1961) in a recent analysis of slope angles. There are few investigations dealing exclusively with field observations of slope angle between 1888 and 1961.

1) Angle of slope.

Thirty years ago it was noted that "In the ultimate analysis, it is the variously inclined facets of intersecting surfaces which must form the units of detailed geographical study - they are the physiographic atoms out o which the matter of regions is built" (Wooldridge, 1932). The technique of morphological mapping (Waters, 1958), once recorded, immediately offers a method of studying slope angle variations in any area. Young (1961) examine the concept of characteristic and limiting angles and effected an analysis for three areas in this country. These three areas were delimited largely on the basis of geological outcrops and the characteristic angles of these different outcrops were examined (Young, 1961).

The drainage basin is a unit more fundamental than the geological outcrop. Although angle of slope is determined by a number of factors these must, to a large extent, be complimentary within the drainage basin framework. Characteristic angles do not occur in a drainage basin considered as a whole. Once angle of slope is considered with respect to particular groups of controlled conditions, such as geology, orientation or position in a slope, characteristic angles do occur and the simple, unimodal relationship between angle and area of slope in a drainage basin is disrupted. For each set of controlled conditions characteristic angles occur for specific types of facets. Ideally an angle - area distribution would have two maxima under controlled conditions representing flat and slope facets, the two fundamental types of facet. In practice however, several types of facet will be encountered and they will be selected from:

A. Flat facets: a) flat slopes, 0 - $\frac{1}{2}$ degree

b) gentle and moderately gentle, 1 - 4 degrees

B. Slope facets: a) moderate, 4$\frac{1}{2}$ - 6 degrees

b) moderately steep, 6$\frac{1}{2}$ - 13$\frac{1}{2}$ degrees

c) steep, 14 - 27$\frac{1}{2}$ degrees

d) very steep, over 28 degrees[1].

In this thesis angle of slope has been considered in relation to controlling factors taken separately. The modal values of the distributions of angle - area, which occur in the sample area, for particular conditions, are noted in each relevant chapter. Weighted mean values have been used throughout to give an indication of the form of the angle - area distribution under particular controlled conditions. The range of weighted mean values which were obtained may now be compared (Table 16).

Table 16. The range of weighted mean values according to different analyses

Weighted mean slope angle	Height Groups	Geology	Height above stream	Orientation	Drainage Basin order	Slopes		
						Stream side	Valley side	Summit
Maximum	7.27	22.24	9.65	8.56	6.03	11.25	4.08	9.24
Minimum	2.95	2.26	1.00	3.80	4.78	3.73	3.43	6.08
Difference	4.32	19.98	8.65	4.76	1.25	7.52	0.65	3.16

[1]The descriptive terms are largely in accordance with a report submitted to the Geomorphological Research Group (1962).

This shows (Table 16) that the several methods of analysis may be placed in order of range of variation. In each case a consideration of the range of mean values allows the following order to be obtained: Geology, height above stream, stream side slope, orientation, height groups, summit slopes, drainage basin order, valley side slopes (least range). Rock type therefor introduces the greatest overall range of angular slope values whereas facets considered above stream and those in stream side slopes also show a substantial range. Variation is minimal when considering drainage basin order and valley side slopes as would be expected from the conclusions reached in Chapter 5.

2) Towards a further quantitative analysis.

The scheme of analysis which has been used is a new method of approach and the experience gained allows several suggestions to be made regarding the possible use of a similar method in future. The present scheme has used area of facet rather than width and this is justified at least as a unique approach and a worthwhile investigation, if not as a metho superior in results to the profile method (see Fig.16). The sample area was selected, not necessarily representative of the whole of Eskdale, but rather as a convenient unit, in size and form, for a trial analysis. However, there is no reason to suppose that the relative values of the results would vary greatly if a similar scheme had been effected for either the entire drainage basin or for another part of the same major drainage basin.

The amount of work involved in mapping, analysis and correlation necessarily leads to a consideration of the possibility of using a sampling method to obtain the basic information. This could be achieved either by i) sampling of points based upon random numbers or ii) sampling along random or controlled lines, placed upon the geomorphological map. The second alternative would be a variation upon the profile method (Savigear, 1956) but although length would replace area, it would be the length between break and changes of slope and not an arbitrary measured length which has been use in profile analysis.

In quantitative analysis some form of mechanical aid is required t effect sorting and accumulation of the data. Punch card equipment was used to evaluate results for the sample area in Eskdale and the punch card is ideally suited to this type of analysis where one card represents one facet. If a computer which takes punch card input was available this would greatly speed the rate of working and would be fairly economical in computer time - more so than the use of punched paper tape input. The use of an electronic computer would also save time and dispense with the use of a desk calculator to digest and reduce the results obtained when punch card equipment is used. For each angle - area distribution, the calculation of percentage areal values, weighted mean values standard deviation and other statistics could be achieved as part of the main program when using a computer. Two programs would still be required however, because the angles of slope must be grouped together in some way, preliminary to the use of the main program.

The method of quantitative analysis will probably achieve its greatest application in a comparative study. A further requirement which would greatly facilitate this would be the development of a means of physic chemical analysis to compare the relative resistance of different lithologies

The theoretical standard could then be compared with the landscape effect of each particular rock type. Most of the records used for each facet in Eskdale (Chapter 2) would all be required in any further analysis elsewhere, although slight modification would be necessary according to the character of the area selected. The actual analysis could be improved by supplementing relative slope of flat facets, here the only means of discriminating between flat and slope facets, by a record of the type of facet. The fact that angle - area distributions have peaks representing specific types of flat and slope facets could be borne in mind during the construction of further schemes of analysis and facets subdivided as:

1) Flats - possibly discriminated on the basis of relative slope
2) Slopes - (i) waning element
   (ii) constant slope
   (iii) free face etc.

Thus when dealing with stream side slopes sorting could be effected first for the type of slope facet, followed by an angle - area analysis. This would provide a more detailed technique as a basis for the study of the morphology and development of slope profiles. This slope analysis could be extended by using the grid references to discriminate between different parts of the area selected and so various profiles could be compared.

A further investigation could consider the effect of several variables simultaneously. In Eskdale angle of slope has been investigated with regard to geology but a combination of two or more factors would be rewarding. Thus the variation of orientation could be examined for a particular rock type or the variation of slope morphology could be examined in drainage basins of specific order. Although "Topography produced by stream channel erosion and associated processes of weathering, mass movement and sheet runoff is extremely complex, both in the geometry of the forms themselves and in the inter - relations of the processes which produce the forms" (Strahler, 1952) it is notable that "The objects which exist together in a landscape exist in inter - relation. We assert that they constitute a reality as a whole which is not expressed by a consideration of the constituent parts separately, that area has form, structure and function, and hence position in a system, and that it is subject to development, change and completion" (Sauer, 1925). The problem of the complex inter - relationship of processes and controls in geomorphology cannot be attacked until the individual significance of factors and forces is known.

3) Factors influencing the angle of slope of facets.

The morphology of facets is essentially a reflection of initiating and modifying factors. Certain processes are responsible for initiation whereas others explain the actual morphological detail of facets. With regard to Eskdale these may be summarised as:

A. Factors initiating facets. These may be relic, in which case the facet is inherited, or they may be continued in the present development.

i) Planation - development geared to river base level

ii) Glaciation - erosional and depositional features

iii) Periglaciation - largely responsible for modification of the existing form rather than the introduction of many new changes or breaks of slope.

B. <u>Factors influencing the angle of slope of facets.</u>

i) Structure - (a) dip of the beds

(b) physical resistance of the lithology

(c) pattern of jointing, bedding and minor structures

ii) Process - (a) controlling agencies - river, stream, water table

(b) infiltration capacity (reflecting soil and vegetation)

(c) rate and amount of runoff - rainwash e

iii) Locational factors -

(a) position in slope type and relations with adjacent facets

(b) orientation of facet - this affects rate and relations of processes to a lesser extent now than under periglaci conditions but the effect must still occur

(c) vegetation cover

(d) varying micro - climatic conditions.

These factors are necessarily inter - related but once initiated, a break or change of slope is a more stable feature of the landscape anatomy than the angle of slope between successive breaks or changes. The angle of slope may increase within a particular environment until limiting equilibrium conditions are reached. Increase in slope angle above this critical value will produce a compensating reaction.

4) The uses of geomorphological mapping.

The fundamental application of morphological mapping (Waters, 1958) is in geomorphic analysis. The method gives an objective way of representing the 'form of the ground'. There are essentially two ways of utilising the field map; in comparative areal analysis and secondly for the extraction of specific types of material. The first use may be treated by one of several methods (Chapter 2) and allows examination of various controls affecting angle of slope. Once made, a geomorphological map may be consulted for the extraction of particular details, subject to the limitations of the mapping scale. Small features are represented by symbols and this will greatly facilitate the extraction of particular items such as types of mass movement feature. A further use of geomorphological mapping may be found in geographical analysis as the map could be used as a source of an accurate slope category map which would be useful as a factor in many geographical analyses. The technique affords an excellent tool of research, it cultivates an appreciation of the detailed form of the ground and it is also a commendable teaching method.

5) The development of Eskdale.

A study of the relations of the angle of slope of facets necessarily leads to an investigation of the causes which initiated the facets and to the stages of landscape evolution. Three major planation surfaces may be deciphered in Eskdale and these developed as a Tertiary contribution to the landscape. The results of an early glaciation are difficult to discern but the impact of the last glaciation is firmly imprinted upon the Eskdale scene.

Since the last glaciation there has been a gradual adjustment, throughout the drainage basin, to the legacy introduced by the Pleistocene. The evolution of Eskdale, if referred to a series of stages, might assume the following pattern:

1. Emergence of the Cretaceous sea floor as a surface inclined to the east.
2. Initiation and development of a major eastward - draining proto - Esk.
3. Capture of the upper Esk, probably by the Tees, and isolation of the North York Moors as an "island".
4. Mid - tertiary movements. Uplift of the region in the form of a dome and deformation of an early Tertiary surface.
5. Production of the Summit Surface and the High Moor Surface both having gentle gradients, and suggesting instigation by processes rather different from those which produce partial peneplains.
6. Production of two partial peneplains (the Low Moor Surface. The end of these two stages of landscape development may be equated with various drainage changes, mainly river captures, which resulted from structural adaptation.
7. The Calabrian transgression. The change of the course of the lower Esk from an east - flowing to a north east - flowing stream and the capture of Lounsdale are both referable to this stage.
8. The early Pleistocene. Glaciation and the production of a

series of valley stages before, during and after this down to the 100 feet (at Whitby) valley floor.

9. Second Glaciation. Ice advanced into the drainage basin from the west and east and also impinged upon the northern scarp of the North York Moors.

10. Deglaciation. Two stages of marginal drainage in the east followed by stagnation. Almost immediate stagnation in the west as a result of the control exerted by relief, leading to detached masses of ice. Central Eskdale was occupied by a mass of stagnant ice.

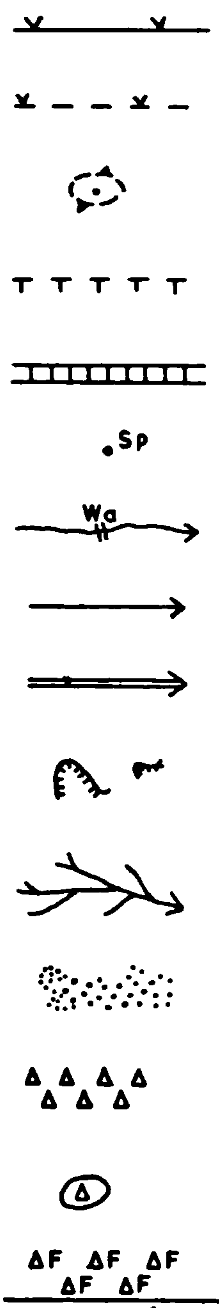
11. Post - glacial. Gradual adaptation of 'normal' erosion to the surface form which obtained after the 'climatic accident'. A new drainage pattern, largely following pre - established lines but incorporating some glacially - inspired anomalies.

The drainage basin today is a dynamic entity and although stages may be suggested the drainage basin is essentially a continuously evolving phenomenon experiencing gradual adaptation to change.

6) Conclusion.

The emergence of several differing approaches and themes has been apparent in the geomorphological literature of recent years. The use of the facet in geomorphic analysis should inevitably lead to the crystallisation of certain elements from these different approaches. This may inevitably implicate some form of quantitative analysis but as Wooldridge has noted "The plea for measurement, or for morphometric work, is wholly sound and salutary, providing it is remembered that the physical map is itself a quantitative statement much of whose information only requires translating or recasting" (Wooldridge, 1958, p.32). The facet or the undivided continent have been described as the ultimate units of geomorphological analysis: "Nature offers us two inescapable morphological unities and two only; at the one extreme the indivisible flat or slope, at the other the undivided continent" (Linton, 1951a). Possibly the drainage basin may be introduced on a level with these two primary realities. The absolute boundaries of the facet, the drainage basin and the continent must change but relatively they persist and are integrated into a general scheme of development. A break or change of slope, the fundamental geomorphic line, is seldom destroyed but more usually adapted, developed and perpetuated in the scheme of landscape evolution.

Appendix I Major symbols used on the geomorphological map



Break of slope

Change of slope (In each case arrows are placed on the steeper side)

Summit

Minor terrace feature (too small to be represented by changes and breaks of slope)

Rock outcrop

Spring

Waterfall

Dry valley or depression (V - shaped cross section)

Dry valley or depression (flat - floored)

Spring - sapped hollow

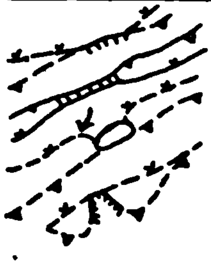
Peat erosion

Boulder - strewn ground

Landslipping (Rotation form)

Isolated hill produced by rotational landslipping

Earthflows



The combination of breaks and changes of slope with symbols. Wherever possible the two should be amalgamated.

APPENDIX 2.

RESULTS OF BASIC INITIAL ROUTINE DESCRIBED IN CHAPTER 3.

Angle of slope (Columns 10 11 12)	Area of slope (Columns 7 8 9)	Angle of slope (Columns 10 11 12)	Area of slo (Columns 7 8
000	0.38	170	0.63
005	7.82	175	0.23
010	10.22	180	0.70
015	6.91	185	0.46
020	4.35	190	0.79
025	4.53	195	0.21
030	5.94	200	0.33
035	6.10	205	0.19
040	5.40	210	0.34
045	4.56	215	0.07
050	5.34	220	0.22
055	2.95	225	0.02
060	3.01	230	0.30
065	2.64	240	0.17
070	3.43	245	0.18
075	1.95	250	0.28
080	2.30	255	0.10
085	1.57	260	0.13
090	1.51	265	0.16
095	1.02	270	0.08
100	1.38	275	0.07
105	1.24	280	0.02
110	1.36	285	0.05

Angle of slope (Columns 10 11 12)	Area of slope (Columns 7 8 9)	Angle of slope (Columns 10 11 12)	Area of slo (Columns 7 8
115	0.59	290	0.16
120	1.38	295	0.05
125	0.71	300	0.06
130	0.87	310	0.16
135	0.52	320	0.15
140	0.49	325	0.05
145	0.59	330	0.01
150	0.58	335	0.05
155	0.69	350	0.05
160	0.62	355	0.08
165	0.31	360	0.05
		375	0.02
		385	0.05
		500	0.07

The areas are given in planimetric units and were used as a basis for the calculation of percentages in the main program. To convert these units to square miles the area value must be multiplied by 200/640.

APPENDIX 3.

PROGRAM FOR PUNCH CARD ANALYSIS.

The main program includes 9 sections and in many cases these involve the use of a basic routine which does not vary.

Basic Routine.

1.	Take all cards	
2.	Sort into 5 groups using column 10 (values 0,1,2,3,4,5)	5 groups
3.	Sort the first 4 of these groups separately into 10 groups using column 11 (values 0,1,2,3,4,5,6,7,8,9)	38 groups
4.	Sort each of these 38 groups into 2 groups using column 12 (values 0,5)	70 groups
5.	Combine these 70 groups into 11 groups on the basis of values in card columns 10, 11, 12 viz.	
	000 & 005	Group 1
	010 & 015 & 020	Group 2
	025 & 030 & 035 & 040	Group 3
	045 & 050 & 055 & 060	Group 4
	065 & 070 & 075 & 080 & 085 & 090	Group 5
	095 & 100 & 105 & 110	Group 6
	115 & 120 & 125 & 130 & 135	Group 7
	140 & 145 & 150 & 155 & 160 & 165 & 170	Group 8
	175 & 180 & 185 & 190 & 195 & 200 & 205 & 210 & 215	Group 9
	220 & 225 & 230 & 235 & 240 & 245 & 250 & 255 & 260 & 270 & 275	Group 10
	280 and remaining cards including 5th. group from 2 above	Group 11

Main Program.

All of the following operations will be followed by the Basic Routine with the exception of 6a.

---

1. a) Take all cards

   b) Sort into 12 groups using column 19 (values 1,2,3,4,5,6,7,8,9, 0,X,Y) — 12 groups

   c) Take the 2nd. group (value 2) and sort into 2 groups using column 20 — 2 groups

   d) Take the 13 groups for BASIC ROUTINE

   e) Yield up to 11 different totals for each of the 13 groups.

---

2. a) Take all cards

   b) Sort into 4 groups using column 22 (values 0,1,2,3) — 5 groups

      Blank column reject is 5th. group.

   c) Sort each of these 4 groups into 10 groups using column 23 — 36 groups

   d) Take the cards of each of these 36 groups and the blank column reject from b) for BASIC ROUTINE

   e) Yield up to 11 different totals for each of 37 groups.

---

3. a) Take all cards

   b) Sort into 2 groups using column 13 (values 0,1) — 2 groups

   c) Sort each of these two groups into 10 groups using column 14 (values 0,1,2,3,4,5,6,7,8,9) — 13 groups

   d) Take the cards of each of these 13 groups for BASIC ROUTINE

   e) Yield up to 11 different totals for each of 13 groups.

4\. a) Take all cards

b) Sort into 5 groups using column 30 (values 1,2,3,4,6) — 5 groups

c) Take each of these groups for BASIC ROUTINE

d) Yield 11 different totals for each of these 5 groups

5\. a) Take all cards

b) Sort into 7 groups using column 24 (values 1,2,3,4,5,6,7) — 7 groups

c) Combine groups 2 & 3 & 4, 5 & 6 & 7 giving 3 groups — 3 groups

d) Sort each of these 3 groups into 10 groups using column 28 (values 0,1,2,3,4,5,6,7,8,9) — 30 groups

e) Take each of these groups for BASIC ROUTINE

f) Yield up to 11 different totals for each of these 30 groups

---

6a. a) Take all cards

b) Sort into 7 groups using column 17 (values 0,1,2,3,4,5,6,) (Keep reject) — 7 groups

c) Combine groups 4 & 5 & 6 into 1 group — 5 groups

d) Sort each of these 5 groups into 2 groups using column 13 (values 0,1) — 10 groups

e) Sort each of these 10 groups into 10 groups using column 14 (values 0,1,2,3,4,5,6,7,8,9) — 65 groups

f) ADD the values of columns 789 for each of these 65 groups producing 65 different totals (area of each group)

6b. a) Take the reject from 6a. b) above

b) Sort into 10 groups using column 28 (values 0,1,2,3,4, 5,6,7,8,9) — 10 groups

c) Take each of these 10 groups for BASIC ROUTINE

d) Yield up to 11 different totals for each of these 10 groups

---

7. a) Take all cards

b) Sort into 6 groups using column 26 (values 0,1,2,3,4,5) — 6 groups

c) Sort each of these groups into 10 groups using column 27 (values 0,1,2,3,4,5,6,7,8,9) — 60 groups

d) Combine groups 0 & 1, 2 & 3, 4 & 5, 6 & 7, 8 & 9 — 30 groups

e) Take each of these 30 groups for BASIC ROUTINE

f) Yield up to 11 different totals for each of these 30 groups

---

8. a) Take all cards

b) Sort into 2 groups using column 13 (values 0,1) — 2 groups

c) Take the first group (value 0) and sort into 8 groups using column 14 (values 2,3,4,5,6,7,8,9) — 8 groups

d) Combine 2 & 3 & 4 & 5 & 6 and 7 & 8 & 9 into 2 groups — 2 groups

e) Take the three groups (including one from b).) and sort each into 4 groups using column 22 — 12 groups

f) Sort each of these 12 groups using column 23 and combine values 0 & 1 & 2 & 3 & 4 and 5 & 6 & 7 & 8 & 9 into 2 groups — 24 groups

g) Take each of these 24 groups for BASIC ROUTINE

h) Yield up to 11 different totals in each of these 24 groups

<u>Note:</u> Reject from e) above not required.

---

9. a) Take all cards

b) Sort into 3 groups using column 1 (values 6,7,8) — 3 groups

c) Take the first group (value 6) and sort into 10 groups using column 2 (values 0,1,2,3,4,5,6,7,8,9) and combine values 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 into 1 group — 2 groups

d) Take the remainder from c) (Values 8,9) and combine with 2 groups from b) as 1 group

e) Take this group and sort into 2 groups using column 4 (value 0,9) — 2 groups

f) Sort the first group (value 0) into 10 groups using column 5 (values 0,1,2,3,4,5,6,7,8,9) and combine values 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 into 1 group — 1 group

g) Put the remainder from f) with the second group (value 9) from e) — 1 group

h) Take each of these 3 groups for BASIC ROUTINE

i) Yield up to 11 different results in each of these three groups

---

The results of the various sections of the Main Program were recorded, by the operators, on duplicated sheets.

REFERENCES.

Works referred to several times in the text are given in large type.
Abbreviations for periodicals correspond with those given in the World List.

Arkell, W.J., 1933. The Jurassic system in Great Britain. Oxford, 681pp.

Atkinson, J.C., 1891. Forty years in a moorland parish. London.

Bakker, J.P. & Le Heux, J.W.N., 1947. Theory on central rectilinear recession of slopes. Proceedings Konink. Nederlandsche Akademie van Wetenschappen, Series B, 49, 959-966, 1154-1162.

Bakker, J.P. & Strahler, A.N., 1956. Report on quantitative treatment of slope recession problems. Union Geographique International, Amsterdam, 1956, 30 -41.

Barry, R., 1961. The punch card and its application in geographical research. Erdkunde, 15(2), 140 - 142.

BARROW, G., 1888. THE GEOLOGY OF NORTH CLEVELAND. Mem. Geol. Surv. U.K., 101pp.

Baulig, H., 1950. Essais de geomorphologie. Paris.

1952. Surfaces d'applanissement. Ann. Géogr., 61, 161 - 183, 245 - 262.

Beaty, C.B., 1956. Landslides and slope exposure. J.Geol., 64, 70 - 74.

1962. Asymmetry of stream patterns and topography in the Bitterroot Range, Montana. J.Geol., 70, 347 - 354.

Belcher, H., 1836. The scenery of the Whitby and Pickering railway. London, 115 + viii pp.

BEST, R.H., 1956. WESTWARD PROGLACIAL DRAINAGE IN CLEVELAND. Proc. Yorks, geol. (polyt.) Soc., 30, 301 - 319.

Bethune, P de & Mammerickx, J., 1960. Slope angle studies at the geomorphological laboratory, University of Louvain, Belgium. Zeitschrift fur Geomorph., Suppl.1, 93 - 102.

Brown, E.H., 1960a. The relief and drainage of Wales. Cardiff, 186pp.

1960b. The building of southern Britain. Zeitschrift für Geomorph., 4, 264 - 274.

1961. Britain and Appalachia: A study in the correlation and dating of planation surfaces. Trans. Inst. Brit. Geogr., 29, 91 - 100.

Bryan, K., 1940. The retreat of slopes. Ann. Ass. Amer. Geogr., 30, 254 - 268.

Carruthers, R.G. 1953. Glacial drifts and the undermelt theory. Newcastl upon Tyne, 42pp.

Chapman, C.A., 1952. A new quantitative method of topographic analysis. Amer. J.Sci., 250, 428 - 452.

Chorley, R.J., 1957a. Illustrating the laws of morphometry. Geol. Mag., 94, 140 - 150.

1957b. Climate and morphometry. J.Geol., 65, 628 - 638.

Clarke, J.I. & Orrell, K., 1958. An assessment of some morphometric method Durham Colleges Department of Geography, Occasional papers, No. 2.

Clayton, K.M., 1957. Some aspects of the glacial deposits of Essex. Proc. Geol. Ass. Lond., 68., 1-21.

Coates, D.R., 1958. Quantitative geomorphology of small drainage basins of southern Indiana. Department of Geology, Columbia University, Technical Report No.10.

Common, R., 1954. The geomorphology of the east Cheviot area. Scot. geogr. Mag., 70, 124 - 138.

1957. Variation in the Cheviot meltwater channels. Geographical Studies., IV, 90 - 103.

Cook, F.A., 1961. Periglacial phenomena in Canada. IN Geology of the Arctic, Vol II., Ed. G.O.Raasch, Toronto. pp. 768 - 780.

Coppock, J.T., & Johnson, J.H., 1962. Measurement in human geography. Econ. Geogr., 38, 130 - 137.

Davis, W.M., 1895. On the development of certain English rivers. Geogr. J., 5, 127 - 146.

Dimbleby, G.W., 1952. Pleistocene ice wedges in North East Yorkshire. J. Soil Sci., 3, 1 - 19.

Drehwald, H.R., 1955. Zur enstehung der spillways in Nord - England und Süd Schöttland Kolner Geographische Arbeiten, Köln.

Dury, G.H., 1959. The face of the earth. Penguin Books, 223 pp.

Dylik, J., 1952. The concept of the periglacial cycle in Middle Poland. Bulletin de la Societe des Sciences et des lettres de Lodz. Classes III, III (5).

1957. Dynamical geomorphology, its nature and methods. Bulletin de la Société des Sciences et des lettres de Lodz, Classes III.

Eakin, H.M., 1916. The Yukon - Koyukuk region, Alaska. Bull. U.S. geol. Surv., 631, 1 - 88.

Elgee, F., 1912. The moorlands of North Eastern Yorkshire. London, 361 + xvi pp.

Ezekiel, M., 1930. Methods of correlation analysis. New York, 427pp.

Fawcett, C.B., 1916. The middle Tees and its tributaries: a study in river development. Geogr. J., 47, 310 - 325.

FLINT, R.F., 1929. THE STAGNATION AND DISSIPATION OF THE LAST ICE SHEET. Geogr. Rev., 19, 256 - 289.

1942. GLACIER THINNING DURING DEGLACIATION. Amer. J. Sci., 240, 29 - 66, 113 - 136.

1957. Glacial and Pleistocene Geology. New York, 589pp.

Fox - Strangways, C.F., 1892. The valleys of North East Yorkshire and their mode of formation. Trans. Leicester lit. phil. Soc., 3, 333 - 339.

FOX - STRANGWAYS, C.F., REID, C., & BARROW, G., 1885. THE GEOLOGY OF ESKDALE, ROSEDALE & C.
Mem. geol. Surv. U.K., 56pp.

FOX - STRANGWAYS, C.F., & BARROW, G., 1915. THE GEOLOGY OF THE COUNTRY BETWEEN WHITBY AND SCARBOROUGH. Mem. geol. Surv. U.K., 144pp.

Gardiner, J.S., 1960. The geomorphology of the basin of the river Ouzel (Bedfordshire - Buckinghamshire). Thesis presented for the degree of M.A. (London).

Geikie, A., 1898. Earth sculpture or the origin of landforms. London, 320pp.

Gifford, J., 1953. Landslides on Exmoor caused by the storm of 15th August 1952. Geography, 38, 9 - 17.

Gilbert, G.K., 1909. The convexity of hilltops. J. Geol., 17, 344 - 350.

Gloriod, A., & Tricart, J., 1952. Étude statistique de vallées asymmetrique Revue de Geomorph. Dynamique., 3, 88 - 98.

Gravenor, C.P. & Kupsch, W.O., 1959. Ice disintegration features in Western Canada. J. Geol., 67, 48 - 64.

Hack, J.T. & Goodlett, J.C., 1960. Geomorphology and forest ecology of a mountain region in the central Appalachians. Prof. Paper. U.S. geol. Surv., 347, 66pp.

Hemingway, J.E., 1958. IN A survey of Whitby and the surrounding area. Ed. G.H.Daysh., Windsor, 254 + xv pp. (See pp. 1 - 47).

Henderson, E.P., 1956. Large nivation hollows near Knob Lake, Quebec. J. Geol., 64, 607 - 616.

HENRY, D.F.C., 1956. THE DEVELOPMENT OF THE ESKDALE (NORTH YORKSHIRE) DRAINAGE SYSTEM IN RELATION TO THE GEOLOGY OF THE AREA. Thesis submitted for the degree of PH.D. (Civil Engineering), University of Leeds.

Hollingworth, S.E., 1952. A note on the use of marginal drainage in the recognition of unglaciated enclaves. J. Glaciol., 2, 107 - 108.

Horton, R.E., 1945. Erosional development of streams and their drainage basins. Bull. geol. Soc. Amer. 56, 275 - 370.

Jahn, A., 1960. Some remarks on the evolution of slopes in Spitsbergen. Zeitschrift fur Geomorph., Suppl.1., 49 - 58.

Johnson, R.H. & Rice, R.J., 1961. Denudation chronology of the south Pennine upland. Proc. Geol. Ass. Lond., 72, 21 - 32.

Judson, S., & Andrews, G.W., 1955. Pattern and forms of some valleys in the driftless area of Wisconsin. J. Geol., 63, 328 - 337.

KENDALL, P.F., 1902. A system of glacier lakes in the Cleveland Hills. Quart. J. Geol. Soc. Lond., 58, 471 - 571.

KENDALL, P.F., 1903a. THE GLACIER LAKES OF CLEVELAND. Proc. Yorks. geol. (polyt.) Soc., 15, 1 - 39.

1903b. SUPPLEMENTARY OBSERVATIONS ON THE GLACIER LAKES OF CLEVELAND. Proc. Yorks. geol. (Polyt.) Soc., 15, 40 - 45.

Kendall, P.F. & Wroot, H., 1924. The geology of Yorkshire. Printed for the authors in Vienna.

Kenney, J.F., 1939. Mathematics of Statistics. Part 1. New York, 248p

Kent, P.E., 1949. A structure contour map of the buried permian rocks of England and Wales. Proc. Geol. Ass. Lond., 60.

King, L.C., 1953. Canons of landscape evolution. Bull, geol. Soc. Amer., 64.

1957. The uniformitarian nature of hill slopes. Trans. Edinb. geol. Soc., 17, 81 - 94.

Klimaszewski, M., 1961. The problems of the geomorphological and hydrographic map on the example of the Upper Silesian Industrial District. IN. Problems of Applied Geography, Warszawa, pp. 73 - 82.

Koons, D., 1955. Cliff retreat in the south western United States. Amer. J.Sci., 253, 44 - 52.

Lamplugh, G.W., 1928. On differential movement in North East Yorkshire during the Jurassic period. Proc. Yorks. geol.(polyt Soc., 19, 383 - 394.

Langbein, W.B., 1947. Topographic characteristics of drainage basins. U.S. Geol. Surv., Water Supply Paper, 968c.

Legget, R.F., Dickens, H.B. & Brown, R.J.E., 1961. Permafrost investigations in Canada. IN Arctic Geology, Vol.II., Ed. G.O.Raasch, Toronto. pp. 956 - 969.

Lewis, W.V., 1939. Snow patch erosion in Iceland. Geogr. J., 94, 153 - 161.

LINTON, D.L., 1951a. THE DELIMITATION OF MORPHOLOGICAL REGIONS. IN. London Essays in Geography. Ed. L.D.Stamp & S.W. Wooldridge., 199-218

1951b. Problems of Scottish Scenery. Scot. geogr. Mag., 67, 65 - 85.

1952. Comments on Professor Hollingworth's notes. J.Glaciol., 2, 108 - 109.

1956. Geomorphology. IN. Sheffield and its region. Ed. D.L.Linton, Sheffield, pp. 24 - 43.

1955. The problem of tors. Geogr. J., 121, 470 - 487.

Logan, R.F., 1945. Glacier border drainage and lobe edge embankments. Amer. J.Sci., 243, 9 - 21.

Macar, P., 1955. Appalachian and Ardennes levels of erosion compared. J. Geol., 63, 253 - 267.

Macar, P., & Lambert, J., 1960. Relations between dip angle and slope angle in the Condroz region, Belgium. Zeitschrift für Geomorph., Suppl. 1., 129 - 132.

Mannerfelt, C.M.Son., 1945. Nagra Glacialmorfologiska Formelement. Geogr. Ann., Stockh., 27, 3 - 239.

1949. Marginal drainage channels as indicators of the gradients of Quaternary ice caps. Geogr. Ann. Stockh., 31, 194 - 199.

Martonne, E.de., 1938. Alignement et dissymetrie des reliefs dans la Region Parisienne. J.Geomorph., 1, 33 - 39.

McConnell, R.B., 1939. Relic surfaces of the Howgill Fells. Proc. Yorks. geol.(polyt.) Soc., 24, 152 - 164.

Melton, M.A., 1957. An analysis of the relations among elements of climate surface properties and geomorphology. Department of Geology, Columbia University, Technical Report.

1960. Intravalley variation in slope angles related to microclimatic and erosional environment. Bull. geol. Soc. Amer., 71, 133 - 144.

Miller, A.A., 1961. Climate and the geomorphic cycle. Geography, 46, 185 - 197.

Miller, V.C., 1953. A quantitative geomorphic study of drainage basin characteristics in the Clinch mountain area, Virginia and Tennessee. Department of Geology, Columbia University, Technical Report, No.3.

Nichols, R.L., 1960. Geomorphology of Marguerite Bay area, Palmer Peninsula Antarctica. Bull. geol. Soc. Amer., 71, 1421 - 1450.

Ollier, C.D. & Thomasson, A.J., 1957. Asymmetrical valleys in the Chiltern Hills. Geogr. J., 123, 71 - 80.

Palmer, J., 1956. The formation of the bridestones in North East Yorkshire and its significance in relation to problems of valley side development and regional glaciation. Trans. Inst. Brit. Geogr., 22, 55 - 71.

Palmer, J. & Radley, J., 1961. Gritstone tors of the English Pennines. Zeitschrift fur Geomorph., 5, 37 - 52.

Parry, J.T., 1960. The erosion surfaces of the south - western Lake District. Trans. Inst. Brit. Geogr. 28, 39 - 54.

Peel, R.F., 1949. A study of two Northumberland spillways. Trans. Inst. Brit. Geogr., 15, 73 - 89.

Peel, R.F., & Palmer, J., 1955. The physiography of the Vale of York. Geography, 40, 215 - 227.

Penny, L.F. 1958. The last glaciation in East Yorkshire. Trans. Leeds Geol. Assoc., VII, p. 65 - 72.

Phillips, C.W., 1961. The Ordnance Survey and archaeology, 1791 - 1960. Geogr. J., 127, 1 - 9.

Pierzchalko, L., 1954. Le problème des vallées dissymmetriques et developpment de la geomorphologie climatique. Czaspismo Geografijny, 25, 359 - 372.

Pinchemel, P., 1954. Les plaines de craie. Paris, 449pp.

Poser, H., 1947. Dauerfrostboden und temperaturhaltnisse wahrend der Wurm Eiszeit. im nicht vereisten Mittek und Westeurop Naturwissenschaften, 34.

Poser, H. & Tricart, J., 1950. Terrasses et phenomenes periglaciaires dans la vallee de l'Huisne en amont du Mans (Sarthe). Bull. Geol. Soc. de France, ser. 5, t 20, 381 - 391.

Pullan, R., 1959. Tors. Scot. geogr. Mag., 75, 50 - 55.

REED, F.R.T.C., 1901. THE GEOLOGICAL HISTORY OF THE RIVERS OF EAST YORKSHIR Cambridge.

Rich, J.L., 1938. Recognition and significance of multiple erosion surfaces. Bull. geol. Soc. Amer. 49, 1695 - 1722.

Rockie, W.A., 1951. Snowdrift erosion in the Palouse. Geogr. Rev., 1951, 41, 457 - 463.

Sauer, C.O., 1925. The morphology of landscape. California Publications in Geography, Vol. 2, No. 2, 19 - 53.

Savigear, R.A., 1956. TECHNIQUE AND TERMINOLOGY IN THE INVESTIGATION OF SLOPE FORMS. Premier rapport de la commission pour l'etude des versants. Union Geographique International, Amsterdam, 1956, 66 - 75.

1960. Slopes and hills in west Africa. Zeitschrift fur Geomorph. Suppl. 1, 156 - 171.

Scheidegger, A.E., 1961. Mathematical models of slope development. Bull. geol. Soc. Amer., 72, 37 - 48.

Schostakowitsch, W.B., 1927. Der ewig gefrorene Boden Sibiriens, Gesell. Erdkunde, Berlin, Zeitschrift., 394 - 427.

Schumm, S.A., 1956. Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. Bull. geol. Soc. Amer., 67, 597 - 646.

Sharpe, C.F., 1938. Landslides and related phenomena. New York 137pp.

Sissons, J.B., 1954. The erosion surfaces and drainage system of south - west Yorkshire. Proc. Yorks. geol. (polyt.) Soc., 29, 305 - 342.

1958a. The deglaciation of part of East Lothian. Trans. Inst. Brit. Geogr., 25, 59 - 77.

1958b. Subglacial stream erosion in southern Northumberland. Scot. geogr. Mag., 74, 163 - 174.

1960a. Erosion surfaces, cyclic slopes and drainage systems in southern Scotland and northern England. Trans. Inst. Brit. Geogr. 28, 23 - 38.

Sissons, J.B., 1960b. Some aspects of glacial drainage channels in Britain. Part 1. Scot. geogr. Mag., 76, 131 - 146.

1961. Some aspects of glacial drainage channels in Britain. Part II. Scot. geogr. Mag., 77, 15 - 36.

Smith, H.T.U., 1949. Physical effects of Pleistocene climatic changes in nonglaciated areas: eolian phenomena, frost action and stream terracing. Bull. geol. Soc. Amer., 60, 1485 - 1516.

Smith, K.G., 1958. Erosional processes and landforms in Badlands National Monument, South Dakota. Bull. geol. Soc. Amer., 69, 975 - 1008.

Strahler, A.N., 1947. Quantitative geomorphic studies in the Verdugo and San Rafael Hills, California. Bull. geol. Soc. Amer. 58, 1230 (Abstract).

1950. Equilibrium theory of erosional slopes approached by frequency distribution analysis. Amer. J.Sci., 248, 673 - 696, 800 - 814.

1952. Hypsometric (area - altitude) analysis of erosional topography. Bull. geol. Soc. Amer., 631, 1117 - 114

1954. Statistical analysis in geomorphic research. J.Geol., 62, 1 - 25.

1956. Quantitative slope analysis. Bull. geol. Soc. Amer., 67, 571 - 596.

1957. Quantitative analysis of watershed geometry. Trans. Amer. Geophys. Union.

Sweeting, M.M., 1950. Erosion cycles and limestone caverns in the Ingleborough district. Geogr. J., 115, 63 - 78.

Te Punga, M.C., 1956. Altiplanation terraces in southern England. Biuletyn Periglacjalny, 4, 331 - 339.

Taillefer, F., 1944. La dissymetrie des vallées Gasconnes. Rev. Geogr. Pyrenees, 15, 153 - 182.

1950. Le versant atlantique des Pyrenees et son avant pays. Revue de Geomorph. Dynamique., 101 - 122.

Thorp, R., 1934. The asymmetry of the 'Pepino'Hills' of Puerto Rico in relation to the trade winds. J. Geol., 42, 537 - 545.

Topley, W., 1866. Notes on the physical geography of East Yorkshire. Geol. Mag., 3, 435 - 439.

Tricart, J., 1960. A subglacial gorge: La gorge due Guil (Hautes Alpes) J. Glaciol., 3, 646 - 651.

Tuck, R., 1935. Asymmetrical topography in high latitudes resulting from Alpine glaciation. J. Geol., 43, 530 - 538.

Twidale, C.R., 1956. Longitudinal profiles of some overflow channels. Geogr. J., 122, 88 - 92.

Valentin, H., 1953. Present vertical movements of the British Isles. Geogr. J., 119, 299 - 305.

Versey, H.C., 1929. The tectonic structure of the Howardian Hills and adjacent areas. Proc. Yorks. geol.(polyt.) Soc., 21, 197 - 227.

1931. Saxonian movements in East Yorkshire and Lincolnshire Proc. Yorks. geol. (polyt.) Soc., 22., 52-58

Versey, H.C., 1937. THE TERTIARY HISTORY OF EAST YORKSHIRE. Proc. Yorks. geol. (polyt.) Soc., 23, 302 - 314.

1942. The build of Yorkshire. Naturalist, Lond., 27 - 37.

1947. The structure of East Yorkshire and Northern Lincolnshire. Proc. Yorks. geol.(polyt.) Soc., 27, 173 - 191.

Visher, S.S., 1941. Climate and geomorphology. J.Geomorph., 4, 54 - 64.

von Engeln, O.D., 1942. Geomorphology: systematic and regional. New York, 655pp.

Walker, E.H., 1948. Differential erosion on slopes of northern and souther exposure in Western Wyoming. Bull. geol. Soc. Amer., 59, 1360 (Abstract).

Warwick, G.T., 1953. Polycyclic swallow holes in the Manifold valley. Premier Congres International de Speleologie., Paris.

WATERS, R.S., 1958. MORPHOLOGICAL MAPPING. Geography, 43, 10 - 17.

Wood, A., 1942. The development of hillside slopes. Proc. Geol. Ass. Lond., 53, 128 - 140.

Wooldridge, S.W., 1932. The cycle of erosion and the representation of relief. Scot. geogr. Mag., 48, 30 - 36.

1958. The trend of geomorphology. Trans. Inst. Brit. Geogr., 25, 29 - 35.

YOUNG, A., 1961. CHARACTERISTIC AND LIMITING SLOPE ANGLES. Zeitschrif für Geomorph., 5, 126 - 131.