THESIS

ON

THE DEVELOPMENT OF THE ESKDALE (NORTH YORKSHIRE) DRAINAGE SYSTEM IN RELATION TO THE GEOLOGY OF THE AREA

Submitted by

F.D.C. Henry, B.Sc., A.M.I.C.E., A.M.Am.Soc.C.E., A.M.I.Struct.E., A.M.I.Mun.E., F.G.S.

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Department of Civil Engineering,
The University of Leeds.

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CONTAINS
PULLOUTS

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CHAPTER I

The Problem in Perspective

In broad terms, this thesis is an attempt to describe the characteristics of the Eskdale Drainage System, North Yorkshire, and to analyse some of the features. The particular aspect of relative land- and sea-levels in pre-Glacial times is one of the foremost considerations. The field techniques employed for the work included surface exploration, spirit-levelling, altimetry, marine echo-sounding, electrical resistivity sub-surface exploration and hand-auger borings. The writer is indebted to Messrs. E. Duncan, D.T. Edmonds, C.T. Marshall, R. Gardener and H.B. Williams of the Civil Engineering Department, University of Leeds, for their assistance in carrying out the instrumental surveys. A note of appreciation is due to Professor R.H. Evans of the University of Leeds for his constant encouragement in pursuing this work. It may be considered that some parts of this thesis are treated at undue length but the writer anticipates that it may be read by persons following quite different professions and detailed accounts may prove useful. For the same reason the presentation is in narrative form and appendices have been avoided. If the reader is familiar with any particular aspects of the work, then a casual glance at the text will suffice.

This investigation appears to be the first in which the equilibrium profile of a river has been extrapolated to determine the levels of former surfaces which are now below preseent ground level. An investigation of this kind has an obvious direct connection with pure geology, but it is worth recording that, from the aspect of applied geology, the possibility of estimating the levels of buried channels by such techniques is of considerable value in civil engineering.

The work embodied in this thesis can be viewed from three different angles. Firstly, it can be regarded as a contribution to the elucidation of the geology of Yorkshire. Secondly, it can be viewed as an exposition of the techniques of analysis of fluvial morphology. Thirdly, it forms an integral part of the comprehensive hydrologic studies which are being carried out by the Department of Civil Engineering of the University of Leeds on the Rivers Esk and Swale in North Yorkshire. The present investigation can be placed in proper perspective by further consideration of each of these viewpoints.

Professor E. J. Garwood (1925) - in his presidential address - drew the attention of the members of the Yorkshire

Geological Society to the suggestion of Professor P. F. Kendall - made in 1914 - that studies of the rivers of Yorkshire might be carried out by members of the Society on co-operative lines similar to those made so successfully in connection with the Underground Waters of the Ingleborough Area. Unfortunately, this proposal received practically no support and the work was never seriously commenced. The only comprehensive study of the Yorkshire river systems is that of Cowper Reed (1901). This reveals that the rivers north of, and including, the Calder-Aire-Humber can be treated as an independent geomorphological unit and are therefore well suited to local investigations of the kind proposed by Kendall and Garwood.

However, no definite programme appears to have been put forward at any time and one may pause to reflect on the nature of the work envisaged. Garwood examined several general problems of river development in his address but they were not specific to Yorkshire. The principal factors with which he dealt were meandering, the effect of the Earth's rotation, the effect of regional tilting and meteorological effects. Cowper Reed's study of Yorkshire rivers was on a regional scale and the next step is therefore to break down the system into smaller units - possibly single rivers. Ultimately, of course, the independent studies must be integrated to place them again on a regional basis which may lead to modifications of Cowper Reed's hypotheses.

Primarily, studies in river development can assist in the elucidation of historical geology. The information which must be sought consists mainly of levels expressed in the form of cross-sections and longitudinal-sections of past and present valleys. Suitable techniques for carrying out this work are discussed in Chapters III and V. The reasons for the existence of meanders in any particular situation can be completely established only through the subject of fluvial hydraulics. In the present work it is not intended to make an extensive study of meandering but well developed meanders - even over short lengths - are noted and an attempt is made to relate their incidence qualitatively to the various factors known to influence meander development. The interesting and unresolved problem of the effect of the Earth's rotation on river development cannot be connected with the west to east flowing Esk but it is possible that some information may be obtained on this when the current studies of the north to south flowing section of the Swale are completed.

Kendall and Garwood may have had in mind further investigations of the mineral content of the Yorkshire river waters, on the lines of the Ingleborough investigations, although there is no evidence to prove this. However, such considerations introduce the possibility of studies in sediment transport, flooding characteristics and dry-weather flow. These aspects are closely connected with geology but the extent to which they can assist in the elucidation of geology is restricted to such factors as rates of denudation. No matter how direct or indirect the connections may be, it is sufficient to admit that such studies are allied to geology and therefore are worthy of pursuit in studying the rivers of Yorkshire.

Turning now to the second viewpoint, since historical geology is concerned largely with submergence and emergence of land masses and the sub-aerial and sub-marine processes of degradation and aggradation which accompany such events, relative levels of land and sea constitute important data in studies of these phenomena. This brings to the fore the necessity for quantitative information and the aids of mathematical sciences. Most investigations of the profiles of river channels and terraces fall into one or other of the following three classes:

1. Investigations in which the levels observed in the field have been interpolated and extrapolated by sketching.
2. Investigations in which a mathematical curve has been evolved solely to fit observed levels most nearly
3. Investigations similar to (2) in which the curve has been extrapolated by calculation.

There are many examples which fall in the first class of purely qualitative interpolation and extrapolation. The investigation of the Ahr by Sittig (1936) - much boosted by Baulig (1940) - consists of a criticism of the earlier work of G.Lafrenz, the reconstruction of valley cross-sections and the correlation of terraces. Other examples are those of Mackin (1937) and Bates (1939). Mackin studied the geomorphology of the intermontane Big Horn Basin, Wyoming, the history of which consisted of relative uplift of the surrounding mountain ranges accompanied by widespread fluvial aggradation of the resulting structural depression followed by partial erosion in this basin leading to the present geomorphological features. Many remnants of gravel terraces at different levels occur in this drainage system and correlation was based on classification of gravels and on longitudinal sections and cross sections. Bates studied the Kickapoo Region, Wisconsin, with particular reference to the development of the upland surface below which the present streams are entrenched and also the development of the present valleys of the drainage system. Part of this work involved correlation of terraces.

Several investigators have endeavoured to derive mathematical equations to represent the equilibrium profile of rivers but few appear to have employed such equations to estimate the levels of former land surfaces. Shulits (1941) evolved an equation and applied it to the Colorado, Mississippi and Ohio. Rubey (1941) records that equations have also been evolved by Sternberg, Putzinger, Schoklitsh and Gandolfo.

The only studies which are truly representative of the third class appear to be those of Jones (1924) and Green et al (1934). Jones constructed longitudinal sections of the Upper Towy and its tributaries, partly from levels taken with a theodolite. He was fortunate in being able to locate the old rock floor in a number of places. An empirical equation was evolved to represent the longitudinal section of the Upper Towy and by extrapolation it was estimated that the earlier base-level was roughly 400 ft. above present sea-level. In the investigation of the River Mole by Green et al. levels were taken with an Abney level from convenient bench-marks to points on the flood-plain and terraces. An equation of the same form as that of Jones was evolved to represent the longitudinal section of the flood-plain of the Upper Mole in which the maximum discrepancy between observed and calculated levels was 3.4 ft. By extrapolation to the lower reaches it was shown that the Upper Mole is graded to the Boyn Hill Terrace of the River Thames. Other terraces and flats were examined in this work without introducing empirical equations.

In connection with quantitative studies, it should be observed that Austen Miller (1939) examined the standards of accuracy which can be attained in estimating pre-Glacial sea-levels by various methods, including that of Jones. He determined that, with two equations of the form proposed by Jones representing the longitudinal section of the Upper Towy and involving discrepancies of 13.8 ft. and 15.5 ft. between observed and calculated levels, the corresponding base-levels are 259 ft. and 415.6 ft. above O.D. - a range of 157 ft. Miller then employed two complex equations which gave better fits and these led to estimates of base-level of 361.8 ft. and

553.5 ft. above sea-level. He justified the use of a complex equation by stating that the processes by which the equilibrium curve of a river is developed in nature are themselves complex but he admits that such equations are unsatisfactory. This practice savours rather of dosing a patient suffering from an undiagnosed malady with every available anti-biotic - it is not a scientific approach though it may be justified by the end-product. Miller is critical of several points connected with these techniques and one feels that he is judging harshly. Without quantitative investigations progress must eventually come to a halt but it should be remembered that simple mathematical laws representing complex geological phenomena can be only approximations to the truth and that it is fundamentally incorrect to assume that geological phenomena are approximations to mathematical laws. It is in the spirit of these words that the present investigation has been conducted.

The third angle from which this particular study of the Esk can be viewed is that of an integral part of a comprehensive hydrologic study of the river. Concurrent with the investigation embodied in this thesis, other studies are in progress and are concerned with the flooding characteristics, the dry-weather flow and sediment transport of the Esk. This river was selected originally because it forms a unit which is not too large for the investigations in mind, certain information on floods during the last hundred years is available and the geology has the attraction of practically horizontal formations - interesting from the aspects of both river development and run-off. At a later stage the River Swale was selected for further studies of a similar nature. This river was chosen because it has a reputation for rapid rise during floods, considerable erosion and shoaling is experienced just below Richmond and geologically one-half is mainly on the Carboniferous Limestone and the other half flows in alluvium in the Vale of York. However, the Swale will not be considered further here - these facts are mentioned simply to place the present investigation in proper perspective.

CHAPTER II

The Geology of Eskdale

Physiography

Eskdale lies in the district known as Cleveland, which covers the northern part of the dissected plateau bounded by the Vale of Pickering, the North Yorkshire coast, the Vale of Mowbray and the valley of the Lower Tees. The stratigraphy and structure of the rocks are reflected broadly in the physiography of the plateau. The highest points on the plateau lie roughly between 1,300 ft. and 1,400 ft. above O.D. on an east-west axis across the centre. The altitudes of the summits decline to the north, south and east. On the north and north-west the boundary is formed by a steep erosion scarp. The Hambleton Hills constitute the western limit of the plateau, with an escarpment of cliffs up to 100 ft. high. The southern boundary is defined by the east-west escarpment cut in the dip slope of the rocks overlooking the Vale of Pickering. The Tabular Hills form the south-east part of the plateau. The eastern boundary is formed by the bold cliffs between Scarborough and Saltburn which rise to nearly 600 ft. at a few points. It is a fair estimate to say that about seventy per cent of the plateau is above 600 ft. and that most of the area is moorland, whereas the surrounding terrain is below or only just above 200 ft. The drainage pattern of the plateau as a whole can be classified as radial, although many of the streams exhibit marked parallelism. On the flat moor-tops the headwaters of drainage systems flowing in different directions are found very nearly linked together.

The catchment of the Eskdale drainage system is about 20 miles long in an east-west direction and an average of about 6 miles wide. The catchment area is about 143 square miles and is very roughly rectangular in shape. The southern watershed follows the east-west line of highest ground mentioned above and the western half is consistently above 1,300 ft. rising to maxima of about 1,420 ft. above O.D. The eastern half of this watershed lies fairly consistently between 800 ft. and 1,000 ft. but about five miles from the coast it commences to decline steadily to the height of the cliffs east of Whitby. The western watershed is about 1,400 ft. above O.D. at its southern end but falls steadily to about 800 ft. in the north. The western half of the northern watershed lies between 800 ft. and 1,000 ft. and the eastern half between 700 ft. and 800 ft. with a steady decline commencing about three miles from the coast and falling to the height of the cliffs west of Whitby.

The floor of the main valley of the Esk rises to an elevation of about 450 ft. at Castleton where it receives the headwaters from Westerdale, Baysdale Beck and Sleddale Beck. The general physical features of Cleveland are shown in Fig.1.

The main tributaries of the Esk rising in the southern part of the catchment, commencing at the estuary, are as follows:

Rigg Mill Beck

Little Beck (Iburndale)

Murk Esk, with its main tributaries

Eller Beck

Wheeldale Beck

Wheeldale Gill

Butter Beck (Egton Grange)

Glaisdale Beck (Glaisdale)

Great Fryup Beck (Great Fryup Dale)

Danby Beck (Danby Dale)

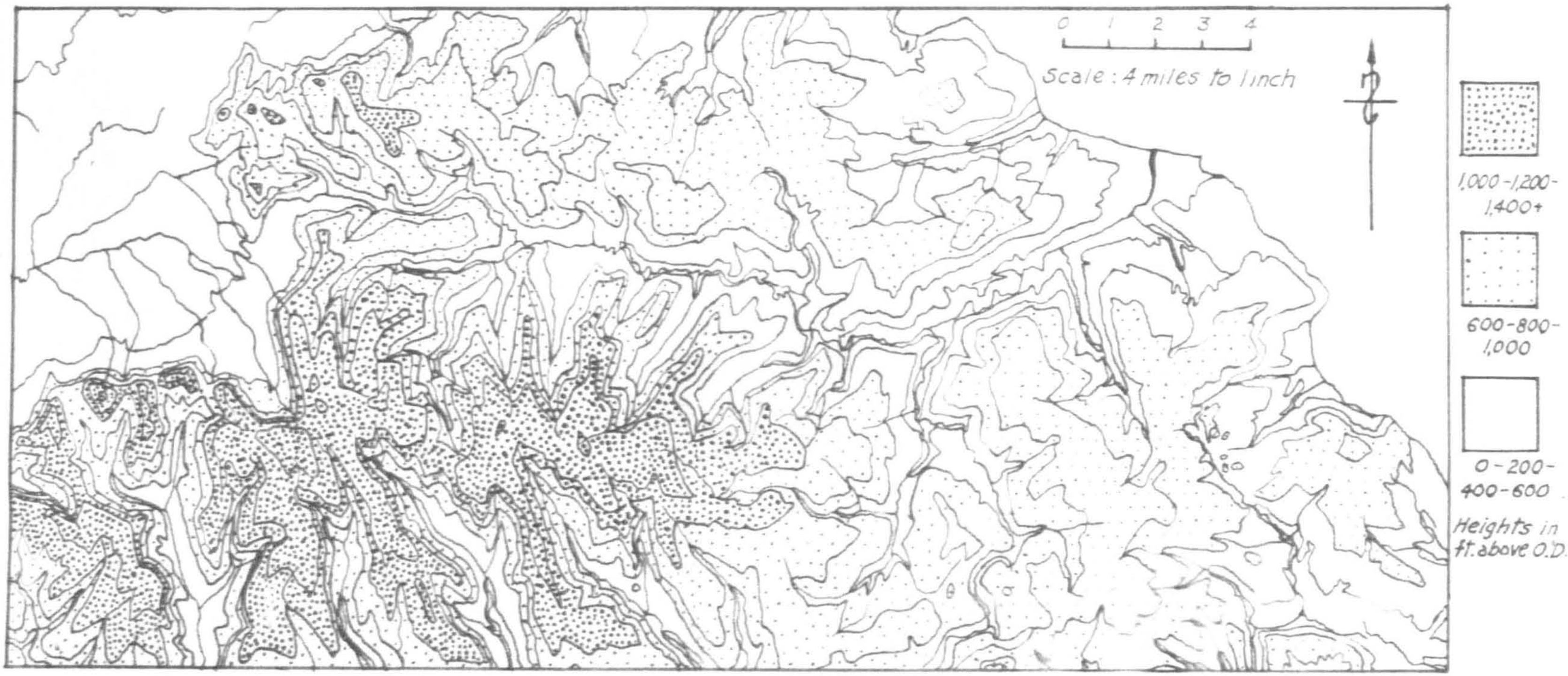
Esk headwaters (Westerdale)

Baysdale Beck (Baysdale)

There are only two main tributaries of the Esk rising in the northern part of the catchment and these are:

Stonegate Beck

Sleddale Beck



The Physical Features of Cleveland

Fig. 1

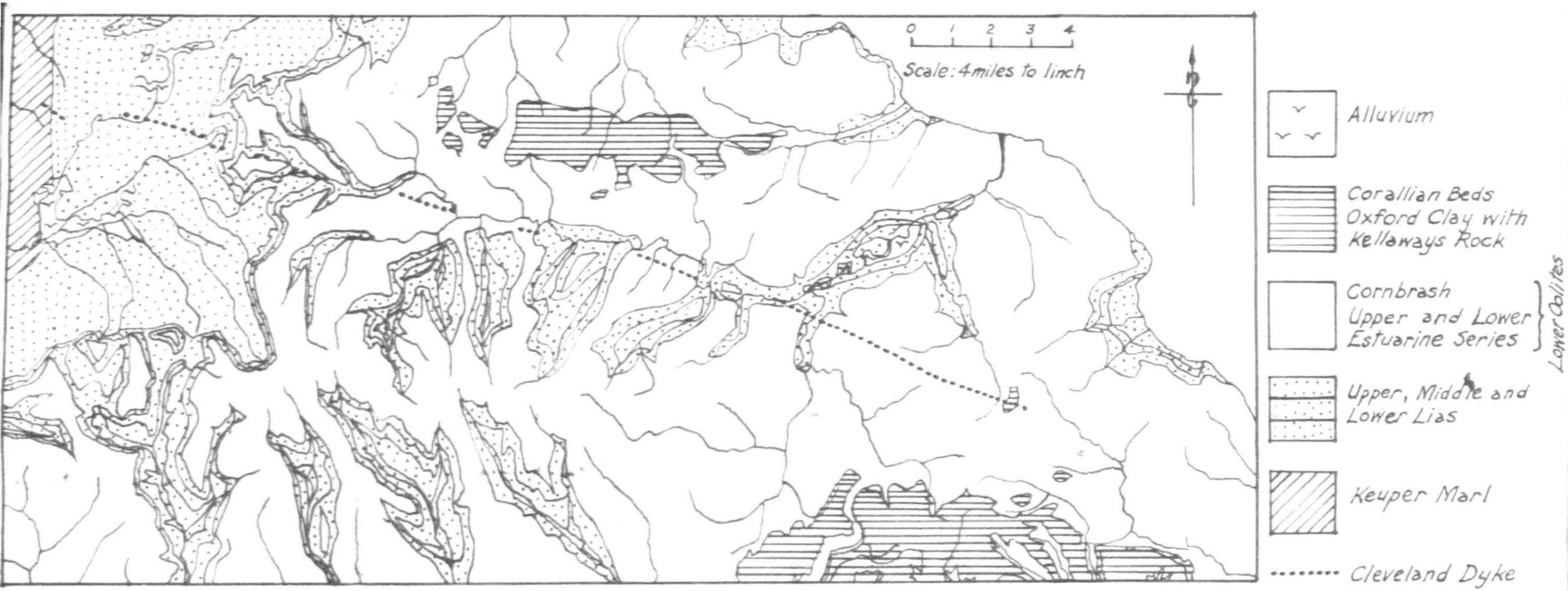
The valley sides of Eskdale and the tributary dales are mostly steep and the sandstones of the Lower Oolites commonly form sharp boundaries to the flatter ground on the moor top. The good state of preservation of the escarpments on the moors above 800 ft. is considered to be proof that they have never been subjected to glaciation and this can be coupled with the fact that there is little Boulder Clay within the catchment above 700 ft. Upstream of a point nearly one mile west of Lealholm the main valley floor attains widths of as much as ¾ mile in which the river meanders but east of this point it is rarely more than ⅛ mile wide with occasional flats of ¼ mile and in this downstream section occur four gorges and several sections of steep cliffs. The pre-Glacial valley of the Esk below Lealholm is largely drift filled but it is obvious that it was both wider and deeper than the present valley. Several of the pre-glacial valleys of the tributaries have been blocked by drift in their lower reaches with the result that new channels have been cut in the solid and appear as gorges. An interesting feature of the Eskdale drainage system is that Eller Beck, Wheeldale Beck and Wheeldale Gill extend roughly two miles beyond the anticlinal axis.

A one inch to one mile scale Ordnance map of the district is enclosed in the pocket in the back cover of this volume.

Stratigraphy

The stratigraphy of Eskdale has been described by Fox-Strangways, Reid and Barrow (1885), Barrow (1888), and Fox-Strangways and Barrow (1915). The oldest formations outcropping in the catchment are Lower Lias. The greater part of the surface of the high ground in the south is occupied by the Estuarine Series of the Lower Oolites and in the north also, together with the Kellaways Rock of the Middle Oolites. The general geology of the area is illustrated in Fig.2. The succession of strata is as follows:

Quarternary	Recent		Alluvium and peat
	Pleistocene		Boulder clay, morainic sands and gravels, glacial lake floor deposits and deltaic gravels
Tertiary			No deposition during this period but the Cleveland Dyke was intruded
Secondary	Cretaceous		Absent
	Jurassic	Upper Oolites	Absent
		Middle Oolites	Corallian, absent. Oxford Clay, just beyond southern watershed Kellaways Rock
		Lower Oolites	
		Upper Lias	
		Middle Lias	
		Lower Lias	



The Geology of Cleveland

Fig. 2

Lower Lias.

The Lower Lias consists of grey micaceous shales with ferruginous doggers. None of the tributary dales descend more than 160 ft. into this formation.

Middle Lias.

The Middle Lias in Eskdale can be divided into a lower Sandy Series (sandstone and sandy shale beds) about 60 ft. thick and an upper Ironstone Series (ferrugineus shales with ironstone bands) 60 ft. to 80ft. thick.

Upper Lias.

The Upper Lias comprises

The Alum Shale
The Jet Rock Series
The Grey Shale

The Grey Shale is soft and of fine material but it is not so well laminated as the beds above. It has a uniform thickness of about 30 ft. throughout Eskdale.

The Jet Rock Series comprises about 90 ft. of laminated shales, with a strong bituminous odour, containing dispersed and nodular pyrites. The true Jet Rock constitutes only the lowest 25 ft. of the series, making a total of 115 ft.

The Alum Shale has a total thickness of about 100 ft.

Lower Oolites.

The succession of Lower Oolites is as follows:

	The Cornbrash
Upper Estuarine Series (about 200 ft. thick)	Shale with thin beds of sandstone
	Sandstone (Moor Grit)

	Grey Limestone Series
Lower Estuarine Series (about 280 ft. thick)	Shale and sandstone with thin coals Millepore Bed (marine band - absent) Sandstones and shales Eller Beck Bed Sandstone and shales with thin coals
	The Dogger Bed

The lithology of the Dogger Bed is variable and in different localities has the composition of a sandstone, a limestone, an ironstone, a shaly bed and a nodular calcareous rock with little bedding. In some places it appears to form a passage bed between the Lias and the Lower Oolites, in others it rests on the eroded surface of the shales and occasionally it is absent and the Estuarine Sandstones rest directly on the Alum Shale.

About 100 ft. above the Alum Shale is the marine Eller Beck Bed. Its boundaries are not clearly defined and there is a gradual transition between it and the beds above and below. It is described as a flaggy, fossiliferous sandstone, or sometimes oolitic ironstone, resting on shales in which occur nodules or thin beds of fossiliferous ironstone. It attains its greatest known thickness of 41 ft. in Wintergill at the head of Glaisdale.

The Grey Limestone Series is a marine bed about 30 ft. thick and consists mostly of fossiliferous shales with thin siliceous and calcareous bands and thin beds of ironstone but westwards the beds become more arenaceous and thick fossiliferous grits occur. Where exposed, the calcareous sandstone commonly has a porous appearance on account of leaching of the lime matrix.

The Moor Grit is a hard, white siliceous sandstone.

The Cornbrash appears most commonly as about 10 ft. of soft shale resting on 4 ft. of sandy, ferruginous marl. Its outcrop forms a ring round the base of the Kellaways Rock on the northern part of Eskdale but neither of these formations appear in the south until the watershed is reached.

Middle Oolites

The Middle Oolites are represented in the catchment only by the Kellaways Rock. The soft Oxford Clay has been completely removed, although it appears just beyond the southern watershed. The Kellaways Rock is a close-grained sandstone with lines of small quartz pebbles andoccurs as a bed of average thickness 80 ft. to 100 ft. It forms the moor top of Moorsholm Moor, Danby Moor and Lealholm Moor and its dryness contrasts markedly with the wet underlying Estuarine Shales.

The Cleveland Dyke.

The only igneous rock occurring within the catchment is the Cleveland Dyke - an intrusion of tholeiite or augite-andesite, bluish-grey in colour, with a devitrified glassy base. The surface width of the dyke varies between 20 ft. and 30 ft. but an adit driven through it near Great Ayton - about 4 miles west of the western watershed - proved a breadth of 80 ft. It enters the western end of the catchment at the head of Kildale, extends south-eastwards in a series of intermittent exposures and terminates at the head of Iburndale. The dyke does not lie along the line of an evident fault. The adjacent sedimentary rocks have been altered for a distance of 5 ft. to 10 ft. from the contact. Where the intrusion occurs in the sandstones of the Oolites, percolating water has facilitated decomposition of the igneous rock- sometimes to a depth of nearly 200 ft. - but ih the Lias Shale it is shielded from percolating water and is unaltered. The Cleveland Dyke appears to have been intruded in the Pyrenaean (Pre-Oligocene) phase. The Esk and several of the tributaries cross the dyke at a number of points but do not appear to be influenced by it to-day.

Glacial Deposits

The Glacial Deposits consist mostly of Boulder Clay with some sands and gravels in pockets in the clay. Morainic and deltaic deposits are described later. The Boulder Clay covers the greater part of the country south-east of the estuary of the Esk and the slopes of Iburndale are completely swathed. North-west of Whitby the base of the Boulder Clay descends below sea-level but rises again as Sandsend is approached. Boulder Clay is found in Eskdale and all the tributary dales in the southern part of the catchment from Whitby to Castleton, the amount decreasing westwards, but it does not occur in Westerdale or Baysdale and in Sleddale there are only two very small patches in the glacial overflow channel from Lake Kildale.

Recent Deposits

The peat within the catchment is not extensive. It is classified arbitrarily as hill peat and slack peat - the latter occurring in the glacial overflow channels.

Alluvium occurs along almost the entire length of the main river in flats of varying width but is absent in the gorges. It occurs also along some of the tributaries, more particularly the Murk Esk, Danby Beck and the Esk headwaters in Westerdale.

Structure

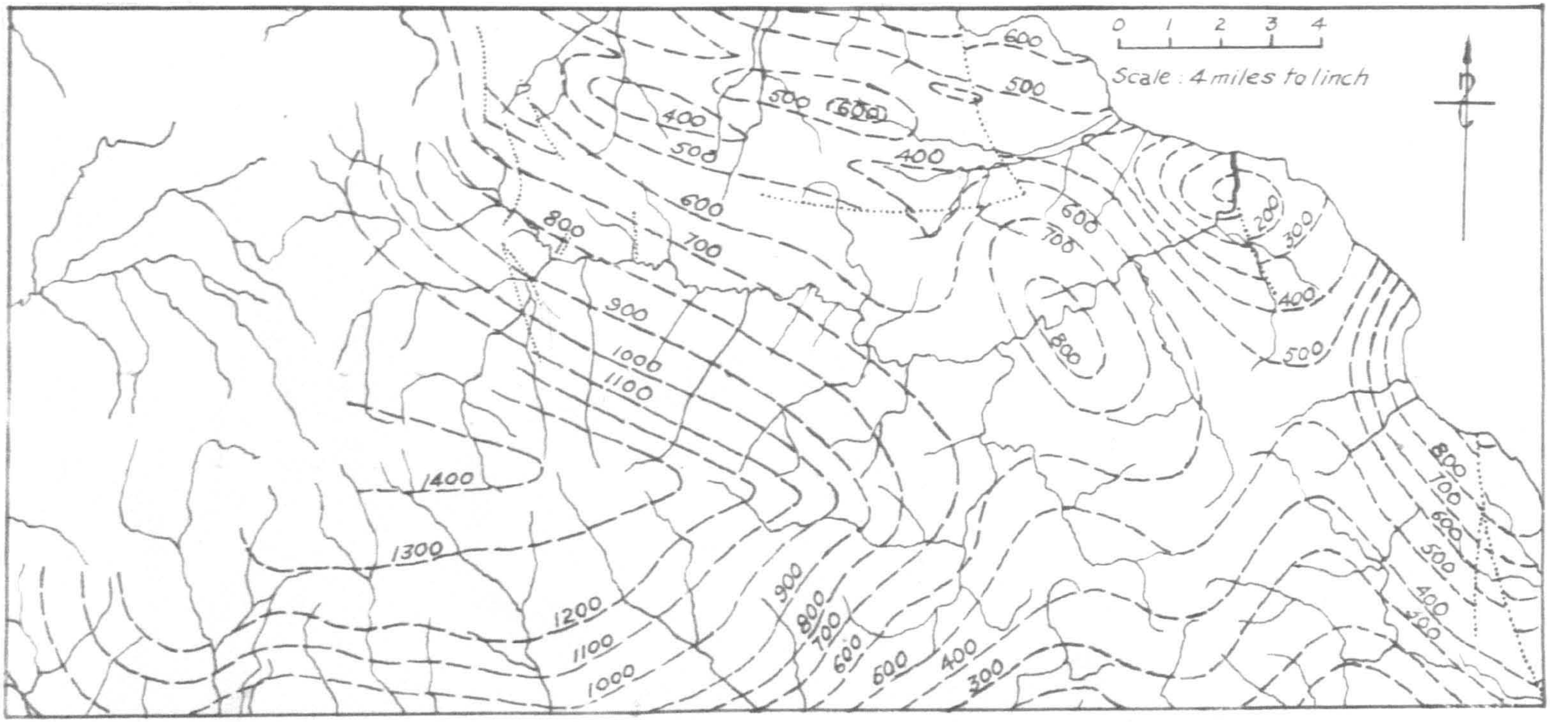
Uplift and Folding

The structure of Cleveland and the surrounding area has been analysed by Versey (1937, 1948) and the following is a summary of probable movements in Kimmerian and later phases.

Wallachian (Post-Pliocene)	Vale of Pickering Fault ?
Attic (Pre-Pliocene)	Arching of Wolds Peneplane in Cleveland
Styrian (Pre-Upper Miocene) and Savian (Pre-Lower Miocene)	Folding of Pennines
	Wolds Folding
	Humber Fault and parallel faults

Pyrenaean (Pre-Oligocene)	Intrusion of Cleveland Dyke
Laramide (Pre-Eocene)	Regional Uplift
	Faulting in Northern Wolds
Sub-Hercynian (Pre-Senonian)	Shallowing in Holaster planus Time
Austrian (Pre-Cenomanian)	Later movement of Market Weighton Anticline
	Caistor Anticline
Kimmerian (Pre-Rhaetic or Pre-Tithonian?)	Main movement of Market Weighton Anticline
	Heslerton Syncline
	Main movement of Howardian Faults
	Minor domes in Cleveland

In order to determine the structure of Cleveland, Versey (1937) plotted the contours of the base of the Grey Limestone Series and these are reproduced in Fig.3. This series was selected because of its extensive development and - as a marine incursion in a deltaic series - can be assumed to have been deposited in a comparatively horizontal plane. It will be seen from Fig.3. that the main Cleveland uplift is an elongated dome with its centre probably just south of Ingleby Greenhow. Subsidiary domes occur at Sleights Moor and Robin Hood's Bay. A basin is centred at Whitby and two feeble depressions will



The Geological Structure of Cleveland as Revealed by Contours of the Grey Limestone Series

After Versey

Fig. 3

also be observed - one is occupied by the Murk Esk and the other lies between Sleights and Robin Hood's Bay.

Faults

The major fault within the catchment is that with a downthrow of 200 ft. on the west which trends roughly north to south through the estuary of the Esk at Whitby and extends to Rigg Mill Beck. In conjunction with the Boulder Clay in the pre-Glacial channel of the Esk, this fault is responsible for the present location of the estuary but it does not appear to affect the present course of Rigg Mill Beck and its tributaries.

A mile-long fault extends roughly west to east from Lealholm Moor to Hutton Mulgrave Moor - the latter is just north of the catchment. The downthrow is on the north side of the fault; the amount is given as 100 ft. on the map and 150 ft. to 200 ft. in the memoir.

There are four minor faults trending roughly north to south with downthrows on the east of magnitude 20 ft. to 40 ft. between Commondale and Danby but these do not appear to influence the drainage pattern. At the mouth of Westerdale is a small trough fault trending roughly north to south but the throw is not given either on the map or in the memoir-comparison with the contours indicates that it is about 40 ft.

Glaciation

A comprehensive study of the glaciation of Cleveland was reported by Kendall (1903). Some of the effects of the glaciation bear no relationship to the present drainage system whilst others influence it profoundly. During the slow retreat of the ice northwards, a number of glacial lakes were formed in Cleveland. The Eskdale series of lakes discharged into Lake Wheeldale and then via Newtondale into Lake Pickering and this in turn discharged through a gap in the Howardian Hills at Kirkham Abbey, near Malton, into the Vale of York.

Lake Eskdale, at its maximum extent, was bounded by a lobe of the North Sea Ice at Lealholm and by the Vale of York Glacier at Kildale and the highest water level was about 725 ft. As the level of the water in Lake Eskdale fell, some of the water at the fringes was cut off to form Lake Kildale and Moorsholm Lake. These secondary lakes discharged into the primary Lake Eskdale and in this way a number of overflow channels were developed, including the channel now occupied by the middle reaches of Sleddale Beck, Ewe Crag Slack, Hardale Slack, Tranmire Slack and Moses Slack. Gravel deltas were commonly formed at the lower ends of these channels and are found near Commondale, Hell Hole, Danby and at the lower end of Tranmire

Slack. Glacio-lacustrine deposits in the form of varved clay are found in the main valley of the Esk between Danby and Houlsike. The outlets from Lake Eskdale to Lake Wheeldale and Newtondale include Lady Bridge Slack, Moss Slack, Purse Dyke Slack, Moss Swang and Randay Mere overflow.

A terminal moraine was deposited across the Esk valley by the lobe of ice at Lealholm and as the drainage of Eskdale began to return to its pre-Glacial pattern, an overflow known as Wild Slack - now deserted - was cut in the south end of the moraine but subsequently the present Crunkly Gill channel was initiated. A deserted in-and-out channel known as Sunny Brake Slack occurs between Lealholm and Glaisdale. Another terminal moraine was deposited at Glaisdale and the river now flows in a gorge at the south end of this. The top of the moraine is at a lower level than the top of the gorge and it is apparent that ice obstructed eastward drainage over themoraine. The pre-Glacial channel was blocked by Boulder Clay just east of Glaisdale and the Esk now flows in another gorge at this point. Scenically, this is the most attractive of the Eskdale gorges - it is about ¾ mile long and is on a grand scale. The pre-Glacial channel was also blocked by a mass of Boulder Clay between Ruswarp and Whitby and the river now flows in the deep but comparatively open gorge at Larpool. Boulder clay blocked the pre-Glacial channels of several of the tributaries and gorges have been cut by Rigg Mill Beck, Little Beck, Eller Beck, West Beck, the Murk Esk, Butter Beck, Glaisdale Beck and Stonegate Beck.

Another glacial lake, known as Iburndale Lake, discharged through a channel forming the present peat filled Biller Howe Dale at the head of the system draining to the River Derwent.

The latter stages of the northerly retreat of the ice are marked by a series of morainic ridges of sand and gravel on the northern slopes above Glaisdale and by a series of overflow channels in the northern watershed above Egton Bridge. The most prominent channels are Middle Carr Slack, Stonedale Slack and a gorge at Barton Howl and these represent overflows from a small lake impounded between the ice margin and the northern flanks of the watershed.

History of the Eskdale Drainage System.

The history of the Eskdale drainage system must be reviewed on a regional basis and reference is made to Cowper Reed (1901) and Versey (1937, 1948). It commences as the Chalk of North Yorkshire slowly emerged from the Cretaceous sea. To date no evidence has been found of the existence of Chalk deposits in Cleveland but the general opinion is that the Chalk of the Yorkshire Wolds extended into this area. As the sea receded eastwards a certain amount of marine erosion of the Chalk undoubtedly took place and the exposed surface sloped gently east or south-east with, of course, deformities due to former crustal movements. The present drainage system was originally developed on this surface. At no subsequent time does there appear to have been widespread inundation although there were minor incursions by the sea.

Prior to this regional emergence, which occurred in the Laramide and which was accompanied by slight tilting eastwards, minor domes had been formed in Cleveland in the Kimmerian and these were truncated by erosion and a peneplane was formed which constituted a northern extension of the Wolds peneplane. A monadnock remained in central Cleveland in the area now standing above about 1,200 ft. The direction of the consequent streams in North Yorkshire was generally south-eastwards and the Esk then constituted the lower reaches of the original Greta-Tees system. The Pennines were then folded in the Styrian and Savian and this initiated a second fluvial cycle in the drainage system. The other Pennine rivers (Swale, Ure, Nidd, Wharfe, Aire) also flowed south-eastwards direct to the sea but ultimately the first four were captured by a subsequent of the powerful Aire-Humber consequent system working northwards along the

Triassic outcrop now beneath the Vale of York. The Greta-Tees was captured by a subsequent stream working southwards from the north and the Esk was left as a beheaded remnant.. The obsequent developed during this process of capture is the Leven, a tributary of the Tees. The marked lack of control of the Esk by various structures confirms that it is superimposed.

The arching of the peneplane in Cleveland on an east to west axis, accompanied or followed by the Vale of Pickering Fault, led to the initiation of the radial drainage pattern which exists in Clveland to-day and this includes, of course, tributaries of the Esk. The directions of dip given by Fig.3. correspond reasonably well with those given on the maps of the Geological Survey - the maximum discrepancy in direction appears to be about 20° on Castleton Ridge. It will be seen that the streams in Westerdale, Danby Dale, the Fryup Dales and Glaisdale flow fairly directly down dip. The headwaters of Baysdale Beck flow directly down dip but the lower reaches flow obliquely down dip. According to Fig.3. Sleddale Beck flows obliquely down dip but the Geological Survey map shows the dip directly downstream in the vicinity of the headwaters. Stonegate Beck is essentially an anti-dip stream. Rigg Mill Beck follows roughly the dip but the course of LittleBeck bears no obvious relationship to the structural contours. The Murk Esk also is not influenced by the dip although its tributaries Wheeldale Gill and Rutmoor Beck flow mainly down dip. Eller Beck is an anti-dip stream. Both Wheeldale Beck and Eller Beck have cut their way southwards beyond the watershed. Wheeldale Beck captured Wheeldale Gill, the original headwaters of the River Derwent, and Eller Beck appears to have captured small portions of the headwaters of Pickering Beck. The headward growth of the obsequent Leven resulted in the capture of Lounsdale Beck and Warren Beck, originally two of the headwaters of the Esk on the north and south slopes of Kildale Gap.

It is generally acknowledged that all the main characteristics of Eskdale had been developed before the Glacial Period although minor alterations occurred during and since that time. It is unlikely that the valleys of Eskdale were deepened by glacial erosion.

CHAPTER III

Field-work

The field techniques employed for the work included surface exploration, spirit levelling, altimetry, marine echo-sounding, electrical resistivity sub-surface exploration and hand-auger borings. It was appreciated that some of this field-work might prove fruitless due to limitations of equipment and other factors but at least the potentialities of the techniques in this type of investigation would be revealed. The conclusions drawn in this respect are discussed in the appropriate sections below.

Surface Exploration

The surface exploration covered the main river, all the major tributaries named in Chapter II under the heading "Physiography" and several minor tributaries where it was considered that their characterisitics might prove significant. Almost the entire lengths of these streams were explored with a view to describing the characteristics of each, noting such features as the depth of incision in the valley, the presence of meanders and the effect of resistant beds of rock. The observations made during this work are given in Chapter IV. It was sometimes necessary to examine other geomorphological features - such as landslips at the heads of Great and Little Fryup Dales, Danby Dale and Westerdale - where it was considered that these might be directly related to the development of the drainage system; these features are referred to in the appropriate sections of Chapters IV and V.

Levelling

Levelling was required for the production of the longitudinal sections of the streams. From Ruswarp to Westerdale cross-sections were taken on the main river by spirit levelling with engineers' tilting levels and staffs. Two Cooke, Troughton and Simms S.300 levels and a Wild N1 level were employed. These sections were commonly taken in groups at intervals of one-quarter of a mile along the winding course of the river and the three sections in each group were spaced at intervals of 50 ft. The object of taking three in a group was to obtain average conditions at each one-quarter of a mile. The staffs were usually read to the nearest 0.01 ft. although on some sections they were read to 0.1.ft. It was generally considered desirable to read to 0.01 ft., even though plotting was to the nearest 0.1 ft. since the second decimal figure might reveal anomalies in the terrain - for example, on a wide alluvial flat. The levels on the river bed were usually taken directly on a staff held either by a man wearing waders or by a man in a boat. A portable boat weighing 40 lbs. with two oars and made of canvas on a light framework was employed and this could be carried by one or two men as convenient when folded. Where the immediate valley sides are steep, the levels were not taken much higher than the top of the river banks but, where there are alluvial flats, the levels were extended as much as several hundred feet from the banks. It was intended that these cross-sections should be used for several purposes and hence the work was done in detail.

Longitudinal sections of streams are normally constructed from levels taken by relativelyapproximate methods or from topographical maps on which the contours are spaced at vertical intervals of 25 ft. or more. It was considered desirable to compare a longitudinal section obtainedby accurate levelling with one constructed from Ordnance Sheets to the scale of 6 inches to 1 mile and to ascertain if the greater accuracy yielded a more revealing section. It is intended that, when similar work on the Swale is completed, the form and dimensions of the river channels should be studied in relation to such factors as surface morphology and geology in addition to the more usual considerations such as run-off. The cross-sections are also being used for the flooding, dry-weather flow and sediment transport studies mentioned in Chapter I.

It is proposed in the near future to take a number of cross-sections in the two mils of tidal estuary between Ruswarp and the coast. The observations will comprise levels of alluvial flats, banks and water surface taken with a tilting level and staff and depths to the bed measured with a sounding line from a boat. The position of the boat at each sounding will be observed with two theodolites. It is unlikely that this work would yield anything of particular interest in connection with this thesis but it will enable a complete picture of the Esk to be drawn.

It was originally intended that the levels on the tributaries should be observed by a combination of altimeter, hand-level and topo-pole. The technique of measuring a cross-section in this way is illustrated in Fig.4. Where a base-altimeter or micro-barograph for recording the variation in barometric pressure throughout the period of the observations is not available - as in this case - it is necessary to check with the altimeter between Ordnance bench-marks at intervals of one hour. Corrections are then made to the altimeter readings assuming a linear variation in pressure on a time base.

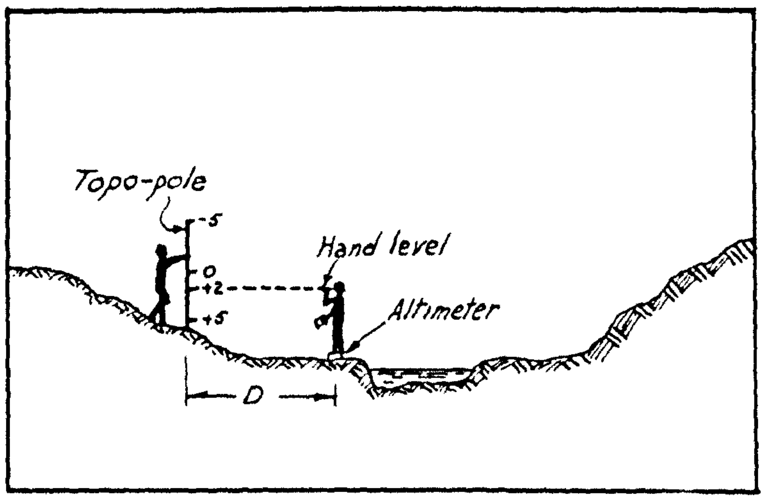


Fig. 4

The altimeter is set on a convenient point on the ground at each cross-section and the reading is noted. The topo-pole consists of a 10 ft. strip of wood hinged in the centre and is graduated in intervals of 0.1 ft. from 0 to -5 ft. from the centre to the top and from 0 to +5 ft.from the centre to the bottom. An adjustable foot enables the zero graduation on the topo-pole to be set to the same height above ground as the eye of the observer. The hand-level consists of a telescope and bubble-tube and is similar to an Abney level but without the means of measuring vertical angles. An Abney level can, of course, be employed for this purpose and the vernier arm is set to zero vertical angle. The topo-pole reading is taken when the bubble and graduation appear coincident in the half-mirror in the telescope. The readings represent heights above or below the feet of the observer who stands by the altimeter. The distance D can be measured by a tape or by pacing. When the ± 5 ft. limit of the topo-pole is reached the observer can more forward to the position occupied by the topo-pole and the levels can be extended for a further interval of ± 5ft. The accuracy of this method is much less than that obtained with a tilting level but is sufficient in rough country provided reasonable accuracy in altimetry is attained. It is preferable, of course, to employ three field altimeters and the mean reading is adopted for the basic level at each cross-section.

Difficulty is experienced in reading the topo-pole where the sights exceed 50 ft. since the hand level is non-magnifying. However, this difficulty is not insurmountable and in any case in rough country the sights are commonly less than 50 ft. Most of the altimetry and some of the topo-pole work on the Murk Esk, Eller Beck and Rutmoor B eck was completed although the altimetry was unsatisfactory and eventually the results were discarded. Before embarking on this particular project, literature on the subject of altimetry was perused. Sparks (1955) emphasizes the effect of weather on the determination of heights by altimeter and states that under good observing conditions an error not exceeding ± 5 ft. can be obtained in a corrected traverse of one hour's duration. One gains the impression from several sources that weather is the most important factor and that the intrinsic accuracy of the altimeter is good enough to permit it to be read to the nearest 1 ft. by vernier. The field-work was pressed forward on this basis but suspicions grew and a halt was called. Tests were then made on two new altimeters and from these it was concluded that the instruments were fundamentally defective and that mechanical hysteresis, friction and backlash were probably the causes of inaccuracies. The instruments did not appear to suffer from creep - manifest in a change of reading with time at constant pressure. Furthermore, either the vernier or the main scale graduations were somewhat inaccurate and did not justify reading to 1 ft. It was clear that, even given good observing conditions, an accuracy better than ± 10 ft. could not be guaranteed and this was not good enough for the investigation in hand. Consequently a search was made for an instrument likely to yield better results than this and eventually it was found that Swedish Paulin altimeters have been obtainable in Great Britain since early in 1955. These instruments are designed so that the defects apparent in the instruments mentioned above are a minimum. One was ordered and received towards the end of 1955 but it had been damaged in transit and was therefore returned to Sweden for repair. Unfortunately, the repaired instrument did not arrive in time for use on the Esk and its tributaries but the writer has made a number of test circuits between Ordnance Bench Marks with it. The results shown in Table 1 are a representative sample.

There are several general observations arising from these tests. A point which is not mentioned by the manufacturers is that levelling of the instrument is vital for accurate work. The writer found that a slight tilt was sufficient to throw the balancing pointer off the null reading, thus leading to errors of 1 to 3 metres.

TABLE 1

Altimeter Trial

Instrument: Paulin No.6621, range -350 to +725 metres
Location: Station Road, Burley-in-Wharfedale. Date: 1Nov.1956.
Weather: 10/10 cloud, steady barometer, occasional slight wind.
Standard latitude for instrument: 45°
Field latitude: 54° N approx., latitude correction to altitudes -0·08% (negligible).
Standard air temperature for instrument: +10°C, corrections determined from Paulin Tables.

Station	O.S. Bench Mark ft.	O.S. Bench Mark metres	Correction to Station m	O.S. Station altitude m	Time	Air Temp. °C	Obs. Alt. m	Obs. Differences m	Air temp. corr. m	Corr. diff. m	Closing error corr. m	Corr. diff. m	Corr. obs. alt. m	Discrepancy m
A	283·0	86·2	0	86·2	09·35	6·2	-77·5						86·2	0
								6·5	-0·1	6·4	-0·8	5·6		
B	301·5	91·9	-0·3	91·6	09·40	6·2	-71·0						91·8	+0·2
								15·7	-0·2	15·5	-1·5	14·0		
C	353·0	107·6	-0·4	107·2	09·50	6·2	-55·3						105·8	-1·4
								10·1	-0·1	10·0	-0·8	9·2		
D	377·3	115·0	+0·2	115·2	09·55	6·2	-45·2						115·0	-0·2
								13·2	-0·2	13·0	-1·7	11·3		
E	416·2	126·8	-0·4	126·4	10·05	6·2	-32·0						126·3	-0·1
								19·5	-0·3	19·2	-1·4	17·8		
F	472·5	144·0	-0·4	143·6	10·15	5·8	-12·5						144·1	+0·5
								22·0	-0·3	21·7	-0·9	20·8		
G	541·2	164·9	0	164·9	10·20	5·6	+9·5						164·9	0
								20·3	-0·3	20·0	+0·4	20·4		
F	472·5	144·0	-0·4	143·6	10·30	5·6	-10·8						144·5	+0·9
								17·0	-0·2	16·8	+0·4	17·2		
E	416·2	126·8	-0·4	126·4	10·40	6·0	-27·8						127·3	+0·9
								10·7	-0·1	10·6	+0·2	10·8		
D	377·3	115·0	+0·2	115·2	10·45	6·2	-38·5						116·5	+1·3
								7·3	-0·1	7·2	+0·4	7·6		
C	353·0	107·6	-0·4	107·2	10·55	6·4	-45·8						108·9	+1·7
								15·2	-0·2	15·0	+0·4	15·4		
B	301·5	91·9	-0·3	91·6	11·05	6·6	-61·0						93·5	+1·9
								7·0	-0·1	6·9	+0·4	7·3		
A	283·0	86·2	0	86·2	11·15	7·0	-68·0							

The discrepancies are the corrected observed station alititudes minus the O.S. Station altitudes calculated from the Ordnance Survey Bench Marks. The mean values of the forward and return observations and the corresponding discrepancies are as follows:

Station	B	C	D	E	F
Mean altitudes m.	92·7	107·4	115·8	126·8	144·3
Discrepancies m.	+1·1	+ 0·2	+ 0·6	+ 0·4	+ 0·7

A small circular spirit level of the type used with a plane table can be placed on the glass face of the instrument and levelling is effected by a pencil, piece of wood, small stones or, best of all on rock or paved surfaces, two rubber window wedges. A further adjunct for accurate reading is a magnifying lens - the writer found the old-fashioned reading lens with a magnification of about four most suitable and this enables the dial pointer to be read to an estimated 0.1 metre with an accuracy of 0.2 to 0.3 metre. Hence the accuracy of reading the dial can be of the order of 1 ft. Given good observing conditions with steady barometric pressure and taking precautions on the lines indicated above, checks between bench-marks indicate that the accuracy of observations is generally better than ± 1.5 metres, or say ±5ft. andis frequently better than ± 3 ft.

For the longitudinal sections of the tributaries it was therefore necessary to resort to the 6 inches to 1 mile sheets of the Ordnance Survey and enquiries were made to ascertain the likely accuracy of the contours. The Ordnance Survey gave a full reply but the most important information concerning the present study is that a check was made recently on contours in the Oldham area, which were derived under the same conditions as those in Yorkshire, and that the standard error of the instrumental contours was found to be 1.45 ft. and of the interpolated contours was 2.46 ft. The standard error to given by $\sqrt{\frac{\Sigma e^2}{n}}$ where e is the height error at any given point on any contour and n is the number of checks made. From this information it can be concluded that levels obtained from the contours will be within $\pm$ 2 to 3 ft. of the true level with few exceptions. In the Cleveland area the vertical intervals on the 6 inches to 1 mile sheets are 25 ft. from 0 to 1,200 ft. and 50 ft. above 1,200 ft. The instrumental contours are 25, 50, 100, 150, 200, 250, 300, 350, 400, 500, 600, 800, 1,000 and 1,200 ft., the remainder are sketched.

The longitudinal profile of the main river (Fig.23) has been plotted both from the 6 inches to 1 mile Ordance Sheets and from the cross-sections obtained by levelling. Each set of three cross-sections was examined and the average level of the bank top was selected for producing the longitudinal profile. Selection was often difficult in gorges and beneath cliffs and even where the terrain was relatively flat. Of the 82 cross-sections, nos.21 and 22 were uncompleted, and the distribution of discrepancies between the remaining 80 and the profile derived from the Ordnance Sheets is shown in the table below. The positive sign implies that the level obtained from the cross-sections is higher than that obtained from the Ordnance Sheets and the negative sign implies that the cross-section level is lower.

	Negative										Positive										
Discrepancies ft.	10	9	8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8	9	10
Occurrences no.	0	0	0	0	0	2	4	5	2	10	21	4	7	7	8	1	2	5	0	1	1

Discrepancies up to $\pm$ 3 ft. can be expected in the light of the comments made by the Ordnance Survey and the proportions of observations within this range is 70 per cent. The reason for discrepancies outside this range must be due largely to the fact that the topographical surveyor producing the Ordnance Sheets has averaged his observations in the field. In order that an average profile can be derived from cross-sections it is obvious that many more than 82 would be required. This result is not unexpected and confirms that Ordnance Sheets yield sufficiently accurate data for most geomorphological studies. However, it also emphasises the care required in taking infrequent spot-levels on banks or flood-plains from which profiles are constructed. The reason for the predominance of positive discrepancies is rather obscure but it may be due to the fact that bank-top levels are usually a little higher than mean ground levels.

Echo-Sounding

An echo-sounding survey was carried out in an area between Whitby Piers and Upgang, extending roughly 1¼ miles seawards from the cliffs, in order to ascertain the levels of the present submarine channel of the Esk beyond Whitby Harbour and to endeavour to locate the buried channel between Whitby and Upgang. At the time when this survey was made it was assumed that the tentative line of Hemingway (1940) (Fig.9) represented the pre-Glacial channel, whereas the present writer subsequently formed the opinion that this particular line roughly follows an inter-Glacial valley, as discussed in Chapter V under the heading of "The General pre-Glacial Course of the Esk", and the pre-Glacial channel is considered to be between Upgang and Sandsend. Consequently, this hydrographic survey ought to have been extended westwards to Sandsend but the writer had not at that time considered the problem in detail and unfortunately this extension of the work was never contemplated.

Several of the Whitby fishing boats are equipped with echo-sounding gear and one of these - the "Provider A" (Skipper J.J.Storr) - was chartered for the work at a total cost of £12. This vessel has a displacement of 39 tons, length 59 ft., beam 18 ft. and draught 6½ ft. laden and unladen. The transmitter and receiver - known collectively as the oscillators - are 5 ft. apart horizontally and are located at a depth of 6 ft. below the water-line. The sounder is a Type MS 20 manufactured by Kelvin and Hughes Ltd. and operates on a frequency of 15,000 cycles per second. The oscillators are 20 ft. aft of the foremast, on which the sights were taken from the shore. The speed of the boat whilst recording was generally about 8 knots.

The MS 20 was designed principally for locating fish shoals and it is not recommended for shallow water soundings by manufacturers, although they considered that it would probably give sufficient results for the present investigation. When hiring equipment of this kind, one is very much in the hands of the owner and it was not possible to make all the desirable tests and adjustments. The local agent of the manufacturers stated that the sounders on the Whitby fishing boats are checked at intervals of about 6 months. The one minute marks were checked during operations and it was found that they were recorded at intervals of 59 seconds. This is not significant in this case since the distance between the dan buoys is divided in proportions taken from therecords. In shallow water it is necessary to deduct an amount from recorded depths owing to the fact that the incidence of the ray from transmitter to receiver on a horizontal bed is not vertical. For an oscillator spacing of 5 ft. the corrections are approximately 6, 3 and 2 in. when the recorded distances from transmitter to bed are 1, 2 and 3 fathoms respectively. In this work the distance is seldom less than one fathom and generally exceeds two fathoms and corrections are made only to readings between one-half and one and a half fathoms. A steel bar was not available for the usual bar test which is made to check the position of zero depth on the record. However, this test was made by the alternative method and the depth recorded when passing over the sand-bar at the harbour mouth was checked against a lead-line reading. The depth below the oscillators was found by lead-line to be ½ fathom, that is 1½ fathoms below the water-line, when the echo-sounder recorded 3½ fathoms. The correction for the inclincation of the ray is about 12 in. at a recorded depth of ½ fathom so that the correction to all chart depths is (21-3-1) = 17 ft. That is, the instrument should have recorded 4 ft. when it was in fact recording 21 ft. Since the oscillators are 1 fathom below the water-line, a deduction of 11 ft. gives the depth below water surface directly. Tide gauge readings were taken from the time of departure to return extending over a period of two hours, low water occurring approximately half-way through the work. The sections were recorded during a period of about ¾ hour and the maximum variation in water-level was about 0.20 ft. The other sources of error in the records do not justify making any correction for this and the water-level is taken as the mean value during the period of ¾ hour - that is, 4.1 ft. below Ordnance datum.

Hence a deduction of (11-4) = 7 ft. to all readings gives the reduced sea-bed level below Ordnance datum directly.

Fig.5 shows the layout of the three shore stations α, β and γ together with the ten sea stations marked by dan buoys A to E and P to T. It is generally considered desirable in sounding to have all observations under the control of the party chief on the boat and the observations for position must then be taken by box sextant. Because one small box sextant only was available, it was decided to employ theodolites at the shore stations and to arrange a system of visual intercommunication between shore and boat parties. One theodolite was established at each of the three shore stations with a second theodolite about 10 ft. from each. The object of duplicating readings in this way was to ensure that no reading was missed in the event of the speed of operations being too fast for the observers and also to provide a check on the accuracy of each fix. Several different types of theodolites were employed reading directly to 1 to 20 secs. A local system of co-ordinates was established for the shore stations by reference to $^1/_{2,500}$ scale Ordnance Sheets.

The track of the boat, as defined by the foremast, is shown in Fig.5 - reduced from the original which was plotted to a scale of $^1/_{5,000}$ with a brass protractor. The dan buoys

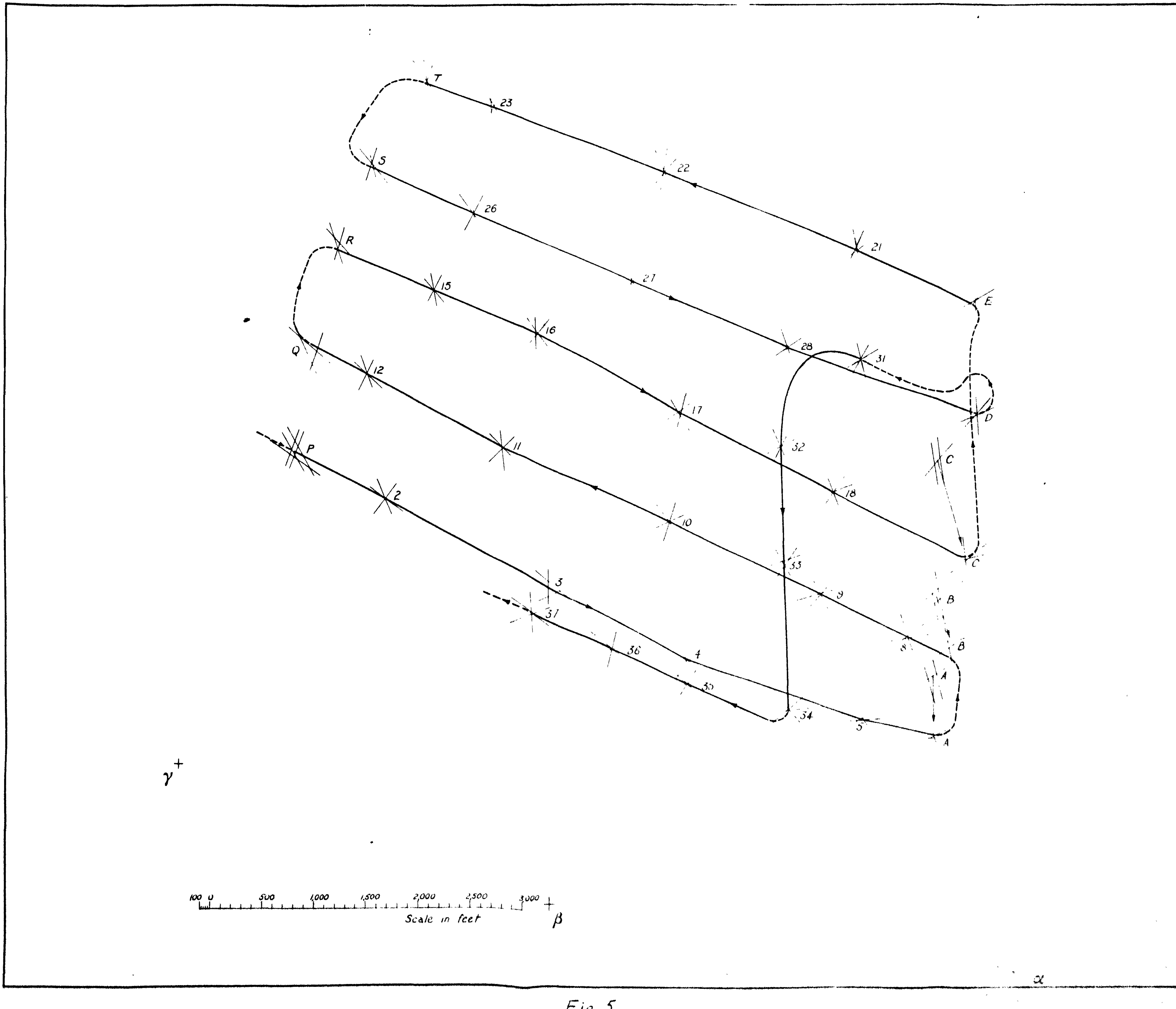

T
23
S
22
26
21
R
27
15
E
16
28
31
Q
12
17
D
P
11
32
C
2
18
10
C
3
33
9
B
31
B
8
36
4
A
35
34
5
A
γ
100 0 500 1,000 1,500 2,000 2,500 3,000
Scale in feet
β
α

Fig. 5

were laid down at what were judged to be appropriate spacings. A dan buoy consists of a float through which passes a pole with a lead sinker at the bottom and a flag at the top; it is moored with a line attached to an anchor. The length of the mooring line should be adjusted to the depth of water at the station but it was not possible to arrange for this to be done. Consequently the buoys drifted with wind and current and the anchors also dragged on the bottom, but repeated theodolite observations showed that the buoys became static very soon after being laid. The sections were run on the buoys in the static positions but examples of the amount of drift are indicated in Fig.5. It was not possible to extend the survey eastwards owing to the rock shelf in front of the east cliff which makes navigation unsafe. The positions of the sections are shown in Fig.6.

All theodolite sights were made on the foremast of the boat and it is necessary to make a correction of 20 ft. in the positions when plotting the location of the sections on the plan. Inter-communication was established with pairs of flags; one signaller at each shore station and the boat signaller by the foremast. Flag signals were evolved for the following orders and replies:

Orders from the boat: | Replies from shore stations:

1. Commence simultaneous observations 

This station is following foremast with top circle unclamped 

2. Clamp top circle and follow foremast with slow-motion screw (held for 5 secs) 

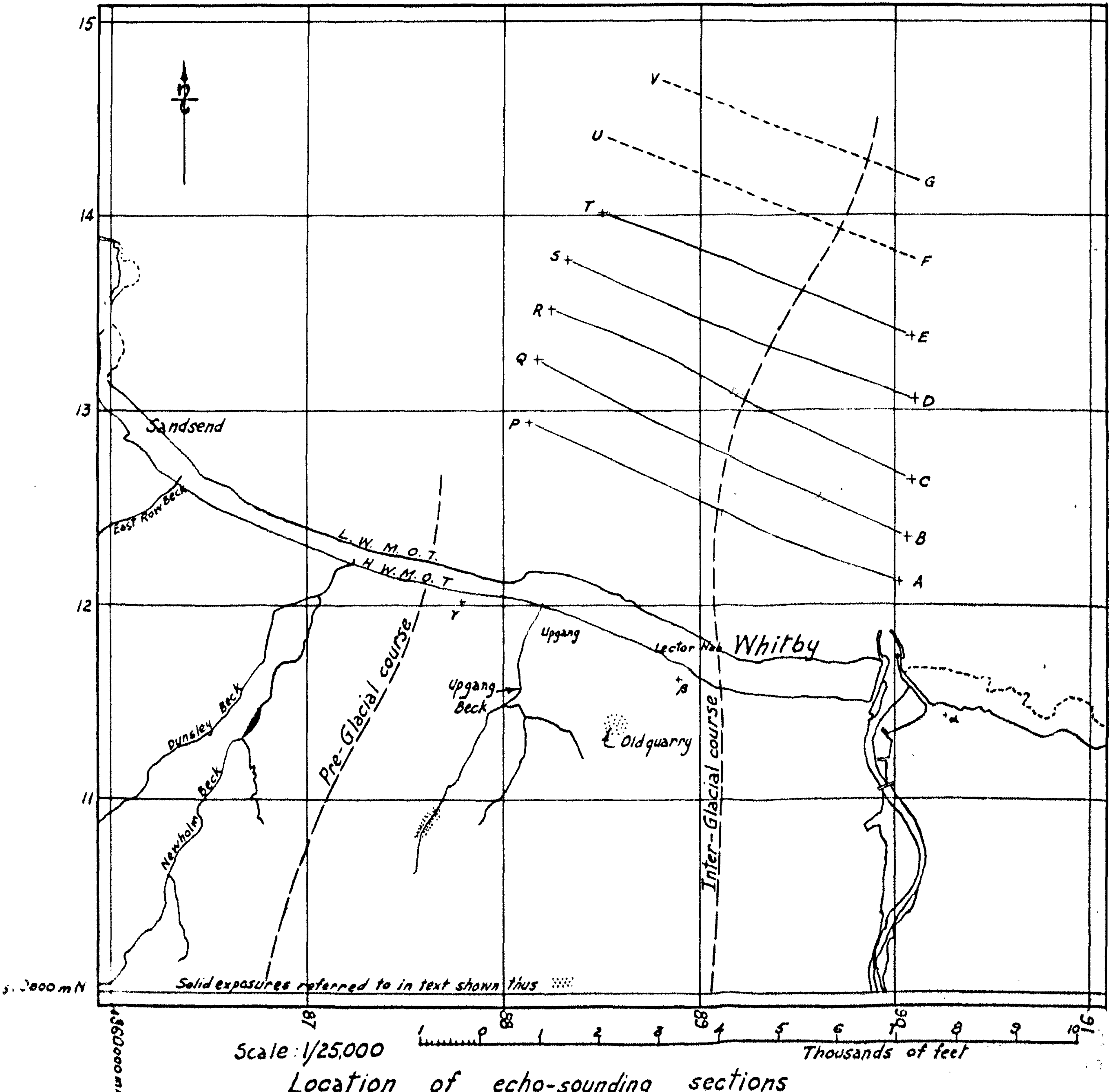
3. Read 

Reading taken 

4. Cease observations until signal (1) is seen 

The instant of passing each of the buoys and the instant of each theodolite observation was inscribed on the echo-sounder record together with the one-minute intervals.

It was found that the observers on the theodolites were able to keep pace with the boat operations and the duplicate theodolites were not, in fact, necessary. As a test at the close of the work, several observations were called for in succession at intervals of about one minute and these were recorded perfectly by the three stations. The positions were established with an encouraging degree of accuracy and in most cases the triangle of error was very small or absent. The least satisfactory fix was at station Q where the error in



Location of echo-sounding sections

Fig. 6

position might be as much as 150 ft. The duplicate theodolites generally confirmed the fixes and, from this aspect also, were not necessary. Copies of the records, approximately one-half the scale of the originals, are shown in Fig.7. The ragged trace of the bed is due to the rise and fall of the boat with the waves. Sections plotted from the records are shown in Fig. 8. Taking into account possible errors in obtaining and reading the records, the writer considers that the vertical measurements are probably accurate to within ± 3 ft. but there is no means of checking this.

After the five records had been examined, it was decided that two further sections -FU and VG - should be run at distances of about 1½ and 1¾ miles from the cliffs respectively. Unfortunately, personnel and instruments were not available for the shore stations and the positions of the sections are indicated approximately by dotted lines in Fig.6. When these sections were run the tide was about 6 ft. higher than before. The deficencies in the project confirm the desirability of a reconnaissance survey covering a wide area before the main survey is undertaken but, in this case, expense and other considerations,precluded this.

It will be noted from the records (Fig.7) that the present

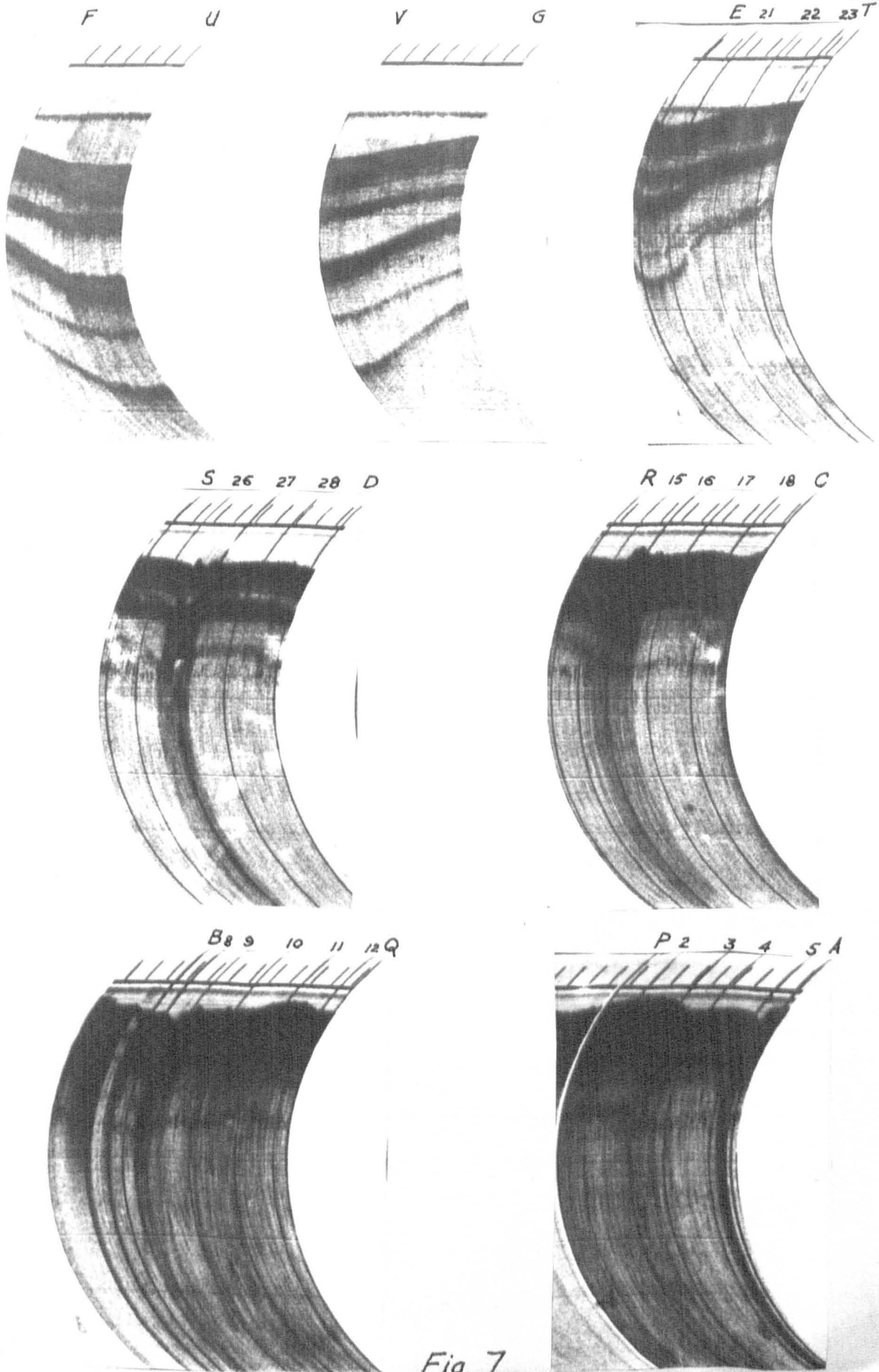
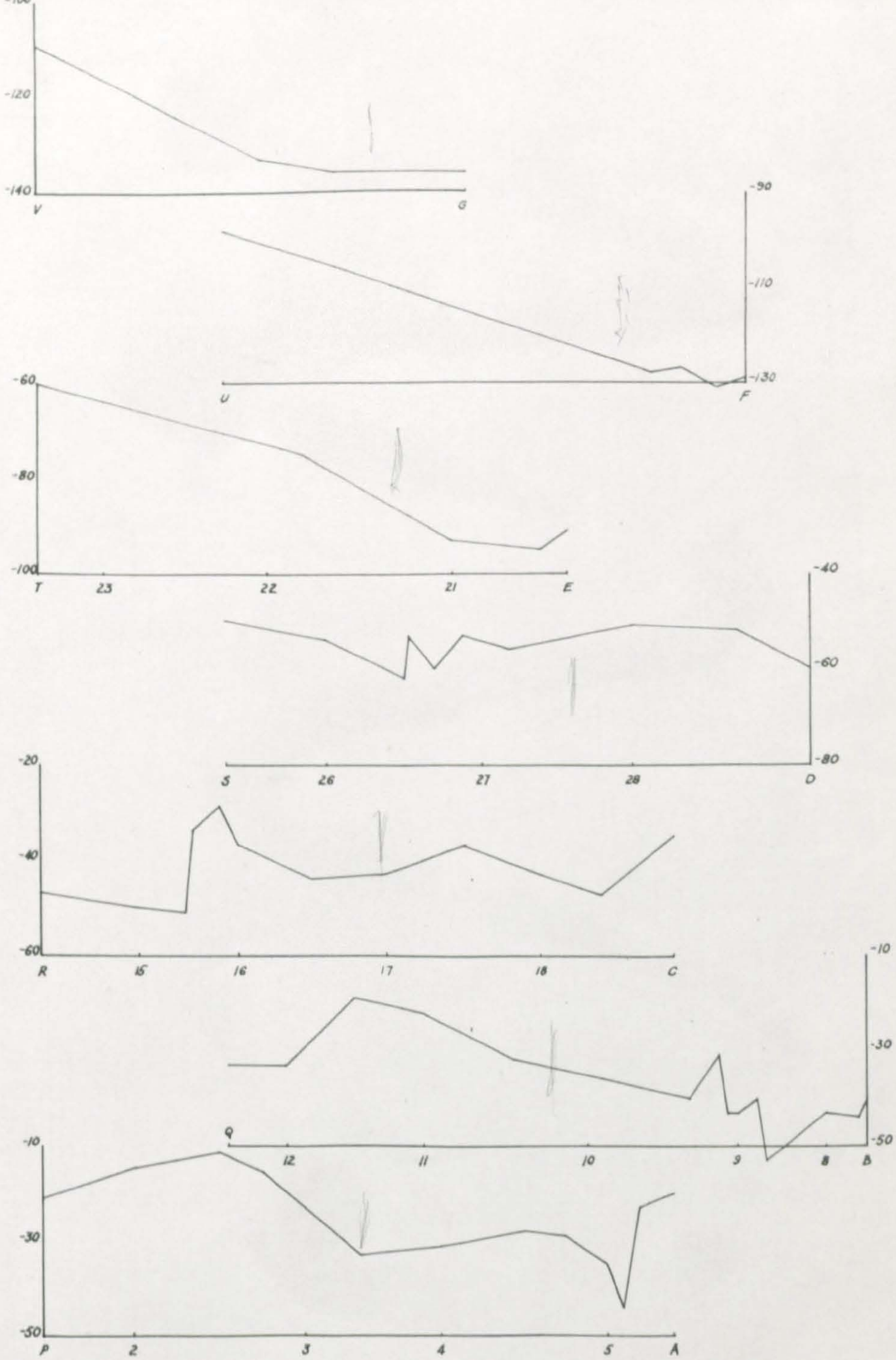


Fig. 7

submarine channel of the Esk is not particularly well defined, although it appears more distinct when the field data are plotted to an exagerated vertical scale, as shown in Fig.8. This channel probably contains natural sand filling and also material brought from the harbour by the dredger and dumped some distance from the shore. However, at a distance of about one mile from the harbour mouth the channel is much wider and can scarcely be recognised as such on the records. It was hoped that some evidence of the inter-Glacial channel would be found in the nature of double reflections. Given the right conditions, it is possible to obtain a reflection from the surface of unconsolidated material and another from the solid rock beneath. No evidence of this kind appears on the records and, if the channel was covered by the survey, then the filling of sand and Boulder Clay must be sufficiently well compacted to yield only one reflection. Whitby fishermen have informed the writer that sand extends seawards for a distance of about 150 yards from the cliffs at Upgang and for a distance of about 250 yds. from the cliffs at the West Pier. Admiralty Plan No.1625 shows sand extending further seawards than this. Beyond these limits the bottom is rock with, presumably, Boulder Clay in places. Samples taken from the bottom between Sandsend and



Scales: Horizontal 1,000 ft. to 1 in. Vertical 20 ft. to 1 in. (ft. below Ordnance datum)
(Reproduced at smaller scales)

Sections of the sea-bed between Upgang and Whitby Harbour

Fig. 8

Whitby might therefore prove the positions of buried channels.

Nevertheless, in spite of the absence of double reflections, three of the sections shown in Fig.8. reveal depressions which might be interpreted as representing the line of two buried channels. These depressions occur in the positions as follows.

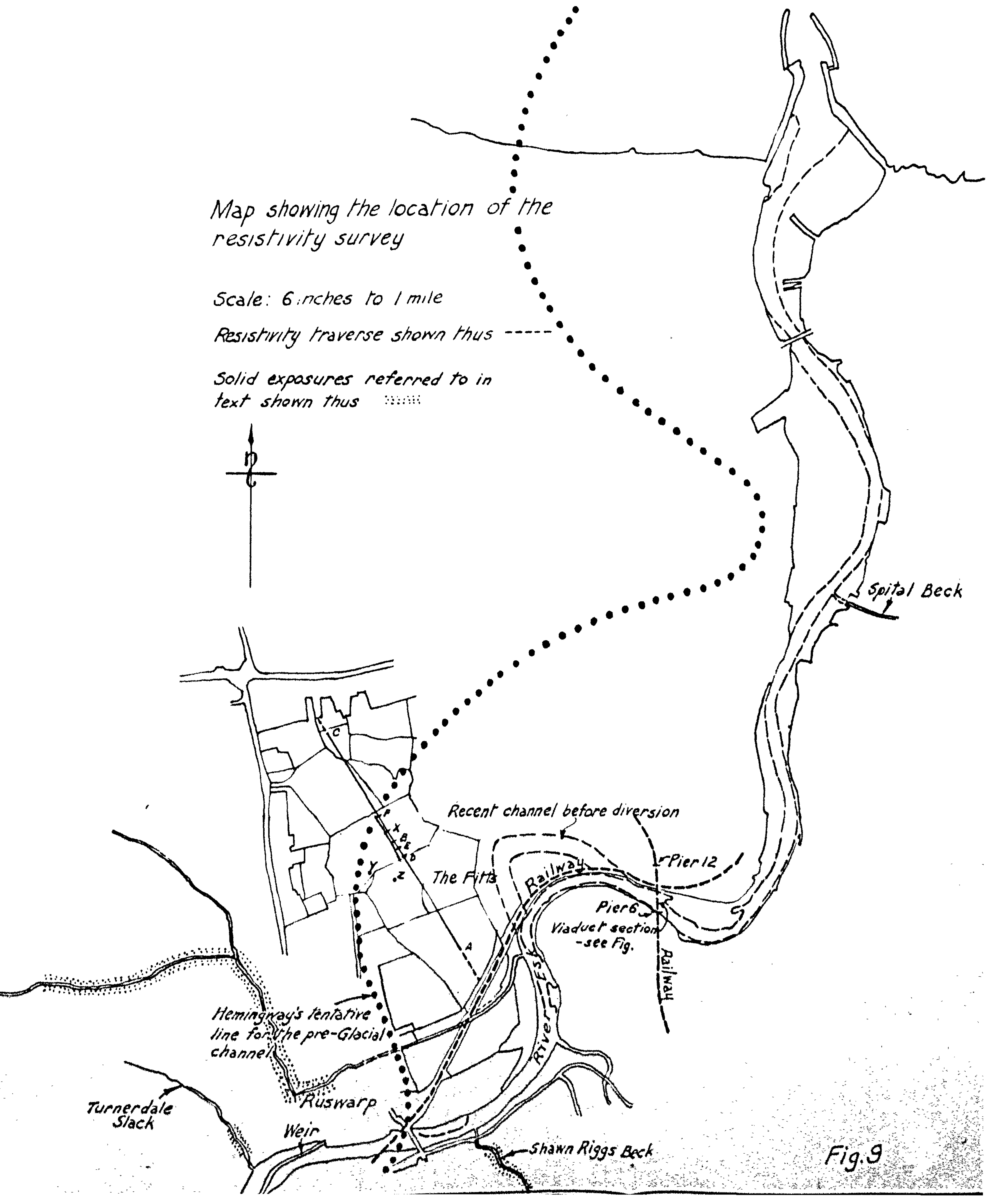
Section AP	West of P	pre-Glacial channel (?)	Between 3 & 4	inter-Glacial channel (?)
Section BQ	West of 12		Between 9 & 10	
Section CR	West of 16		Between 16 & 17	

The depression between 9 and 10 does not accord with the other two which fall in line with the landward inter-Glacial course, as shown in Fig.6. This course was derived from Esk Cross Sections 5 and 6 (Figs.33 and 34). Only one depression appears in Sections ET, FU and GV and it can be inferred that the inter-Glacial and present channels coalesce at a distance approaching two miles from the present cliffs. These inferences must be regarded as conjectural since sub-marine erosion or early post-Glacial sub-aerial erosion may be wholly or partly responsible for these depressions. The pronounced cliff between Stations 15 and 16 is worthy of note although its significance is not apparent.

Admiralty Plan No.1625 of Whitby Road shows a lobe of rock projecting seawards between Upgang and Lector Nab and this suggests a ridge between pre-Glacial and inter-Glacial valleys. The configuration of the sea-bed contours also suggests a valley between Sandsend and Upgang and another between Lector Nab and Second Nab at The Spa, with a ridge between them. There is no indication that the pre-Glacial valley joins the united inter-Glacial and present channels. Admiralty Chart No.1191 - covering the East Coast between Flamborough Head and the River Tyne - reveals nothing which can be interpreted as seaward extensions of these inshore depressions.

Electrical Resistivity Survey

A tentative course for the pre-Glacial channel of the Esk between Ruswarp and the coast has been delineated by Hemingway (1940) and this is shown in Fig.9. The present writer considers that this represents an inter- Glacial valley, as indicated in Chapter V, and it will be referred to as such in the following discussion. As a preliminary to the work described below, the present writer examined the west bank of the railway just south of Whitby where this course is shown swinging furthest east but no solid rock can be seen here. The bank is covered with top-soil but the slope indicates that it may be cut in Boulder Clay. The Chief Civil Engineer, North-Eastern Region of British Railways, York, was approached but the construction plans which are still in existence do not reveal the nature of the material


Map showing the location of the resistivity survey
Scale: 6 inches to 1 mile
Resistivity traverse shown thus
Solid exposures referred to in text shown thus
Spital Beck
Recent channel before diversion
Pier 12
The Fitts
Railway
Pier 6
Viaduct section -see Fig.
Railway
River Esk
Hemingway's tentative line for the pre-Glacial channel
Ruswarp
Turnerdale Slack
Weir
Shawn Riggs Beck
Fig. 9

in which the railway is situated except at the viaduct, as shown in Fig.15. It should be noted that the recent post-Glacial channel was diverted immediately before it enters the gorge at Larpool in order to facilitate construction of the railway, as shown in Fig.9. The large loop in the tentative line (Fig.9) towards the present course of the Esk just above the harbour appears to be an unwarrantable anomaly - it is much more likely that the inter-Glacial course seawards from Ruswarp was relatively straight or gently curved. The low bed-rock topography near this loop is more likely to be due to a pre-Glacial or inter-Glacial tributary roughly following the course of Spital Beck.

On the assumption that the inter-Glacial course was roughly as shown, it was decided to make an electrical resistivity survey across the alluvial flat, known as the Fitts, between Ruswarp and Larpool in an endeavour to locate the channel. The Wenner-Gish-Rooney layout of electrodes was employed for this work and the general arrangement is shown in Fig.10. In the apparatus used, current for the electrodes is supplied from a 6 volt accumulator and is passed through a commutator which delivers it to the electrodes as a low-frequency alternating current. The commutator is operated by a motor supplied with power from another 6 volt accumulator. A null method of reading is used to measure

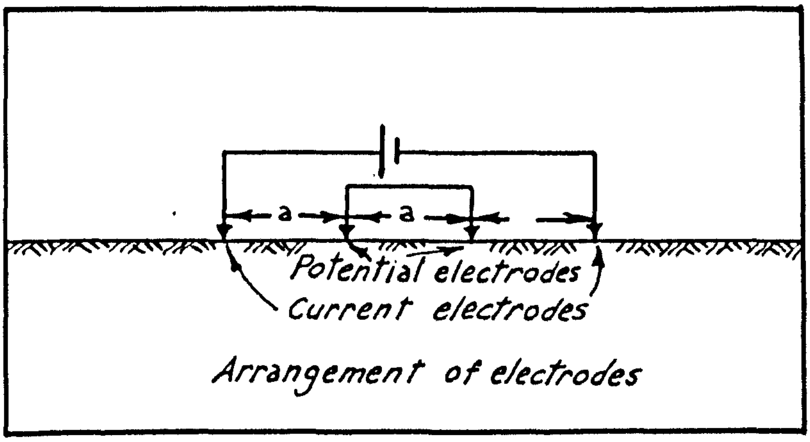
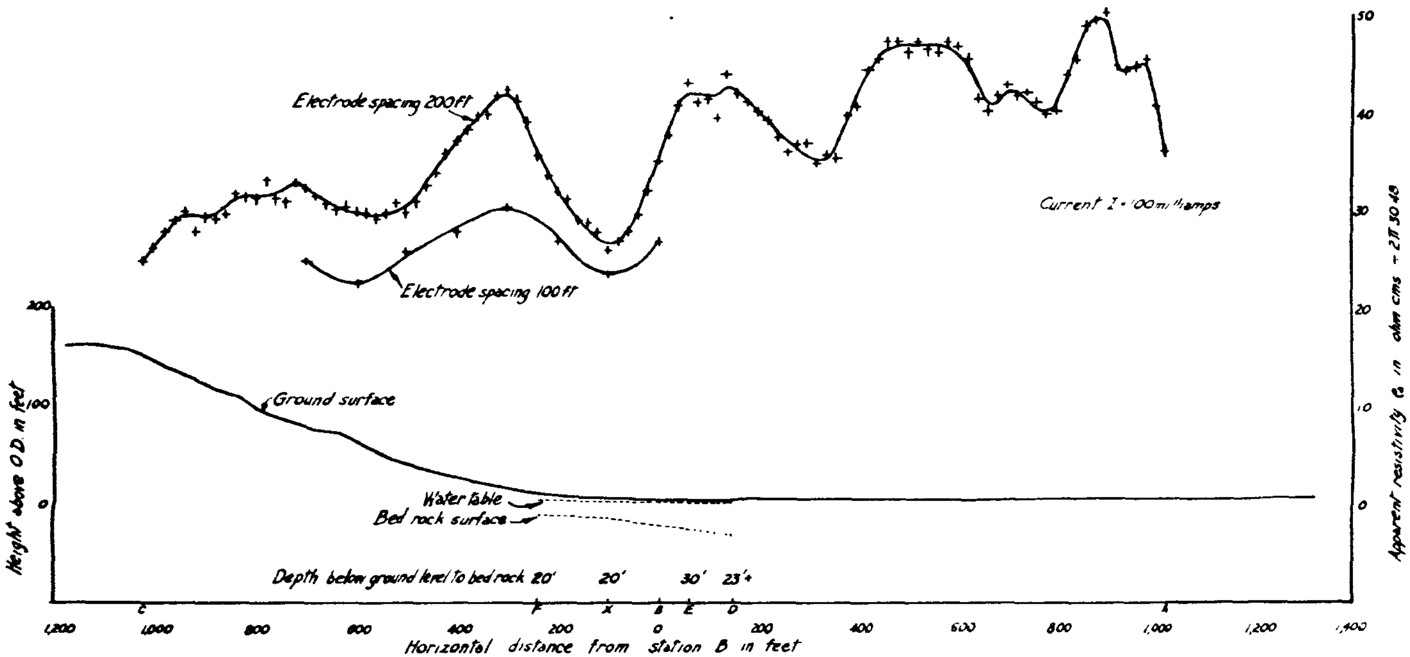

a
a
Potential electrodes
Current electrodes
Arrangement of electrodes

Fig. 10

the potential difference between the potential electrodes, the balancing voltage being taken from a potentiometer connected across a 9 volt dry battery.

A straight traverse was run from A to C with a constant electrode spacing a of 200 ft. and station intervals of 20 ft. The section BC was also partly run with an electrode spacing of 100 ft. and stations at 100 ft.intervals. At that time it was anticipated that the buried channel would be about 100 ft. below the surface, the depth increasing beneath the higher ground west of the alluvial flat. Consequently it was considered that electrode spacings of 100 and 200 ft. would be most likely to reveal the presence of the channel. The estimate of depth was based partly on Barrow (1888) who states that a series of borings proved the old Tees valley to be 90 ft below present high water mark. The locations of these borings are not given but it would be fortuitous if they covered the lowest part of the old valley, hence the depth may be reasonably assumed as 90 ft. below O.D. Allowing for the fact that ground level at The Fitts is about 10 ft. above O.D. the estimate of 100 ft. below this surface is reasonable. However, subsequent study led the writer to believe that the channel under review is inter-Glacial and there is no reason to assume that this also lies at a depth of 100 ft.



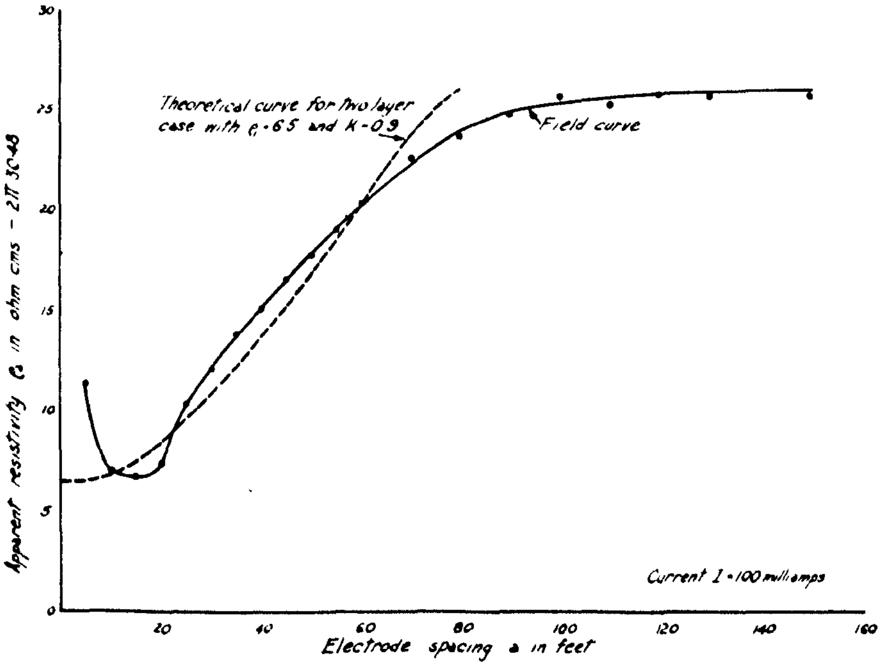
Constant electrode resistivity traverses and ground level section along line ABC

Fig 11

The results of the resistivity traverses together with levels taken along the line are shown in Fig.11.

An expanding electrode probe was made at the point X in order to obtain data on the variation of resistivity with depth and the electrode spacing was varied from 5 ft. to 60 ft. in units of 5 ft. and from 60 ft. to 130 ft. in units of 10 ft. with a final reading at 150 ft. The results derived from this probe are shown in Fig.12.

These results are typical of a three layer problem up to the sharp curve leading to the constant value of about 22.7 units and correspond to the case in which, relatively, a layer of medium resistivity overlies a layer of low resistivity which in turn overlies a layer of high resistivity. The resistivity of the soil above the water-table is probably between 12 and 15 units but the spacing of the electrodes was not reduced sufficiently to determine this precisely. A hand auger boring proved the water-table at a depth of 2 ft.6in. and the electrodes were inserted to a depth of about 9 in. in the soil. Consequently, it is not unreasonable to ignore the effect of the surface layer and to treat the readings as relating to a two-layer problem, thus enabling an estimate of depth to bedrock to be obtained. In this case, the resistivity of the layer of soil below the water-table is ρ_1 and that of the bedrock is ρ_2. The recorded



Expanding electrode probe at station X

Fig. 12

value of ρ_1 is probably high on account of the medium resistivity surface layer but the recorded apparent resistivity will also be rather high for the same reason although probably by a smaller percentage. Hence the ratio ρ_1/ρ_a may be rather high and hence also h/a and consequently the depth to the interface h can be expected to be slightly overestimated. The calculations based on Tagg's curves for a two-layer case are shown in Table 2. There is no point in plotting the usual families of curves since the table indicates the most probable value within a foot or so.

In Table 2 the electrode spacings of 20 ft. and those over 50 ft. yield inconsistent values - the first probably because of the effect of the surface layer and the remainder probably because of the relatively rapid trend towards a constant resistivity. The most reliable estimate of depth should therefore lie within the range of electrode spacings of 25 to 50 ft. and is seen to be 22 to 23 ft. at K = 0.9. This gives ρ_2 = 124 units . The reliability of the estimated depth h is enhanced by the fact that it is obtained with electrode spacings from about h to $2h$ and optimum results may be expected within this range in terms of effective depth ofpenetration.

The value ρ_1 = 1,240 ohm cms. is reasonable for saturated

TABLE 2

Calculations for Expanding Electrode Probe at X

a(ft)	20		25		30		35		40		45		50		55		60	
ρ_a(units)	7·2		10·0		11·7		13·3		14·5		15·7		16·7		17·8		18·7	
ρ_1/ρ_a	0·90		0·65		0·56		0·49		0·45		0·41		0·39		0·37		0·35	
K	h/a	h	h/a	h	h/a	h	h/a	h	h/a	h	h/a	h	h/a	h	h/a	h	h/a	h
0·7	1·60	32·0	0·77	19·2	0·60	18·0	0·50	17·5	0·43	17·2	0·36	16·2	0·35	17·5	0·31	17·0	0·30	18·0
0·8	1·70	34·0	0·84	21·0	0·68	20·4	0·56	19·6	0·50	20·0	0·43	19·3	0·43	21·5	0·38	21·0	0·36	21·6
0·9	1·75	35·0	0·90	22·5	0·74	22·2	0·64	22·5	0·56	22·4	0·50	22·5	0·49	24·5	0·44	24·3	0·43	25·8
1·0	1·84	36·8	0·96	24·0	0·82	24·6	0·70	24·5	0·64	25·6	0·56	25·2	0·55	27·5	0·51	28·2	0·50	30·0

a(ft)	70		80		90		100		110		120		130		150	
ρ_a(units)	20·7		21·6		22·4		23·0		22·6		22·8		22·6		22·4	
ρ_1/ρ_a	0·31		0·30		0·29		0·27		0·29		0·28		0·29		0·29	
K	h/a	h	h/a	h	h/a	h	h/a	h	h/a	h	h/a	h	h/a	h	h/a	h
0·7	0·21	14·7	0·20	16·0	0·20	18·0	0·14	14·0	0·20	22·0	0·17	20·4	0·20	26·0	0·20	30·0
0·8	0·31	21·7	0·30	24·0	0·29	26·1	0·27	27·0	0·29	31·9	0·28	33·6	0·29	37·8	0·29	43·5
0·9	0·36	25·2	0·35	28·0	0·34	30·6	0·31	31·0	0·34	37·4	0·33	39·6	0·34	44·4	0·34	51·0
1·0	0·43	30·1	0·42	33·6	0·41	36·9	0·37	37·0	0·41	45·1	0·40	48·0	0·41	53·5	0·41	61·5

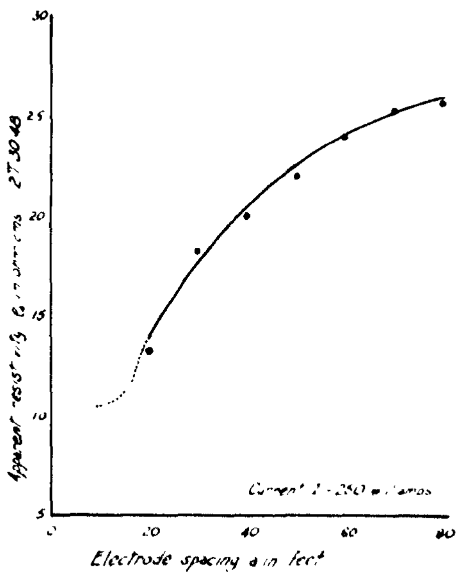
From Fig.13 take ρ_1 = 6·5 units = 1,240 ohm cms.
$K = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$ and when K = 0·9, ρ_2 = 124 units = 23,700 ohm cms.
In these calculations the units are $\left(\frac{aV}{I}\right)$ ohm ft. and to convert to true resistivity in ohm cms. these must be multiplied by $2\pi 30{\cdot}48$

silt and clay and ρ_2 = 23,700 ohm cms. is reasonable for saturated sandstone but is rather high for saturated shale. The constant resistivity to which the curve tends is 22.7 units = 4,340 ohm cms. and this is more consistent with saturated shale. Hence it is reasonable to assume that the base of the sandstone is at a depth of the order of 100 ft. It must be appreciated, however, that estimates of depths obtained from this probe must inevitably be in the nature of crude approximations because of the number of layers involved.

Having made this assessment of the results of the probe at X, it was decided to seek other information relating to the problem. Barrow (1888) records a borehole put down in a field just south of the Esk opposite Ruswarp in 1821 under the direction of Colonel Wilson. The exact location is not given although Barrow appears to have known the position at least approximately since he states that the borehole commenced about 30 ft. below the base of the Grey Limestone, which can be traced in the field above. It seems likely that the location was just south or south-west of the present road bridge over the Esk at Ruswarp. The log of the boring shows 22ft. of soil and gravelly clay (alluvium) followed by 220 ft. of Lower Estuarine Series to the top of the Dogger. The boring was extended about 100 ft. into the Lias. The original thickness, below the Grey Limestone, of the Lower Estuarines and the Dogger at this point is thus about 280 ft. According to Fig.3 the original elevation of the base of the Grey Limestone at X is about 70 ft. a.O.D. Allowing alluvium down to -15 ft. b.O.D, at X, the thickness of Lower Estuarines is (280 - 85) or say 200 ft. The general lithology of the Lower Estuarines is that sandstone predominates in the upper part of the series above the Eller Beck Bed and shales and shaly sandstone in the lower part, these latter being about 100 ft. thick (Barrow 1888) in the Whitby District. It was suggested above that the thickness of sandstone was of the order 100 ft. less 20 ft. of alluvium according to the resistivity probe at X and this estimate of 80 ft. corresponds wellwith the geological evidence which leads to an estimate of 100 ft. However, too many uncertainties exist in the data on which both these estimates are based and the correlation may be more apparent than real.

Further information on the depth to bed rock was obtained subsequently by hand-auger borings at F, X, E and D. The position of the water table obtained from the borings is shown in Fig.11 together with the depth to bed rock. In borings F, X and E penetration was eventually halted by hard, gritty rock but, because of the water in the holes, only a few small fragments were brought to the surface. This resistant material gave the impression of solid rock or a boulder more than of gravel and, because the depth below surface was fairly consistent, it was considered to be most likely bed rock, although this form of interpretation is by no means positive. The depth of 20 ft. at X corresponds with the estimate of 22 to 23 ft. obtained with the resistivity probe at this point. The boring at D was abandoned at a depth of 23 ft. owing to jamming of threads on the rods. The material found in all four boreholes was mainly silt andclay but identification of different layers was almost impossible because the material was churned in the water.

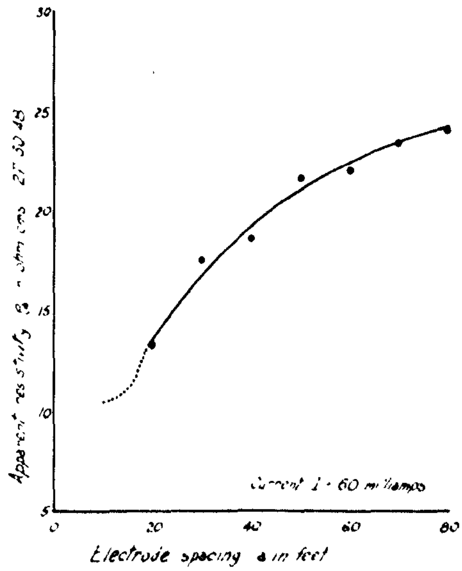
It was hoped that the borings would explain the reasons for the highs and lows in the constant electrode spacing traverse shown in Fig.11 - in the form perhaps of gravel at the highs and silt and clay at the lows. Since saturated silt and clay have low resistivities, the fact that these materials are present in depressions in bed rock surface-according to the borings - should lead to lows over the depressions, whereas the evidence is contrary to this. Unfortunately, the electrode



Expanding electrode probe at station V
Fig 13

spacing, and hence also the effective depth of penetration, was too great for optimum results where bed rock lies at depths between, say, 20 and 40 ft. The fact that the highs and lows are accentuated with an electrode spacing of 200 ft. compared with 100 ft. indicates that the reasons for these are deep-seated, yet there is no apparent explanation for this.
It is true, of course, that various combinations of quite different resistivities in near-surface features may be included in a spacing between current electrode of 600 ft. but the resistivity anomalies due to these would be very difficult to interpret. The uniformity of the results, including the gradual decline in average resistivity from A to C, give confidence in their veracity - the difficulty lies in the interpretation. The next step is to repeat the traverse with electrode spacings of 20 ft. and 40 or 50 ft. together with further borings along the line and the writer hopes to put this work in hand early in 1957.

Expanding electrode probes were also made at Y and Z with electrode spacings of 20 to 80 ft. by 10 ft. increments. The results of this work are plotted in Figs. 13 and 14. Calculations weremade similar to those in Table 2. and the relevant data are as follows.



Expanding electrode probe at station 2
Fig 14

Station Y

I = 250 milliamps. Estimated ρ_1 = 10.5 units = 2,000 ohm cms

K = 0.55 . Depth to bedrock h = 17 ft. ρ_2 =36.2 units = 6,900 ohm cms.

Station Z

I = 60 milliamps. Estimated ρ_1 = 10.5 units = 2,000 ohm cms

K = 0.5. Depth to bedrock h = 16 ft. ρ_2 = 31.5 units = 6,000 ohm cms.

A boring was made at Y and, after passing through silts and clays, bed rock was considered to be met at a depth of 22 ft.6 in. The depth calculated from the resistivity probe was 17 ft. The water table stood at a depth of 2 ft. below the surface. The ground level is about 7 ft. a.O.D. at Y. It will be observed that at Y and Z the value of ρ_2 is of the order one-third to one-quarter of the value obtained at X. This is a considerable variation in resistivity of the Lower Estuarines which may be expected to be relatively uniform. If, however, such variations exist, then the reason for the highs and lows in Fig.11 are obvious, but a closer electrode spacing wouldreduce the effects.

This resistivity investigation was disappointing insomuch as it failed to locate earlier river channels but at the same time it presents features which encourage further investigation.

Borings and Related Data.

In an endeavour to secure levels of the rock floor of the pre-Glacial Esk, thereby facilitating extrapolation to base-level, it was decided to sink boreholes in the centre of the valley between the Lealholm moraine and Castleton. However, the depths proved too great for the hand-auger equipment so that the scheme was modified to obtain levels of the old valley sides, where it was anticipated the boreholes would be shallower, and from this data it was hoped to construct cross-sections of the old valley, sketching the centre part. Even this proved too arduous a task as the boring records given below demonstrate. The equipment consisted of a 2 in. diameter ship-auger of thehelical-spring type weighing 10 lbs and a 1½ in. diameter ship-auger of the Archimedean-spiral type weighing 5 lbs; both were 3 ft. long. The hollow mild-steel rods were 1 in. diameter externally and 4 ft. long and each weighed 9 lbs. This equipment was heavy to operate and to transport on foot but in practice it was found to be only just robust enough for the work. One man can operate the equipment for borings down to 10 or 12 ft. but below this two men are required and then the maximum depth which can be attained under favourable circumstances is about 30 ft. Gravel often brought borings to a halt and water in the hole washed sand out of the auger and turned clay into slurry. It was sometimes possible to bore into solid sandstone or sandstone boulders. Indentification of the material was sometimes difficult owing to the disturbed nature of the samples. Rates of drilling ranged between 2½ to 20 minutes per foot and were most commonly 10 to 12 minutes per foot.

The data obtained from five mid-valley borings between Bow Bridge, Castleton, and Danby Lodge together with data obtained from 14 cross-valley borings at Duck Bridge, Ainthorpe, are given below under National Grid references. Where levels are stated to be approximate they are likely to be accurate to within ± 3 ft. or at most ± 5 ft. A minus sign after a level indicates that the rock floor is at some depth beneath the bottom of the borehole.

A1

508380 mN
468530 mE
Bow Bridge, Castleton
Ground level 427 ft. a.O.D.
0 to 9 ft. sandy silt
9 ft. to 10 ft. gravel
Rock floor 417 ft.- a.O.D.
Drilling time 1½ hrs

A2

508330 mN
469640 mE
Howe Wath Bridge, Castleton
Ground level 415 ft. a.O.D.
0 to 5 ft. sand and sandy clay
5 ft. layer 2 in. thick of sand with thin flakes of shale and plant fibres
5 ft. to 7 ft. light brown sandy clay
7 ft. to 9½ ft. sandy silt
9½ ft. to 10 ft. gravel
Rock floor 405 ft.- a.O.D.
Plant remains 410 ft. a.O.D.
Drilling time 1½ hrs.

A3

508190 mN
470790 mE
Ainthorpe Bridge, Danby
Ground level 207½ ft. a.O.D.
0 to 5 ft. sand, gravel and silt
5 ft. to 5½ ft. gravel
Rock floor 202 ft.- a.O.D.
Drilling time 1 hr.

A4(a)

508270 mN
471480 mE
Danby Lodge, Danby
Ground level 398 ft. a.O.D.
0 to 9 ft. sand, red at top, light yellow at bottom, with small percentage of clay
9 ft. to 12 ft. gravel
Rock floor 386 ft.- a.O.D.
Drilling time 2½ hrs.

A4(b)

508280 mN
471480 mE
Danby Lodge, Danby (adjacent to A4(a))
Ground level 387 ft. a.O.D.
0 to 3½ ft. silt
3½ ft. to 11 ft. clay with faint purple tinge, traces of laminations near bottom
Rock floor 376 ft.- a.O.D.
Drilling time 2½ hrs.

B1

507370 mN
471710 mE
Danby Castle, Ainthorpe
Ground level 530 ft. a.O.D. a approx.
0 to 3½ ft. sandy soil with fragments of sandstone
Rock floor 526½ ft.- a.O.D. approx
Drilling time 1 hr.

B2

507470 mN
471840 mE
Danby Castle, Ainthorpe
Ground level 450 ft. a.O.D.
0 to 3 ft. clay, light brown at top, dark grey at bottom, with sandy layers.
3 ft. to 3½ ft. pebbles and sand with black particles (? jet)
3½ ft. to 6 ft. light brown clay with sand at top graduating to fine, light grey sand at bottom.
6 ft. to 8½ ft. light grey sandstone (? sandy shale)
This borehole appears to be located near the contact between the Grey Shale and the Jet Rock.
Rock floor (?) 444 ft. a.O.D.
Drilling time 1½ hrs.

B3

507480 mN
471800 mE
Danby Castle, Ainthorpe
Ground level 465 ft. a.O.D. approx.
0 to 3 ft. weathered clay
3 ft. to 5½ ft. fine to coarse fragments of red colour (? transported Dogger) with white sandstone below (? boulder)
Rock floor 459½ ft.- a.O.D. approx.
Drilling time ½ hr.

B4

507485 mN
471800 mE
Danby Castle, Ainthorpe
Ground level 455 ft. a.O.D. approx.
0 to 3 ft. brown clay with stones
3 ft. to 5 ft. brown sandy clay with stones of sandstone and ironstone
5 ft. to 8½ ft. white to red sand at top graduating to sandy clay with pebbles at bottom
Rock floor 446½ ft.- a.O.D. approx.
Drilling time 1¼ hrs.

B5

507580 mN
471865 mE
Duck Bridge, Ainthorpe
Ground level 425 ft. a.O.D.
0 to 2½ ft. clay with fragments of sandstone
Rock floor 422½ ft.- a.O.D.
Drilling time ¼ hr.

B6

507581 mN
471865 mE
Duck Bridge, Ainthorpe
Ground level 425 ft. a.O.D.
0 to 4 ft. clay with fragments of decomposed sandstone and traces of plant fibres.
4 ft. to 19 ft. clay with traces of laminations and a thin woody layer at 5 ft.
19 ft. to 21 ft. sand and clay
21 ft. to 25 ft. weathered shale becoming stiffer with increasing depth
Water issued from borehole under artesian head after sand and clay penetrated
Rock floor 404 ft. a.O.D.
Plant remains 420 ft. a.O.D.
Drilling time 6½ hrs.

B7

507920 mN
472080 mE
Park House, Danby
Ground level 395 ft. a.O.D. approx
0 to 4 ft. grey clay with woody fragments
Water table at 2 ft.
Rock floor 391 ft.- a.O.D approx
Plant remains about 393 ft. approx.
(?clay and plant remains transported)
Drilling time ½ hr.

B8

508010 mN
472125 mE
Park House, Danby
Ground level 400 ft. a.O.D. approx.
0 to 4 ft. red clay
4 ft. to 27½ ft. dark brown clay with traces of laminations, very consistent in composition
Rock floor 372½ ft.- a.O.D. approx.
Drilling time 5 hrs.

B9

508060 mN
472170 mE
Park House, Danby
Ground level 412 ft. a.O.D. approx.
0 to 2ft. weathered clay
2 ft. to 4 ft. light brown clay
4 ft. to 6 ft. soft fine grained sandstone (boulders) of various colours - red, brown, blue, grey
6 ft. to 7 ft. grey and brown clay
7 ft. to 8 ft. soft fine grained sandstone (boulder)
Rock floor 404 ft.- A.O.D. approx
Drilling time 1½ hrs.
Data from this borehole does not accord with data from adjacent boreholes since lacustrine clay occurs at higher levels elsewhere - it may represent filling of an old ditch or an excavation by man or pre-Glacial debris.

B10

508100 mN
472190 mE
Park House, Danby
Ground level 422 ft. a.O.D. approx.
0 to 3 ft. weathered clay
3 ft. to 6 ft. dark brown clay with layers of grey clay and a woody layer at 5 ft.
6 ft. to 12 ft. dark brown clay with traces of laminations, very consistent in composition
Rock floor 410 ft.- a.O.D. approx
Plant remains 417 ft. a.O.D. approx
Drilling time 1 hr.

B11

508105 mN
472193 mE
Park House, Danby
Ground level 423 ft. a.O.D. approx.
0 to 3ft. weathered clay
3 ft. to 9 ft. brown clay, increasingly darker with depth, traces of laminations and wood fragments at 7 ft.
9 ft. to 10½ ft. sandstone (?pre-Glacial boulder)
water issued from borehole after entering sandstone
Rock floor 414 ft.- a.O.D. approx.
Plant remains 416 ft. a.O.D. approx.
Drilling time ½ hr.

B12

508118 mN
472197 mE
Park House, Danby
Ground level 424 ft. a.O.D. approx.
0 to 2ft. weathered clay
2 ft. to 8½ ft. brown and grey clay with traces of laminations
8½ ft. to 11 ft. sandstone (? pre-Glacial boulder)
Water issued from borehole under artesian head after entering sandstone
Rock floor 415½ ft(?) a.O.D. approx.
Drilling time 1 hr.

B13

508127 mN
472213 mE
Park House, Danby
Ground level 425 ft. a.O.D. approx.
0 to 2 ft. weathered clay with coarse sand particles
2 ft. to 6½ ft. yellowish to greyish clay with traces of laminations and plant fibres
6½ ft. reddish sandstone (Dogger)
Rock floor 419 ft. a.O.D. approx
Plant remains 420 ft. a.O.D. approx.
Drilling time 1 hr.

B14

508135 mN
472210 mE
Park House, Danby
Ground level 430 ft. a.O.D. approx.
0. to 2 ft. weathered clay
2 ft. to 4 ft. greyish brown clay
4 ft. to 6 ft. sand with red sandstone (Dogger)
Rock floor 425 ft. a.O.D. approx
Drilling time ¼ hr.

The thicker deposits of uniform dark brown clay with traces of laminations at, for example, B6 and B8 are undoubtedly lacustrine, mainly Glacial but perhaps also partly early post-Glacial.

It will be noted from theboring records that plant remains appear most commonly between 415 and 420 ft. a.O.D. and that they occur near the top of the lacustrine clay and often below about 5 ft. of post-Glacial colluvium or eluvium. This range of levels accords with an early overflow sill level at the head of Crunkly Gill - possibly established by the Estuarines above the Dogger Bed, the level of which is just below 400 ft. at this point. The present level at the head of the Gill is about 360 ft. Samples from boreholes B6, B10 and B11 were submitted to Miss L.I.Scott and Professor R.D.Preston, of the Botany Department, University of Leeds. Miss Scott identified the specimens as birch. The smaller fragments were dead at the time of burial but one comparatively large piece was obviously alive at burial since it shows a well preserved structure and there is cellulose in thewalls. There is no evidence of top-soil, peat or moss associated with this plant matter.

There appears to be lacustrine clay above some of the plant remains and the point arises as to whether these represent the decaying roots of recent birches or drift wood on the sides of a post-Glacial lake. Professor Preston has examined specimens in the electron microscope and considers that the matter is comparatively recent - particularly in view of the absence of an inhibiting agent such as water - but this is not absolutely certain. The roots of recent birches would need to penetrate to depths of as much as 7 ft. according to the borings. If the matter is recent, then it has little geological significance. On the other hand, if it is immdiately post-Glacial, a radio-activity C14 test will yield chronological data and indicate whether or not a lake existed in post-Glacial times. With this aspect in view, it is hoped to sink further borings 4 in. diameter in the near future.

Two cross-sections of the Lower Esk have been drawn from boring records obtained for engineering construction and these are shown in Fig.15. The Chief Civil Engineer, North -Eastern Region of British Railways, York, kindly supplied boring data obtained in 1882 for the construction of the railway viaduct at Larpool. The data given below for Pier 9 are taken from the construction record instead of the boring record. The Chalk which appears in the record for Pier 6 is probably material dumped from ships in which it was used as ballast. The second cross-section is derived from data obtained about 1930 for the construction of the present cantilever and suspended span road bridge over the Esk at Sleights. The original nomenclature employed in the records is retained in the data given below.

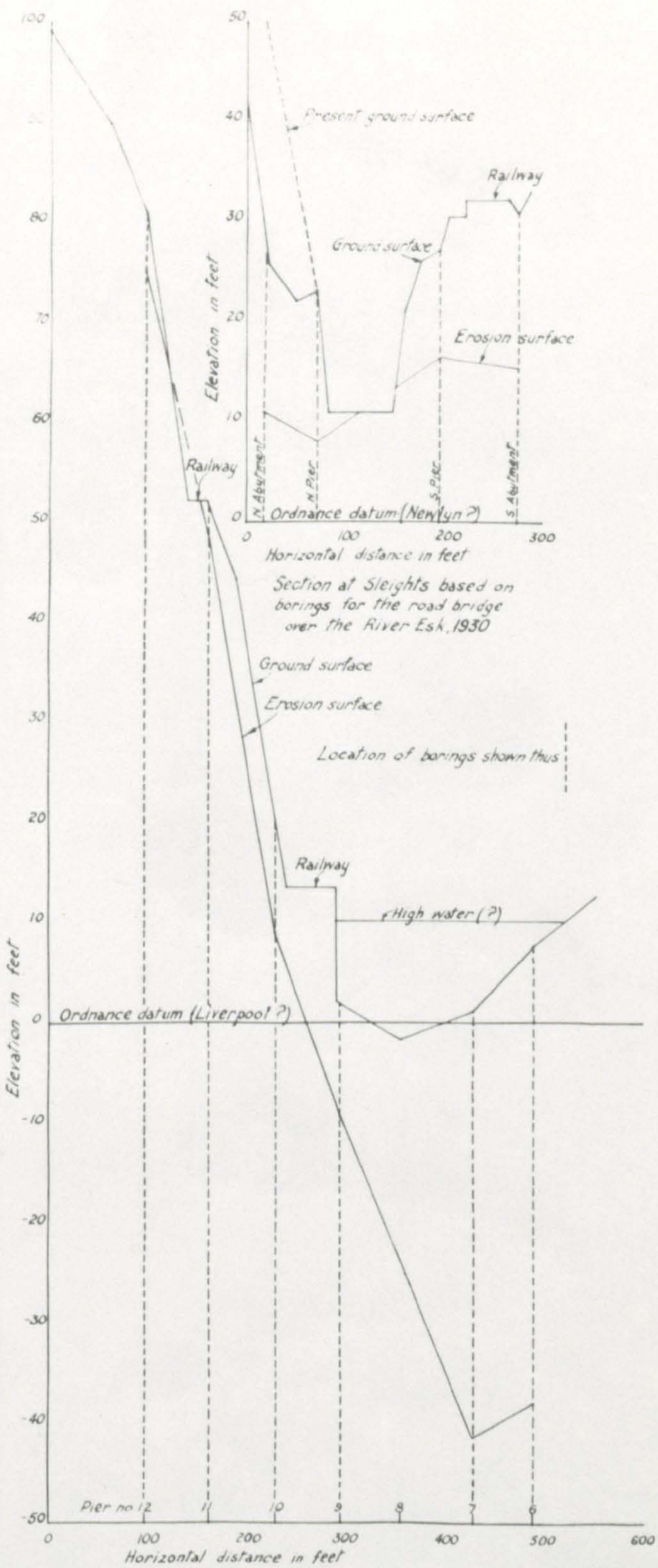


Fig. 15 Section at Larpool based on borings for the railway viaduct over the River Esk, 1882

The records of the six borings at the Larpool railway viaduct are as follows:

Pier 6

Ground surface 7.6 ft. a.o.d.
20 ft. 0 in. Chalk and gravel
25 ft. 0 in. slurry and mud
1 ft. 6 in. Freestone
5 ft. 6 in+ Hard grey shale

Pier 7

Ground surface 1.0 ft.a.o.d.
36 ft. 6 in. Gravel
4 ft. 0 in. Broken freestone
1 ft. 0 in. Gravel
10 ft. 0 in+ Hard grey shale

Pier 9

Ground surface 1.7 ft. a.o.d.
12 ft. 0 in. River deposits
4 ft. 0 in. Freestone
4 ft. 6 in. Fireclay
10 ft. 3 in. Shale
4 ft. 0 in.+ Freestone

Pier 10

Ground surface 19.8 ft. a.o.d.
10. ft. 6 in. Clay
3 ft. 6 in. Freestone
9 ft. 0 in. Hard shale
5 ft. 0 in. Freestone
3. ft. 0 in.+ Hard shale

Pier 11

Ground surface 51.2 ft. a.o.d.
3 ft. 0 in. Clay
3 ft. 6 in. Sandstone in layers
9 ft. 0 in. Solid freestone
1 ft. 6 in. Brown shale
3 ft. 0 in. Blue shale
4 ft. 0 in.+ Hard brown shale

Pier 12

Ground surface 80.8 ft. a.o.d.
6 ft. 0 in. Clay
14 ft. 0 in. Shale and fireclay
3 ft. 4 in. Freestone
15 ft. 0 in.+ Freestone and shale in layers

The records of the four borings at the Sleights road bridge are as follows:

North abutment
Ground surface 26.5 ft. a.o.d.
15 ft. 9 in. Brown clay
8 ft. 6 in. Soft shale
13 ft. 0 in. Leafy shale
13 ft. 0 in. Grit shale

North Pier
Ground surface 23.0 ft. a.o.d.
10 ft. 3 in. Sand and clay
4 ft. 9 in. Gravel
7 ft. 6 in. Soft shale
8 ft. 6 in. Leafy shale
19 ft. 0 in. Grit shale

South pier	South abutment
Ground surface 27.0 ft.a.o.d	Ground surface 30.6 ft. a.o.d
9 ft. 9 in. Clay	12 ft. 6 in. Clay
4 ft. 0 in. Rough gravel	2 ft. 9 in. Rough gravel
8 ft. 0 in. Soft shale	10 ft. 0 in. Soft shale
14 ft. 9 in. Hard shale	14 ft. 0 in. Hard shale
13 ft. 0 in. Grit shale	10 ft. 0 in. Grit shale

Records of two borings and excavations through drift have been given in Geological Survey Memoirs. Fox-Strangways, Reid and Barrow (1885) state that a boring was put down at Danby Brick and Tile Works - about ¼ mile west of Duck Bridge - to a depth of about 60 ft. in laminated clay without reaching the Lias. The grid reference of the Works is about 507800 mN and 471500 mE. The present general ground level is about 425 ft. a.O.D. at the Works and the present bank level of the Esk is 392 ft. The pre-Glacial valley floor level is thus below about 365 ft.

At Glaisdale Iron Works the depth to bedrock was about 53 ft. and the present ground level before excavation was between 250 and 300 ft. a.O.D, with the average about 260 ft. so that the pre-Glacial rock floor level can be taken as about 207 ft. a.O.D. The grid reference of the centre of the Works is about 505650 mN and 478000 mE.

At Grosmont Iron Works the depth to bedrock was about 45 ft. and the present ground level beforeexcavation was between 90 and 100 ft. a.O.D. Calculated from mean ground level, the pre-

Glacial rock floor level is about 50 ft. a.O.D. The grid reference of the centre of the Works is about 505400 mN and 482600 mE.

Fox-Strangways and Barrow (1915) record in detail the log of a boring put down at Raven Hill, about ½ mile south/south-east of Sandsend. After passing through 84 ft. of Glacial clays and sand with transported shale and limestone and finally 3 ft. of decomposed shale (?), the intact Lias is met. The present ground level is about 175 ft. a.O.D. and the level of the pre-Glacial rock surface is thus about 91 ft. a.O.D. The grid reference of Raven Hill Reservoir is about 512150 mN and 486450 mE.

Hemingway (1940) records a well just over ¼ mile west of Whitby West Cliff Station at about 511200 mN and 488450 mE which encountered solid rock at 155 ft. a.O.D.and also a boring just east of West Cliff Station at about 511150 mN. and 489150 mE. which met solid at 55 ft. a.O.D.

Imperial Chemical Industries Ltd., Wilton Works, kindly supplied the logs of nine boreholes in the Esk catchment but only three of these are located conveniently for the present investigation. The relevant data as are follows.

E5
506480 mN
485930 mE
1¼ miles south/south-west of Sleights
Ground level 216 ft. a.O.D. approx
0 to 45 ft. Drift
45 ft. + Lias
Rock floor 171 ft. a.O.D. approx

E6
511790 mN
488000 mE
Whitby Golf Links by Upgang Beck
Ground level 70 ft. a.O.D.approx
0 to 120 ft. Drift
120 ft. to 128 ft. Dogger
128 ft. + Lias
Rock floor - 50 ft. b.O.D. approx.

E9
505300 mN
483700 mE
½ mile east of Grosmont
Ground level 497 ft. a.O.D.
0 to 10 ft. Drift
10 ft. + Estuarine Series
Rock floor 487 ft. a.O.D.

British Petroleum Ltd. in association with Seismograph Service (England) Ltd. kindly supplied the logs of thirty-nine boreholes put down as shot-holes for a seismic survey. The writer has examined all of these very carefully but unfortunately not one can be usefully employed in the present work either because the boreholes are inconveniently situated or because the details are insufficiently complete. This is not, of course, a criticism of the borehole programme since it was intended primarily for seismic work and the writeris very appreciative of the ready co-operation of both companies.

Finally, mention must be made in this section of various solid rock exposures. The old quarry in the Estuarine Series, centred at 511390 mN. and 488570 mE. about ¼ mile north-west of West Cliff Station, has been filled and is now beneath a housing estate but the solid rock level at this point is about 175 ft. a.O.D. Estuarine sandstone is visible in the cliff face beneath Boulder Clay at Lector Nab, which is slightly west of due north from West Cliff Station; it also outcrops in the beach below the Nab.

There is an Estuarine outcrop at the surface centred at 511170 mN and 483720 mE at the village of Dunsley and here the average surface level is about 350 ft. a.O.D. Another outcrop of the same series occurs at Lythe Bank and is centred at about 513200 mN and 485400 mE and the levels range roughly between 250 ft. and 350 ft. a.O.D. The top of the outcrop and cliffs on the west side of Whitby Harbour along the line of Esk Cross Section 6 appears to be about 100 ft. a.O.D. On the east side of the Harbour, solid rock is obviously at no great depth below ground surface and for the purpose of constructing Esk Cross Section 6 it is assumed to be at a uniform depth of about 10 ft.

Hemingway (1940) records exposures in several streams in the vicinity of Ruswarp. The present writer has examined these, with the exception of the one in Upgang Beck which could not be found. The exposures in Turnerdale Slack and the unnamed stream just north of it are all at, or no more than a few feet above, stream bed level. The exposures in

Shawn Riggs Beck extend from about 10 ft. above stream bed upstream to about 20 ft. above stream bed near the confluence with the Esk.

On the northern side of the main valley at Lealholm is an unnamed ¾ mile long stream which flows southwards, passing just east of the railway station, and joins the Esk immediately on the upstream side of Lealholm Bridge. There are some exposures of the Lower Estuarine in the stream bed but the form of the side of the main pre-Glacial valley must be judged from the changes in slope of the tributary valley sides and a few doubtful exposures. It seems that the pre-Glacial surface was between 20 and 30 ft. above the present bed of the stream. The writer examined parts of Low Wood Beck on the southern side of the main valley at Lealholm but no exposures were found - except beyond the upper limit of Boulder Clay as shown on the Geological Maps of the district - and evidence points to the fact that bed rock must be at least several feet below the stream and the immediate valley sides.

Rock floor levels taken from borings and outcrops are plotted on the longitudinal section of the Esk (Fig.23) and on the Esk Cross Sections 1 to 6 (Figs. 32, 33 and 34). An arrowhead on a horizontal line implies that rock floor occurs at the level of the line and an arrowhead breaking through a line implies that rock floor occurs at some unknown level below that represented by the line. Since the locations of borings and outcrops rarely occur on the lines of the various sections, it has been necessary to project the positions normally onto the cross-sections and the fact that these represent levels either upstream or downstream of the sections has been taken into account in reconstructing pre-Glacial profiles.

CHAPTER IV

Characteristics of the Eskdale Drainage System

This chapter is concerned primarily with the observed characteristics of the Eskdale drainage system but it is desirable to discuss initially some of the general principles of river development. The three factors to be considered are base-level, graded streams and meanders. In the survey and discussion of the characteristics of the Eskdale drainage system which follows, the tributaries are dealt with first, commencing with those on the south side of the catchment from Rigg Mill Beck in the east to Baysdale Beck in the west and then the two major tributaries on the north side of the catchment - Sleddale Beck and Stonegate Beck. The main river from Castleton to Whitby is treated last.

Base-Level

Before an equation describing the longitudinal section of a stream-bed or valley-floor can be established it is necessary to define the positions on the surface of the Earth of a vertical axis - representing the origin of distances measured along the river or valley - and a surface perpendicular to it. If a river or valley is relatively short the surface can be treated as a horizontal plane but when it is relatively long the surface is more correctly a level surface conforming to the appropriate geodetic spheroid or, to be strictly true, conforming to the geoid. The vertical axis and the surface are represented, of course, on paper by two perpendicular axes. The surface is commonly called the base-level - a term originally proposed by J.W. Powell in 1875 and discussed at length by W.M. Davis in 1902 and by C.A. Malott in 1928. A paper by D. Johnson (1929) is probably the last written on this topic and in it he examined five possible surfaces of reference related tothe ideal fluvial cycle.

It is clear that there are only two types of base-level - major base-levels at or near mean sea-level and minor base-levels established by lakes, resistant beds of rock and similar features. The major base-level can be regarded as being more permanent than the minor base-level. The writer prefers to use the term local control to define a minor base-level and to reserve the term base-level for the major reference surface. In any case, the major base-level is not strictly permanent and when defining a particular graded river, or part of a river, it is desirable to refer to the prevailing base-level - that is, the reference surface prevailing at the time of the grading of the river.

It will be realized that the definition of base-level as being at or near mean sea-level is a loose one - obviously the reference surface could be located anywhere between the level of the inshore sea-bed and the maximum flood level in the estuary. A more precise definition depends on the concept of a graded stream but this also is not yet clearly defined. The error involved in Great Britain by assuming that it is mean sea-level is not likely to exceed ± 20 ft. in the elevation of the surface of reference for current fluvial erosion cycles. A more precise definition must be left in abeyance until the fluvial hydraulics of the problem are better known. One point must be clearly understood in connection with the base-level of any particular river and it is that such changes in the position of the reference surface as one is able to determine represent relative changes between sea-level and ground-level expressed in terms of emergence or submergence. The amount of uplift or depression of the land surface or rise or fall in sea-level is more difficult to assess.

Graded Streams

The concept of a graded stream has been discussed at length by Mackin (1948) who defined it in the following way:

"A graded stream is one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for transportation of the load supplied from the drainage basin. The graded stream is a system in equilibrium; its diagnostic characteristic is that any change in any of the controlling factors will cause a displacement of the equilibrium in a direction that will tend to absorb the effect of the change".

The longitudinal section of a graded stream is referred to as the profile of equilibrium. In its simplest form this curve appears continuous and concave upwards. However, a more correct representation is probably a series of straight, or nearly straight, chords extending between the confluences of the tributaries. Sometimes a tributary influences the equilibrium conditions such that a cusp is formed with the gradient increasing downstream and Mackin (1948) cites the case of the Missouri which, in 1931, had an average gradient of 0.74 ft./mile over a distance of 31 miles above the confluence with the Platte River and an average gradient of 1.24 ft/mile over a distance of 44 miles below that point - this is ascribed to the influx of gravel from the Platte River, which has a gradient of 3.2 ft/mile in its lower reaches. Apart from cusps formed in this way, the marked breaks in the curve - known as nickpoints - lead to an interrupted profile and these may be due, of course, either to local controls or to cycle changes brought about by diastrophic or eustatic changes in base-level.

It is not intended in this thesis that a mathematical curve should represent the longitudinal profile of a river, or part of a river, exactly but instead it is a mean curve of simple form which eliminates the irregularities in the profile and enables an estimate of base-level to be made. Furthermore, since it is not easy to determine whether or not a particular profile is an equilibrium profile - more particularly when a pre-Glacial channel is considered - it might be preferable to refer to it as a mature profile, although the term equilibrium profile is employed here.

To date, the line or surface which is taken to represent the profile of equilibrium does not appear to have been defined. It could be, for example, the stream-bed, the flood plain, the dry-weather water surface or the maximum flood water surface. From the standpoint of fluvial hydraulics it is likely that a water surface is the most correct, since it defines the hydraulic grade line at which the static head is zero. The problem is to select a suitable river stage for this surface. It is reasonable to assume that the stage should conform to the dominant discharge which Inglis (1947) defines as the discharge at which equilibrium of sediment transport is most closely approached. Evidence indicates that the dominant discharge stage is normally a little higher than bank-full stage and the discharge is then roughly 50 to 60 per cent of the maximum flood. It follows therefore that a reasonable surface to define the equilibrium profile of the river is that of the flood plain adjacent to the river bank and this should be sufficiently close to the dominant discharge surface. Thus the longitudinal section to be plotted is the talweg or valley-way and not the stream bed. This appears rational when viewed from the geomorphological aspect, since the important features to delineate are those of land-surface morphology - the stream is merely the agent by which these features are formed.

The profiles presented in this chapter are based on the concepts discussed above and, excluding errors in levelling, the position of the equilibrium profile of the present Esk is unlikely to be more than +10 ft or - 5 ft. from the true equilibrium profile, if such a thing exists. On the tributaries such discrepancies should be no more than two to five feet. In preparing the profiles, horizontal distances have been measured along the mean course of each stream and not along the sinuous course. This conforms to the idea of plotting the talweg instead of the stream-bed. The positions of certain beds, such as the Dogger, have been taken from 6 inch to 1 mile geological maps and plotted on the profiles but, no doubt, some slight misplacements occur leading to apparent anomalies between controlling formations and the profiles.

Meanders

In common with other aspects of fluvial hydraulics, the raison d'etre ofmeanders is imperfectly known. Matthes (1941) has set out as follows, in order of apparent importance, the five fundamental factors controlling meanders:

1. General valley-slope (talweg). This is the general slope of the land-surface traversed by the stream measured along the axis of the valley as defined by the general course of the river. The profiles presented in this chapter conform to this.
2. Bed-load. Composition and quantity-rate of movement.
3. Discharge (a) average yearly discharge
   (b) duration of low, medium and high stages.
4. Bed-resistance. Controlled by the characteristics of the materials composing the alluvium, in particular grain-size, specific gravity, cohesion and the composite roughness of the channel surface.
5. Transverse oscillation. The change in slope of the water-surface at right-angles to the axis of flow - a phenomenon

simulated by the appearance of superelevation at bends on a highway. It is influenced by shoals, obstructions to flow and wind.

Matthes states that sediment in suspension does not appear to be a basic factor in meander development. Friedkin (1945) carried out extensive laboratory experiments on meandering and Inglis (1947) has put forward his views based on a lifetime of experiment and field observation. Although agreement has been reached on much of this work, there are still a number of controversial points but there is no need to prolong this discussion since in this study of Eskdale the factors can be considered only in a general way. More comprehensive investigations are worthy of an independent study. Inglis considers that the primary cause of meandering is fluctuations in the discharge and sediment-charge of streams. However, it is clear that meanders can develop only where sufficient energy is available for the stream to follow a tortuous course instead of a direct one and hence meanders are found where the valley is steeper than is required by the stream. The delicacy of equilibrium conditions in a stream is illustrated by an estimate made by Rubey (1933) in which frictional losses are assessed as 96 to 97.5 per cent of the total energy in some debris-carrying streams and the remaining energy is utilized for transportation. Thus relatively slight changes in channel characteristics can cause marked changes in transportation power which must inevitably be reflected in such features as meanders. In this thesis the meanders in the Eskdale drainage system are noted and an endeavour is made to explain their presence. Unfortunately, significant changes in slope may not be apparent over short lengths of stream since most of the longitudinal sections are plotted from the Six Inches to One Mile Ordnance Survey Maps on which the vertical interval of the contours is 25 ft.

Cock Mill or Rigg Mill Beck (Fig.16).

Cock Mill or Rigg Mill Beck rises as Soulsgrave Slack at about 680 ft. in the Upper Estuarine Series. The first half-mile is a straight artificial ditch and in this length it descends rapidly over the Moor Grit and Grey Limestone Series and enters the Boulder Clay. For the first quarter-mile in the Boulder Clay the valley is relatively wide and flat with the moorland sloping gently down to it but beyond this the stream begins to cut into the clay and is soon 20 to 40 ft. below the level of the moorland at the valley sides. The V-shaped valley is about 100 ft. wide at the top and the sides are steep. In this steep sided valley are two short lengths of elementary meanders. Although the first batch of meanders

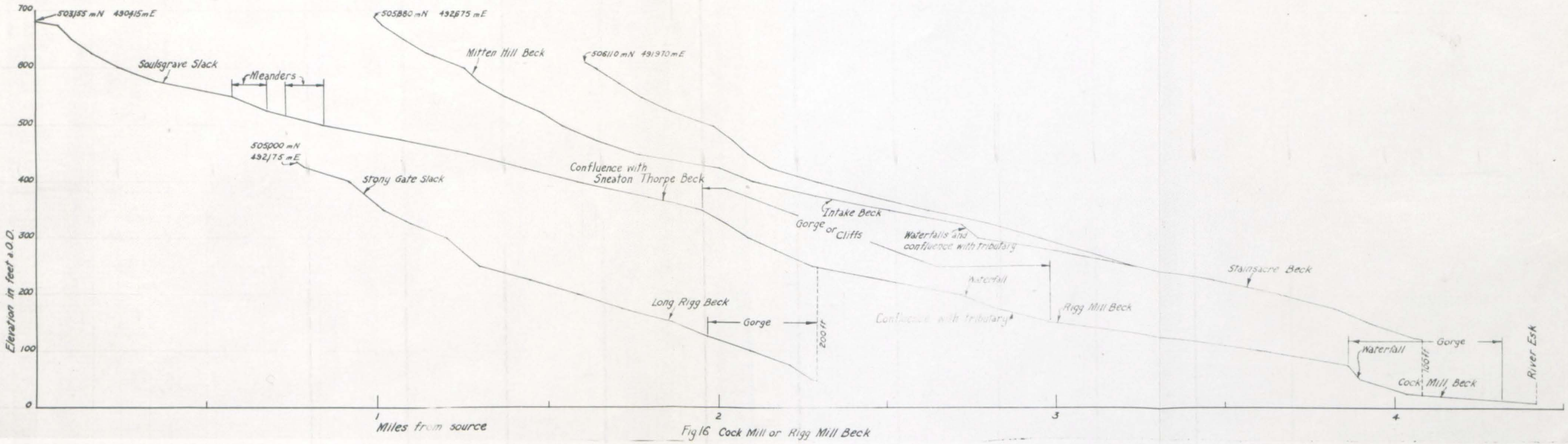


Fig 16 Cock Mill or Rigg Mill Beck

may be due partly to excessive gradient, it seems likely that particle size may be an influential factor since coarser material of cobble and small boulder dimensions is found just downstream. This rounded material may have its origin in the Upper Estuarine Beds or may be derived from the Boulder Clay.

At a point roughly one mile from the source of Rigg Mill Beck, the stream known as Long Rigg Beck rises toeastwards in close proximity and flows parallel to the former at a separation of 100 to 300 yards. Both streams enter steep sided gorges at a point about two miles from the source of Rigg MillBeck. A rapid survey revealed no distinct solid exposures in the gorge of Long Rigg Beck, although there are large boulders in the bed, but in the gorge of Rigg Mill Beck there are precipitous cliffs of Lower Estuarine Series with boulders in the bed up to one cubic yard or more in size. These particular exposures are not mapped on the "one-inch" drift sheet. The confluence of the two streams is at the same level although both descend in low waterfalls and rapids through the gorges.

The augmented Rigg Mill Beck continues to flow in a gorge and cliffs in the Lower Estuarine Series are seen on the west side. At a point about 2¼ miles from the source of Rigg Mill Beck is a natural 20 ft. waterfall at Rigg Mill. The deep gorge continues for a further quarter-mile but beyond this point the stream flows in Boulder Clay, the valley opens out, the valley sides are convex and at a few points the floor is flat and nearly 100 ft. wide. At a point nearly four miles from the source there is another 20 ft. waterfall, over the Moor Grit, and the stream then flows for another half-mile in a gorge in the Upper and Lower Estuarine Series, brought down by the Whitby Fault, before entering the Esk.

East of a point about 1½ miles downstream of the source of Rigg Mill Beck, another stream known as Stainsacre Beck rises and eventually flows parallel with, and 100 to 200 yards from, Rigg Mill Beck, which it joins in the gorge below Cock Mill. The origin of the twin parallel streams of Cleveland is discussed in detail in Chapter V.

Iburndale Beck or Little Beck (Fig.17)

Iburndale Beck or Little Beck and the Murk Esk are the only tributaries of the Esk which extend appreciable distances onto the moorland table; the remainder extend very little beyond the dales in which they are situated. Little Beck has three main tributaries; Blea Hill Beck, May Beck and Parsley Beck. Blea Hill Beck rises at about 820 ft. in gently rolling moorland in the Upper Estuarine Series but within about a half-mile it cuts deeply into the moor with steep valley sides

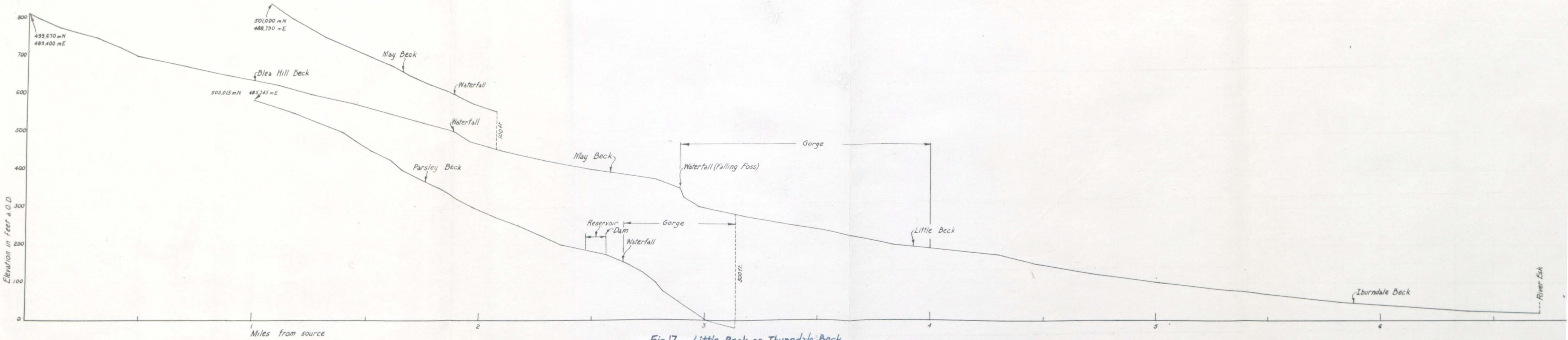


Fig.17 Little Beck or Iburndale Beck

as high as 30 ft. In the next half-mile or so there is evidence of former meanders in terraces about 5 ft. above the present bed but the stream now follows a straighter course, cutting some of the spurs. In the next half-mile to the 20 ft. waterfall over the Moor Grit there is evidence of active lateral erosion in the steep valley sides. Obviously the local control has been lowered comparatively recently and, since the beds dip obliquely upstream, recession of the waterfall is indicated. The effective dip is of the order 100 ft. in 2 miles and for a reduction in control level of 5 ft. a retreat of about 100 ft. would be necessary. However, careful levelling of the older meander terraces is required before the earlier profile can be constructed and it is possible that additional evidence could be obtained by detailed studies of May Beck. If the waterfall is to be replaced at the confluence of Blea Hill Beck and May Beck then the reduction in level must be about 25 ft. but, of course, the gradient of the earlier stream would then be very much flatter at this section.

May Beck rises at about 740 ft. just above the outcrop of the Moor Grit and for a distance of rather more than a half-mile it practically follows the strike and cascades over the Moor Grit, the Grey Limestone Series and the topmost beds of the Lower Estuarine Series. At several places an earlier channel - now moss filled - can be seen a few yards from, parallel to and about 5 ft. above the present channel. Although Blea Hill Beck is the major tributary, the combined stream below the confluence is known as May Beck as far as the confluence with Parsley Beck, which is about one mile downstream. In this length the stream cuts deeper and the valley becomes more gorge-like. About a quarter-mile above the confluence with Parsley Beck is the waterfall over the Dogger known as Falling Foss which is about 40 ft. Below this the stream flows in a gorge cut in the less resistant Upper Lias.

Parsley Beck rises at about 880 ft. in flat to gently undulating moorland in the Upper Estuarine Series but after about a half-mile it descends rapidly over the Moor Grit - the beds dipping downstream at an effective gradient less than that of the stream. Just over a mile from the source is an earlier higher channel - apparently an arcuate bypass about 100 yards long. It is regular and well formed but the bottom is now moss filled. The upper end is about 20 ft. above the present stream but the lower end steadily declines to it. The drift map shows the margin of the Boulder Clay at this point and it seems likely that the pre-Glacial channel was blocked and the bypass was cut in the Boulder Clay but shortly afterwards the pre-Glacial channel was re-opened. Beyond this point the valley of Parsley Beck opens out with a relatively flat floor, although the stream now flows on a bed of boulders under a steep bank on the south side. The trace of an earlier straight channel about 10 ft. above the present one can be seen on the north side of the floor and there is evidence of former meanders in the centre. The stream then enters a small artificial lake impounded by a dam. Below this Parsley Beck drops over a waterfall formed by the Dogger and enters a deep, steep-sided gorge cut in the Upper Lias.

The confluence of Parsley Beck and May Beck - which forms Little Beck - is in a heavily wooded, deep, steep-sided gorge and the streams meet at the same level. The gorge, with precipitous cliffs of shale, continues to just above the hamlet of Little Beck. Downstream of this point the valley becomes broader and the sides are less steep but there are slips in the Boulder Clay, indicated by hummocky ground. The stream is cut principally in Boulder Clay, with occasional exposures of Lias, and for the last 1½ miles to the confluence with the Esk there are more or less continuous flats of alluvium. Active lateral erosion is apparent intermittently from a point about one mile from the

Esk but the relatively steep valley sides persist almost to the end.

The Murk Esk and Tributaries (Fig.18)

The principal tributaries of the Murk Esk are Eller Beck, Wheeldale Beck - which divides into Blawath Beck and Rutmoor Beck - and Wheeldale Gill. The source of Eller Beck is at 830 ft. on the edge of the Kellaways Rock in gently undulating moorland. In the first 1½ miles the stream follows a regular course in a shallow valley, descending into the Upper Estuarine Series. Then for about a half-mile there are meanders, lateral cutting is in evidence and in some places there are comparatively deep and still pools. The local control leading to these conditions is effected by the Moor Grit, at the outcrop of which there is a waterfall. In the following three-quarter-mile to the head of Newton Dale the course is again regular and is entirely in the Moor Grit and Grey Limestone Series, flowing westwards practically along the strike. The immediate valley sides are much steeper in this length. Flowing northwards for a further three-quarter-mile in the head of the glacial over-flow channel the course is relatively straight and the stream does not cut more than 5 ft. below the present valley floor, which is composed of alluvium (?) and peat, just exposing the Lower Estuarine Series in places. For the next 1¼ miles

Fig 18 Murk Esk and Tributaries

the valley opens out and there are elementary meanders in the course. In this length is Boulder Clay and some alluvium. The local control leading to the formation of meanders is at the head of the gorge at Goathland where there are waterfalls and weirs - it is likely that the waterfall known as Mill Force, which appears to have served as a weir, afforded the original local control. It will be seen from Fig. 18 that the gradient in the glacial overflow channel is slightly greater than that in the length of meanders. Since the banks in the overflow channel are principally of easily eroded material it is reasonable to assume that meandering might be in evidence but in fact it is absent. The reason must be that the stream is still cutting into the Lower Estuarine Series in the floor. This example indicates the subtlety of the meander processes. The gradient in the overflow channel is, however, less than that in the meandering length above the Moor Grit one mile upstream. Where a stream flows alongside a road or railway, as it does in the overflow channel, consideration must be given to possible artificial training but there is no evidence of this in Eller Beck. The 1½ mile gorge below Goathland is cut principally in the Lower Estuarine Series and at the lower end the stream joins West Beck to form the Murk Esk. There are waterfalls and rapids in this length and the waterfall known as Thomason Force is over the Eller Beck Bed. The reason for the formation of Eller Beck and West Beck gorges is, of course, the blocking of the pre-Glacial channel or channels with Boulder Clay.

The source of Blawath Beck is at about 770 ft. and for nearly two miles it flows in the gently undulating moorland in the Upper Estuarine Series. In the first 1¼ miles it flows parallel to the outcrop of the Cornbrash and about 100 yards from it. After passing over the Moor Grit escarpment it falls rapidly to meet Rutmoor Beck in the Lower Estuarine Series in less than a quarter-mile. Just above the Moor Grit are two short lengths of elementary meanders.

The source of Rutmoor Beck is at 880 ft. and almost connects with one of the tributaries of Wheeldale Gill flowing in the opposite direction. In the distance of nearly 4 miles to the confluence with Blawath Beck it flows entirely in the Upper Estuarine Series and the terrain is mostly gently undulating moorland. Generally the course is fairly regular but for about a half-mile beneath Trigger Castle - an outlier capped with Kellaways Rock 200 ft. above the valley bottom - there are elementary meanders. The immediate valley sides are steep and a number of stream-cut cliffs are visible. On the hillside below Trigger Castle hummocky ground provides evidence of extensive slips which are now well covered with vegetation. It seems that some of the elementary meanders which occur at this point may have been enforced by rock falls from the cliffs, though if insufficient energy is available to maintain these conditions the stream must eventually straighten its course. Similar conditions obtain in the upper part of Sleddale Beck.

In the 1½ mile stretch from Trigger Castle to the confluence with Blawath Beck can be seen portions of terraces from 5 to 10 ft. above the present stream and in these several moss filled meander loops mark an earlier caurse. The passage over the Moor Grit and Grey Limestone is by a series of low waterfalls, never more than 2 ft. high and commonly just a few inches and nearer the confluence are large blocks of sandstone up to one cubic yard or more in size. At this point Rutmoor Beck flows almost along the strike whereas Blawath Beck flows up dip over the Moor Grit and the descent is rapid. The sandstone blocks in Rutmoor Beck are the remains of the Moor Grit which fell from the valley sides as the waterfalls gradually receded to their present position. Although steep, the immediate valley sides are not markedly so. It will be observed that conditions at this confluence are very similar to those at the confluence of Blea Hill Beck and May

Beck, the tributaries of Litte Beck discussed earlier. In both cases one receives the impression that the break down of the local control has been rapid when the waterfalls receded beyond the confluences. The meanders below Trigger Castle may, of course, be related to the terraces observed downstream but the extent to which both can be related to a former local control is not obvious. Here also more accurate data is required to enable conclusions to be drawn. It may be that the meanders at Trigger Castle are very temporary and have been enforced by rock falls, as mentioned above.

Wheeldale Beck consists of a one mile length of stream between the confluence of Blawath and Rutmoor Becks and its junction with Wheeldale Gill. The stream flows in a relatively broad valley with a relatively flat floor and a few elementary meanders.

The principal tributary of Wheeldale Gill is Bluewath Beck, which rises at 1,240 ft. in the Lower Estuarine Series in gently undulating moorland. It flows down dip along the main anticlinal axis. The gradient of the stream in the first 3 miles is fairly uniform and averages 130 ft. per mile. The dip of the beds near the source averages about 90 ft. per mile but 2½ miles from the source it is about 150 ft. per mile. Consequently the Grey Limestone Series dip just below the stream between 2 and 2½ miles from the source and the course is entirely in these beds for a half-mile whilst the Moor Grit is just severed. From a point about 3 miles from the source the stream gradient gradually increases to an average maximum of about 160 ft. per mile and the stream descends into the Lower Estuarine Series but the gradient and the dip are so nearly equal that the Eller Beck Bed is just penetrated for a distance of about one mile to form a very elongated inlier. At this point the stream has cut well below the moorland surface, the immediate valley sides are very steep with trees in the bottom and the stream is truly a gill. The tributary known as Wheeldale Gill rises at about 1,020 ft to the north and joins Bluewath Beck at about 2½ miles from the source of the latter but this can hardly be regarded as the main headwaters of the united stream known as Wheeldale Gill. In a three-quarter mile length above the confluence with Wheeldale Beck the valley opens out and the stream gradient becomes slacker.

Wheeldale Beck and Wheeldale Gill unite to form West Beck which soon enters a gorge cut entirely in the Lower Estuarine Series except for a short length in the Upper Lias before the confluence with Eller Beck. Two noted waterfalls occur in West Beck - Nelly Ayre Force, formed by the Eller Beck Bed, and Mallyan Spout. Another waterfall occurs downstream over the Dogger.

At the confluence of Eller Beck and West Beck at Beckhole the united streams constitute the Murk Esk. Beyond this point the valley opens out although the sides are steep. In the 2¼ mile length from Beckhole tothe confluence with the Esk at Grosmont, the lower parts of the valley sides consist principally of Upper Lias but above thisare Glacial Sands and Gravels on the west side and Boulder Clay on the east. In the valley bottom is alluvium in varying widths up to a maximum of nearly a quarter-mile and remnants of terraces can be seen. The Murk Esk enters a half-mile long gorge at Grosmont which terminates immediately above the confluence with the Esk. This gorge is due to blocking of the pre-Glacial channel with Boulder Clay.

Butter Beck (Fig.19)

Butter Beck is the 3½ miles long stream which flows in the dale known as Egton Grange. The two main tributaries Birchwath Slack and Birchwath Gill rise at 1,010 ft. in the Grey Limstone Series and 980 ft. in the Lower Estuarine Series respectively. Within about a half-mile from their sources they leave the moor-top and are deeply incised in the Lower Estuarines. The passages over the Eller Beck Bed exhibit no marked features. The two tributaries are 1¼ miles and 1½ miles long respectively at their confluence, which is located in Boulder Clay. The

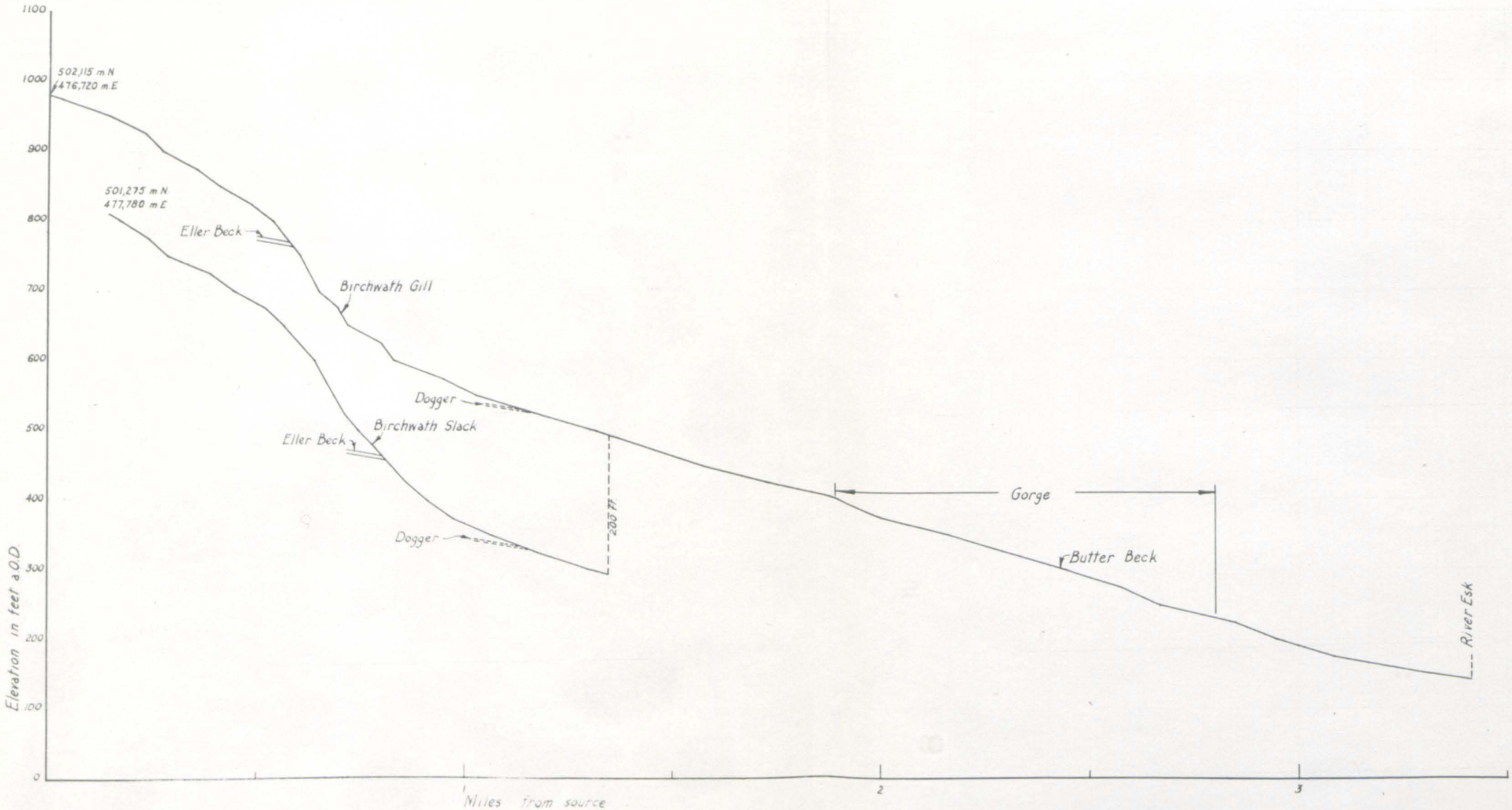


Fig. 19 Butter Beck

head of the dale is relatively wide and open but Butter Beck cuts progressively deeper and enters a three-quarter mile long gorge initially in Boulder Clay and then in the Upper Lias. Below the gorge the valley opens out in the three-quarter mile length, mainly in Boulder Clay, to the confluence with the Esk. There is evidence of slips in the form of rough ground along this lower length.

Glaisdale Beck (Fig.20)

Apart from the headwaters, which rise at 1,080 ft., Glaisdale Beck receives two main tributaries, Winter Gill, which rises at 1,050 ft., and Hardhill Beck, which rises at 1,250 ft. Wintergill just reaches onto the Grey Limestone Series on the moor top but within about one mile it has descended through the Lower Estuarines into the Upper Lias and the valley is sharply incised in the landscape. A waterfall of about 4 ft. occurs at the passage over the Eller Beck Bed. The headwaters of Glaisdale Beck extend a short distance onto the Lower Estuarine Series on the moor top but within a quarter-mile the stream descends into a sharply incised valley, in the Upper Lias. Any waterfalls created by the Eller Beck and the Dogger are obscured by large boulders. Hardhill Beck rises on the moor top almost on the boundary between the Grey Limestone Series and the Lower Estuarines and its characteristics are similar to those of Winter Gill.

The passages of all three streams over the Upper Lias are

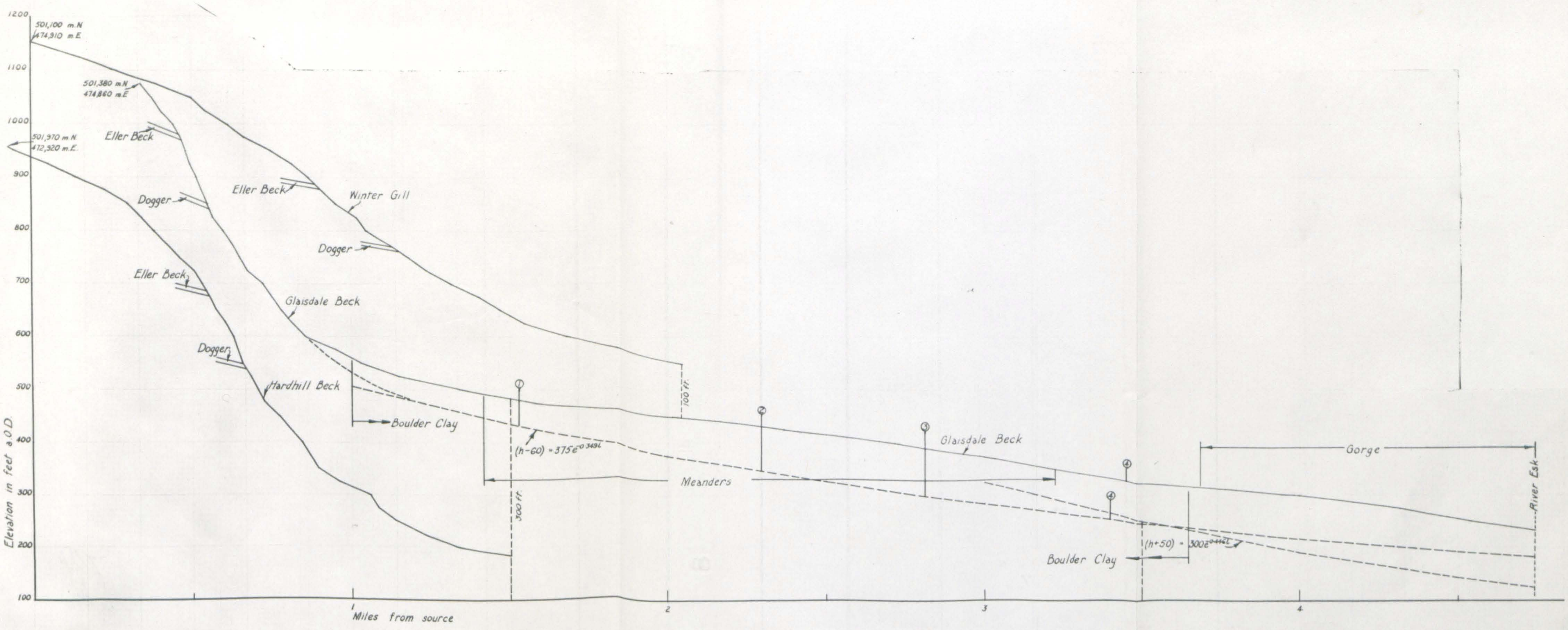


Fig. 20 Glaisdale Beck

short half-miles and their beds and that of Glaisdale Beck are then cut wholly in Boulder Clay as far as the head of the gorge where there is a 2 ft. waterfall. From the confluence with HardhillBeck to within a half-mile above the gorge, Glaisdale Beck follows a meandering course but there is no sign of a floodplain and little evidence of lateral erosion. The gradient is slightly reduced before entering the gorge and this no doubt contributes to the marked reduction in meandering in the half-mile above the gorge. Boulders up to about a half-cubic-yard occur in the bed in , and some distance above, this length and this factor must also contribute. On both sides of the stream is hummocky ground evolved partly by slips and partly by minor lateral drainage. The stream appears to be incised in the clay and because of these various characteristics there is no doubt that the meanders deserve a close study. The gorge through West Arnecliffe Woods to the Esk is cut in the Upper Lias and is about one mile long.

Great Fryup Beck (Fig.21)

Great Fryup Beck rises at 1,360 ft. in the Grey Limestone series on the moor top. It descends rapidly over the Lower Estuarines and the Dogger into the Upper Lias in about a half-mile. The Eller Beck Bed is absent. In another half-mile it passes into the Middle Lias. On entering the head of the dale, the main stream and other small headwater tributaries cut deeply into the rocks and the main stream flows in a ravine, about

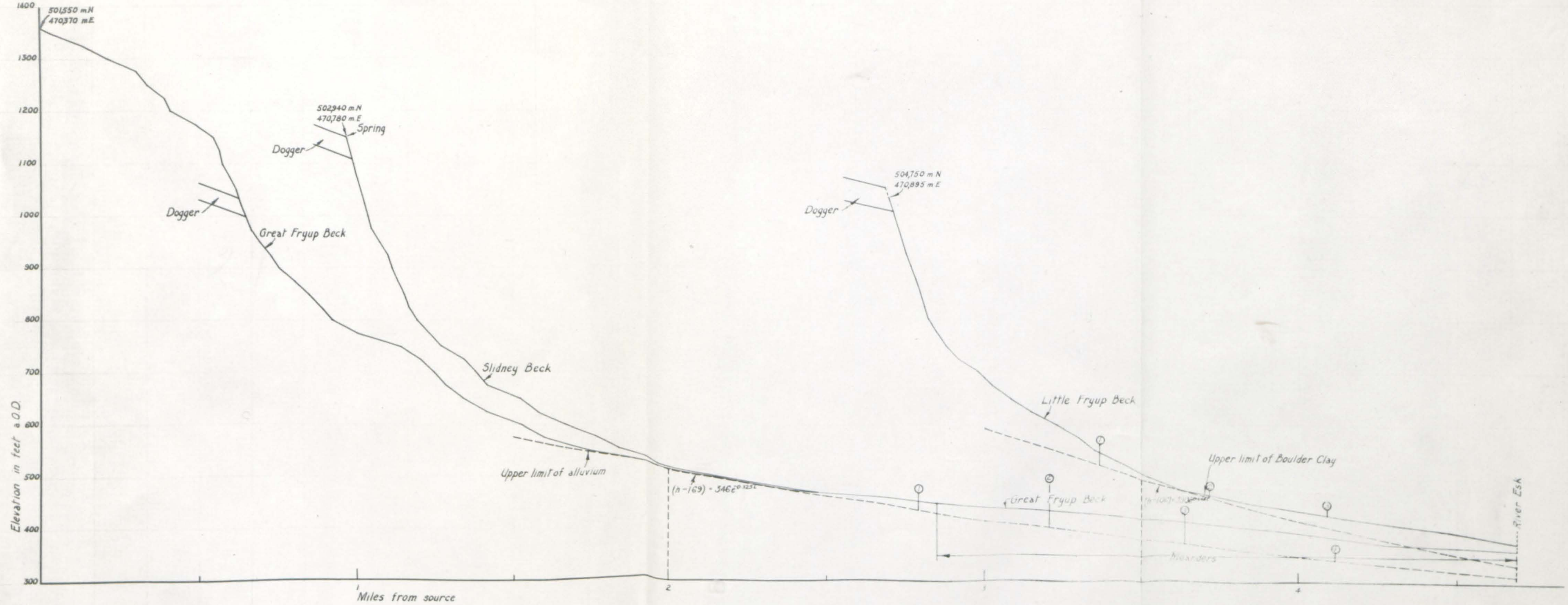


Fig 21 Great and Little Fryup Becks

50 ft. deep, for nearly a half-mile in the Upper Lias. Then follows a narrow three-quarter-mile alluvial strip with a few elementary meanders but the adjacent valley sides are moderately steep to steep and low river cliffs expose shale, although some of this may be slipped material. Slidney Beck joins the main stream in this length and this tributary rises at 1,150 ft. as a spring at the edge of the top of the Dogger which caps the valley sides. The characteristics of this stream are similar to those of the Fryup Beck headwaters.

The main stream leaves the alluvial strip mentioned above and flows in Boulder Clay for about 1¼ miles and then follows another three-quarter-mile strip of alluvium to the confluence with the Esk. Meanders are quite well developed in a length of about two miles above the confluence with the Esk - some of these occur in alluvium and the remainder in Boulder Clay. Active lateral erosion is seen accompanying the upstream meanders but this becomes less as the confluence is approached.

The meanders of Great Fryup Beck form an interesting problem, like those of Glaisdale Beck. The profile of the main stream from just above the confluence with Slidney Beck to the Esk is regular and the gradient declines steadily except for a slight increase about a half-mile above the Esk. There are several straight stretches in the upper alluvial strip, yet meanders are practically continuous in the Boulder Clay downstream. One may ask therefore how this alluvium has been deposited and why meanders are comparatively absent in it to-day? The alluvium must be filling behind the dam of Boulder Clay downstream but the gradient in it must be sufficiently slack to preclude the formation of meanders. The presence of Boulder Clay implies fine material in the stream and inspection of the bed reveals that in the meandering zone there is rather more fine material than upstream in the alluvium.

Little Fryup Beck (Fig.21)

Little Fryup Beck is a rather characterless stream which rises at 1,030 ft. in the Dogger Bed and tumbles down through rough ground into the dale. For the greater part of its length it is rarely more than 2 ft. wide and 2 ft. deep and looks more like an artificial ditch than a natural stream. Even at the confluence with the Esk its bed does not exceed 4 ft. in width but it is incised to a depth of about 10 ft.

Danby Beck (Fig.22)

Danby Beck rises at about, 1,315 ft. on the edge of the Grey Limestone Series. In about a half-mile it descends

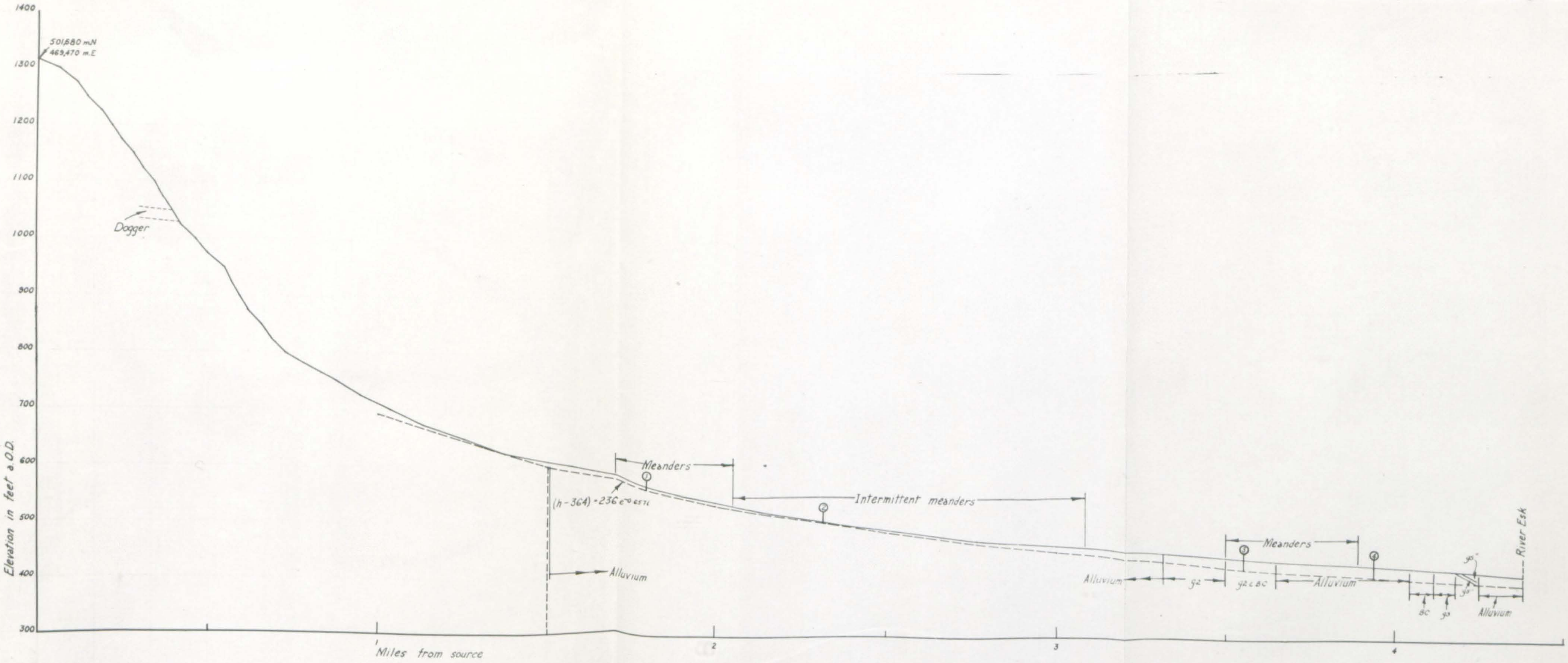


Fig. 22 Danby Beck

through the Lower Estuarines, over the Dogger and into the Upper Lias in a sharply incised course, then through the Middle Lias into the Lower Lias. Meandering commences nearly two miles from the source and this persists, though intermittently in places, for about two miles. Most of this length of the stream is in alluvium with flats up to about 100 yards wide. The adjacent valley sides are moderately steep and are gorge-like in several places where the immediate valley floor is narrow. The floor of Danby Dale is a flat V in section, with the stream slightly incised in the centre, whereas the Fryup Dales and Glaisdale possess a U section. This characteristic can be clearly seen from view-points high on the valley sides at the head of the dale. In about the last mile to the Esk, Danby Beck passes over the Middle Lias, the Boulder Clay and then into the alluvium of the main valley. It will be seen that there is a batch of meanders upstream in alluvium and another downstream in the Middle Lias onthe fringe of Boulder Clay. The reduction in meandering in a downstream direction is presumably due to the reduction in gradient but the reason for the re-appearance of meanders in the Middle Lias is obscure. There appears to be little or no difference between the bed material in this zone and that upstream although the presence of the Boulder Clay suggests a greater proportion of fine material at this point.

The Esk Headwaters in Westerdale (Fig.23)

It will be observed that Westerdale has a more complex form than any of the other dales; this is discussed in Chapter V. The tributary Tower or Whyett Beck in the eastern limb of Westerdale rises at about 1,285 ft. in the Lower Estuarines, descends in an incised course through the Upper Lias and in a distance of ¾ mile from the source it reaches the valley floor in the Middle Lias. Downstream of this point there are some elementary meanders, cliffs up to about 20 ft. in shale - possibly slipped material - and occasional valley flats up to about 60 ft. wide, although no alluvium is shown on the geological map. From a point about two miles from the source to the confluence with the Upper Esk the meanders are better developed but there are low cliffs in places and valley flats are of negligible width, except near the confluence, where they are up to 50 ft. wide.

The headwaters of the Esk are commonly regarded as rising at the head of the western limb of Westerdale at about 1,235 ft. in the Lower Estuarines. Actually several tributaries converge at the head of this limb, forming an elongated basin by centripetal drainage. The valley becomes slightly narrower downstream for a distance of about a half-mile but it opens out again just before the confluence with White Gill. In this length the stream is incised in the valley floor. The basin lies over the anticlinal axis where the strata are almost horizontal and this accounts for the centripetal drainage and the consequent valley morphology. From the confluence with White Gill to near the confluence with Tower Beck meanders occur intermittently. Some of the meanders are well developed and oxbows can be seen - particularly good waterlogged examples of the latter occur just upstream of Westerdale village. River cliffs also occur, mostly on the east side of the stream. There is a small mill dam near The Grange leading to a difference in water level of about 6 ft. and, although this affects both water level and stream bed for a distance of about a quarter-mile upstream, it does not appear to influence the riparian topography. Alluvial flats are most fully developed in the vicinity of Westerdale village and attain widths up to about 100 yards. The exit of the Esk from this limb of Westerdale is through a narrow defile with banks up to about 40 ft. high and with a flat floor about 60 ft. wide. This defile must be due originally to the lowering of the Dogger by the trough fault. After Tower Beck joins the Esk, the course to the confluence with

Fig. 23 River Esk, Baysdale Beck and Sleddale Beck

Confluence with Great Fryup Beck
Meanders
Gorge (Crunkly Gill)
Dogger
Dogger
Esk Cross Section 2
Intermittent meanders
(h+0) = 240e^-0.223L
Confluence with Stonegate Beck
Gorge
Glaisdale Iron Works Excavation (20')
Confluence with Church Dale Beck
Confluence with Glaisdale Beck
Gorge
Confluence with pre-Glacial Glaisdale Beck
(h+150) = 250e^-0.223L
Confluence with Butter Beck
Weir
Confluence with Murk Esk
Grosmont Iron Works Excavation (50')
Grosmont Iron Works Excavation (50')
Esk Cross Section 3
Esk Cross Section 3
Profile derived from cross-sections (raised 100 ft)
Esk Cross Section 4
Confluence with Lady Hilda's Beck
Esk Cross Section 4
Sleights Weir
Bridge
Confluence with Little Beck
(h+95) = 110 e^-0.223L
Esk Cross Section 5
Esk Cross Section 5
Tidal
Ruswarp Weir
Esk Cross Section 6
Line of base of present cliffs between Upgang and Sandsend
Confluence with Rigg Mill Beck
Gorge
Railway viaduct
Confluence with Spital Beck
Esk Cross Section 6
Line of base of cliffs at Whitby
11
12
13
14
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26

Baysdale Beck is through a relatively narrow but shallow gorge in the Lower Estuarines. No meandering occurs here but shoals and alluvial flats are in evidence.

White Gill and Clough Gill become incised after leaving the moor top. Clough Gill produces a small inlier encircled by the Dogger and there is a low waterfall where it passes over this bed for the third time. Like many other moorland streams, Stockdale Beck is an insignificant watercourse on the moor top and cannot readily be identified but, on descending from the Lower Estuarines into the Upper Lias, it is deeply incised for about a half-mile before the valley opens out into Westerdale. Stockdale Beck rises at about 1,400 ft. - the highest altitude of any of the sources in the Eskdale system - although Black Hagg Beck in Baysdale rises at 1,370 ft. and several other streams rise at well above 1,300 ft.

In view of the fact that the course of the Esk before beheading probably followed the lower half of Baysdale Beck (see "The Baysdale-Sleddale Fluvial Complex" in Chapter V), it is debatable whether Baysdale or Westerdale should be regarded as comprising the headwaters of the Esk. However, if the course of the Esk shown on the Ordnance maps is followed from inside Westerdale to the estuary at Whitby, it will be found that it always has the greatest proportions at the confluences with the other streams, thus substantiating the assignment of the headwaters to Westerdale. It should be remarked that the differences in stream proportions at the confluences are sometimes only small and, as an example, the Murk Esk and the Esk at the Grosmont confluence are very similar.

Baysdale Beck (Fig.23)

Baysdale Beck rises at 1,370 ft. in the Lower Estuarines. The descent from the moor top through this Series is steady and the valleys of the three tributaries (Black Hagg Beck, Rowantree Gill and an unnamed stream) which converge to form Grain Beck are relatively open. The passages over the Eller Beck and Dogger Beds are not well marked, although the Dogger forms a conspicuous scarp along the sides of the main valley. Seen from downstream, the Dogger closes in to pinch the stream and one expects to see a waterfall at the outcrop in the stream bed but, if this exists, it is obscured by the large boulders formed in abundance by rock falls from the Dogger in the valley sides. The stream then cuts deeply into the Upper Lias, the immediate valley sides are steep and in a length of about a half-mile it flows in a narrowly wooded gorge with cliffs in the shales up to about 80 ft. high. In spite of the steep banks there is a relatively flat valley floor averaging 20 to 30 ft. in width. This is an illustration of a stream attaining a comparatively mature profile whilst the morphology of the main valley is still young - a characteristic which depends to a large extent on the relative ease with which vertical excavation is effected by the stream. Slips are visible in the valley sides in a length from about one mile to a half-mile above the confluence with Black Beck. Some elementary meanders are seen in the lower one mile of Grain Beck. Black Beck rises at 1,220 ft. in the Lower Estuarines and its characteristics are similar to those of Grain Beck.

For a distance of about one mile below the confluence of Grain Beck with Black Beck there are alluvial flats, meanders, a few waterlogged oxbows, shoals and indications of lateral erosion. The immediate valley sides are steep in places and there are some river cliffs - mostly on the south side of the stream. The reason for uni-lateral erosion is discussed below in connection with Sleddale Beck. There are second passages over the Dogger and Eller Beck Beds thus enclosing the Baysdale Inlier. Neither of these beds makes a conspicuous topographical impression on the stream at this point but the transition from the quiet waters flowing in shale to the noisy waters tumbling around boulders derived from the Dogger and Lower Estuarines is very noticeable. The meanders mentioned above cease a little more than a half-mile above the outcrop of the Dogger but the profile indicates that there is a very slight increase in gradient below the meanders. Therefore the termination of the meanders must be due largely to the increase in particle size of the bed and to the consequent increased resistance to flow. For nearly two miles after crossing the Dogger the course of the stream is relatively straight, the immediate valley sides range from moderately steep to steep with cliffs - which are about 70 ft high at one point - and the flat valley floor varies in width from about 20 to 100 ft. In the last half-mile to the confluence with the Esk the valley opens out and there are wide alluvial flats and some meanders.

Sleddale or Commondale Beck (Fig.23.)

Two tributaries - each about one mile long - constitute the headwaters of Sleddale Beck. One, known as Codhill Slack, rises at about 765 ft. in peat overlying the Upper Lias and the other, known as Sleddale Beck, rises at about 925 ft. on the edge of the Lower Estuarines. Most of the course as far as Commondale lies in a thin strip of Upper Lias but the valley does not show the same sharp scarp at the contact between the Estuarines and the Lias as seen in many other dales and the break in slope is marked in varying degrees of clarity. This may be due partly to the fact that the resistant Dogger Bed appears to be absent in a considerable length of the valley. The width and depth of the valley is not as great as in most other dales.

Both tributaries are characterized by the presence of straight or gently curved stretches and the absence of meanders The shallow banks are cut in sandy-clay alluvium and the bed is gravel. The gradients of the two tributaries are not as steep as the upper reaches of other streams in the Esk catchment. Below the confluence the course becomes slightly tortuous although there are numerous comparatively straight stretches and recent flooding has led to considerable deposits of sand on the banks in many places. It appears that the energy of the individual tributaries is insufficient to lead to the development of incipient meanders but the energy of the combined streams is just sufficient.

About a half-mile below the confluence intermittent cliffs up to about 25 ft. high occur in the shales, invariably on the south-west side of the stream, and extensive marshes occur on the north-east side. These conditions obtain for about one and a half miles to the head of the glacial overflow channel. The stream flows practically along the strike in this length and the lateral cliff-cutting is up-dip. A few earlier meander loops can be seen on the north-east side and the stream appears to be cutting laterally in a south-west direction. Some of the few current meanders may have been initiated by rock falls from the cliffs, in a manner similar to those which occur in Rutmoor Beck below Trigger Castle.

The probable reason for uni-lateral up-dip erosion which leads to cliffs on the south-west side of Sleddale Beck and on the south side of Baysdale Beck is as follows. Where rocks dip up away from the exposed face of a valley they are structurally less stable than where they dip down away from an exposed face. Whilst a stream is cutting vertically it is also eroding laterally to a greater or lesser extent and in this case, as indicated in Fig.24, the stream finds lateral erosion easier on the up-dip side where the cliffs fall more readily. Consequently there is a progressive uni-lateral movement of the stream accompanying vertical cutting. Lithology must play a part in this phenomenon and a given dip may be insufficient to lead to uni-lateral instability and erosion with one type of rock, such as sandstone, whereas it may be sufficient with another type, sudh as shale.

The true glacial overlow channel extends from the head of Kildale to Commondale, although the glacial waters

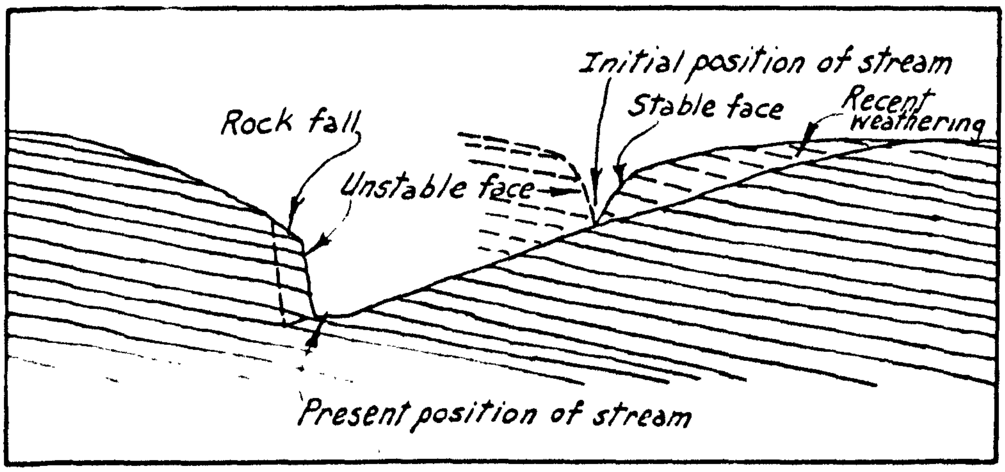

Initial position of stream
Rock fall
Stable face
Recent weathering
Unstable face
Present position of stream

Fig. 24

flowed further in the well-defined pre-Glacial valley of Whitely Beck/Commondale Beck to Castleton. The stream is trained by short, straight lengths of wall at a few points alongside the railway in the overflow channel but, even so, the natural course is remarkably straight and regular. There are a few elementary meanders in the second-half of this length in which the gradient increases slightly. The low banks of the stream are in alluvium. The passage over the Dogger onto the Lower Estuarines occurs in this length but it has no apparent effect on the stream. There is a low artificial dam just above Commondale leading to a difference in water-level of about 3 ft. and below it a recording weir belonging to the Cleveland Water Company leading to a difference in water-level of about one foot.

Below the confluence with Whiteley Beck at Commondale there is an extensive strip of glacial sand and gravel mostly on the south-west side of the valley and the ground surface is undulating and often rough. The tendency towards meander formation increases steadily from the confluence downstream to the Esk. The gradient is practically the same as that in the second-half of the glacial overflow channel so that meander formation is probably due largely to the increase in energy of the combined Whiteley and Sleddale Becks.

The exit of Commondale Beck from the tributary valley is through a short gorge in the Estuarines. This Series is visible en masse on the north-east side of the valley and a few exposures on the south-west side can be seen in the railway cutting. The stream has been displaced by the deltaic sands and gravels and the pre-Glacial course must have been about 200 yards south-west of the present course through the gorge. This does not appear to have been noted in earlier studies of the area. The deposit blocking the valley has the morphology of a terminal moraine but according to Kendall (1903) it is a deltaic plateau and this must have been considerably eroded to reduce the flat top to its present narrow width. The available evidence does not, in fact, support any suggestion that this feature is a moraine. Thus, for example, Boulder Clay is absent on the adjacent moor tops where it could be expected to occur if ice extended to this position.

Stonegate Beck (Fig.25)

Stongate Beck rises at 635 ft. at the summit of a galcial overflow channel just in the Kellaways Rock, although the channel floor is covered with peat and glacial deposits. The source is actually linked with that of one of the tributaries of Roxby Beck which drains to the north of the divide. The overflow channel is shallow at the source and the stream is ditch-like. The characteristics of an overflow channel persist for about two miles downstream of the source, with

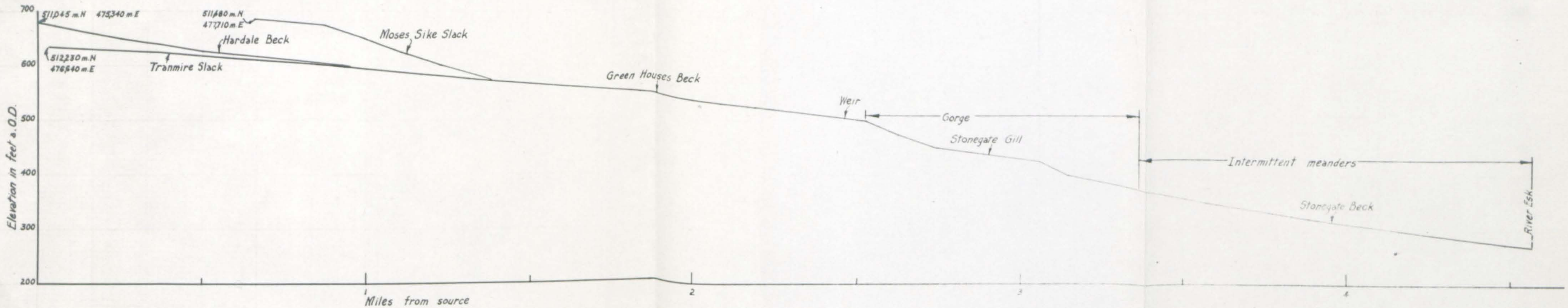


Fig. 25 Stonegate Beck

occasional lateral expansion revealing hummocky ground of Boulder Clay on the flanks. At a distance of about 2½ miles from the source the stream crosses a fault with a downthrow of 100 to 200 ft. (see Chapter II) on the upstream side. The effect of this is to bring up the Grey Limestone Series to near stream level and Stonegate Beck then flows in a gorge in the Lower Estuarines about one mile long. The fault does not appear to influence the stream in any other way. There are two dams each about 5 ft. high at the head of the gorge which once fed a mill now disused. In the one mile length below the gorge to the confluence with the Esk there are some elementary meanders and valley flats up to 60 ft. wide. The undulating valley sides in this length are largely covered with glacial gravels although the stream is cut in Boulder Clay. The valley opens out just before the confluence with the Esk. Two tributaries rise at slightly higher altitudes then the main stream - Hardale Beck at 680 ft. and Moses Sike Slack at 685 ft.

The River Esk from the Baysdale Beck Confluence to the Estuary at Whitby (Fig.23)

From the confluence with Baysdale Beck to the head of Crunkly Gill the Esk flows in alluvium according to the geological map but it flows also in varved clays in the neighbourhood of Howlsike and probably elsewhere. Immediately after the confluence with Baysdale Beck the river is roughly 15 ft. wide and 8 ft. deep from bank top to bed but these dimensions increase to about 20 ft. and 10 ft. respectively just below the confluence with Sleddale Beck and these proportions are maintained almost to Crunkly Gill where the depth decreases to about 5 ft. There are meanders along the entire 5½ mile section, although some are rather attenuated; the best examples lie between Ainthorpe Bridge and the head of Crunkly Gill. Shoals occur at numerous places. Good alluvial flats extend along the full length and the meanders swing from one side of the belt to the other. Between Castleton and Danby the valley appears to be narrow for a river of the proportions of the Esk and this is due to the deposits of glacial sands and gravels, more particularly at the lower end of Danby Dale. Slips occur in the high banks on the outside of bends at Castleton, but there is little evidence of erosion at bends elsewhere. Beyond the alluvial belt, rough ground can be seen in some places -for example, between Little Fryup Beck and Great Fryup Beck - and is due to minor slips in the Boulder Clay and to minor lateral drainage. A few hummocks in the alluvial belt represent meander cores. All the major and minor tributaries join the main river on the outside of bends. There is a weir just above Castleton Bridge and another just above Ainthorpe

Bridge; both of these raise the water level by about 5 ft. but the effect on the valley profile cannot be discerned.

In this section between Castleton and Crunkly Gillthe width of the meander belt defined by the meanders and also by the alluvial deposits varies between 300 and 1,200 ft. and is most commonly 600 to 900 ft. The river averages about 50 ft. between the bank tops and hence the meander belt width M_b varies between 6 W and 24 W, being most commonly 12 W to 18 W, where W is the stream width. The meander length M_l is generally slightly more than M_b. From data given by Inglis (1947) it appears that in flood plains M_b is of the order 3 M_l and, although particle size and other factors must influence these ratios, these figures indicate that the meanders are not those of a late mature river and this is confirmed by the irregularities in the meander pattern. Nevertheless, M_b lies between the limits of 10 W and 20 W which are commonly associated with early maturity. However, the age of a river or part of a river is only relative and early maturity has been reached in this part of the Esk only through the changes wrought by the Glaciation. Hence it is reasonable to assume that in this section the pre-Glacial river was unlikely to have attained conditions consistent with more than late youth.

Crunkly Gill is about ¾ mile long and is excavated in the

Lower Estuarines. At the bottom end of the gorge are shoals of coarse material. There are some meanders in the section from Lealholm to the head of the Glaisdale Gorge but there is also one practically straight half-mile stretch. There is a little shoaling and some lateral erosion. The immediate valley sides are moderately steep to steep, and are principally of Boulder Clay, with some sands and gravels on the north side. In the valley bottom there are alluvial flats up to 200 yards wide. On the north side of the valley between Stonegate Beck and Glaisdale Gorge is a terrace about 20 ft. above the present valley floor. Glaisdale Gorge is about a quarter-mile long and is deep but relatively open. It is cut in the Lower Estuarines on the south side and mainly in Boulder Clay on the north. A half-mile long spread of alluvium brings the river to the head of East Arnecliffe Gorge which is about ¾ mile long and is cut in the Upper Lias. Rapids and low waterfalls can be seen in the bed and at the lower end of the gorge are shoals of coarse material. In the eastern half of East Arnecliffe Wood is a high-level overflow channel - believed by the writer to be hitherto unrecorded. It follows the directional trend of the present Esk in the upper half of the gorge and is about 150 ft. above the present bed but descends very steeply to the alluvial flats above Egton Bridge.

This channel is blocked at one point by a high dam of debris and this may have been responsible for the diversion to the present course. Alternatively, northward retreat of the ice margin may have disclosed an outlet at a lower level. The diversion might, of course, be due to a combination of these effects.

From the lower end of theEast Arnecliffe Gorge to the Larpool Gorge between Ruswarp and Whitby the Esk flows in an alluvial belt varying in width from several yards only to a half-mile. Just below Egton Bridge the river lies beneath cliffs on the south side in the Upper Lias. There are some intermittent meanders in this length but they are not good examples. The Murk Esk joins the Esk on the outside of a hairpin bend. There are numerous shoals between Egton Bridge and Sleights. A weir has been constructed just above Egton Bridge, another at Sleights and a third at Ruswarp - each of these cause a difference in water level of 5 to 10 ft. It should be observed that the extensive alluvial flat below Grosmont and another below Ruswarp are unlikely to have been developed by the Esk cutting laterally in solid rock in post-Glacial times. Their dimensions must be due solely to the ease of excavating laterally almost entirely in Boulder Clay and consequently they must extend over an earlier valley floor.

The gorge at Larpool is very deep but open and is just less than a half-mile long. It is excavated mostly in the Upper Estuarine Series on the east side and partly in Boulder Clay on the west. The estuary at the harbour lies between high cliffs which, in effect, constitute a short, wide gorge. The Esk is tidal from the weir at Ruswarp.

CHAPTER V

Analysis of Various Features in the Eskdale Drainage System

In this chapter a number of features in the Eskdale drainage system are analysed. The considerable amount of morphological material to be discovered in this system is surprising. No doubt it is partly due to the relatively horizontal disposition of the beds and, indeed, structure and lithology are admirably reflected in the morphology of the dales and in the characteristics of the streams. There is obviously much still to be discovered. More detailed field studies and the plotting of additional sections should be particularly rewarding. The features discussed in this chapter include the anomalous courses of Baysdale and Sleddale Becks, the general course of the Esk, various morphological characteristics of the tributary dales, the origin of twin parallel streams and the pre-Glacial profile of the main river.

The Baysdale-Sleddale Fluvial Complex

The lower half of Baysdale Beck and the middle part of Sleddale Beck appear to follow anomalous courses. Baysdale Beck abandons its initial down-dip course and turns to flow obliquely across the strike. Initially Sleddale Beck flows roughly along the strike, following the north-west to south-east trend of most streams on the northern part of the catchment, then turns sharply eastwards and finally resumes its original orientation. The questions which arise are: Do either of these streams follow the course of the Esk before its early beheading? If not, to what are the anomalous parts of their courses due?

The early Esk could certainly have followed Sleddale Beck as far as the head of Kildale, then either following the present course of the River Leven or flowing directly across Coate Moor although there are no remanent topographical features here to confirm this supposition. In any case, the course to be followed by the Esk is rather tortuous compared with its lower pre-Glacial course to the sea. On the other hand a less tortuous and more likely course follows Baysdale Beck roughly as far as Baysdale Abbey and then passes through the shallow notch at just over 1,000 ft. on Warren Moor or a similar notch at about 1,025 ft. on Battersby Moor. An early tributary drainage pattern can be fitted to this course for the main river in the following way. The upper north-west to south-east section of Sleddale Beck can be projected south-eastwards through a notch at just above 900 ft. between two knolls rising to 990 ft. and 963 ft. This course must have persisted for some time after the Esk was beheaded at Warren Moor or Battersby Moor since the gradient on the main river would be of the order 50 ft. per mile and this is excessive for the lower reaches of the combined Tees and Esk. Undoubtedly the present headwaters of the River Leven, rising on Warren Moor, constituted a tributary of the early Sleddale Beck and this was captured by the Leven at some time after the beheading of the Esk. The lower section of the present Sleddale Beck - known as Commondale Beck - originally constituted the lower half of Whiteley Beck which flows through Commondale.

The question now arises as to whether the early Sleddale Beck was captured by a tributary of Whiteley Beck or by the Leven. There is little doubt that a tributary of Whiteley Beck followed the middle section of the present Sleddale Beck for some distance in order to form the notch in the ridge between the early Sleddale and Whiteley Becks which became the overflow channel from Glacial Lake Kildale. Furthermore, such a tributary would follow the south-west to north-east trend of the headwaters of the Leven and minor tributaries of the present Commondale Beck. However, this tributary would need to be powerful to cut back nearly 2 miles - mainly in the Lower Estuarines - to capture the early Sleddale Beck.

On the other hand the Leven was obviously very active in excavating Kildale and capturing its present headwaters and little additional effort would be required to capture Sleddale Beck also. This work was facilitated by the fact that the Leven was partly, if not wholly, in the Upper Lias. The recapture of Sleddale Beck by the Esk drainage system is due to the overflow from Lake Kildale which provided a channel with a downward gradient eastwards. The geological map shows small deposits of Boulder Clay at the western end of the channel and these may have facilitated the capture by blocking the pre-Glacial captured course of Sleddale Beck to the west.

One other problem arises in connection with this fluvial complex and concerns the Leven tributary known as Lounsdale Beck which lies just west of the watershed on the north side of Kildale. It is accepted that this was originally a tributary of the Esk system but the question arises whether its confluence was with the Esk or with Sleddale Beck. Here again one has to rely on the general pattern of streams in the area. One or other of the two notches at a little over 900 ft. on Kildale Moor on the north watershed of Baysdale Beck lend weight to the suggestion that Lounsdale Beck connected directly with the Esk just below Baysdale Abbey, although these notches are not conspicuous on the site. On the other hand, an eastwards trend of Lounsdale Beck from the lower end of Lounsdale to the initial Sleddale Beck would provide a valley which would be readily followed by the piratical Leven and the balance seems to weigh in favour of Lounsdale Beck being initially a tributary of Sleddale Beck. The tributary of the early Sleddale Beck - or Lounsdale Beck - which now constitutes the headwaters of the Leven on Warren Moor was obviously very much shorter at that time but capture by the Leven undoubtedly led to its rapid development.

The General Pre-Glacial Course of the Esk

It has been suggested in the previous section that the upper reaches of the beheaded Esk are represented to-day by the lower half of Baysdale Beck. In this section the general pre-Glacial course of the Esk is traced from the lower end of Baysdale Beck to the sea and Figs. 32, 33 and 34 show six cross-sections of the valley reconstructed from the boring and other data described in Chapter III. Where there is a marked divergence between pre- and post-Glacial channels, the earlier course is indicated by red dotted lines on the map in the pocket at the end of this thesis.

From the confluence of Baysdale Beck with the Westerdale headwaters to the Lealholm moraine it is likely that the pre-

Glacial course of the Esk was not very different from the present course. Immediately below the moraine, however, the earlier course was between ¼ mile and ½ mile north of Crunkly Gill but Cross Section 2 (Fig.32) - which is located just above Lealholm Bridge - indicates that it must have passed 100 to 200 yards south of the present course at the bridge.

From Lealholm to the Glaisdale moraine it is probable that the pre-Glacial course lies roughly beneath the present channel. From the moraine to Egton Bridge the course was north of the two existing gorges and probably passed nearly ½ mile north of Glaisdale Bridge. This northerly disposition of the old course persists almost to Sleights, as Cross Section 3 (Fig.32) shows. Several former spurs in the Lias have been cut through by the present channel between Grosmont and Sleights and the interesting question arises as to whether those revealed at present as low cliffs on the north side of the river represent spurs on the north or the south side of the pre-Glacial valley. A survey of this length in detail would no doubt provide a complete answer but each exposure would have to be treated independently.

Before discussing the course from Sleights to the sea it is necessary to examine the cliff section between Whitby and Sandsend. Just to the west of the present channel of the Esk at

Whitby are cliffs in the Estuarine Series but about ¼ mile westwards at the Spa the bed-rock surface descends below beach level, rising again in a little more than a ¼ mile at Lector Nab (see Chapter III for details). In about another ¼ mile, bed-rock descends below beach level again and does not rise until Sandsend is reached nearly 2 miles westwards. The filling in these two depressions is Boulder Clay. It appears that in the past the depression between the Spa and Lector Nab has been commonly accepted as representing the pre-Glacial course of the Esk.

Now it is reasonable to assume that the depression between Lector Nab and Sandsend can be accounted for either by marine erosion or by fluvial erosion. In respect of marine erosion, there is no obvious structural reason for the embayment, such as the dome of Robin Hood's Bay where opening of the joints in the top of the dome has undoubtedly facilitated erosion. Again, one may ask if there is any reason why the Estuarine Series should be more susceptible to marine erosion than the Lias. It is true that the joints in the sandstones would permit water-hammer under wave forces. The joints in intact Estuarines are not wide but in marine cliffs they are opened considerably. Nevertheless, there is no evidence of the Estuarines being particularly susceptible to marine erosion in the extensive cliffs between Robin Hood's Bay and Scarborough. In any case the form of the depression is much more consistent with that of a valley than a bay and there is no doubt that it is of fluvial origin. Furthermore, there is no reason to suspect that the depression between the Spa and Lector Nab is of anything other than fluvial origin.

There are thus two buried valleys - one much larger than the other but the smaller of the two is sufficiently large to preclude the possibility of it being a tributary of the greater, apart from the fact that the channels are almost parallel. The writer formed the opinion that the larger valley represents the pre-Glacial Esk, with a tributary entering fromroughly along the line of Sandsend andEast Row Becks at Sandsend, and the smaller valley represents an inter-Glacial course of the Esk, the earlier one being blocked by Boulder Clay or ice from Sleights northwards. The cross-sections shown in Figs. 33 and 34 have been reconstructed from evidence outlined in Chapter III in order to substantiate these suggestions. The hydrographic survey did not cover the pre-Glacial course and the evidence relating to the inter-Glacial course is not as strong as one would wish although it does not, of course, mean that the channel is non-existent - a glance at the cliffs is sufficient to show that it does exist.

If these two valleys are pre- and inter-Glacial, then it is reasonable to expect that Glacial deposits occur in the bottom of the pre-Glacial valley which are absent in the inter-Glacial. The sequence visible in the cliffs in both depressions is similar and consists of 20 to 30 ft. of fox-red clay overlying about 10 ft. of sand and gravel beneath which is a thick bed of venetian-red or purple clay. The writer examined these deposits in both valleys but was unable to trace any erosion surfaces and the erratics which were collected yielded nothing of significance. The I.C.I. borehole E.6 at Upgang showed that the sandstone boulder content of the Boulder Clay increases below about 5 ft. a.O.D. and there is an increase in shale and sand content below about -25 ft. b.O.D. This suggests that the basement clay does not extend much above beach level and will rarely be seen in the cliffs because of slipped material from above. Unfortunately no suitable boring has been made in the inter-Glacial channel for comparison. Thus the existance of pre- and inter-Glacial channels cannot be proved at present. The writer has been unable to find any record of other inter-Glacial channels in Great Britain although they must surely exist.

The width of the inter-Glacial valley is rather greater than the present valley of the Esk at Whitby. Consequently a sufficient length of time is required for its development and the Great Interglacial is the first choice on this basis. During this period there would undoubtedly be extensive erosion of the BoulderClay in the pre-Glacial channel and the surface may well have been reduced to near present beach level.

If the postulate of these two valleys is acceptable, then the next step is to trace the possible courses from Sleights to the sea. It is most unlikely that the pre-Glacial course flowed from Sleights to Ruswarp, making a deflection of 90° to the left at that point to flow north/north-west to the sea. There appears to be nothing to oppose the suggestion that the river turned gently to the left at Sleights to flow due northwards to the sea. On the other hand thà inter- Glacial Esk probably followed the present course from Sleights to Ruswarp where it turned northwards to the sea. These two tentative valleys can be fitted quite well into Cross Sections 5 and 6 (Figs. 33 and 34).

It should be observed that the pre-Gladal Esk followed the western part of the rim of the Whitby Basin and - it seems - studiously avoided the Whitby Fault. It is conceivable that the formation of a basin would lead to the formation of a lake on the surface and one possible path of least resistance to the sea would be via the fault. In Chapter II reference was made to the fact that the present drainage system has been superposed on the present structure. It seems likely therefore that the pre-Glacial course of theEsk from Sleights to the sea was well established before the development of the Whitby Basin.

It is now possible to turn to a broader view of the pre-Glacial course of the Esk. The almost due west to east trend of the Esk before beheading can be traced from Barnard Castle, past south Darlington and into Eskdale as far as Grosmont. At Grosmont it turns to flow north-eastwards as far as Sleights where it turns due north out to sea. The west to east trend with a slight bias to south-eastwards conforms to Reed's (1901) hypothesis for the original drainage pattern for east Yorkshire. The beheading of the Esk is ascribed to a subsequent flowing to the north or north-east which is now represented by the lower Tees. One cannot fail to observe, however, that the present course of the Esk is a presentable replica of that of the Tees in miniature. The deviation from the west to east course appears so strong that it can hardly be regarded as a local phenomenon. A number of questions now come to mind but a careful study of the paleomorphology is required before an attempt can be made to answer them and this is beyond the scope of the present investigation. The questions one may ask are on the following lines:

1. Does the lower Esk represent the course of a subsequent which effected a capture?
2. If so, to what river was the subsequent a tributary?
3. Since neither the structure nor the lithology appear to offer any special facilities, why should it effect a capture?
4. If this is an example of a very early capture, what course did the Lower Esk originally follow? Did it flow eastwards over Robin Hood's Bay? The bay is undoubtedly due to the facility offered to erosion by the structural dome and cannot be taken to represent the position of an early valley.
5. If this is not a case of capture, does it represent the effect of regional tilting, with a northward dip, about a line oriented roughly west to east and passing through south Darlington and Grosmont? There is no obvious elbow of capture on the Tees, although there may have been one south-east of Darlington which has been obliterated by later meandering. There may be an elbow of capture on the Esk at Sleights but this is indefinite owing to the overlay of Boulder Clay. Comparatively easy curves to the north-east and north would be indicative of a gradually increasing dip in this direction.
6. What structural evidence is there for tilting?
7. Did the tilting occur before or after the original drainage system was initiated?
8. How is Reed's hypothesis of capture by the present lower Tees affected by the postulate of tilting?

9. Can additional evidence - for or against - be drawn from the Wear or the Tyne?

In an endeavour to answer Question 2, the writer studied a paper by Lewis (1935) on the orography of the North Sea Bed but there is insufficient detail to show any relationship between the Esk and the Silver River (Rhine extension).

As a final note on the general course of the Esk attention is drawn to the fact that the present middle Esk and the Cleveland Dyke are coincident in places and never more than ¾ mile apart. The question arise - did the Dyke influence the location of the Esk? In view of the susceptibility to weathering of the Dyke, one might expect that the Esk would follow the path of least resistance but if this were so the coincidence should be more precise and more extensive. Furthermore, the Cleveland Dyke was intruded after the original drainage system had been initiated. One may ask, as an alternative, to what extent the Esk influenced the location of the Dyke? Taken over the entire length of Dyke it is obvious that the influence is not great but it is worth recording that a comparatively straight valley constitutes a notch in the crust of the Earth and therefore defines an incipient plane of weakness. Whether or not the Esk valley influenced the location of the Cleveland Dyke in this way is debatable but - fortuitously or otherwise - the Dyke follows the west to east trend east of Grosmont and causes one to reflect on a possible early part of the course of the Esk along this line, extending south of Robin Hood's Bay.

Characteristics of the Tributary Dales

In this section several morphological features of tributary dales are discussed. The tributary dales examined are Glaisdale, Great and Little Fryup Dales, Danby Dale, Westerdale and Baysdale - these are the tributary valleys least affected by glaciation.

Great and Little Fryup Dales were the first to be visited by the writer which exhibited marked landslides. The head of Great Fryup Dale is wall-like and there are vast quantities of slipped material which present the appearance of tips from extensive hillside mines. Although this debris is found at all elevations at the head of both dales, the accumulations just below the cliffs capped by the Dogger are by far the most impressive and these extend almost continuously from the south-west flank of Great Fryup Dale head into the head of Little Fryup Dale. In the localities visited there was no evidence of recent landslides and the debris is well covered with vegetation. Commonly, a ridge has been formed parallel to, and roughly 100 ft. from the base of the cliff and the terraces or flats between ridge and cliffs are moss filled.

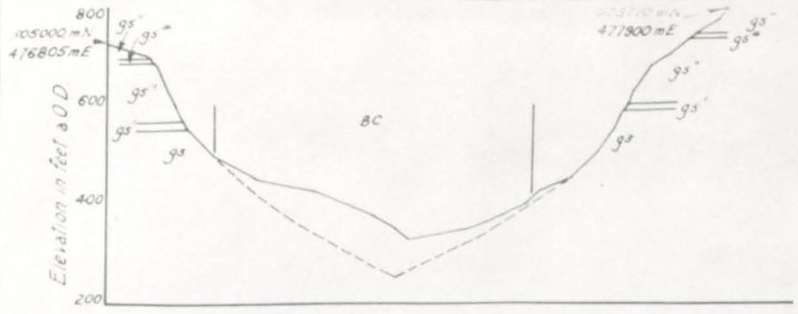
Extensive slips are seen at the head of Danby Daleon the south-west flank and lesser slips on the south-east flank. In Glaisdale there are a few minor landslides at the head. At the head of Tower Beck in Westerdale there is evidence of slips on the south-west flank but this is partly masked by debris from old jet workings. On the east flank of the basin at the head of the western arm of Westerdale is a half-mile length of landslides below the cliffs capped with the Dogger. These show the characteristic debris ridge with a flat between it and the cliffs. At the north end of these slips is a tension crack about 100 ft. long and averaging about 3 ft. wide in the Dogger. Slips are found in the upper parts of Baysdale but these are obviously due to the rapid downcutting in the shales, as mentioned in Chapter IV.

Since these landslides occur almost exclusively at the heads of the dales it is most likely that they are due to the headward erosion of the streams and, if not recent, they are at least connected with the current cycle of fluvial erosion. The tension crack in Westerdale is certainly recent sinceit is unfilled with debris for depths down to 10 ft. or more. The highest slips occur at elevations of the order of 1,000 ft. in all the dales and according to Kendall (1903) the maximum level of Lake Eskdale was about 725 ft. The shear strength of the shales which were saturated by the waters of the lake would be less than the pre-Glacial strength and it is likely that sub-aqueous slips would occur just below the water-line. These would inevitably lead to slips above the water-line under sub-aerial conditions. Although landslides would be most likely to occur under these conditions where incipient failure had been induced by pre-Glacial headward erosion - that is, at the dale head - it is reasonable to expect that they would occur also at other points throughout the length of the dales, whereas there is no evidence of extensive high level slips at the lower ends of the valleys.

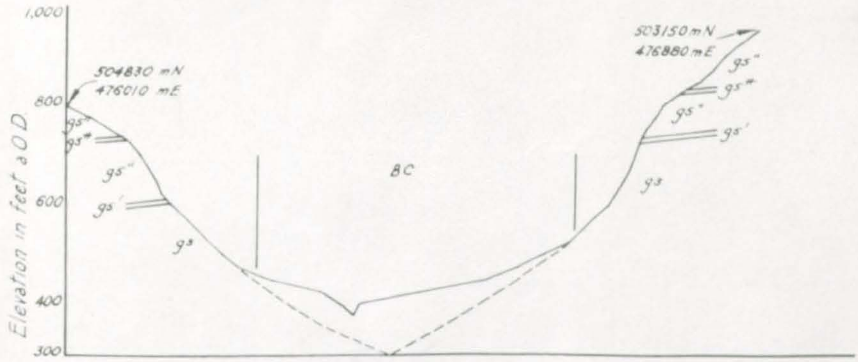
Most of the landslides occur on the south-west flanks of the dales and this consistent orientation suggests either a climatological or a structural influence. The fact that landslides occur on the east flank in Westerdale rather invalidates the suggestion of a climatological influence, apart from the fact that the character of such an influence is not apparent. The structural influence is primarily dip and, although this is almost always down-dale, in all the dales, with the exception of the western arm of Westerdale, there is a small component of dip at right-angles to the axis of the slips where these are most extensive. The western arm of Westerdale extends south of theanticlinal axis and the indefinite nature of the dip over the axis may explain the anomaly. It may be that this small component of dip is sufficient to encourage uni-lateral erosion, as discussed in Chapter IV in connection with Sleddale Beck.

A final controversial point in connection with the landslides is the reason for the comparative absence of slips in Glaisdale. Extensive current landslides of the type under discussion must be accompanied by rapid downcutting of a stream and this is most readily achieved by a large moor-top catchment, numerous channels for speedily concentrating the run-off at the dale head and steep gradients to yeild high velocities. There are no marked differences between the gradients of the headwater streams in the dales but Great Fryup Beck has a relatively large headwater catchment and adequate drainage channels and it is at the head of Great Fryup Dale that the landslides are most impressive. Danby Dale has a fair headwater catchment and Glaisdale a smaller one but neither have a sufficient number of channels for effective concentration of run-off. The slips in the Tower Beck arm of Westerdale are difficult to assess because of the old jet workings but the headwaters of the western arm have a large catchment and adequate drainage channels. Evidence points to these run-off characteristics as being the most likely causes of the variations in the extent of landslides in the different dales. However, if sub-aqueous slips during the existence of the glacial lakes are admitted then the Boulder Clay filling in Glaisdale up to about 550 ft. would act to some extent as a stabilizing influence in reducing the slips but this would be only a minor effect.

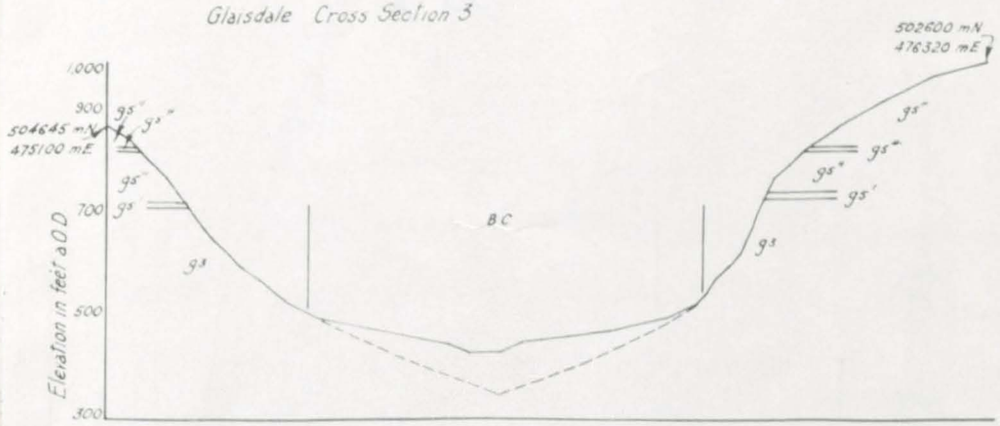
Another feature which can be discussed conveniently in this section is the saddle connecting Great and Little Fryup Dales. The width of Little Fryup Dale is almost the same as that of Great Fryup Dale, yet Little Fryup Beck is very much smaller than Great Fryup Beck. It seems unlikely that a stream with the length, proportions and catchment of Little Fryup Beck, should excavate a dale of these dimensions. An example of what might be expected is found in Low Wood Beck, between Great Fryup Dale and Glaisdale, which joins the Esk a little more than a quarter-mile below Lealholm. This stream is about 1¾ miles long and Little Fryup Beck is about 2 miles. It does not appear to have formed a dale but the lower mile is now in Boulder Clay. The trace of the Dogger on the geological map indicates a narrow valley in the Lias about ¾ mile long. Nevertheless, the ability of a short stream to excavate a dale of appreciable proportions is demonstrated by a possible early second stream in Danby Dale which is discussed below. The saddle between Great and Little Fryup Dales, together with the comparatively similar widths, suggests stream capture or,



Glaisdale Cross Section 4



Glaisdale Cross Section 3



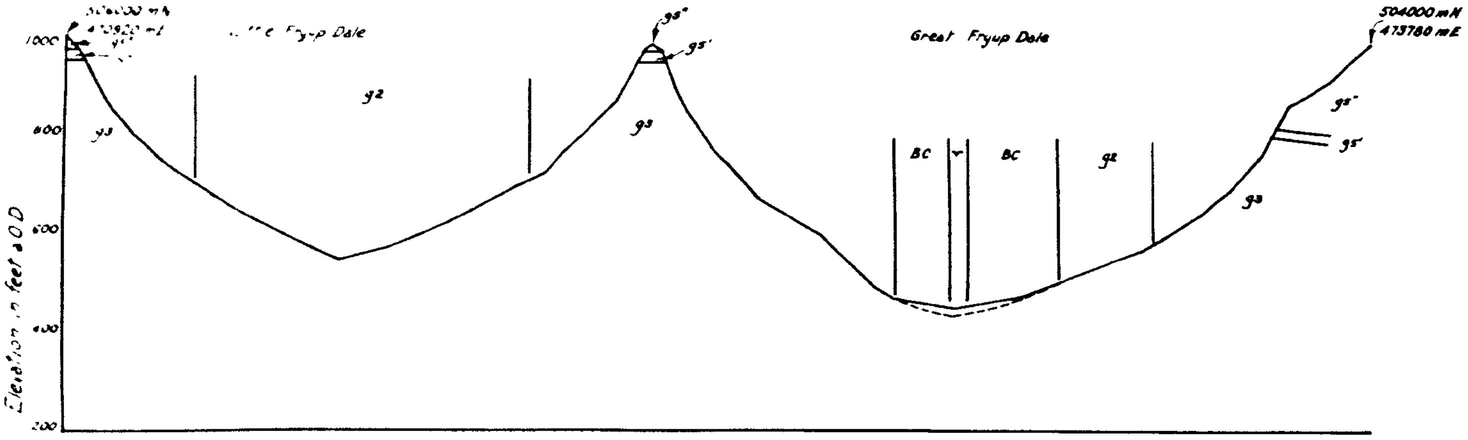
Glaisdale Cross Section 2

Glaisdale Cross Section 1

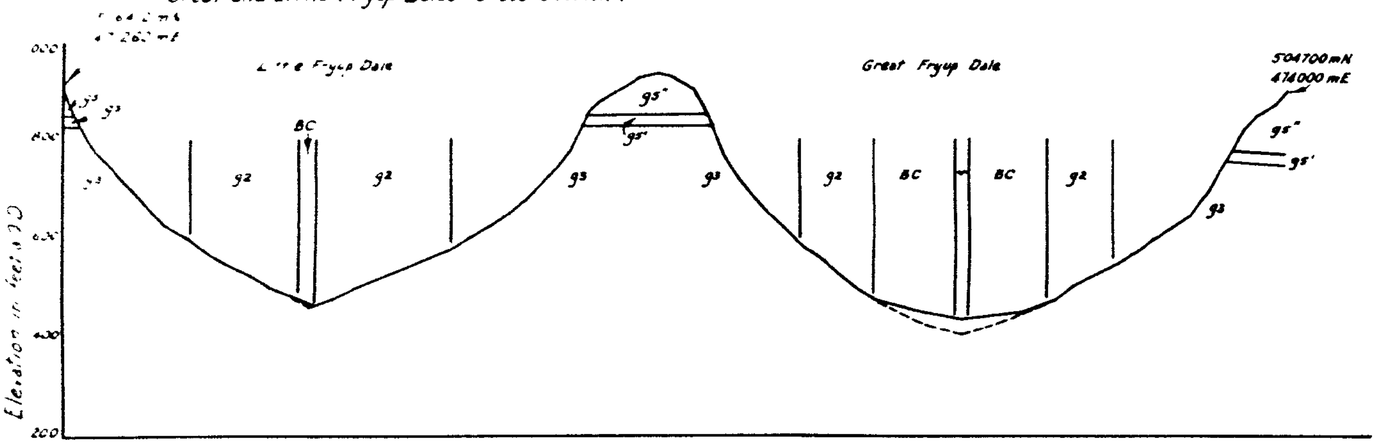
Fig. 26

perhaps more correctly in this case, catchment capture. Originally Little Fryup Beck must have possessed a tributary rising south-east of the saddle and above the Dogger. Such a stream would flow obliquely down-dip and analogous examples are Winter Gill, a tributary of Glaisdale Beck, and Falcon Beck, a tributary of Danby Beck. The knoll known as Round Hill, which rises to just over 825 ft., suggests that the tributary was bifurcated and may thus have drained a relatively large area.

The width of a dale at any point is governed largely by the height of the Dogger Bed above the valley floor. This is discussed further at the end of this section. It is the principal reason why the exits from Westerdale and Danby Dale are narrow. However, the morphology of the lower end of Danby Dale calls for comment. There is no doubt that the present lower course of the stream, follows fairly closely the pre-Glacial one, yet considerable excavation has been effected at the eastern side of the lower end of the dale. Although covered with gravel, the saddle to the east of the knoll known as The Howe is lower than that feature by roughly 100 ft. The Howe is an outcrop of Lower Estuarines and the geological map indicates that this is continuous with the outcrop of Lower Estuarines of Danby Ridge. There is no reason to suspect a comparatively recent duplicate exit from the dale although one



Great and Little Fryup Dales Cross Section 1

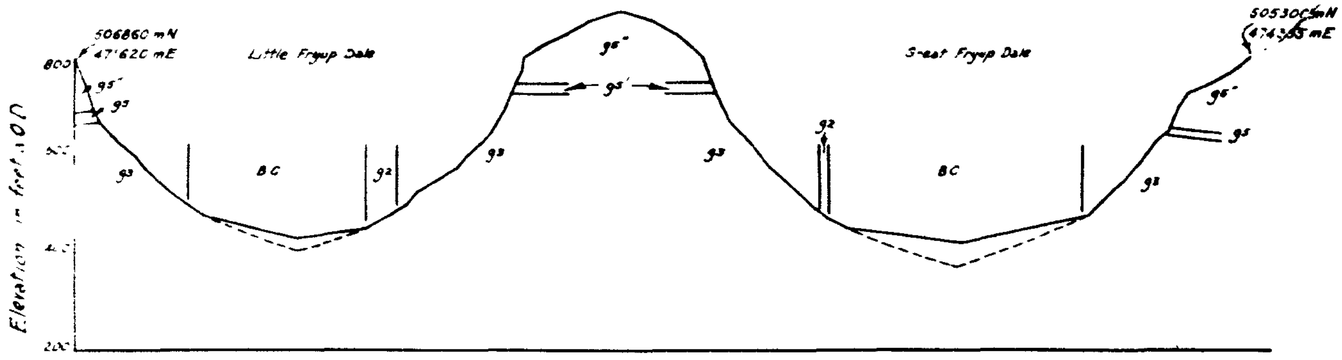


Great and Little Fryup Dales Cross Section 2

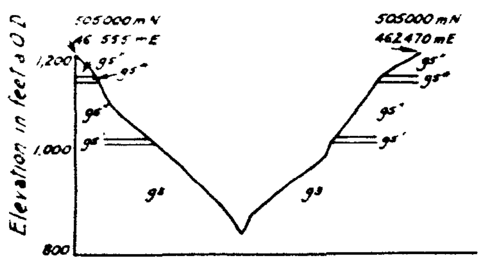
Fig. 27

can conceive an early exit, even over the Lower Estuarines, with an inlier of Upper Lias in the dale floor. Once the Dogger has been penetrated, excavation can be readily effected. However, desertion of this exit can be accomplished only through capture and this requires a parallel stream about ¾ mile westwards to do this. There does not appear to be any satisfactory alternative to this supposition.

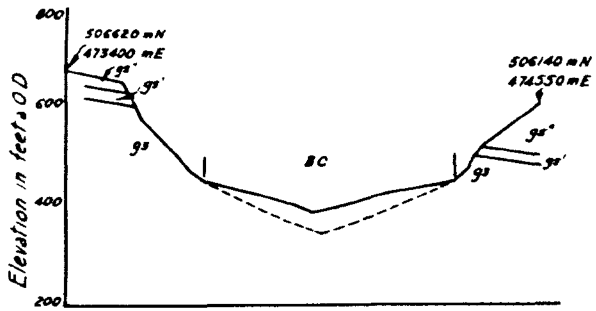
The discrepancy between the dip given on the geological map and the dip obtained from the structural map of Versey (Fig.3) was commented on in Chapter I. According to the former the dip on each side of Danby Dale is in the direction of the axis of Castleton Ridge and Danby Ridge and the divergence between the directions is 20° to 30°. Originally the morphology of Danby Dale must have been rather similar to that of Great and Little Fryup Dales but the dividing ridge was eventually erased except for the remnant The Howe. No capture of a stream is required and this case is also in the nature of catchment capture. Just south-east of The Howe the contours are oriented east-west and are widely spaced and, although they are governed partly by the lobe of gravel, there is a shelf on the Upper Lias which conforms to the requirement of an early valley floor (see Fig.29). The absence of lateral drainage from this bulge in the dale is



Great and Little Fryup Dales Cross Section 3



Baysdale Cross Section 1



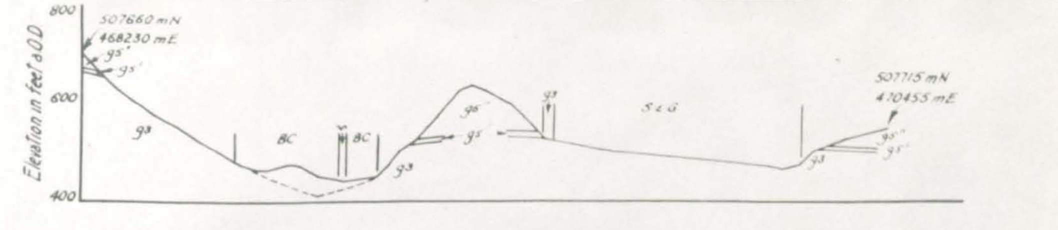
Great Fryup Dale Cross Section 4

Fig 28

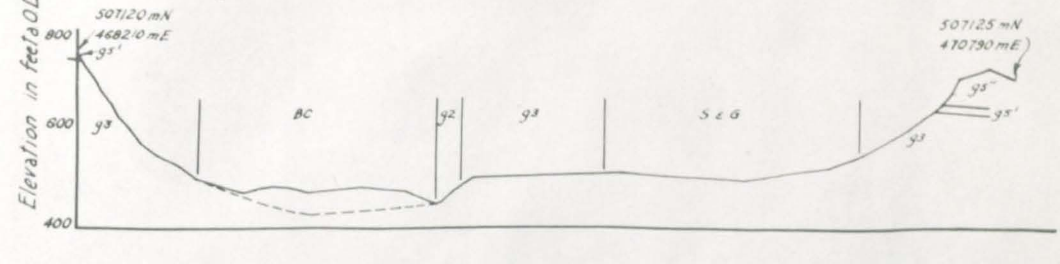
remarkable but numerous springs appear and lead to short watercourses which soon disappear. It is probable that much of this drainage finds its way to the Esk by subsurface courses through the gravel which extends to the bank of the main river in places. This confirms the presence of a bedrock surface gradient down towards the Esk, thus conforming to the supposition of an earlier valley beneath the gravel.

The early east and west streams of Danby Dale must have possessed nearly equal erosive capacities, with the western stream slightly the more vigorous of the two. The length of the eastern stream was probably, about a quarter-mile less than the length of Little Fryup Beck and it excavated a dale of appreciable dimensions, though probably much less than Little Fryup Dale in volume of rock removed.

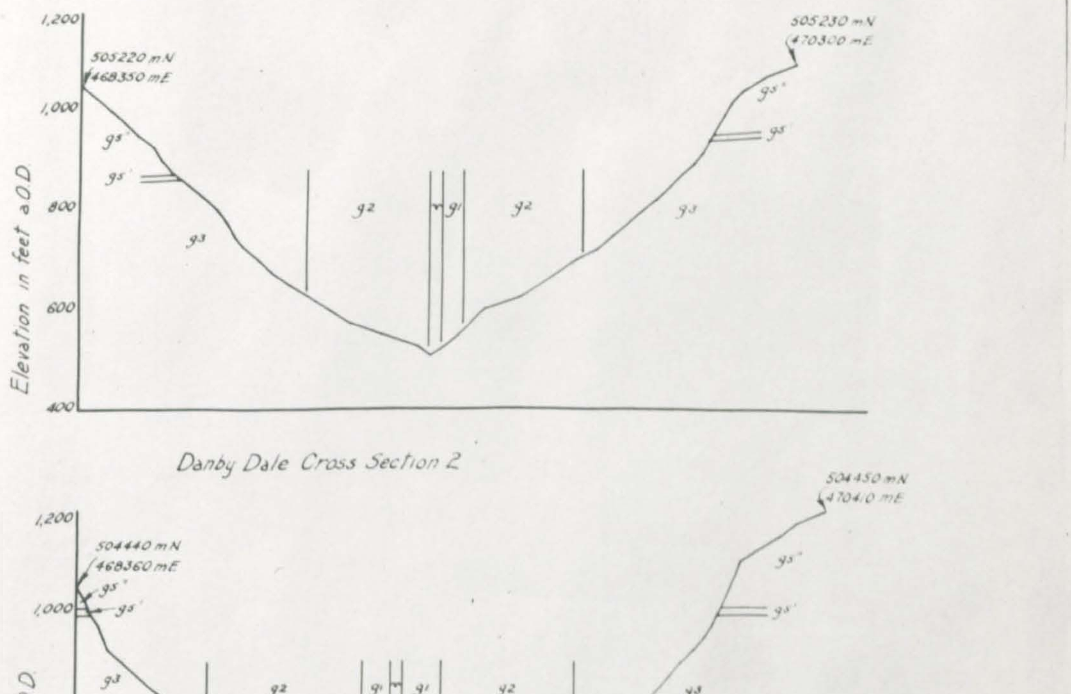
The anomalous course of the headwaters of the Esk in the western limb of Westerdale also calls for comment. The reason for the S-bend below the confluence with Stockdale Beck is not apparent but the sharp bend west of Westerdale village suggests capture which can be substantiated in the following way. There is a shallow notch just above 725 ft. in Westerdale Moor due north of this elbow. This is much lower than the early confluence of Sleddale Beck with the Esk mentioned in the first section of this chapter and therefore the capture must have been



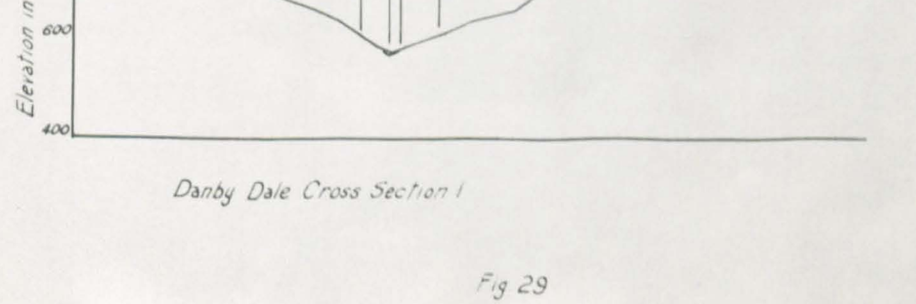
Danby Dale Cross Section 4



Danby Dale Cross Section 3



Danby Dale Cross Section 2



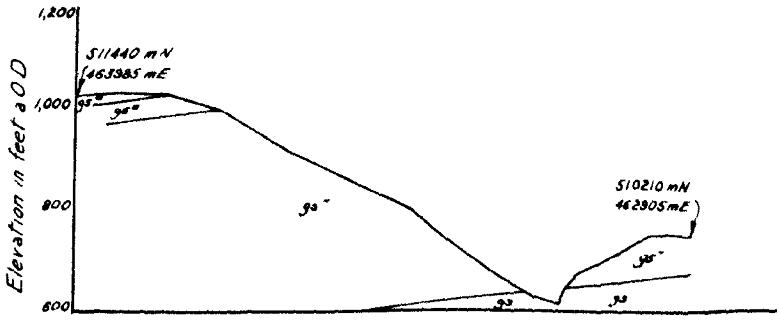
Danby Dale Cross Section 1

Fig 29

later than the first capture of Sleddale Beck. The geological map shows that this early Westerdale stream would be wellabove the Dogger at its confluence with Baysdale Beck, and may even have been at a sufficiently high elevation in its middle reaches not to produce an inlier similar to that formed by Baysdale Beck. Consequently this stream would excavate relatively slowly in the Lower Estuarines. Undoubtedly the confluence of Tower Beck with the Esk has been located by the small trough fault at the mouth of Westerdale. At a comparatively early stage in the grading to pre-Glacial levels, Tower Beck, together with a tributary cutting back into the western limb of Westerdale, had broken through the Dogger into the easily excavated Lias so that development here was rapid. As a result of this the tributary of Tower Beck cut back with sufficient speed to capture the stream in the western limb of Westerdale.

Although the early drainage pattern of the Esk and its tributaries was not greatly different from what it is today, the early morphology must have presented a vastly different picture in which the valleys formed a series of undulations compared with the present extensive escarped topography. This change has been wrought, of course, solely by a change in base-level. In the mature parts of the tributary dales it will be observed that the greater the depth of the stream below the

Dogger, the wider



Sleddale Cross Section 1

Fig 30

the valley. For the purpose of the following discussion the beds can be considered horizontal. If the crude assumption of uniformity in the Lias can be accepted, then the width and depth of the valley are related tothe uniform strength of the Lias. This argument considers only slip phenomena and ignores such factors as chemical weathering and rain-wash but providing only comparatively recent but mature parts of the dales are considered, then one can expect tolerable results. The relationship is not likely to be linear and therefore it is necessary to consider each side of the valley separately, plotting "half-widths" against depth below Dogger as shown in Fig.31.

The cross-sections shown in Figs. 26, 27, 28, 29 and 30 have been constructed from 6 inches to 1 mile Ordnance Survey maps and the positions of strata have been taken from Geological Survey maps to the same scale. The notation for stratigraphical series in the cross-sections is that employed by the Geological Survey but, in addition, Boulder Clay is indicated by B.C. and Sand and Gravel by S and G. For easy reference the notation is as follows:

~	Alluvium
BC	Boulder Clay
S & G	Sand and Gravel

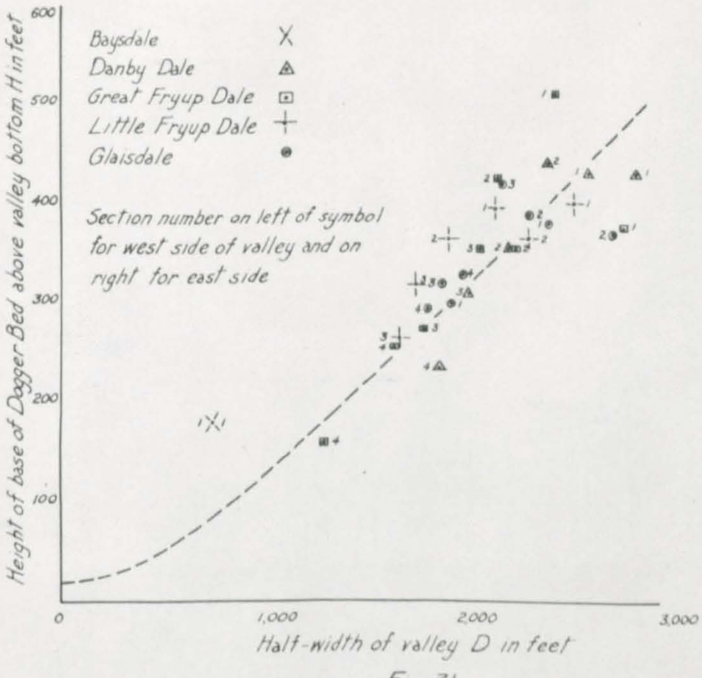
TABLE 3

Analysis of Valley Cross-Sections

Section No. and side	Baysdale		Danby Dale		Great Fryup Dale		Little Fryup Dale		Glaisdale	
	D	H	D	H	D	H	D	H	D	H
1 West	760	180	2,660	430	2,500	510	2,200	395	2,460	380
East	760	180	2,900	430	2,840	375	2,580	400	1,940	320
2 West	-	-	2,260	355	2,210	425	1,970	365	2,780	370
East	-	-	2,460	440	2,300	355	2,360	365	2,360	390
3 West	-	-	2,060	310	2,120	355	1,720	265	1,980	300
East	-	-	-	-	1,840	275	1,880	320	2,240	420
4 West	-	-	1,920	235	1,680	255	-	-	1,860	295
East	-	-	-	-	1,340	160	-	-	2,030	330

D is half-width of valley in feet

H is height of base of Dogger Bed above valley bottom in feet



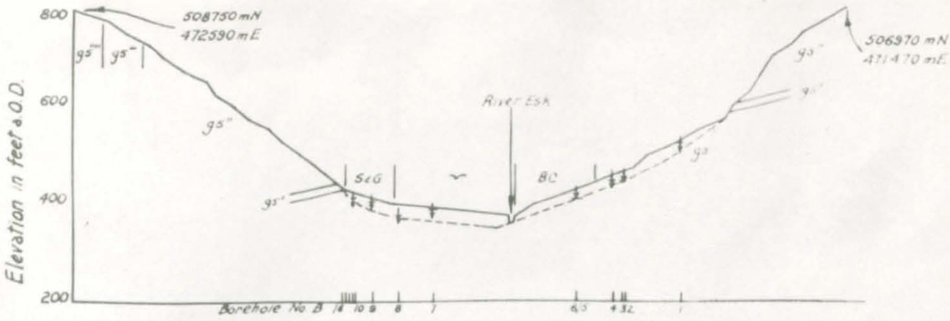
Baysdale
Danby Dale
Great Fryup Dale
Little Fryup Dale
Glaisdale
Section number on left of symbol for west side of valley and on right for east side
Height of base of Dogger Bed above valley bottom H in feet
Half-width of valley D in feet
0
100
200
300
400
500
600
1,000
2,000
3,000

Fig. 31

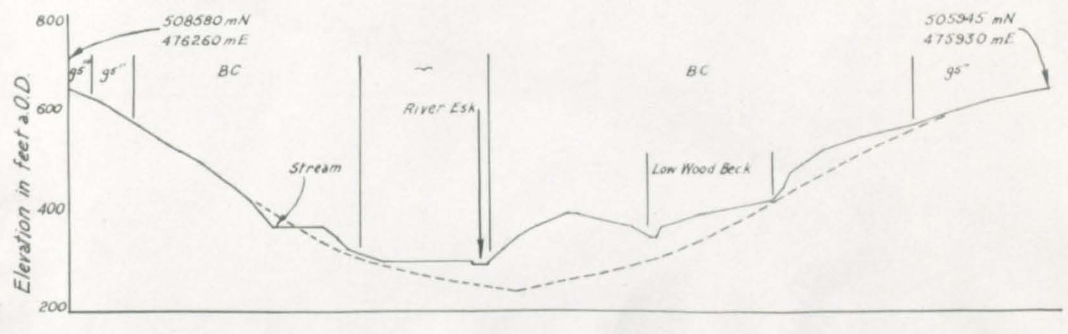
g5''''	Upper Estuarine Series
g5'''	Grey Limestone Series
g5''	Lower Estuarine Series with $g5^{++}$ Eller Beck Bed
g5'	The Dogger
g3	Upper Lias
g2	Middle Lias
g1	Lower Lias

The changes in slope in Figs. 26, 27, 28, and 29 generally coincide well with the outcrop of the strata - the break at the outer edges of Boulder Clay valley-filling is quite marked.

If an average line is drawn through the points plotted in Fig.31., values to the left of the line can be taken to represent immature valley sides and those to the right fully mature. With active unilateral erosion, cross-sections should present an immature profile on the up-dip side and a slightly over mature profile on the down-dip side. There is a tendency for these characteristics to be exhibited by cross-sections (the "1s" and "2s") at the heads of the dales although there are the anticipated inexplicable exceptions. Where vertical cutting is slow at the lower ends of the dales, unilateral erosion will also be slow and there will be a tendency for both valley sides to attain mature proportions. This may

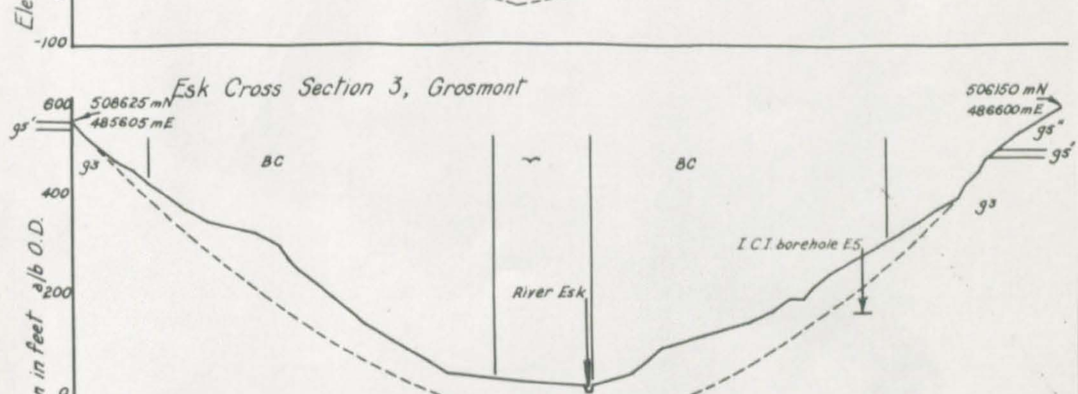


Esk Cross Section 1, Duck Bridge



Esk Cross Section 2, Lealholm

Esk Cross Section 3, Grosmont

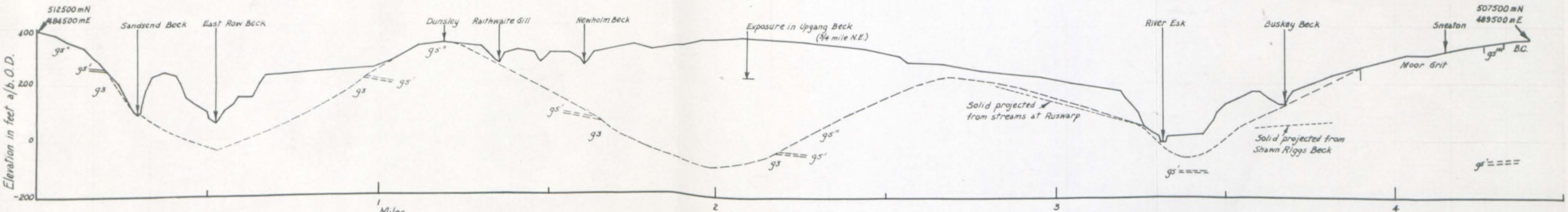


Esk Cross Section 4, Sleights

Fig. 32.

account for the fact that in Fig.31. the data plotted for cross-sections (the "3s" and "4s") at the lower ends of the dales lie more nearly on a single line than data plotted for the heads of the dales. It is, of course, true that the data plotted in Fig.31 have been measured on partly reconstructed profiles and there are undoubtedly errors in reconstruction although these should not be large since the general forms of the cross-sections are satisfactory and, as will be seen in the last section of this Chapter, are directly related to longitudinal profiles which also appear rational.

The single cross-section of Baysdale (Fig.28) shows remarkable symmetry and is V-shapedinstead of the more nearly U-shape of the other dales. The plot of data from this section on Fig.31 confirms clearly the immaturity of the valley cross-section. Reference to Grain Beck in Fig.21 indicates, however, that the longitudinal profile of the valley bottom is well on the way to maturity. The immaturity of this upper part of Baysdale is due largely to the fact that the stream has broken through the Dogger comparatively recently, so that the efficient method of excavation by undercutting this bed and the easier excavation in the Lias is belated. The fact that a fairly regular longitudinal profile has almost been achieved in this part of Baysdale Beck encourages the writer to believe that the



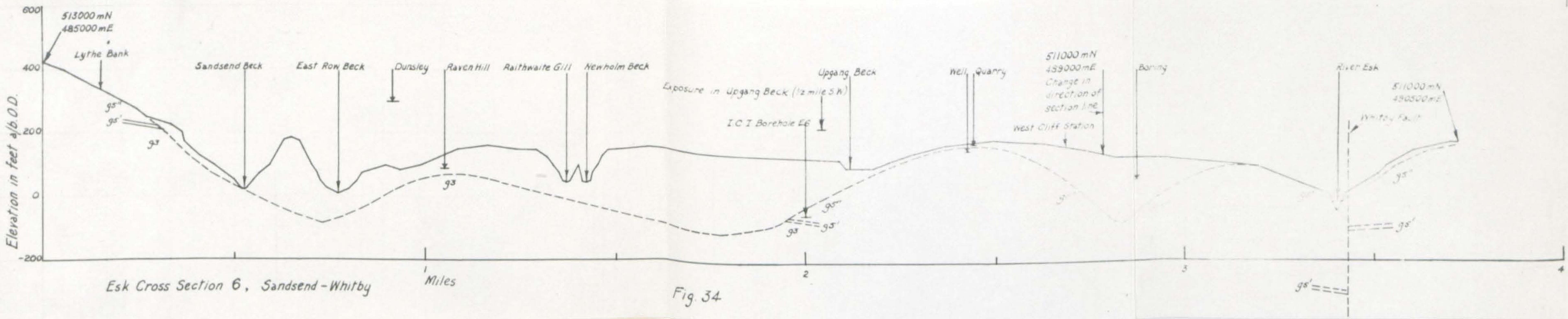
Esk Cross Section 5, Ruswarp

Fig. 33

pre-Glacial longitudinal profiles of the more mature Glaisdale, Great and Little Fryup Dales and Danby Dale were sufficiently regular to be represented by a simple mathematical curve, as demonstrated later.

The single cross-section of Sleddale (Fig.30) illustrates the effects of unilateral erosion which have been discussed in Chapter IV. This phenomenon does not appear to have existed in the Lower Estuarines, judging from the profile, but is quite marked in the Upper Lias and, as mentioned previously, the strength of the strata obviously plays a part in the mechanics of the problem.

Returning to the general problem of valley shape, if it is assumed that a deep, vertical incision of narrow width is made by a stream in a block of homogeneous, isotropic strata, then a landslide would develop and if the resulting debris were removed immediately, then the shape and dimensions of the valley cross-section could be defined by soil mechanics. If the depth of incision is relatively small - say 20 to 30 ft. in shale - then the tensile strength of the strata will be sufficient to permit the valley sides to remain vertical. Hence down to some depth, the half-width of the valley should bepractically zero and this has been taken into account in sketching the



Esk Cross Section 6, Sandsend - Whitby

Fig. 34

curve shown in Fig.31. However, the process of valley development is progressive and this, together with the debris which has not been removed, leads to complications in the form of the valley cross-section. Further complications arise due to variations in the physical properties and moisture content of the strata.

Twin Parallel Streams

Twin parallel streams occur within the Esk catchment in the Rigg Mill Beck system. Several occur also beyond the north-eastern watershed where the best examples are Easington and Roxby Becks, which unite and discharge as a single stream into the sea at Staithes, and Sandsend and East Row Becks, which discharge independently into the sea at Sandsend. The parallel sections of these streams are one-quarter of a mile or less apart. Easington and Roxby Becks are rather more spectacular than Sandsend and East Row Becks but both pairs are more impressive than the Rigg Mill Beck system. The top of the ridge between Easington and Roxby Becks is barely wide enough in places to accommodate the 10 ft. wide road which runs along its entire length. According to Fox-Strangeways (1894), the explanation of this phenomenon is that the streams have excavated their courses at the contacts between the Boulder Clay and the solid rock and that each stream is located on a flank of a pre-Glacial valley. This may be the case at a few points along the courses but it is not the principal cause. If the drainage has been initiated in post-Glacial times wholly in Boulder Clay, two parallel streams must have been developed in the clay fortuitously in close proximity to the valley sides and it is inconceivable that the phenomenon should be common in this, or any other, area. It is probable that the Boulder Clay would be depressed to some extent over the centre of a pre-Glacial valley owing to the greater amount of consolidation of the thicker clay deposit. Without an external agent, this would lead to a single stream following roughly the course of the old valley. Furthermore, the Boulder Clay, shales and sandstones are all relatively inert chemically whereas the explanantion given by Fox-Strangways would be more acceptable if one of the rocks at the contact is liable to comparatively rapid decomposition. Thornbury (1954) cites an example of this in the Bighorn Mountains of Wyoming in which a subsequent stream flows along the contact of granite and sedimentary rocks. Field observations and examination of geological maps show that, in fact, the streams rarely follow contacts. Nevertheless, one can concede the rather remote possibility of twin streams being initiated along contacts downstream and of parallel courses being extended upstream by normal upstream erosion in Boulder

Clay. It is of interest to note that on a section on the "one-inch" drift map (sheet 35, 44, Whitby) the parallel streams between Sandsend and Whitby are shown cut principally in Boulder Clay.

It follows from the above discussion that the contact erosion explanation is unsatisfactory and an alternative must be sought. There is no doubt that the modifications in the pre-Glacial drainage system were wrought principally during the collapse of the Glacial conditions in Cleveland and that only to a minor extent can they be ascribed to post-Glacial development. Several alternative solutions come to mind but most of these can be ruled out for one or more reasons and are given only briefly below. The most probable explanation is treated last at greater length.

In some way parallel streams might be due to the formation of drumlins, eskers or similar features but examination of aerial photographs of the Rigg Mill Beck area reveals nothing that can be interpreted as such, quite apart from the fact that the area is not drumlin country.

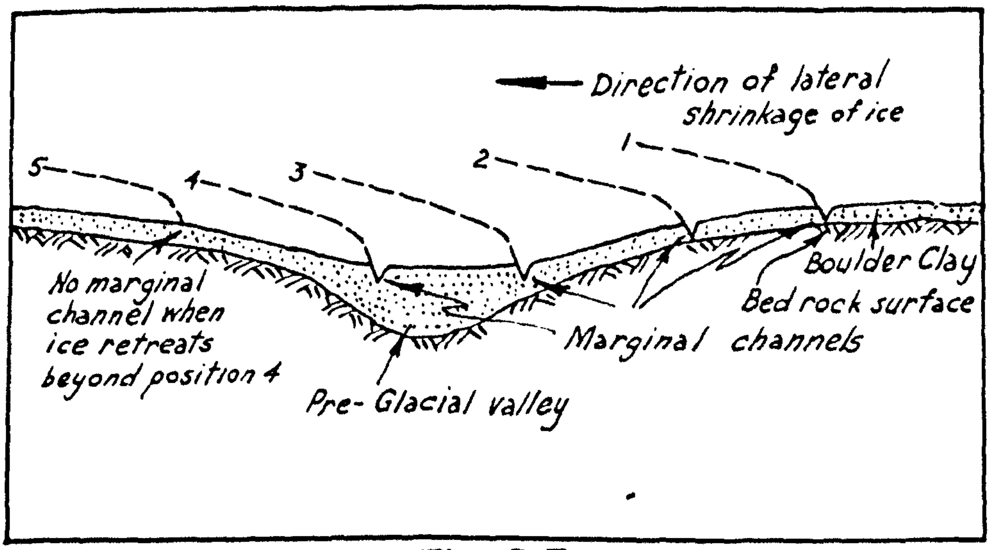
A possible explanation can be given if one can postulate the existence of local ice caps, which in Cleveland would be stagnant and ill-nourished. The glacier tongues from such caps would extend down the depressions in the exposed sub-glacial surface including drift-filled pre-Glacial valleys unless the drift was irregularly deposited. Twin streams could be developed by melt water flowing along the sides of the ice tongues or along lateral moraines or sub-glacially in cracks along the edges of the ice. However, according to Kendall (1903) the high ground at the head of Iburndale and Rigg Mill Beck - that is, Sneaton High Moor and Fylingdales Moor - was not covered with ice and this is supported by ample evidence. Furthermore, Roxby High Moor and Ugthorpe Moor above Easington and Roxby Becks and Sandsend and East Row Becks were clear of ice before the lower ground to the north and east and at one stage were occupied by lakelets. This evidence rules out the possibility of the Cleveland twin streams being formed along the margins of tongues from ice caps. In actual fact, when ice is stagnant and ill-nourished, evidence shows that the upper parts melt, revealing nunataks, at the same time as the margins shrink. The writer has been unable to trace examples of local stagnant ice caps, so that the initial postulate cannot be supported, but given the right conditions there is no reason why parallel streams should not be formed in this way.

It remains now to ascertain to what extent twin streams may be due to stagnant valley ice. If a depression is occupied by a tongue of stagnant ice, then parallel streams can be formed along each side of the tongue as it retreats downhill. Nevertheless, this is morelikely to lead to the formation of a series of short lateral channels in echelon, nearly all of which would be deserted at the present time, and such an arrangement cannot be found in the area. Mannerfelt (1945) studied the development of lateral drainage channels along the margins of stagnant ice sheets, lobes and tongues. Where the channels occur at regular intervals slightly inclined across the contours of a valley side, it is considered that they were formed at yearly intervals asthe ice shrank. In parts of Scandinavia ten or more of these lateral channels can be seen and at one place there are nearly eighty. The gradient of these channels is commonly 1 in 25 to 30. There appear to be several examples of twin streams located in lateral drainage channels although the present drainage system is faintly printed on Mannerfelt's maps. Anotherpoint of interest is that in Scandinavia some ice - dammed lakelets drain annually through sub-glacial channels opened by lifting of the ice when the water has risen sufficiently.

Returning to the parallel streams of Cleveland, it is noteworthy that the three principal sets occur below the site of former glacial lakelets. Consequently one should consider the possibility of annual sub-glacial drainage from the lakelets, as described by Mannerfelt, but the course of sub-glacial streams is generally winding whereas the Cleveland twin streams have fairly regular courses.

The most probable explanation of the twin streams in Cleveland is that they have been formed along the margin of the ice, either in contact with the ice or between ablation moraines. Ablation moraines commonly lead to hummocky ground but there is no marked evidence of this characteristic in the vicinity of the Cleveland twin streams. Hence it is probable that the channels were developed by water flowing in contact with the ice margin.

Kendall's work shows that Glacial Lake Iburndale discharged initially into Biller Howe Dale at a sill level of about 650 ft. Eventually a re-entrant was formed in the ice in a north-easterly direction roughly along the present main Whitby-Scarborough Road (A171). The writer suggests that this trend in the shrinkage of the ice continued, the eastern margin of the lobe lying over Sneaton became oriented roughly north/south and the several parallel streams of the Rigg Mill Beck system were formed during the westward retreat of this edge. The water eroding the channel may have been marginal water only but it is more likely that it was derived principally from Lake Iburndale. The head of the Rigg Mill Beck system is the nearest alternative outlet to Biller Howe Dale. The littoral belt - extending one or two miles

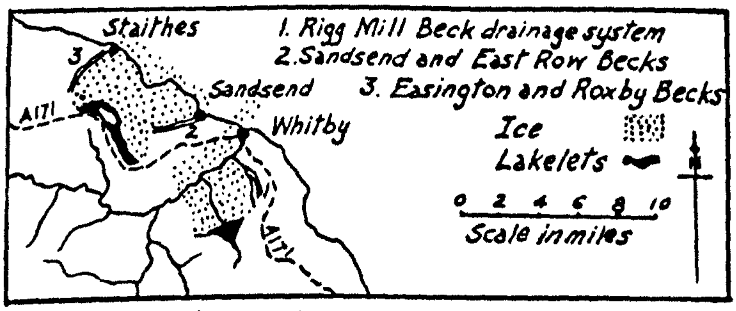


Direction of lateral shrinkage of ice
5
4
3
2
1
Boulder Clay
Bed rock surface
No marginal channel when ice retreats beyond position 4
Marginal channels
Pre-Glacial valley

Fig. 35

beyond the present cliffs - was clear of ice as far north as Whitby whilst inland the sheet still extended some distance south of the Esk. The Rigg Mill Beck water must have drained north-eastwards to the sea, possibly along the present line of the Esk estuary and may have been instrumental in establishing a course which was later followed by the main river. The surface of the Boulder Clay was probably depressed slightly by consolidation in the pre-Glacial valley of Rigg Mill Beck. When the icemargin reached the western flank of this depression, the surface began to slope upwards and drainage from Lake Iburndale persisted in the newly formed lateral drainage channels, which were thus well developed. It may be that no new channels were formed in this way west of Rigg Mill Beck, although Shawn Riggs Beck and Buskey Beck are possibilities. The earlier channels are represented, for example, by Mitten Hill Beck but some poorly developed channels may have been lost through post-Glacial erosion. It is not to be expected that the positions of the ice margin should lie regularly over the pre-Glacial valley and consequently the Rigg Mill Beck streams cut into solid rock in places although they were probably initiated almost entirely in Boulder Clay.

Some time after the initiation of the Rigg Mill Beck drainage system, a lobe of ice extended south-westwards from the coast



Map showing portions of ice lobes in locations suitable for the initiation of the Cleveland twin streams

Fig. 36

roughly to the Whitby-Guisborough Road (A171) andlakelets were formed between the ice and the present watershed in the vicinity of Roxby High Moor, Ugthorpe Moor and Briscoe Moor (Kendall,1903) The present writer suggests that the twin Easington and Roxby Becks and Sandsend and East Row Becks were formed in a manner similar to that in which the Rigg Mill Beck streams were developed and that at their initiation the lobe of ice was contained roughly in an area bounded by these two sets of twin streams and the road (A171). Both sets were probably firmly entrenched by water from the glacial lakelets. Between Whitby and Sandsend there are two minor sets of twin streams and these are probably earlier lateral channels which were supplied with insufficient water to establish them conspicuously. The sharp turn at the lower end of Easington Beck may have been initiated as a sub-glacial chute. Between Sandsend and Staithes is another set of twin streams - Borrowby Dale Beck and Newton Beck - probably initiated when the western margin of the lobe had retreated to this position.

The prerequisites for the formation of twin streams are an adequate supply of water and the retreat in stages - possibly annual - of an ice margin laterally across a channel-like depression in the sub-glacial surface. This latter is commonly the depressed surface of drift filling a pre-Glacial valley. Other examples of twin channels are found in Eskdale, such as Wild Slack and Crunkly Gill at Lealholm and East Arnecliff Wood Gorge and the channel recorded by the writer in Chapter IV. One of each of these twins is at a relatively high level and deserted, primarily because it has no appreciable catchment of its own whereas the twin streams discussed at length above all have reasonable catchments.

The writer has examined Ordnance maps at the scale of one-quarter inch to one mile in an endeavour to locate other examples of twin parallel streams in the east coast belt of Northern England and Scotland but, although there are numerous examples of parallel streams, none have the same characteristics as those in Cleveland. The uniqueness of the Cleveland twin streams must therefore be significant but the reason for this is not obvious and a knowledge of the Pleistocene geology of other areas may be required before it becomes apparent.

Summing up, the most probable explanation of the twin parallel streams of Cleveland is that they were formed by water flowing in contact with an ice margin which retreated in stages laterally across depressions in the sub-glacial surface - commonly following drift filled pre-Glacial valleys - and that the water which firmly established them was derived principally from Glacial lakelets. These streams represent, in fact, the last stages of drainage of the lakelets. The process of formation of twin parallel streams is illustrated in Fig.35 and the positions of the ice margins during the formation of the twin streams in Cleveland are shown in Fig.36.

The Valley Profile

The expression of a river or valley profile empirically in mathematical terms appears to have been suggested first by Jones (1924) who employed a rectangular hyperbolic function for the gradient curve of the Upper Towy. The exponential curve of decay is obviously a suitable curve and is employed in this thesis. One can conceive arguments for and against several different types of curves but since they are all empirical functions such arguments carry little weight. The range of curves which could be employed is demonstrated by experience of curves of very large radii which indicates that an arc of a circle could be employed to fit the profile of a graded river within tolerable limits, although extrapolation might lead to difficulties. It is interesting to note that Shulits (1941) derived an exponential function for the curve of river-bed profile from considerations of bed-load transport but, since the premises are largely empirical, the final equation is also empirical.

The decay curve employed in this thesis is shown in Fig.37

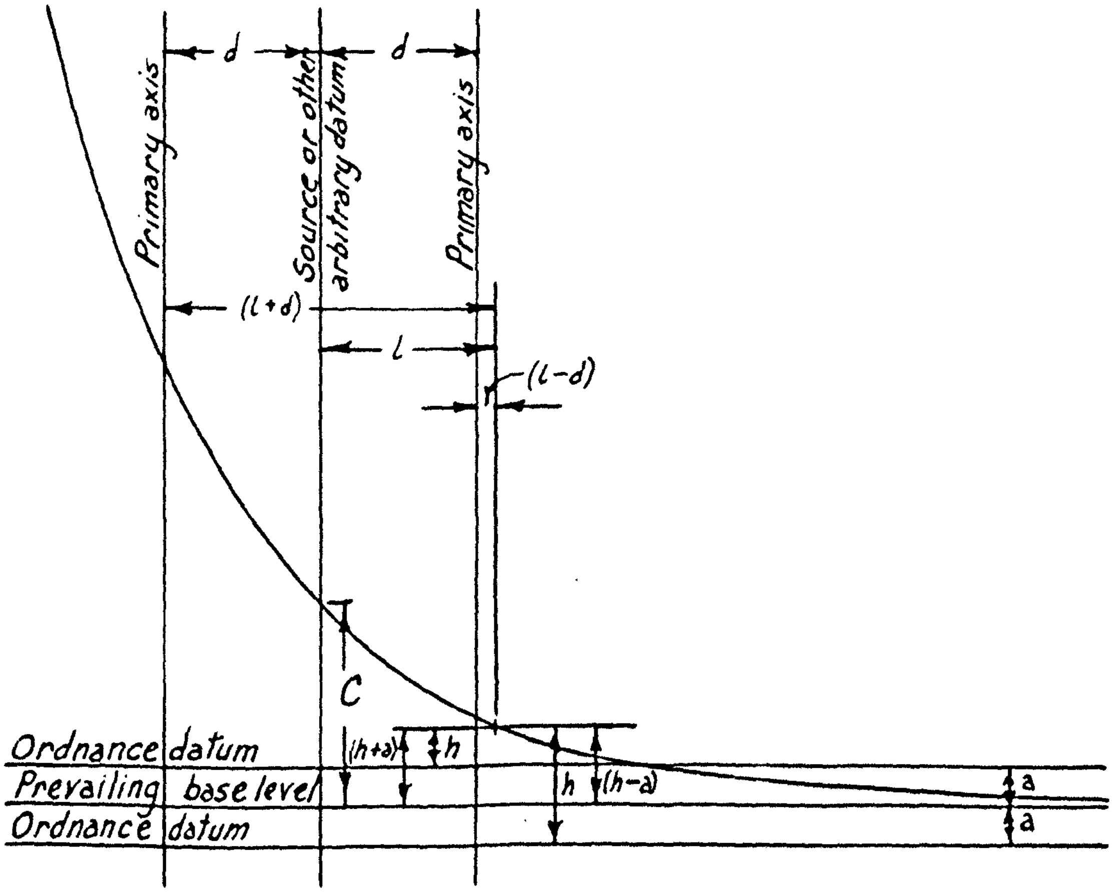

d
d
Primary axis
Source or other arbitrary datum
Primary axis
(l+d)
l
(l-d)
C
Ordnance datum
(h+a)
h
Prevailing base level
h
(h-a)
a
Ordnance datum
a

Fig. 37

Horizontal and vertical distances are measured respectively from a vertical line through the source of a river - or other arbitrary axis - and from Ordnance Datum but neither of these can be taken as the primary axes on which the curve of profile is based. Consequently it is necessary to relate the primary axes to the field axes by positive or negative constants d and a of unknown magnitude, as shown in Fig.37. The exponential function expressing the graded valley profile is therefore

$$(h \pm a) = ce^{-k(l \pm d)} \qquad \ldots.(1)$$

where a, c, k and d are constants. The signs relating to a and d are indicated for specific cases in Fig.37.

The most important axis from a geological point of view is the prevailing base level and the position of the vertical primary axis is not significant. Now

$$(h \pm a) = ce^{-kl}\, e^{\mp kd} = Ce^{-kl} \qquad \ldots.(2)$$

where $C = ce^{\mp kd}$ is another constant and represents the value of $(h \pm a)$ when l is zero. This eliminates the insignificant unknown d from (1).

Equation (2) can be expressed in the logarithmic form

$$-kl = \log_e\left(\frac{h \pm a}{C}\right) = 2.303 \log_{10}\left(\frac{h \pm a}{C}\right)$$

or simply

$$-kl = \ln\left(\frac{h \pm a}{C}\right) = 2.303 \log\left(\frac{h \pm a}{C}\right) \qquad \ldots.(3)$$

The sign of a can generally be judged from the geological history of the area and the plotted profile. In the case of the pre-Glacial valley of the Esk it is positive. So far, a simple change in relative levels of land and sea has been envisaged. If tilting of the land is taken into account, then one additional term is normally sufficient to cater for it and equation (2) becomes

$$(h \pm a) = Ce^{-kl} \pm l \tan \alpha \qquad \ldots.(4)$$

where α is the angle of tilt in the direction of the valley axis and constitutes an additional unknown quantity. The positive sign applies when the tilt is up towards the estuary and the negative sign when the tilt is down. This simple method of catering for tilt applies only where α is no more than a few degrees, otherwise complications arise in the measurement of distances which were originally horizontal but are now tilted. Furthermore, the method obviously applies to a straight valley only. Nevertheless, equation (4) may prove useful in some cases in spite of these limitations.

The current vertical movements of the British Isles have been studied by Valentin (1953) and tilting in the region of Eskdale is shown to be downwards in an almost due east direction at the rate of 0.5 mm per year over a distance of about 120 kilometres. Assuming that the average rate over the past 24,000 years was 1.0 mm., the tilt developed during post-

Glacial times along the main Esk valley is 0.2 metre per kilometre. The main river is about 32 kilometres long and the total difference in level is thus 6.4 metres or, say, 20 ft. Unfortunately the accuracy with which it is possible to assess buried pre-Glacial valley levels is unlikely to be closer than ± 10 ft. andprobably it is worse than this. These crude estimates indicate that tilt is unlikely to be revealed by calculations for the pre-Glacial profile of the Esk valley but the possibility of this taking place may provide a reason for discrepancies. It is unfortunate also that the vertical movements taking place immediately before and during the Glaciation are unknown. One may expect these movements to be the reverse of the current trends but the time internal of one to two million years is very much greater. Hence the pre-Glacial Esk profile may not yet have attained its early orientation.

The constants a, C and k in equation (2) can be determined by several methods with varying degrees of rigour. If the observed values of the co-ordinates of three points on the profile are $(h_1 l_1)$, $(h_2 l_2)$ and $(h_3 l_3)$ such that their ordinates are spaced at equal intervals b, then

$$\frac{h_2 - h_3}{h_1 - h_2} = \frac{C\left(e^{-k(l_1 + b)} - e^{-k(l_1 + 2b)}\right)}{C\left(e^{-kl_1} - e^{-k(l_1 + b)}\right)}$$

or

$$\frac{\Delta_{23}}{\Delta_{12}} = e^{-kb} \qquad \ldots.(5)$$

where $\Delta_{23} = h_2 - h_3$ and $\Delta_{12} = h_1 - h_2$. Equation (5) yields k and then C is calculated from

$$C = \frac{\Delta_{12}}{e^{-kl_1}}\left(\frac{1}{1 - e^{-kb}}\right) \qquad \ldots.(6)$$

and

$$\pm a = Ce^{-kl_1} - h_1 \qquad \ldots.(7)$$

Unless the observations have been taken at equal horizontal distances along the mean course of the river it is necessary to sketch a curve through the plotted points and the co-ordinates $(h_1 l_1)$, $(h_2 l_2)$ and $(h_3 l_3)$ are taken from this. Several sets of co-ordinates can be employed and the computations repeated to give several values of a, C and k from which the means are calculated.

It will be observed that (5) can be expressed in the general form

$$\frac{\Delta_{(m+1)(m+2)}}{\Delta_{m(m+1)}} = e^{-kb} \qquad \ldots.(5a)$$

and that this is a constant ratio for a given curve. This fact is useful when plotting tentative profiles and has been employed for preliminary estimates of k for the main river and for re-constructing the profiles in main and tributary valleys. It implies that the ratio of differences between any three successive ordinates is always the same and, having selected a value for the first difference Δ_{12} and estimated the ratio (e^{-Kb}), the remaining ordinates are easily calculated on a slide rule for the entire profile.

If the method of least squares can be applied to the observed values, then it will yield the best fit, according to the premises of the method, and precisely the same fit will be obtained by everybody using the same data. Strictly the method should be used only when the standard errors can be determined for all the observations and weights based on these are assigned to the observations, thereby influencing the least squares computations. It is impossible to calculate standard errors for levels on the Esk and consequently the weight to be assigned to each observation can be assumed only as unity. The least squares method is regarded in this thesis simply as a technique which gives a good fit to the observed data and which yields the same results for every computer using that data.

Certain difficulties arise in connection with the application of the method to transcendental functions, as will be seen below. In the following discussion it is assumed that the most probable values of a, C and K - satisfying the least squares conditions - are employed and that $(h_1 l_1)$, $(h_2 l_2)$,

.....$(h_m l_m)$, ...$(h_n l_n)$ are the observed quantities. Then the observation, error or residual equations are all in the form

$$r_m = Ce^{-kl_m} \mp a - h_m \qquad \text{....(8)}$$

where r_m is the residual. To satisfy the conditions of the method the sum of the squares of the residuals $\sum_1^n r_m^2$ must be a minimum where n is the number of observation equations. The minimum condition obtains when the partial derivatives of $\sum_1^n r_m^2$ with respect to a, C and k individually are each equal to zero.

Thus from $\dfrac{\partial \sum_1^n r_m^2}{\partial a}$ $\qquad \mp C\sum_1^n e^{-kl_m} + an \pm \sum_1^n h_m = 0$ ....(9)

and from $\dfrac{\partial \sum_1^n r_m^2}{\partial C}$ $\qquad C\sum_1^n e^{-2kl_m} \mp a\sum_1^n e^{-kl_m} - \sum_1^n h_m e^{-kl_m} = 0$ ....(10)

and from $\dfrac{\partial \sum_1^n r_m^2}{\partial k}$ $\qquad -C\sum_1^n l_m e^{-2kl_m} \pm a\sum_1^n l_m e^{-kl_m} + \sum_1^n l_m h_m e^{-kl_m} = 0$...(11)

These are three simultaneous equations with three unknowns which normally can be expected to be readily solved but the main difficulty arises due to the fact that they are transcendental functions and e is raised to a variety of powers (kl_m) where k is unknown and hence the summation cannot be effected. Therefore some artifice must be introduced to effect a solution. If an approximate value for k is determined, by the application of equation (5) or otherwise, it can be employed in the summations in equations (9), (10) and (11). The C and a can be calculated from (9) and (10) but if these values are substituted in (11) it will be found that there is a small residual R. The problem is to determine the value of K when R is zero. If computations are repeated with two, three or more values of K, then a graph can be drawn of K against R from which the value of K yielding R = 0 can be obtained to a close approximation. It is desirable, of course, to obtain both positive and negative values of R for this purpose. The values of a and C can be calculated from this value of K and these will all satisfy the condition of least squares to a close approximation. Values of R can be computed most simply by employing determinants and it is not necessary to compute a and C to do this.

For simplicity let the various summations between 1 and n in which an approximate value of K is employed be represented as follows

$$S_1 = \sum_1^n e^{-kl_m} \qquad S_2 = \sum_1^n h_m \qquad S_3 = \sum_1^n e^{-2kl_m} \qquad S_4 = \sum_1^n h_m e^{-kl_m}$$

$$S_5 = \sum_1^n l_m e^{-2kl_m} \qquad S_6 = \sum_1^n l_m e^{-kl_m} \qquad S_7 = \sum_1^n l_m h_m e^{-kl_m}$$

Then equations (9), (10) and (11) are

$$\mp S_1 C + na \pm S_2 = 0 \qquad \ldots(9)$$

$$S_3 C \mp S_1 a - S_4 = 0 \qquad \ldots(10)$$

$$-S_5 C \pm S_6 a + S_7 = 0 \qquad \ldots(11)$$

These can be expressed and solved in determinant form as follows:

$$D = \begin{vmatrix} \mp S_1 & n & 0 \\ S_3 & \mp S_1 & 0 \\ -S_5 & \pm S_6 & -1 \end{vmatrix} = \mp S_1 \begin{vmatrix} \mp S_1 & 0 \\ \pm S_6 & 1 \end{vmatrix} - S_3 \begin{vmatrix} n & 0 \\ \pm S_6 & -1 \end{vmatrix} + 0$$

$$= -S_1^{\,2} + nS_3 \qquad \ldots.(12)$$

$$D_1 = \begin{vmatrix} \mp S_2 & n & 0 \\ S_4 & \mp S_1 & 0 \\ -S_7 & \pm S_6 & -1 \end{vmatrix} = \mp S_2 \begin{vmatrix} \mp S_1 & 0 \\ \pm S_6 & -1 \end{vmatrix} - S_4 \begin{vmatrix} n & 0 \\ \pm S_6 & -1 \end{vmatrix} + 0$$

$$= -S_1S_2 + nS_4 \qquad \ldots.(13)$$

$$D_2 = \begin{vmatrix} \mp S_1 & \mp S_2 & 0 \\ S_3 & S_4 & 0 \\ -S_5 & -S_7 & -1 \end{vmatrix} = \mp S_1 \begin{vmatrix} S_4 & 0 \\ -S_7 & -1 \end{vmatrix} - S_3 \begin{vmatrix} \mp S_2 & 0 \\ -S_7 & -1 \end{vmatrix} + 0$$

$$= \pm S_1S_4 \mp S_2S_3 \qquad \ldots.(14)$$

$$D_3 = \begin{vmatrix} \mp S_1 & n & \mp S_2 \\ S_3 & \mp S_1 & S_4 \\ -S_5 & \pm S_6 & -S_7 \end{vmatrix} = \mp S_1 \begin{vmatrix} \mp S_1 & S_4 \\ \pm S_6 & -S_7 \end{vmatrix} - S_3 \begin{vmatrix} n & \mp S_2 \\ \pm S_6 & -S_7 \end{vmatrix} - S_5 \begin{vmatrix} n & \mp S_2 \\ \mp S_2 & S_4 \end{vmatrix}$$

$$= -S_1^{\,2}S_7 + S_1S_4S_6 + nS_3S_7 - S_2S_3S_6 - nS_4S_5 + S_1S_2S_5 \qquad \ldots.(15)$$

Hence

$$C = \frac{D_1}{D} \qquad \text{....(16)}$$

$$a = \frac{D_2}{D} \qquad \text{....(17)}$$

$$R = \frac{D_3}{D} \qquad \text{....(18)}$$

It should be observed that the computed values of C and R, and hence also K, are independent of the sign of a.

Having outlined the method of analysis, the first stage in the application of the method is to test the suitability of the exponential decay equation (2) to represent the equilibrium profile of a river or part of a river. The obvious section of the Esk to use for this purpose lies between the mouth of Westerdale and Crunkly Gill. The least squares analysis was employed and sample computations are given in Table 4 The equation representing the profile to a close approximation was found to be

$$(h - 195{\cdot}11) = 437{\cdot}36\, e^{-1{\cdot}58 \times 10^{-5} l} \qquad \text{....(19)}$$

where h and l are in feet. The levels calculated from this equation are compared with the corresponding levels obtained from the 6 inches to 1 mile Ordinance sheets in the following table.

TABLE 4

Profile of the Present Esk from the mouth of Westerdale to Crunkly Gill

Zero for horizontal distances l is the vertical axis in Fig.23.
Datum for heights h is Ordnance Datum. Heights determined from contours on 6 inches to 1 mile Ordnance Sheets
Approximate value for $k = 1{\cdot}58 \times 10^{-5}$ with l in feet, determined from trial with $e^{-kb} = 0{\cdot}92$ where b is 1 mile

Station	l in ft.	h in ft.	kl	$2kl$	e^{-kl}	e^{-2kl}	he^{-kl}	le^{-kl}	le^{-2kl}	lhe^{-kl}
1	34,370	450	0·543046	1·086092	0·580976	0·337533	261·439	19,968·1	11,601·0	8,985,670
2	40,490	425	0·639742	1·279484	0·527428	0·278181	224·157	21,355·6	11,263·5	9,076,110
3	47,800	400	0·755240	1·510480	0·469898	0·220804	187·959	22,461·1	10,554·4	8,984,450
4	56,310	375	0·889698	1·779396	0·410780	0·168740	154·043	23,131·0	9,501·7	8,674,130
5	65,800	350	1·039640	2·079280	0·353582	0·125020	123·754	23,265·7	8,226·3	8,142,990
		S_2 2,000			S_1 2·342664	S_3 1·130288	S_4 951·352	S_6 110,182·5	S_5 51,146·9	S_6 43,863,400

$D = 0{\cdot}16334$ $D_1 = 71{\cdot}44$ $D_2 = 31{\cdot}87$ $D_3 = 0$

$C = \frac{71{\cdot}44}{0{\cdot}16334} = 437{\cdot}36$ ft. $a = \frac{31{\cdot}87}{0{\cdot}16334} = 195{\cdot}11$ ft. $R = \frac{0}{0{\cdot}16334} = 0$

Equation of profile is $(h - 195{\cdot}11) = 437{\cdot}36\, e^{-1{\cdot}58 \times 10^{-5} l}$ where h and l are in feet

TABLE 5

Station	l in ft.	h in ft. Ordnance sheets	h in ft. Computed from equation (19)	Discrepancy in ft.
1	34,370	450	449.21	-0.79
2	40,490	425	425.79	+0.79
3	47,800	400	400.62	+0.62
4	56,310	375	374.77	-0.23
5	65,800	350	349.75	-0.25

The discrepancies over this 6 mile stretch of river are all less than 1 ft. - a result which is remarkable, particularly in view of the fact that the accuracy of the elevations determined from the Ordnance Survey contours may be no closer than 2 or 3 ft. according to the details given in Chapter III. The inference is that in this case the accuracy of the elevations is much better than 2 ft. The closeness of the correspondence can hardly be coincidental, since the discrepancies are consistently small. The mathematical tables employed for the computations were Chamber's Six-Figure Mathematical Tables (1949) but the writer considers that the use of ten-figures taken from the 18 and 15 decimal Tables of the Exponential Functions e^x and e^{-x} (1939) produced in the U.S.A. for the National Bureau of Standards Mathematical Tables Project would lead to a slight improvement in the fit, probably with discrepancies not exceeding ±0.5 ft. This result gives a measure of confidence in the application of equation (2) to equilibrium profiles. In the work which follows it is necessary to assume that the Esk had attained equilibrium profiles in earlier stages of its development.

Unfortunately there are no reliable levels from which to establish buried profiles of the Esk and the levels given at Glaisdale Iron Works and Grosmont Iron Works - which at first sight appear encouraging - prove, in fact, misleading because of the displacement of the river to the north and this is sufficient to lead to errors in levels approaching 100 ft. All the profiles described below were established by trial and error using equation (5a). The operation may appear hazardous, yet the following three conditions must be satisfied in estimating levels of buried valleys.

1. The longitudinal profile must be rational.
2. The re-constructed cross-sections of partly buried sections of valleys must conform to the general patterns of the cross-sections of unburied mature sections.
3. In the mature sections of tributary dales, the ratio of the height of the Dogger Bed

above the re-constructed valley bottom to the half-width of the valley must not show a marked divergence from the data plotted in Fig. 31

Condition (1) implies that at some upstream point the early profile approaches or becomes tangential to the present profile and that nowhere is the early profile obviously too deep nor too shallow. Furthermore, the downstream reaches must have reasonable gradients. In the case of the main river this means that the estuary gradients must be of the order 3 or 4 ft. per mile for mature pre-Glacial profiles - and not more than about double these values for inter- and post-Glacial profiles. The writer has found that imposition of these conditions places distinct limits on the constants a, C and k in equation (2). It is assumed that the early valley floor is covered with about 5 ft. of alluvium in upstream reaches and about 15 ft. in downstream reaches. In all the profile equations quoted below, h is in feet and l in miles. It should be noted that some of the Esk cross-sections are not at right-angles to the axis of the valley - the skew is greatest on cross-section (5). This has been taken into account in reconstructing the valley cross-sections. The positions of the cross-sections of the tributary dales are indicated on the longitudinal profiles by corresponding numbers in cycles, and on the map in the end pocket in a similar way.

The first trials were aimed at establishing a continuous profile for the pre-Glacial course from the mouth of Westerdale to the sea. Although it was stated in Chapter IV that the valley of the middle/upper pre-Glacial Esk was no older than late youth, it is reasonable to assume that an equilibrium profile had been attained - an assumption confirmed by the present stage of development of upper Baysdale Beck. However, it was found impossible to fit a continuous curve representing the pre-Glacial profile - for example, the values of a were obviously much too large. Hence the profile must have been broken at one or more points and this must be due either to structural and lithological local controls or rejuvenation of dynamic or eustatic origin.

The geological map reveals that north of Crunkly Gill the Dogger lies at a level such that it undoubtedly established a local control at some time on the pre-Glacial Esk, with the upstream reaches in the Lias. Trial profiles were then based on a level of 438 ft. a.O.D. at 7 miles from the axis on the section shown in Fig.23. and on a level for the Dogger of about 290 ft. a.O.D. at Lealholm moraine. The level of 438 ft. is just below the present valley level. It was found that the equation

$$(h - 108) = 330e^{-0\cdot105l} \qquad \ldots.(20)$$

conformed reasonably well to these levels, Esk cross-section (1), various borehole levels and the profiles of the tributary dales. The profile based on this equation is shown in Fig.23. with the zero for horizontal distances at 7 miles. The Dogger and Lower Estuarines at the mouth at Westerdale probably constitute a local control for the Esk headwaters and there is a break in both pre- and post-Glacial profiles at this point. The reconstructed portion of Esk cross-section (1) shows erosional bias towards the up-dip side of the valley.

An attempt was then made to devise a continuous profile from Lealholm to the sea but the results were unsatisfactory and, because of the absence of any obvious local control the writer suspected dynamic or eustatic rejuventaion and devised profiles based on this. A level of 240 ft. appeared to be reasonable at Esk cross-section (2). It was found that a base-level of -100 ft. b.O.D. led to estuary gradients of 5 to 10 ft. per mile and these are steep for a mature river. However, a base -level at O.D. yielded estuary gradients to 2 to 4 ft. per mile and the corresponding equation is

$$(h+0) = 240\, e^{-0.223l} \qquad \ldots.(21)$$

The zero for horizontal distances is at 13 miles on Fig.23. This profile reveals that the Dogger had been broken through at Lealholm and that rejuvenation was reducing the upper reaches to the base-level of O.D.

The next step is to devise a profile conforming to the valley levels which are obviously below O.D. between Upgang and Sandsend. The I.C.I. borehole E6 at Upgang indicates that the pre-Glacial Esk must have been at a depth of roughly -100ft. b.O.D. at cross-section 6. Consequently it is necessary to ascertain the approximate position of the marine cliffs when the sea-level was -100 to -200 ft. b.O.D.. Admiralty Chart No.1191 shows sea-bed at about 25 fathoms at 5 miles from the present shore and 30 fathoms at 10 miles. The sea-bed is shown principally as sand with very few rock exposures. These depths are about -150 ft. and -180 ft. below L.W.S.T. and to these must be added about -7 ft. to reduce them to O.D. In round figures the present elevations of the sea-bed can be taken as -160 b.O.D. at 5 miles from the present shore and -190 ft. b.O.D. at 10 miles. Thus for an early sea-level at -150 ft. b.O.D. the cliffs can be expected to be at a distance of 2 to 5 miles from the present shore. This information is required in order to examine estuary gradients.

A profile following the equation

$$(h+150) = 250e^{-0.223l} \qquad \ldots.(22)$$

was devised which has estuary gradients of 3 to 5 ft. per mile and which fits Esk cross-sections (3), (4), (5) and (6) reasonably well. The base-level for this profile is -150 ft. b.O.D.

The zero for horizontal distances is at 16 miles on Fig.23.

For this particular profile it was necessary to take into account the difference in length between the pre-Glacial and post-Glacial courses but this was not necessary for the two upstream pre-Glacial profiles.

The pre-Glacial profiles of four tributary dales wererecon-structed at the same time as those for the main river in order to check the correspondence. The pre-Glacial Glaisdale Beck followed a course west of the present gorge at the mouth of the dale and extended further northwards to the confluence with the pre-Glacial Esk. A profile was evolved for the early pre-Glacial Glaisdale Beck conforming to the equation

$$(h-60) = 375e^{-0.349l} \qquad \ldots.(23)$$

with zero for horizontal distances at 1½ miles on Fig.20 and this yielded satisfactory cross-sections. However, in order to conform to the rejuvenation of the main river it was neces-sary to introduce another profile with the equation

$$(h+50) = 300e^{-0.446l} \qquad \ldots.(24)$$

with zero for horizontal distances at 3½ miles on Fig.20 to cater for rejuvenation in the lower part of Glaisdale Beck.

Profiles were also devised for three other tributary dales and the equations to which they conform are as follows:

Great Fryup Beck $(h - 169) = 346e^{-0.325l}$ ....(25)

with zero for horizontal distances at 2 miles on Fig.21.

Little Fryup Beck $(h - 106) = 390e^{-0.446l}$ ....(26)

with zero for horizontal distances at 3½ miles on Fig.21.

Danby Beck $(h - 364) = 236e^{-0.657l}$ ....(27)

with zero for horizontal distances at 1½ miles on Fig.22.

Although Danby Beck is shown graded to the pre-Glacial Esk, the geological map shows the Dogger outcropping in a resistant attitude at the mouth of the dale and it is possible that Danby Beck may have been graded to this at or just below present ground level, with waterfalls to the Esk. However, the cross-sections in Danby Dale conforming to the plotted profile are satisfactory and, although a profile can be produced graded to ground level at the Dogger, cross-sections (3) and (4) are less satisfactory when adjusted to conform to it.

It was stated above that it was impossible to devise a continuous curve for the pre-Glacial Esk from the mouth of Westerdale to the sea and that it was necessary to invoke breaks in the curve due to local control afforded by the Dogger and to rejuvenation of dynamic or eustatic origin. It may be considered that regional tilting in a downstream direction offers an alternative explanation and, although this accounts for steep estuary gradients, it does not alter the apparent anomalies in upstream depths and reconstructed cross-sections which obtain when a continuous curve is employed. Obviously post-Glacial tilting has occurred in the area and the rough estimate made earlier in this section indicates that it may lead to an overestimate of the depth below O.D. of earlier sea-levels. Nevertheless, the factors which had to be taken into account in producing profiles indicate that the effects of local control and rejuvenation are greater than any due to tilting.

Unfortunately there are no data on which to construct a curve for the inter-Glacial Esk. The only reconstructed section is Fig.33. and this is based on the form of immature valley sides in the Estuarines at the lower end of Sleddale Beck. The valley floor is about -77 ft. b.O.D. - that is, about 30 ft. above the pre-Glacial valley on the same section. Allowing for a slightly steeper estuary gradient, it seems likely that the inter-Glacial sea-level was approximately the same as the immediately pre-Glacial - that is, about -150 ft. b.O.D.

The profile for the post-Glacial Esk is based on the data presented in Fig.15. Although the early post-Glacial bed is about 8 ft. a.O.D. at Sleights, the bank level was probably about 18 ft. a.O.D. At the Larpool Railway Viaduct the bed is about - 41 ft. b.O.D. but it is assumed that bank level was about -25 ft. b.O.D. The zero for horizontal distances was taken at 23 miles on Fig.23. and two profiles were evolved which can be taken as upper and lower limits. They are

$$(h+65) = 80e^{-0.357l} \qquad \text{....(28)}$$

and

$$(h+95) = 110e^{-0.223l} \qquad \text{....(29)}$$

conforming to base-levels of -65 ft. and -95 ft. b.O.D. respectively. The estuary gradients for (28) are 6 to 8 ft. per mile and for (29) are 9 to 11 ft. per mile. It is reasonable to assume that this short length of rejuvenated river would have comparatively steep estuary gradients and both curves yield reasonable values. The profile calculated from (29) has been plotted on Fig.23 but the profile based on (28) has been omitted to avoid confusion.

During the process of evolving profiles it was found that the ratio e^{-kb} was commonly between 0.8 and 0.9, with occasional values just below and just above. The significance of this is that values above 0.9 tend to a straight line which obtains when e^{-kb} is unity and such values lead to steep gradients in lower reaches. Values less than 0.8 lead to upstream gradients which are steeper than the gradients at which streams reach equilibrium profiles and consequently lead to excessive depths for buried valleys in the upstream reaches.

Barrow (1888) mentioned a raised beach at Saltburn and the present writer considered that this might yield data on post-Glacial sea-level and accordingly visited the site. Several recent shells were foundat a level of about 30 ft. a.O.D. in Boulder Clay and one of these was identified by Mr. J.S. Turner of the Geology Department, University of Leeds, as Littorina littorea. Barrow estimated the elevation of the raised beach at the same level and included the same species in his list of shells. However, the supposed beach which was visible 70 years ago has been obliterated by man-placed deposits of soil and fragments of brachiopods and molluscs are found liberally sprinkled on the cliffs at all levels. Lamplugh (1919) considered that there was insufficient evidence to support the contention of a raised beach and the present writer subscribes to the same opinion.

The following is a summary of the probable stages in the development of the Esk revealed by the present investigation.

1. Grading of the middle and lower Esk to sea-level at about O.D. in early pre-Glacial time.
2. Contemporary with (1), grading of the upper Esk between Lealholm and the mouth of Westerdale to the control established by the Dogger at Lealholm.

3. Rejuvenation of the lower Esk by a reduction in sea-level to about -150 ft. b.O.D. in late pre-Glacial time. The period during which this occurred must have been adequate for producing mature valley cross-sections and for extending the profile to the middle Esk. The process did not extend much above Glaisdale before the onset of the Glaciation but was sufficient to induce partial rejuvenation in Glaisdale.
4. The rejuvenation of (3) was probably accompanied by the middle and upper Esk breaking through the Dogger at Lealholm, leading to partial rejuvenation of the upper Esk.
5. Partial filling of the valleys with Glacial drift during the Early and Antepenultimate Glaciation with the Esk following its preGlacial course during the Antepenultimate Interglacial Phase.
6. Re-opening of the pre-Glacial course during the Great Interglacial Phase from the headwaters to Sleights where drift filling in the valley led to a diversion of the estuary into the inter-Glacial valley past Ruswarp, graded to a sea-level of roughly -150 ft. b.O.D. This course was presumably followed also during the last Interglacial Phase, since there is no evidence of another diversion during this period.

7. More extensive filling of the valleys with drift during the last Glaciation.
8. Re-opening of the Eskdale drainage system with diversions created by moraines and drift filling and with the establishment of consequent new controls in the solid, principally at Lealholm, Glaisdale (two controls) and Larpool.
9. Grading of the immediately post-Glacial lower Esk to sea-level between -65 and -95 ft. b.O.D.O
10. Rise in sea-level to the present position.

It must be emphasised that the evidence on which these conclusions are based is largely morphological and other evidence, such as Pleistocene and Recent Stratigraphy, is needed to weigh with or against it.

CHAPTER VI

Summary of Conclusions

This chapter consists of a summary of the main conclusions drawn in this thesis with a final note on suggestions for further work. A number of conclusions of minor importance are recorded in various parts of the preceding text but the following are the major inferences.

1. Meanders

The factors given by Matthes (1941) in order of importance -quoted in Chapter IV - which control meandering are general valley-slope, bed-load, discharge, bed-resistance and transverse oscillation. It has not been possible to examine bed-load, discharge and transverse oscillation in the present investigation but the influences of valley-slope and bed-resistance are more apparent. In any case, bed-load and bed-resistance are related by particle-size and consequently the two can be linked together under the composite heading bed-material. The tributaries offering the best evidence are Glaisdale Beck, Great Fryup Beck, Danby Beck and Baysdale Beck. Conditions in these streams confirm that meandering occurs in a given material where the gradient is steeper than is required to provide just sufficient energy for straight channel flow and transport of bed-load. At a given gradient, if meandering occurs with bed-material of a given size it will cease where the bed-material becomes sufficiently coarse to offer discernible increase in resistance to flow and to require additional energy for transport. From the evidence in Sleddale Beck it appears that, where the gradient is comparatively uniform, the tendency to meander increases with increase in total energy derived from the union of two tributaries. It should be remarked that none of the meanders in the tributaries or the main river can be regarded as perfectly formed. This is confirmed by the fact that, in the Esk between Castleton and Lealholm, the ratio of meander-belt width M_b to meander length M_l is just less than unity, whereas for a late-mature river the ratio is commonly about three.

2. Rates of Erosion

The remnants of terraces in Blea Hill Beck just above the confluence with May Beck and the large boulders and deserted meander loops in Rutmoor Beck just above the confluence with Blawath Beck point to a comparatively rapid retreat of the waterfalls over the Moor Grit and Grey Limestone Series. This indicates that, where a stream is split into two tributaries, the erosive power of the pair of streams in the vicinity of the confluence is greater than that of the united streams. The apparent effect is only local in these particular cases but it raises the important issue as to whether the erosive power of a number of small streams is greater or less over a given area than that of a single stream over the same area.

3. Uni-lateral Erosion

Uni-lateral erosion by a stream occurs where it flows along, or nearly along, the strike of rocks and the direction of lateral movement is towards the up-dip side of the valley. The phenomenon depends on the relative stability of rocks at the exposed faces on the up-dip and down-dip sides of the valley and the ratio of uni-lateral to vertical erosion is governed partly by the magnitude of the dip and the lithology of the strata. Uni-lateral erosion is exhibited in upper Sleddale and middle Baysdale.

4. The Baysdale-Sleddale Fluvial Complex

Evidence has been examined which points to the fact that, before beheading at Kildale, the Esk followed the course of lower and middle Baysdale Beck. At that time upper Sleddale Beck connected directly with middle Baysdale Beck and

Whiteley Beck/Commondale Beck was an independent stream following its present general course. Lounsdale Beck was probably a tributary of upper Sleddale Beck. Subsequently, the Leven captured Lounsdale and Sleddale Becks by headward erosion. During the Last Glaciation, the formation of an overflow channel from Glacial Lake Kildale led to the ultimate re-capture of Sleddale Beck by the Esk system through Commondale Beck.

5. The General Pre-Glacial Course of the Esk.

From Castleton to the Lealholm moraine the pre-Glacial course of theEsk was roughly beneath the present course but it was north of the present course at Crunkly Gill. From Lealholm to Glaisdale the early course was little different from the present. At Glaisdale it followed a course north of the two gorges and this northerly disposition persists almost as far as Sleights where the pre-Glacial Esk turned northwards to the sea. The channel north of Sleights was partly or wholly blocked by drift during the Early and Antepenultimate Glaciation and a new channel was excavated in the Great Interglacial Phase between Sleights and Ruswarp where it turned northwards to the sea. This course was probably followed also in the Last Inter-Glacial Phase but during the Last Glaciation it was blocked by drift and the present channel was excavated along the Whitby Fault.

6. Characteristics of the Tributary Dales

The slips at the heads of Glaisdale, Great and Little Fryup Dales, Danby Dale and Westerdale are due primarily to headward erosion and down-cutting of the streams. Headward erosion is accentuated by a large moor-top catchment, numerous channels for speedily concentrating the run-off at the dale head and steep gradients to yield high velocities.

The saddle and knoll between Great and Little Fryup Dales, in association with the equal widths of these dales, suggests the capture by Great Fryup Beck of the catchment of a major bifurcated tributary of Little Fryup Beck.

The sand and gravel-filled saddle to the east of The Howe at the lower end of Danby Dale represents the mouth of an early valley excavated by a stream flowing roughly parallel to the present Danby Beck. The ridge between the two valleys was eventually completely removed and the catchment of the stream was almost entirely transferred to Danby Beck.

The present headwaters of the Esk in Westerdale originally flowed northwards to join the main river in the present lower reaches of Baysdale Beck. The adjacent Tower Beck flowed through the gorge created by the trough fault at the mouth of Westerdale and just upstream was entrenched in the Lias so that a tributary flowing from the south-west was able to effect headward erosion rapidly by under-cutting the Dogger and in this way capture the Esk head-waters.

7. Twin Parallel Streams

The twin parallel streams of Cleveland are considered to have been initiated by water flowing in contact with an ice margin which retreated in stages laterally across depressions in the sub-glacial surface - commonly following drift filled pre-Glacial valleys - and that the water which established them was derived principally from glacial lakelets. These streams represent the last stages of drainage of the lakelets.

8. History of the Development of the Esk

By comparison with the longitudinal profile of the present Esk between Castleton and Lealholm it has been shown that the exponential curve of decay fits the equilibrium profile of a river, or part of a river, within tolerable limits. The history summarized below has been determined by reconstructing longitudinal profiles of the main river and tributaries, during various stages in the development of the system, based on the assumption that the equilibrium profiles had been attained in the portions of the streams under review. The stages in the development are as follows:

(a) Grading of the middle and lower Esk to sea-level at about O.D in early pre-Glacial time.

(b) Contemporary with (a), grading of the Esk between Castleton and Lealholm to the Dogger local control at Lealholm.

(c) Rejuvenation of the lower Esk up to Glaisdale by a reduction in sea-level to about -150 ft. b.O.D.

(d) The rejuvenation of (c) was probably accompanied by the middle/upper Esk breaking through the Dogger at Lealholm.

(e) Partial filling of the valleys with Boulder Clay during the Early and Antepenultimate Glaciation.

(f) During the Great Interglacial Phase, re-opening of pre-Glacial course from the headwaters to Sleights where Boulder Clay filling led to a diversion of the estuary into the inter-Glacial valley past Ruswarp, graded to a sea-level of about -150 ft. b-O.D. This course was followed also after the Penultimate Glaciation.

(g) More extensive filling of the valleys with Boulder Clay during the Last Glaciation.

(h) Re-opening of the Eskdale System with diversions due to moraines and Boulder Clay filling.

(i) Grading of the immediately post-Glacial Esk to sea-level at -65 to -95 ft. b.O.D.

(j) Rise in sea-level to the present position.

Several problems which are wholly or partly unsolved have been revealed in this thesis but the following three topics are suggested as suitable for independent studies:

1. A complete investigation of meandering in the Eskdale System, in which records of discharge, bed-material and bed-load are obtained.
2. A study of valley shape, with particular reference to the strength of the strata. Laboratory tests for strength of rocks would be required and the effects of rain-wash , deposition of debris in the valley bottom and other factors should be taken into account in the

final analysis of form.

3. Further studies of mathematical and actual equilibrium profiles, including the possible effects of regional tilt. Confirmation of the universal suitability of the exponential curve of decay and analytical techniques based on it would place a powerful tool in the hands of geomorphologists.

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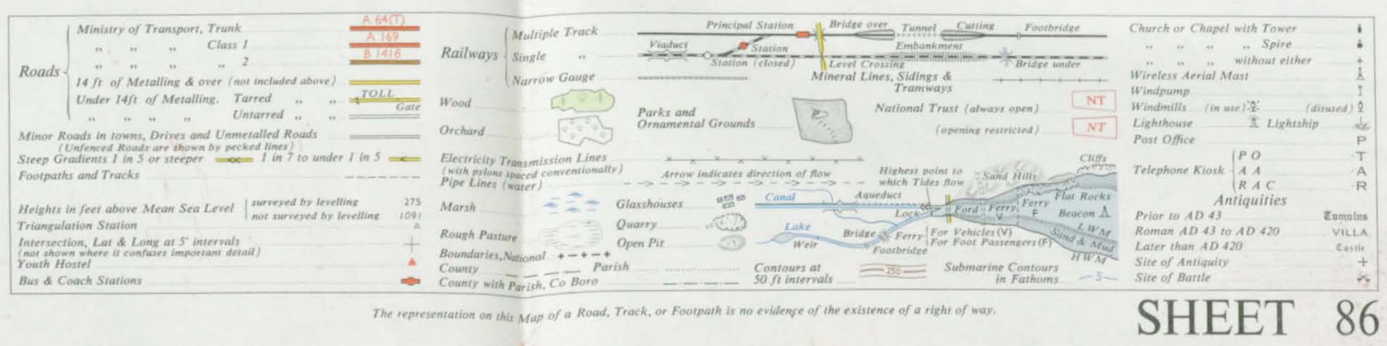

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