Frontispiece. Roslin Till overlying thick glacio-fluvium at Oatslie.

MAPS AND DIAGRAMS (Cont.)

Figure

Table 4.4. There are a number of reasons why such stone counts cannot be directly compared with those from till: of particular importance is the transporting process, which causes the comminution of softer lithologies in a way not necessarily true of ice-borne deposits. For example, the harder of the many different Carboniferous lithologies are much better preserved than the softer ones. Bearing this in mind, the high proportion of igneous volcanic rocks in Table 4.4. is not surprising, but the virtual absence of the tough Southern Upland greywackes becomes doubly significant. Of these same deposits, McCall and Goodlet report:

> "... abundant Carboniferous sediments, dolerites and basalts; very abundant Old Red Sediments and lavas of Pentland Hill types; and fairly common greywackes. Felsites are common and Highland rocks are fairly frequent." (1952, p.406).

This agrees with the evidence in Table 4.4 except in respect of greywackes.

Frozen-ground phenomena. The processes producing frozen-ground phenomena include frost-wedging, frost heaving and some kinds of mass-movement, notably solifluction. Contemporary frost heaving has been proved for Tinto Hill (2335 ft.) in Lanarkshire (Miller, Common and Galloway, 1954) and mild periglacial activity may be experienced in other parts of the Southern Uplands and just possibly in the Pentland Hills.

In lowland areas of Central Scotland these processes are generally considered absent under the contemporary climatic conditions, but have given rise to relict features dating from the glacial period.

Frost-wedges occur quite commonly in the glacio-fluvial deposits of the area. In all cases they are found at the top of bedded sands. The filling may be of Roslin Till, or some analogous upper till, or gravel. The earliest known reference to a frost-wedge is by Richardson (1874) and Henderson (1874a) in separate papers describing the same section. The

TABLE 4.4

STONE COUNTS FROM GLACIO-FLUVIUM - ESK BASIN

		Lithological suites (%)				
Location and site number	Total collection	Carb. ls. ss. and blaes	Ign. Volcanics	O.R.S.	Greywacke	Others
Melville Mains sand pit (91)	520	8	65	5	0	22
Clippens sand pit (92)	318	41	40	4	0	15
Cameron Wood esker (93)	152	39	40	4	1	16

description that may be compiled from the two papers is exactly that of a frost-wedge, although it is recognised by the authors only as a fissure. Basal till grades upward into gravel and sand. A wedge-shaped fissure 10 feet deep extends down from the top of the sand, and is filled with the same "unstratified clayey gravel" (upper till) that forms the top 4 feet of the section. The edges of the bedded sand and the stones in the fissure are described as all bending downwards at their junction, in the way characteristic of true frost-wedges.

Frost-wedges from the glacio-fluvium underlying Roslin Till were described by Anderson (1940). At Bilston sand pit, for example, he recorded a wedge 6 feet deep and 2½ feet wide at the top, filled with Roslin Till. It was largely the presence of these features that provoked the correspondence between Carruthers (1941; 1942) and Anderson (1941; 1942) previously referred to. Carruthers' assertion that wedges in sand can be formed and filled with till in one operation is most unconvincing. The presence of the ice-wedges and absence of any other contortion in the sands is ascribed by Anderson and later workers to severe freezing of ground left bare before ice readvanced over the sands.

Further examples of frost wedges in the sands underlying the Roslin Till have been described by Common and Galloway (1958) who note seven wedges from Oatslie, Langhill, Bilston, Wadingburn, and Melville Mains sand pits; and fresh examples were recorded by the writer from Clippens and Burghlee sand pits.

At Clippens, a frost-wedge was revealed in plan as well as section during removal of the Roslin Till overburden (fig. 4.23; photos. 15 and 16). The frost wedge as exposed had been destroyed at both ends but still measured 49 feet in length. The main wedge was aligned east-northeast to west-southwest; a branch wedge extended for 6 feet on the northwesterly side. The wedge tapered downward for 5 feet, the till filling extending down for 4 feet, with some disturbance of sand for another foot.

A narrower frost-wedge at Burghlee (fig. 4.24; photo. 17) is mostly filled with slumped sand and gravel, rather than with the overriding till. The till thickens by about 4 inches over the frost wedge, but otherwise does not extend downwards. Also in the sand at Burghlee has been exposed a much broader wedge, filled with till. The filling does not show any obvious vertical plunging of particles, nor does the bedding of the sand show the slumping usual in frost-wedges, but continues horizontally against the till (photo. 18). A set of nearly fifty faint and thin dark lines in the sand form pseudo-bedding at a steep angle parallel to the side of the wedge for a distance of three feet. The lines are streaks of coal dust, coarser nearer the till and becoming finer further away, and the set of lines is interpreted as a secondary feature due to water percolating through the sand from the wedge. The feature is regarded as a water-cut gully, later filled by the readvance till, and is typical of several such features noted in various sand-pit exposures.

Apart from these frost-wedge fissures in glacio-fluvial deposits, some curious vertical fissures were recorded by Tait (1939) from central Edinburgh in basal till. Although these fissures are filled with the overlying sand, Tait concludes that they are not frost-wddges but tear-fractures due to the passage of the ice.

Frost-wedges, or fossil ice-wedges, are of considerable palaeoclimatic significance. It has been agreed that they indicate the former presence of permafrost, and recent work indicates that wedges will form only where the mean air temperature is -6 to -8°C. or colder for many years (Charlesworth, 1957; Péwé, 1964). In these circumstances, they indicate that arctic conditions prevailed prior to the readvance glaciation.

Solifluction, implying frost heaving and downslope flowage, does not give rise to widespread deposits on low ground in the Lothians, even though it may be widespread in the Southern Uplands. Strictly, solifluction deposits may include till, alluvium, or glacio-fluvium that has been moved downslope subsequent to deposition; there is often great difficulty in recognising any secondary movement of any of these materials. Local solifluction deposits have been described recently by Tivy (1962) and by Ragg and Bibby (Geogr. Ann., in press), the latter using fabric analysis to good effect. Although the present study excludes regional solifluction deposits as such, some of the till fabric analyses give results best interpreted as the result of solifluction movements, as will be seen by the comparisen with test solifluction fabrics to be described later.

Vegetation remains. Of much greater palaeoclimatic significance than frost-wedges are plant remains of interglacial or interstadial age. These are uncommon in Scotland; it may be that the climatic ameliorations between glaciations were not sufficient to allow much plant colonisation. At the time of writing no site has been found where plant remains are overlain by a readvance till.

Nevertheless, in the Esk Basin, vegetation remains have been noted in a position which at first suggested most strongly that they were of at least interstadial age. The remains occur at four sites occupied by the

Roslin Till. Two of the occurrences were noted by the writer; and two were recorded in 1840 by Milne.

The best exposures showing vegetation remains occurred at NT 2668 6555 in a temporary trench (open May, 1963) at the south end of New Pentland adjacent to the A701 road. This section has been mentioned previously as indicating two tills, at one point in direct contact and at another point separated by bedded sand and silt (see figs. 4.7A and 4.7B). The vegetation remains occur within the sand and silt (fig. 4.25; photo 19), and appeared to have been washed into position. Pockets of matted small roots occur in the grey silt and extend up into the overlying yellow sand. More confined to the sand are numerous thick roots up to 2 inches in diameter. These are more commonly flat-lying or inclined than vertical. At two further points along this section, there are more roots in the sand, up to 1 inch in diameter. These terminate at the top of the sand and are vertical and sub-divide as though in their original position.

There is little possibility that the uppermost 3½-feet thick layer is something other than Roslin Till. The site is an almost flat field with no higher ground immediately adjacent, so slumping onto the site can be ruled out. The material appears to be identical with that in other exposures of Roslin Till; and fabric analysis (till fabric analysis 41) gives a result comparable with other analyses in the neighbourhood.

The second site (NT 273 671) was also temporary (open August, 1962), being part of an excavation for an extension to the electricity transformer station at Burdiehouse. Although the section showed the usual succession of Roslin Till overlying bedded sand with a sharp break between them, the till is poorly represented, being partly washed and with extensive sand lenses (fig. 4.26). The vegetation remains in the sand are not exclusively of a pre-Roslin Till age. Some root remains in a vertical position may have grown down from the present surface; one root in particular has obviously done this as it passes from till down into sand, in doing so deviating around a boulder in the till. But also found were some broken pieces of tree and some moss or lichen-covered pebbles within the Roslin Till. These appeared to have been caught up by the readvance glacier and held with the basal load.

It is significant that the only other known evidence of vegetation remains within the local glacial deposits relates to exactly the same area as the two sections already described. This evidence is of an extremely early date (Milne, 1840) and the descriptions are unsatisfactory, although typical of the period. If there were no contemporary evidence, Milne's descriptions would have little weight in themselves.

Milne's first site is described as being on the west bank of Bilston Burn, about a half mile <u>north</u> of Pentland village, and at about 520 ft. above the sea. No location fulfills these conditions, but the 500-foot contour follows the bank of Bilston Burn a half mile <u>south</u> of New Pentland, and this is taken to be the site referred to (NT 266 648). There is now no section exposed at this location but the general drift succession in this vicinity is known to be a few feet of Roslin Till overlying a variable thickness of glacio-fluvial sand. This was seen in a temporary trench at NT 265 649 adjacent to the A701 road. The section drawn by Milne is reproduced at fig. 4.27. His description of the section is as follows:

> "In the lowest deposit are numerous roots of trees, which shoot down from the peat, but which do not rise to the surface of the peat. It is obvious that the trees have grown in the clay, - if not before the peaty stratum was formed, at all events before the bed of sand and the layer of gravel were deposited." (Milne, 1840, p.326).

The Roslin Till was not recognised by Milne, and certainly cannot be reconciled with layer 5, 'boulder-clay; at least 8 to 10 feet thick'. The most obvious explanation is that layer 5 is the basal till of the area, succeeded by an attenuated thickness of outwash sand (layer 3), and that layer 2 is Roslin Till, the stated thickness being appropriate for Roslin Till. If this is the case, the vegetation remains are earlier than both Roslin Till and outwash sand.

The second site described by Milne cannot be located precisely, and the description of the section is so brief that it may be conveniently quoted in full; it is too short to allow any conclusions.

> "About a quarter of a mile above Straiton Mill, roots of large trees, apparently hazel, are also to be seen in the boulder-clay, - covered by a deposit of yellow gravel about 3 feet thick. This spot is 470 feet above the sea." (Milne, 1840, p.326).

Considering these four sites together, there seems to be fairly substantial evidence for genuine vegetation remains of a date earlier than the Roslin Till. The vegetation remains are not very substantial in amount and for the most part are not in their original position. Milne's peat layer at Bilston Burn would be conclusive if it were a recent report, but little weight can be given to much of Milne's writings. However the fact that the Bilston-Straiton area is the only one where such vegetation remains have previously been reported at all must be considered of some significance. At New Pentland the thinness of the glacio-fluvial sand and silt containing the root remains contrasts with the very thick glacio-fluvium all about, as at Old Pentland, Pentland Mains, and Bilston.

In order to explain the vegetation remains as genuine insterstadial plant growth, the following conditions would have to be necessary. The drift at New Pentland conceals the south-westerly extension of the Gilmerton Ridge. The top of this ridge raised by a covering of thick basal till (12 feet proved) would then have had to have been at an altitude marginal to the basins of glacio-fluvial deposition all around. A marginal situation would explain the thin-bedded silt deposit. Root remains would then have had to have been washed into the quiet silty margins. The site at Burdiehouse overlies similar fine sand and clay layers but, by their appearance, the older vegetation remains here would have had to have been caught up from their position of growth by the over-riding ice.

The above speculation was ended and a conclusion reached when a sample of the vegetation remains from New Pentland was taken for dating by radio-carbon methods. The date given for the vegetation remains, a collection of the larger root fragments and the matted small roots, is:

4010 ± 105 years B.P. (Isotopes Inc., 1965, ref. I - 1837).

This date makes the vegetation remains of Zone VIIb age, or Sub-Boreal (Alder-oak forest), corresponding to part of the Neolithic period.

To represent a true interstadial vegetation growth, the date would have to be at least 10,000-12,000 years B.P., as indicated by other evidence in Scotland. Although only a single radio-carbon dating was made, there is no reason for not accepting it at face value. It must therefore be concluded that, in spite of their present appearance in the section, the vegetation roots must have grown down into the sand from the surface of the Roslin Till. This conclusion in turn means that there were substantial roots in the Roslin Till, all sign of which has disappeared with time; and furthermore, that the till fabric in the Roslin Till (fabric 41), which gives a result not ideal but quite acceptable, must be the modified pattern resulting from root action.

Pollen analysis carried out by W. W. Newey from the centre of the grey silt layer at New Pentland (fig. 4.25) failed to reveal any recognisable pollen grains. This supports the radio-carbon date in suggesting that the roots grew into position. Had the vegetaion remains been washed into the sand, pollen grains would have been found there in association with the roots.

There are two further sites, both in the south-west district of Edinburgh, where vegetation remains beneath till were described in the nineteenth century (see Peach et al., 1910, p.329 and Appendix, Part 1C). At Hailes Quarry, a layer of peat 1-18 inches in thickness was recorded by J. Geikie in 1878, overlain by sandy clay and thick till. Some of the plant remains were confirmed as of late glacial age, but the over-lying material from its description is not conclusively that of a glacial re-advance. Hailes Quarry is now disused, flooded and inaccessible. At Redhall Quarry near Hailes Quarry, a layer of peat between boulder clay was described by Henderson (1874b) but this description is faulty, the vegetation being later pronounced of post-glacial age.

LIST OF PHOTOGRAPHS

Photo.

CHAPTER V

TILL FABRIC ANALYSIS: THEORY

> "It would probably be vain to take any
> one structure in till and expect it
> to be universally characteristic."
> Mr. Hugh Miller on Boulder-Glaciation,
> 1884.

Uses of the method. The principal research method used on the glacial drifts described in the preceding chapter is that of analysing the three-dimensional fabric of the sediments in situ. This rather specialized field method has the blanket title of fabric analysis. It is quite recently that fabric analysis has become a standard field method in description of glacial drifts; and the mechanics of the method are still subject to revision. There is certainly need of exact methods, as discrepancies and inaccuracies in results can be traced to differences in field technique. The fabric analysis technique and subsequent treatment of data used in this work vary somewhat from those described elsewhere and so are presented here in considerable detail, together with a synopsis of comparative results achieved by other workers.

Any investigation of the three-dimensional structure of a glacial sediment will provide some clues to the process of deposition of the sediment - its genesis. This is most evident in the case of distinctly bedded glacio-fluvium where the dip of the bedding indicates the direction in which the depositing agent - the water - was flowing. In any drift deposit, the thickness of beds and internal structures within any one bed will also give clues as to the genesis, as the previous chapter illustrated. Where there is no bedding or small scale structure, attention is transferred to the attitude of individual particles. A plot of an assemblage of carefully chosen particles will produce a fabric pattern characteristic of that deposit.

Fabric analysis is most commonly applied by geomorphologists to till, but will produce order from apparent chaos in both glacial and extra-glacial deposits. Till is the name given to one end number of a continuous sequence of glacial deposits, varying in the amount of water-washing, and fabric patterns can be found in all members of the succession. The fabric pattern of a water-sorted glacio-fluvial deposit is produced by a different agency than that responsible for the fabric pattern of a till, and each pattern may be characteristic of the process responsible. It has already been shown that textural graduation between till and bedded deposits does occur in the field. A corresponding change in fabric pattern may be anticipated.

A fundamental use of fabric analysis is therefore in explaining the processes of glacial and glacio-fluvial deposition. It is surprising that this use of fabric analysis is as yet undeveloped, for it is unlikely that anyone will ever see at first hand the operation by which a glacier of continental proportion deposits its washed and unwashed products beneath itself; examinations of the structure of the deposits must be the next best thing. In spite of the attractions of this method, results of fabric analysis concerned with the genesis of deposition have been poor, because the field and laboratory techniques employed have been excessively crude. The work of Seifert (1954) and Sitler and Chapman (1955) on microfabrics and G. S. Boulton (pers. comm., 1964) on the fabric of clay minerals within till point to the care that is necessary. Harrison's work (1957b) on a clay till is also among the most detailed; it combines macro- and micro-fabric analyses with laboratory and englacial fabric studies in attempting to explain the origin of the till.

The great majority of published studies including fabric analysis have been concerned not with genesis but with a second use of the method, whereby the pattern of the plotted particle assemblage is an indication of the direction of movement of ice or water responsible for the deposit. In other words, the fabric analyses have been used in regional studies of glaciation in order to indicate the direction of movement of former glaciers and ice-sheets. Experience has shown that this is a reliable field-method, and that quite rapid field technique will produce an answer sufficiently accurate for the purpose. There may be little practical connection, therefore, between the method of using till fabric to determine the processes of deposition, and the methods empirically determined for using fabric patterns to interpret directions of former ice and water movement. Little assumption on genesis need be involved in the second use.

The fabric analysis work described in this text is broadly designed to fulfil the second use, in providing information on regional movements. However, thd measurements were aimed to be accurate enough to allow some comment on the relation of the fabric pattern to the type of deposit, and hence indirectly on its formative process.

Characteristic fabric patterns. The great majority of fabric analyses in glacial geomorphology have been derived from tills. There is overlap in experimentation here with solid geology, from till through tillites to sedimentary structures, and also through the washed glacial sediments to fluvial structures. As has been described in the preceding section, the fabrics of glacio-fluvial sediments do show meaningful patterns but, in the presence of bedding, there is normally less need to be concerned with such fabrics. The following remarks refer essentially to till, and have only limited reference to glacio-fluvium.

As is now well known, the disarranged and chaotic arrangement of particles within till is more apparent than real. Although it is seldom to be seen from casual observations, particles will normally show a consistent arrangement, the arrangement depending among other things on the shape of the particles selected to produce the pattern and the mechanics of deposition of the till. The arrangement was called a fluxion-structure by Miller (1884) who described many forms of it.

For the purpose of determining the attitude of a particle, measurements are usually taken of the geographical orientation of its long axis, the a-axis, and often of some other parameter as well. The particles must first of all be of a shape to have a long axis; the simple-sounding operation of deciding which is the line corresponding to the long axis of any particle can in practice produce variation in choice as, for example, in a jagged oval-shaped particle. The three possibilities of elongation direction have been listed by Dapples and Rominger (1945) and, in spite of the infinite variety of shape of elongate particles, it is possible with some practice to choose the long-axis unambiguously, following one or other of their criteria.

The shapes of elongate particles have been further classified by many workers, usually in the stages showing that different shaped elongate particles have different characteristic attitudes. An early non-vigorous classification was that of Zingg (1935), the classification used by the writer in some earlier work (Kirby, 1960). This divides elongate particles into discs, blades and rods, according to the ratio of the length of their a-, b-, and c-axis, and is perhaps the easiest classification to apply, where only a simple sub-division is required. A more elaborate classification of shapes into six types was used by Holmes (1941) in the first modern major research on till fabric. Holmes showed conclusively that "stones of certain forms and degrees of roundness have a greater-than-average statistical chance for deposition either parallel or transverse to direction of transport".

The particular shape of elongate particles is a complicating factor in analysing the fabric of a till. For example, rod-shaped particles will often have a long-axis orientation at right angles to that shown by the less extremely elongated blades and discs, so that the resulting fabric plot might show two contrasting orientations. Therefore the interpretation of the fabric results involves understanding the significance of the part played by the shapes of the particles measured.

The most common element in till fabric patterns is an alignment of particles to give an overall preferred orientation. The preferred orientation is almost always parallel to the direction of former ice movement, and is relied on in a glacial deposit to give the directions of movement in the same way that a suite of striations will record direction of movement over bedrock.

The particles will not all have an identical orientation. In the words of the junior Hugh Miller: "many stones have veered to this side or that ..... but these variations often cancel one another out in favour of the mid-line along which the best index-boulders lay their axes" (Miller, 1884, p.185). See also fig. 5.1; fig. 5.2.

This is the principal till fabric characteristic, found by all workers concerned with the meaning of till fabrics, for example: Richter (1932); Krumbein (1939) Holmes (1941); Glen, Donner and West (1957); Harrison (1957b), and Rusnak (1957a). In each case, the direction of ice movement was proved by other laboratory or field evidence, and the preferred orientations found to agree with this. It must not be assumed that the orientations at different sites within one deposit will be entirely consistent in direction. As with striations, there is only a general accordance within 15-20°, even on quite open ground.

From careful field observation, it was recorded by Bell (1895) that in till ... "the sharper or lighter end of the boulder points in the direction towards which it was being moved, and the broader or heavier end in that from which it had come". This tendency for boulders to lie with their larger end up-current has also been noticed and recorded as the 'tear-drop' effect in fluvial deposits (Dapples and Rominger, 1945). If the tendency is normal to all tills, then this and the main characteristics above would together serve to determine source direction uniquely. However the evidence here is equivocal. Nowhere has the writer recognised this effect in the field. And, on the contrary, Miller (1884, p.167), records that "the pointed end is frequently, but by no means always, towards the ice".

An alternative preferred orientation in a till fabric is one transverse to the flow direction. This never exists as a single peak, but only together with the longitudinal orientation, which it may however exceed in magnitude. In the writer's experience this transverse orientation can often be immediately related to the shape of the particles, a particularly elongated shape being well adapted to rolling around its a-axis, as has been mentioned. Holmes' detailed study (1941) also suggested that the particles' inherent shape should determine whether they adopt longitudinal or transverse attitudes, with very elongate particles adopting a transverse attitude. Contradicting these views, work by Virkkala (1951) in East Finland showed that the more elongated the axis, the more clearly is the particle orientated in the direction of glacial flow. But Virkkala's conclusion may be biased from working with Finnish metamorphic lithologies, where extremely elongated particles are uncommon.

Experiment by Glen, Donner and West (1957) indicated that particles in a flowing liquid for a protracted period will build up a transverse peak irrespective of their shape, this following after the normal parallel orientation resulting from a short period of flow. The existence and strength of a transverse peak may thus be related to the time the particular process of deposition is operative. Since this work was done with particles in a flowing liquid, it may not be true of ice deposits. However, as support to their thesis, Glen, Donner and West pointed to the transverse orientations found in narrow bands of till. In anticipation of the full till fabric results, it may be stated here that none of the four analyses in thin band tills in this study showed exceptional transverse peaks.

At least one other worker in modern times does not find transverse orientation at all. In spite of the extreme detail of the work carried out by Harrison (1957b) on a clay till, he does not mention and obviously does not find a transverse orientation; but describes instead a horizontal girdle of axial plots with a single clear maximum parallel to former ice movement. It will be seen in describing the results of the writer in a later section that a horizontal girdle is often present, but a transverse peak shows through this. Harrison's results are consistent with the theory he proposes for the formation of till deposits whereby the till fabric is inherited from the englacial fabric, but are not consistent with other studies.

The orientation of the a-axis is the most meaningful particle parameter to use in regional studies of glacial drift. A second useful parameter is the inclination or dip of this a-axis to the horizontal. In the case of fluvial deposits, it is clearly recognised that particles tend to dip upstream into the current, the attitude of least resistance to water movement. Examples of this can usually be seen in the stony beds of rivers at low water, and is mentioned as commonplace and correctly accounted for as early as 1859 by Fleming. The phenomenon has also been investigated in many field and laboratory studies, of which those of Rusnak (1957a) and Schlee (1957) are representative.

It has been assumed that inclination of particles up-current is a property true also of tills, and if this is so, then the dip direction of a majority of particles aligned parallel to the direction of former ice movement should provide a second means of locating source-direction, the first being the "tear-drop" effect mentioned earlier.

Little attention has been paid to accurate field measurement of dip of till particles in ground moraine. The limited field evidence for this, which is summarised by Wright (1957, p.57), suggests there is no strong preference for plunge either in the inferred up-glacier or down-glacier direction. The strongest support for the assumed dip up-glacier is by Dreimanis and Reavely (1953) who found that "the long axes of most stones dip slightly against the ice flow", but have no numerical observations to support this. The direction of dip has been found by West to be very varied (pers. comm. 1962), while Hoppe, who has done much pioneering work with till fabric techniques in Scandinavia, agrees that the dip is often misleading in regional analyses (pers. comm., 1963). The results of several thousand measurements of dip by the present writer are discussed in the next chapter. The conclusion will be seen to agree with the majority opinion above, and with earlier work by the same writer (Kirby, 1960).

In the light of these comments it is seen that the measurement of simple parameters will produce an indication of trend of former ice movement, for example, either west-east or east-west. This it will do very adequately. The unique direction of movement can not be inferred with the same facility, and in practice it may be necessary to rely on other internal features of the till or quite separate field evidence to resolve this.

Till fabric analyses have occasionally been employed on till forms other than featureless ground moraine. For example, fabric analyses of orientation and dip have been used to investigate hummocky till (Hoppe, 1952), drumlins (Wright, 1957), and cross-valley moraines (Andrews, 1963).

In each case the results are strikingly individualistic and considerably help to explain the genesis of the features being examined. However, in the case of the drumlins and cross-valley moraines, the features were already recognisable as such from their siting and appearance; only in the case of the hummocky till did the fabric analyses serve to suggest the original identity of the hummocky till, as ice-pressed forms.

Difficulties in interpreting till fabric results. The "strikingly individualistic" till fabric results mentioned above show how possible it is to have patterns of very varied appearance. Where there is a relationship between an unusual fabric and a particular type of till landform, as in these cases, then the result is welcome and no problem arises. But quite often, a till fabric derived from seemingly featureless ground moraine, will show an anomalous pattern where a regular fabric pattern would be thought most probable. Both West (pers. comm., 1962) and Hoppe (pers. comm., 1963) admit to finding inconsistent patterns, particularly isotropic distributions, (showing a random orientation), and to ignoring them in regional studies. The writer also has produced a small number of isotropic fabrics.

In certain cases an isotropic or anomalous orientation fabric can be traced to the selection of particles. It has long been known that the attitudes of particles are influenced by neighbouring stones (Miller, 1884). The particles most likely to have the regional preferred orientation are the 'dominant' or larger particles; the matrix between them will frequently show a streamlined flow pattern around the larger particles (see fig. 5.3). The flow pattern, which is essentially similar to that in such lavas as trachyte, is best seen in thin section, as illustrated for example by

LIST OF PHOTOGRAPHS (Cont.)

Sitler and Chapman (1955) and by Ostry and Deane (1963). Only where the matrix is free from dominants will the finer particles in it register the true regional direction.

An example of this is thought to be provided by till fabric analysis 30 from Swineburn. In this case most of the dominant particles are cobbles and boulders too rounded to be used, and too close together for the matrix not to be affected. In this material it is not possible by the methods used to obtain a preferred orientation. The same disturbance of the matrix by the longer particles has been shown in the case of fluvial deposits by Schlee (1957).

Ruling out unhelpful particle shapes, personal errors of selection and the effect of secondary movement of the deposit, other anomalous results must be significant in terms of the mode of till deposition, but such significance is not understood. Variations from strongly orientated to randomly orientated particles within a seemingly homogeneous ground moraine deposit have to be explained in terms of a general theory of till deposition but this is not yet available. The long-established majority opinion regarding deposition of till favours lodgment or "plastering-on". The process of deposition of till by lodgment has never been proved satisfactorily but the argument is supported by the occurrence of paired deposits, the lower called lodgment and the upper ablation till. These are far rarer, in the writer's experience, than normally suggested, for example, by Flint (1957, p.120). If known examples of this associated pair proved on re-examination to be something else, this would lend strength to the second hypothesis that till is deposited by slow melting out from the debris-charged basal zones of stagnant glacier ice and that the fabric is inherited from that fabric developed in the transportational environment. This conclusion is based in the work of Harrison (1957b) on a comparison of englacial and ground moraine fabrics, and based in the work of Carey and Ahmad (1961) on more theoretical considerations.

Research at the moment is not sufficiently advanced to allow all-embracing conclusions on the genesis of till. Until the mechanisms of depositions are understood, isotropic patterns will continue to be a puzzle in areas of ground moraine lacking distinct surface morphology.

One clue has been provided by till fabric analyses from ground moraine in an area shown by other evidence to be near a continental ice divide (Kirby, 1961a). Two analyses here show no preferred orientation, and it has been argued that this may be indicative of deposition under semi-stationary conditions at the point where ice begins to flow outwards in opposite directions. But this specialised case will not explain the great majority of isotropic patterns.

On a wider scale, the effect of topography in influencing direction of ice movement is well documented. The general direction of ice movement of a thick ice sheet is outward from the ice divide, which does not necessarily correspond with the topographic divide (Flint, 1957; Ives, 1959; Hoppe, 1959). Local relief of a few hundred feet does have some modifying effect on flow direction, as shown by the differential flow of the Greenland ice sheet, but always subject to the overall control of the ice divide. Thinner ice, as at the beginning and end of a glacial period, is much more likely to be controlled by local relief. If glacierization started by amalgamation of cirque-glaciers, then during the development of the ice sheet, the movement of the coalescing glaciers would be controlled by the local valleys and hills. During the maximum glaciation, the movement is controlled more by the regional ice centre. During glaciation, if there were active glacierization to a fairly late stage, the movement of the residual lobes would again be controlled by local relief.

Two directions of ice movement, relating to the maximum and waning periods of glaciation, have been demonstrated in central and northern Scandinavia (Strøm, 1956; Hoppe, 1959) and in central Labrador-Ungava (Kirby, 1961a).

In consequence of this, in certain localities a single thick till may show different directions of particle orientation, reflecting the control exerted at different times by the ice divide and by the local topography. In theory, the till could show different orientations at its base, middle and top, assuming a lodgment mechanism of till emplacement. This variation in orientation of particles is analogous to the variation in striation patterns that can be produced by the oscillation of an ice-front (Chamberlin, 1888).

In east-central Scotland, with a similar climatic regime but less local relief than central Scandinavia, some control of the direction of ice movement by local relief might be expected; and in this way, there could be achieved considerable variation in orientation within a single thick bed of till.

There are a number of entirely localised factors that modify till fabrics and so present further difficulties to the interpretation of fabric patterns. The first of these is the effect of local topography and local slope. The fabric of a till deposited on a slope will be affected by the slope. If the ice movement affecting the till were normal to the contour of the ground, then only the dip of the particles would be influenced by reflecting the underlying bedrock surface. If the ice movement were oblique to the slope, then it is possible for the a-axis orientation to be influenced as well as the dip, possibly producing the vector resultant of the directions of ice movement and maximum slope. Thus, an analysis seeking a true regional movement should be sited on level ground, away from hill slopes.

A quite different factor that might have influenced the till fabric is that of secondary movement of the deposit. The effect of frost heaving in producing an isotropic pattern is discussed briefly by Kirby (1961a). It is found near the surface in areas with many annual freeze-thaw cycles, but can be avoided by working below the active level. The effect of soil development, roots and burrowing fauna can be avoided in the same way. More insidious in the case of a slope site is the effect of soil creep or its frozen-ground equivalent, solifluction. A down-slope flow of till will be indicated by a rearrangement of the particles so that their a-axes are orientated parallel to the flow (Lundquist, 1949; Hoppe, 1952; Harrison, 1957b). A strong orientation downslope should therefore be regarded very critically. Where this downslope orientation is likely to be the regional direction also, the dip of the particles may be diagnostic in separating them. As has been noted above, however, the dip of the a-axis in undisturbed till is not reliable; but in certain solifluction deposits, the a-axes are imbricated towards the source of movement (Hoppe, 1952; Harrison, 1957b). Further evidence to help in separating the fabrics of till and soliflucted till is given in the next chapter, where the fabrics of true solifluction deposits (head) are described and compared with till solifluction fabrics.

Historic till fabric discoveries in the Edinburgh area. The earliest work on the glacial fabrics mentioned above is of Richter in 1932, but in fact, Richter's conclusions represent a rediscovery of relationships noticed long before. The original observations were by some of the pioneers of glacial geomorphology in the second half of the nineteenth century. Holmes (1941) gave a historical statement that partly recognised this fact. As the early work was in the Edinburgh area, the observations are of some of the deposits described in the preceding chapter and so are directly relevant to the present study.

The discoveries into till structure and till fabrics came by stages. Milne (1840) described the boulder-pavements visible at that time along the coast at Joppa and Seafield, the flat upper surfaces of the boulders being striated consistently in the direction "west-half-south". Smith (1846) then related as equivalent boulder-striations and striations on bedrock, and Miller (1850) noted that on pebbles and boulders in till, "lines of scratching occur, in at least four cases out of every five in the lines of their longer axis". The then-obvious relationships between ice movement direction and long axis orientation came in 1860 for glaciofluvial deposits (Jamieson, 1860; interpreted as marine) and in 1884 for till (Miller, 1884). Figure 5.4, taken from Miller (1884) shows the agreement between rock striations and boulder striations in the neighbourhood of Edinburgh, as recorded to that date. The paper by Miller shows acute observation and accurate description of the physical structure and genesis of till, and remains a primary reference on till structure.

Finally Bell (1895) suggested that the long axis direction of fragments was imparted by the direction of the ice while the fragments were within the glacier, the basis of the modern "englacial" hypothesis for till deposition.

Contemporary work into till fabric analysis has produced theories that are a development on these original observations, as has already been seen in this chapter. Little of this recent work has been done in Britain, and none in Scotland since Bell's work before the turn of the century.

Field and Laboratory procedures of fabric analysis. The field techniques used in till fabric analysis vary according to whether the problem is to help explain the processes of glacial deposition or to indicate direction of former ice movement. Work on fabric genesis requires detailed field and laboratory procedure, as for example, Sitler and Chapman (1955) and Harrison (1957b). Work on regional studies of glaciation need not be so painstaking. Dreimanis (1959a) stressed that, in regional studies, rapid two-dimensional field measurements are preferable to more accurate but more time-consuming three-dimensional studies. Certainly it is better to have a larger number of approximate fabric analyses than a few extremely accurate ones because, as local deviations of glacial movements are common, many wellspread locations will show the regional trends more clearly. Harrison (1957b) has shown that considerable variability exists both horizontally and vertically within one ground moraine at a single large exposure. But the difference for each particle between recording one parameter (two-dimensions) as Dreimanis suggested and two (three-dimensions) is a matter of seconds only, and it is well worth while to record two parameters in terms of the extra information gained. In any case much more time is likely to be spent in finding and preparing the particle than in actual measurement. In weathered tills in particular considerable care is necessary in preparing the particles to get a true result at all; the time spent in measurement is negligible by comparison.

Most of the till exposures used for fabric analysis in this study are either river bank sections or the edge of man-made sand pits. When the face is fresh and not slumped, till particles often seem to show pronounced orientation; this is almost always false, and due to the protrusion or partial exposure of a few stones. A careful fabric analysis will frequently give an orientation quite unsuspected from a rapid examination of the face. This seems to stress the importance of a standardized procedure with as little scope as possible for subjective judgments.

In early work particles were measured in a vertical face of known orientation. The protruding edge or end of any particle was marked with a cross, the cross being in the place of the vertical face. Then the particle was extracted and the a-axis recorded with respect to the cross. This method was first described by Wadell (1936), was modified by Krumbein, (1939) and Karlstrom (1952), and is being currently (1964) employed by P. Beaumont (pers. comm.) on the grounds of its absolute objectivity.

It is much easier and hardly less objective to work on a horizontal surface, cut as a shelf into the side of the till face. This is done by most workers, including the present writer. A surface of about one foot square is prepared and particles exposed by gentle brushing or scraping. In this way their top surfaces will be exposed without disturbing their attitudes and they may be measured in situ (photo. 20).

Only suitably-shaped particles need be measured, unlike the method on a vertical face where initially all projecting particles are marked, their shape being hidden. On the horizontal surface, as suitable particles are exposed, measured and removed, the surface is lowered, the total reduction necessary to produce one hundred particles seldom exceeding one foot. Wright (1962) removed the particles immediately and used toothpicks to mark the casts; measurements were then made against these.

In this study, the parameters measured were the usual ones, the azimuth and the dip of the long axis, the a-axis. The elongation direction of the long axis is taken as the diredtion of the two parallel lines touching the particle with least separation (Dapples and Rominger, 1945), but where there was possible confusion, as in the case of a broad diamond-shaped particle, the particle was rejected. The dip of the long axis is taken as the mean of the dips of the upper surface long axis, and the lower surface long axis (fig. 5.5). The dip of the undersurface is usually best recorded by removing the particle and measuring the dip of its cast. With tabular particles,

$$\begin{aligned} d_1 &= d_2, \\ m &= d_1, \end{aligned}$$

and so only one measurement is necessary. In sixteen of the early particle analyses, the dip of the upper surface and the dip of the lower surface were drawn on separate diagrams, but the plots show only slight differences. As the overall dip pattern is not affected, this practice was discontinued.

Measurements of azimuth and dip were read by a Suunto or by a Silva Type 2 compass-clinometer, each to 5°. Repeated measurements on the same particles were made to check accuracy, and gave a range of values 3-4° for azimuth and 4-6° for dip. This indicates the general standard of particle measurement but does not exclude the possibility of gross error in any one measurement.

The part of the operation requiring most discrimination is the selection of suitable particles. The shape of particles chosen followed the Zingg classification (1935), all those recorded being discs, blades or rods. The size of particles measured varied according to the deposit. At a typical site (till fabric analysis 32), particles with the following characteristics were used:

Maximum length		81 mm.
Minimum length		8 mm.
Median length		29 mm.
Average length		24.6 mm.
Standard deviation		13.8 mm.
Particle shapes:	discs	11
	blades	39
	rods	48
	others	2

The particle sizes used at selected till fabric sites are shown in fig. 5.6. From this figure can be seen the considerable range of particle lengths. It will be noted, however, that the median length tends to be between 20 and 30 mm. Occasionally at other sites particles as short as 5 mm. and as long as 250 mm. were used. Contiguous dominant particles were rejected, and the matrix near dominant particles was avoided. It was found difficult to decide on the azimuth of particles dipping steeply and for this reason particles dipping in excess of 60° were rejected.

All fabric patterns therefore have an error due to the exclusion of the very small number of near-vertical particles. This does not appreciably alter the result.

All but eight of the fabric analyses were completed in situ. In the case of the remainder, a block of till was cut out, a suitable orientation and dip having first been measured on the top surface (photo. 21). The block was then set up in the laboratory with the same orientation and dip, and the material worked as usual. The laboratory method is slower than that on the site and not noticeably more refined; it was made necessary in the few cases by weather conditions or a very distant site. Till fabrics 2 and 24 (Chapter VI) are from the same location, the first being done in the field, the second in the laboratory. Inspection of the plots will show they are very similar as regards both directions and strength of orientations.

In all cases, 100 particles were measured. In one exceptional case, 150 particles were measured. One hundred is usually sufficient to show a weak or random preferred orientation, and is the minimum number suitable for applying a statistical test. Pincus (1951) supports this number of samples, from similar work. It is a limitation in the till fabric analyses of Norris (1962) that the 50 measurements he makes are insufficient to provide clear results when dealing with weak orientation fabrics. On the other hand 50 measurements are sufficient if the orientation is marked. The complete measurement of one hundred particles required 3½-4½ hours, not including the time spent in preparing the working face.

Treatment of data. The particle measurements were recorded on a prepared form (Appendix B) and subsequently plotted from this on to a polar equal

LIST OF AERIAL PHOTOGRAPHS

area net. No attempt was made to plot the results as they were obtained, as any definite pattern emerging at this stage can consciously or unconsciously influence the search for the remaining particles. In this respect the till-fabric rack described by MacClintock (1959) reduces objectivity in that the emerging fabric pattern is seen, this being the main among several disadvantages of such a rack.

On the polar equal-area net, the circumferential scale represents azimuth and the radial scale dip. Horizontal particles, with two possible positions on opposite edges of the net, are plotted on the side of the projection in numbers proportional to the dip position of the non-horizontal particles; this does not upset the balance of any general dip-direction arrangement. At this stage, orientation direction is adjusted from magnetic north as recorded by the compass to geographical north.

The resulting scatter diagram of axial-plots gives a good visual impression of the fabric characteristics. The details can be even more clearly seen if the diagram is then contoured in the manner customary in studies of structural petrology (Phillips, 1954, Chapter VII) but the additional time required for this seldom makes it profitable. The simpler star-diagram also gives a good visual impression of orientation but it cannot represent the dip dimension. It is used perforce in till fabric analysis 4 (Chapter VI) where the dip measurement was not recorded.

The scatter diagram or star diagram often provides adequate representation of the fabric. However, a number of the fabric scatter-diagrams display isotropic or a very weak linear distribution of the axial-plot points, and are not easily interpreted. To give more confidence when handling these and for comparing results from different areas or different types of deposit, it is convenient to go a stage further by analysing the raw data numerically. Curray (1956) suggests that the fabric is most meaningful if it is summarised by statistics representing: a preferred orientation direction, the degree of preferred orientation, and the probability that preferred orientation is real and not merely due to chance. A scheme that meets these requirements is the chi-square test as adapted for a circular distribution by Tukey and described in this context by Harrison (1957a) and Rusnak (1957b). Recent work incorporating this chi-square test has been published by Kirby (1961a) and Andrews (1963).

The chi-square test is non-parametric and, as used for azimuth distribution, decides whether or not there is significant departure from a random distribution at a chosen level of significance. If there is significant departure, the preferred orientation direction can be derived. The 99th percentile was chosen as the level of significance; this means that the results will show with ninety-nine per cent probability whether or not the distribution is isotropic. The value for χ^2 at the 99th percentile for two degrees of freedom is read from appropriate tables as 9.21; values of χ^2 less than 9.21 indicate greater probability of random orientation and values greater than this, preferred orientation. The strength of orientation increases as χ^2 increases. Appendix B gives a worked example of this, and further details, including a correction factor for class intervals that provides a more accurate answer than that of Harrison. The full results of the chi-square tests, are given in Tables 6.1 and 6.2 in the next chapter, where the results of the till fabric analyses are presented and discussed in the context of the drift succession.

A summary of the more critical statistical tests that have been proposed to deal with general orientation problems in sedimentary petrology is given by Miller and Kahn (1962). The chi-square test has been used here because it is relatively easy to compute manually and appears to give satisfactory results. However there is some objection to it on purely theoretical grounds; it has been correctly criticised by Flinn (1958 and 1963) because the sample is compared by class intervals with a uniform rather than with a random distribution; testing against a random distribution is more correct but in practice makes little difference.

A distinct limitation of chi-square in this context is that it is two-dimensional, like other accepted statistical tests on this type of data. Since the present study was begun, a simple computation for a three-dimensional vector analysis has been outlined by Steinmetz (1962). This is more attractive for summarising and comparing results as it considers strength and direction of dip as well as of orientation. Based on Steinmetz's work, a computer programme has been prepared by J. T. Andrews. This programme has been applied to two sets of fabric data to be described in the next chapter. The results on orientation agree within the working limits with those obtained by chi-square, and there is the added advantage of numerical values for direction and strength of dip as well as for orientation.

CHAPTER VI

TILL FABRIC ANALYSIS: RESULTS AND INTERPRETATIONS

> "Errors like straws upon the surface flow;
> He who would seek for pearls must dive below."
> John Dryden, "All for Love," 1678.

Following the procedural methods described in the last chapter, a total of 72 fabric analyses were made from several seemingly different till layers throughout the Midlothian Basin, along the Firth of Forth to east and west of Edinburgh, and in central East Lothian. The locations of these fabric sites are shown in a general reference map, fig. 6.1. Two further fabric analyses were carried out in southwest England for purposes of comparison. The fabric results are summarized in Tables 6.1 and 6.2; the fabric diagrams and simplified rose-diagram equivalents are grouped together after the main text, while the rose-diagram equivalents are used in this chapter. The numbers allotted to fabric analyses have no significance except to indicate the approximate order in which they were completed.

The only detailed till fabric analyses from Britain to have been published are those of West and Donner (1956), and Norris (1962). These use the method successfully in order to determine regional direction of ice movement, but do not provide a precedent for the systematic dip measurement programme attempted in this work. Therefore, there was some

TABLES 6.1 and 6.2

List of contents of fabric analyses summary tables 6.1 and 6.2

1. Designation number of fabric. The order of numbers has no significance in grouping the fabrics. It indicates the approximate order in which they were completed.
2. Location. All locations occur on O.S. 1-inch sheet 62, Seventh Series.
3. Grid reference. All locations occur within National Grid 100-km. square ref. NT.
4. Altitude of fabric site in feet O.D.
5. Direction and amount of slope of ground surface at the site in degrees. This is not relevant at the base of deep sections and is omitted.
6. Type of till, as described in the text, Chapter IV.

   (b - basal till
   (i - intermediate till
   (R - Roslin Till
   (r - tills related to R.

7. Total thickness in feet of till layer from which fabric analysis taken.
8. Working depth in feet of analysis from top of till layer.
9. χ^2 . Strength of orientation as derived from chi-square test.
10. θ . Orientation trend as derived from chi-square test.

    * indicates a laboratory orientation.

11. Transverse orientation. Noted if apparent in rose-diagram.

12. **Particle dips: direction and ratio.** This indicates the dominant dip direction of the particles within the two 90° quadrants centred along the orientation axis as calculated, together with the ratio of particles occurring in the two quadrants.

Table 6.1
D - downflow
U - upflow
N - no preferred dip direction.
N/R - not recorded

Table 6.2
D - downslope
U - upslope
N - no preferred dip direction

TABLE 6.1

SUMMARY OF REGIONAL FABRIC ANALYSES

1	2/3	4	5	6	7	8	9	10	11	12
1	Bilston 266 643	550	0°	R	4¾	3	49.5	N16°E- S16°W	Yes	N
2	Bilston 265 643	550	0°	R	4	3	0.05	-	-	-
3	Bilston 266 642	550	SW 5°	R	6	4	33.0	N41°E S41°W	Yes	N
4	Oatslie 263 628	525	0°	R	7	4	42.8	N48°E- S48W	Yes	N/R
5	Keith Water 449 636	525	N60°W 5°	r	7	3	27.5	N68W- S68E	Yes	N
6	Boghall Burn 258 647	525	0°	R	5	3½	47.8	N35E- S35W	Yes	U 2/1
7	Keith Bridge 453 638	500	0°	r	7	2½	9.4	N80W S80E	No	N
8	Keith Water 448 636	450	-	b	1½+	½	41.0	N44E S44W	No	U 2/1
9	Keith Water 448 637	450	-	b	8+	1	2.6	-	-	-
10	Costerton 438 631	550	-	i	13	1½	17.0	N4E S4W	Yes	U 3/2
11	Dolphington 159 771	125	N20°E 10°	b	5+	3	18.6	N75W- S75E	No	N
12	Bilston 266 643	550	0°	R	5	3	46.4*	N20E- S20W	Yes	U 3/2
13	Costerton 438 631	525	-	b	20+	2	32.3	N54E S54W	No	U 2/1
14	Straiton 279 667	475	SE 5°	r	8½	4	4.4	-	-	-
15	Straiton 281 668	475	S20°E 5°	r	7	3½	28.4	N34W- S34E	Yes	N

TABLE 6.1 (cont.)

1	2/3	4	5	6	7	8	9	10	11	12
16	Costerton 438 631	525	-	b	20+	3	9.6	N85W- S85E	No	N
17	Keith Water 443 633	475	-	i	3+	1	10.2	N10E- S10W	Yes	N
18	East Water 450 617	625	N 2°	i	9+	6	18.5	N38W- S38E	Yes	U 2/1
19	New Pentland 267 660	500	W 1°	R	6	3	57.6	N17W- S17E	Yes	N
20	New Pentland 267 660	500	0°	R	6	1½	42.2	N9W- S9E	Yes	U 3/1
21	Burghlee 277 652	500	0°	R	2½	1½	51.8	N25W S25E	Yes	D 3/1
22	Boghall Burn 258 647	525	0°	i	2+	1	24.1	N35E S35W	Yes	N
23	Middleton 355 581	700	-	i	3-12	2	4.3*	-	-	-
24	Oatslie 263 628	525	0°	R	7	3	32.1*	N46E- S46W	Yes	N
25	Gladsmuir 472 736	300	0°	?	4½+	3	17.2*	N56W- S56E	Yes	N
26	Gladsmuir 465 734	300	0°	?	5	3	32.2*	N22W- S22E	Yes	N
27	Gladsmuir 467 735	300	0°	?	4½	3	6.7*	-	-	-
29	New Pentland 268 659	450	-	i	1	½	22.1	N 8E- S 8W	Yes	D 2/1
30	Swineburn 103 761	250	S20E 2°	b	6	3	0.7	-	-	-
32	Glencorse House 243 629	575	-	i	15+	4	22.1	N27E- S27W	Yes	U 4/3

TABLE 6.1 (cont.)

1	2/3	4	5	6	7	8	9	10	11	12
33	**Milton Bank** 251 627	500	-	i	4	1	19.9	N40E- S40W	Yes	D 4/3
34	Haveral Wood 293 661	400	0°	r	4	2½	42.4	N 2E S 2W	Yes	U 3/2
35	**Black Burn** 229 574	775	-	i	3	1	49.9	N15E S15W	Yes	U 3/1
36	Liberton Hospital 279 689	350	0°	r	4	3½	40.7*	N34W- S34E	No	U 3/1
37	Blackford Hill 266 705	250	E 3°	b	3	2	17.6	N77W- S77E	Yes	U 3/2
38	**Jerusalem** 465 706	275	S20E 2°	b	12+	7	13.0	N67W- S67E	Yes	N
39	**Black Burn** 227 572	800	-	i	4	2-3	14.9	N67E- S67W	No	N
41	**New Pentland** 267 655	525	0°	R	3½	2	15.1	N 1W- S 1E	No	D 2/1
42	Lead Burn, Howgate 244 579	750	-	i	12+	3	13.0	N46W S46E	Yes	U 3/1
43	Glencorse Burn 226 631	650	-	i	18+	10	34.7	N49E- S49W	Yes	U 2/1
44	**Braidwood Burn** 200 593	825	-	i	?20	?15	15.8	N63E- S63W	Yes	N
45	North Esk, Auchendinny 248 612	475	-	b	3+	1	59.5	N86E- S86W	No	N
46	Dalmore Mill Auchendinny 255 617	500	-	i	?60	7	48.3	N 4E- S 4W	Yes	U 2/1
47	Shiel Burn, Rosewell 288 618	500	-	i	15+	4	27.9	N 1E- S 1W	Yes	U 5/2

TABLE 6.1 (cont.)

1	2/3	4	5	6	7	8	9	10	11	12
48	Dalhousie Burn 305 623	375	-	b	3	2	34.2	N89W- S89E	Yes	N
49	Straiton 277 668	475	N60W 5°	r	3	2½	23.4	N24W- S24E	No	N
50	Straiton 277 668	475	N60W 5°	b	3+	1	36.2	N78E- S78W	Yes	U 5/2
51	Milton Bridge, Birns Water 458 668	300	-	b	3+	2	45.7	N74E- S74W	Yes	N
52	Birns Water 457 665	300	-	i	12+	6 & 10	36.3	N 8E- S 8W	Yes	U 3/2
53	Park Burn, Dalkeith Park 332 689	100	-	b	9½+	4	52.4	N63E- S63W	Yes	U 5/2
54	as 53	100	-	b	1½	9 inches	73.5	N61E- S61W	Yes	U 2/1
55	as 53	100	-	b	4 inches	-	53.0	N63E- S63W	Yes	U 2/1
56	Lead Burn, Lockhart Halls Farm 240 579	750	-	i	3+	1	69.3	N40W- S40E	Yes	U 3/1
57	Pomathorn 239 592	700	-	i	30+	7	59.3	N29W- S29E	Yes	U 2/1
59	Kirkhill, Penicuik 236 602	625	-	i	3	1½	30.5	N 7W- S 7E	Yes	U 5/3
60	Cuiken Burn 229 609	675	0°	b	12	7	41.4	N81W- S81E	Yes	U 4/1
61	Silver Burn 212 601	850	-	b	1½+	1	65.0	N87E S87W	Yes	U 3/1
62	Silver Burn 212 601	850	-	b	3+	2	67.4	N78W- S78E	Yes	U 3/2

CHAPTER I

INTRODUCTION

> "Now at the present time it is only by patient research and investigation that we can trace out the havoc that was wrought when the ice king reigned supreme in our land." Mr. Brown, on some of the Glacial Phenomena of the Neighbourhood of Edinburgh, 1874.

Relation of the thesis to other work. This thesis is concerned with the Pleistocene glaciation over three hundred square miles of the Lothians, the region in Central Scotland on the south side of the Firth of Forth adjacent to Edinburgh. Evidence for glaciation is not difficult to find, and the research has incorporated a range of aspects, including the morphology of the present landscape and the drift stratigraphy underlying the surface forms.

The writer came to this part of Britain with certain interests, either developed or latent, in quantitative field techniques; and the region was one where a considerable amount of forward-looking glacial geomorphological research had already been completed. From the combination of these factors a suitable area, that had not been covered by other workers, was readily defined, and this area has been investigated by a selection of relevant methods of interest to the writer.

TABLE 6.1 (cont.)

1	2/3	4	5	6	7	8	9	10	11	12
63	Cuiken Burn 229 609	675	0°	i	6	4	37.9	N11E-S11W	Yes	U 2/1
64	New Saughton Hall 290 652	225	-	b	20+	9	18.5	N48E-S48W	Yes	N
65	Black Burn 227 572	775	-	i	12½+	8½	72.2	N39E-S39W	Yes	U 2/1
66	Fullarton Water 282 568	775	-	i	8+	5	65.5	N40E-S40W	Yes	U 2/1
67	Kirkhill Bank 325 622	300	NE 2°	i	15+	6 & 11	52.7	N14W-S14E	Yes	N
68	Kirkhill Cut 325 623	250	-	b	24	6	31.1	N57E-S57W	Yes	U 4/3
69	Keith Water 443 633	475	-	i	2+	1	28.3	N22E-S22W	Yes	U 3/2
70	Keith Marischal 450 640	500	0°	r	2¾	1½	0.4	-	-	-
72	Cotty Burn 388 667	375	0°	i	5+	4	21.5	N16W-S16E	Yes	U 2/1

TABLE 6.2

SUMMARY OF NON REGIONAL FABRIC ANALYSES

1	2/3	4	5	8	9	10	11	12
28	Haveral Wood 293 661	400	S10°E 7°	4	70.0*	N20°W- S20°E	Yes	D 3/2
31	Flotterstone 238 632	600	N30°W 15°	5	11.3	N18°W- S18°E	Yes	D 2/1
40	Esperston 344 568	900	W 5°	2½- 3	120.9	N89°E- S89°W	Yes	U 3/1
58	Pomathorn 239 592	700	S65°W 5°	3- 3½	79.9	N74°E- S74°W	Yes	U 3/2
71	Partridge Burn 428 607	650	N20°W 8°	19	87.6	N13°W- S13°E	Yes	N
H 1	Wembury SX 513 484	15	S15°W 2°[1]	-	82.2	N14°W- S14°E	Yes	U 3/2
H 2	Wembury SX 513 484	15	S15°W 2°[1]	-	91.0	N10°E- S10°W	Yes	N

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[1] Head material has moved out from the base of a much steeper bedrock slope.

initial doubt concerning the value of attempting measurements in three dimensions. Such detailed fabric work has justified itself as laboratory work (Harrison, 1957a; Dreimanis, 1959b), and in the field in the arctic and subarctic where the glacial deposits are fresh and unmodified. But there seemed a strong chance that the fabric of tills in central Scotland would have been modified by solifluction, by mass-movement or by root-pressure, especially near the surface where most analyses inevitably have to be done. The effects of these factors under the climatic conditions of northern Britain are just beginning to be investigated (Tivy, 1962).

If the original fabric has been modified post-glacially, by heaving and resettling, by lateral movement or by local wedging, it is likely that the dip pattern will have been the first characteristic to be obliterated. This is because most particles are initially near-horizontal and angular rotation of a few degrees would more readily upset the dip pattern than the orientation pattern. If the dip pattern is consistent, or at least can be reasonably accepted as one unmodified by any post-depositional change, then the fabric pattern has greater intrisic value, providing much more information about both the direction, (as opposed to one of two directions: the trend), of ice movement and the processes of deposition.

In the light of this, the fabric studies were very experimental in the early stages until the reliability and consistency of the results could be gauged. The first analyses were carried out in groups for mutual support; the results obtained in one till deposit at Bilston by fabric analyses numbers 1, 2, 3, and 12 give a standard of comparison for later results.

With fabric analysis 4, only the orientation of the a-axis was measured and not the dip. This was a mistake and was not repeated; the very slight economy in time does not justify the limitations of interpretation imposed by having only a two-dimensional plot.

There were also some mistaken interpretations of deposits. One complete fabric analysis was discarded and two partly-complete analyses were abandoned for various reasons: at one site the material was found to be not coarse till but glacio-fluvium showing soil development; at another site the material proved to be a hill-wash; and at a third site near Straiton, there appeared to be faulting within the till, which an aerial photograph showed to be the result of mining subsidence.

As the main objective was to obtain fabric indicative of regional ice-movement, sites were chosen on level or nearly level ground, clear of local topographic effects and local disturbances. Many exposures of till had to be eliminated as possible fabric sites because the ground surface slopes too much, or because the till had so slumped that it was not possible to cut through to unslumped material behind, or because there is clear evidence of local subsidence due to coal, oil-shale or limestone workings. In addition many fine sections of fresh till along the River North Esk near or at the base of the drift succession are reachable only by ropes, and are too sheer to allow more than cursory examination.

The number and location of drift sections available for study varies rapidly in any fieldwork area, of course, and the programme has to be sufficiently flexible to utilize the most ephemeral of temporary sections. Of the sites that were chosen, rather more than a half are river bank sections and a small number are at the sides of open shale or limestone quarries. Sites of these two types are semi-permanent, and might be expected to endure for a number of years. The remainder are more temporary, and in many cases the exact site cannot be examined at the moment of writing, but would have to be reconstructed from photographs or written description. Of these, fourteen were sections where till was exposed incidentally in sand and gravel workings, and eleven were trenches for pipe-laying, or sections in roadway construction and building sites.

The great amount of extractive industry in the Midlothian Basin, together with the considerable domestic and industrial building in Edinburgh and the fringing towns and villages assists in a drift study such as this, and offsets the problems of working in semi-built-up areas. One of the disadvantages is that all the ground surface has been worked over by generations of farmers, engineers, builders or walkers, and there is no chance of recording any significant natural phenomena such as the position or even the orientation of free-standing erratic boulders. It is possible to decide on trend of ice movement from the orientation of free-standing erratics in Canada and Scandinavia, (Andrews, 1965), and might be possible in certain more remote parts of Scotland, but could not be considered in the Midlothian Basin or its fringing hills.

When all the till fabric analyses had been plotted and examined, it was found that all but five could be reasonably argued to relate to regional ice movements. The exceptions all indicate a local or secondary rather than a regional or original direction of movement of till, the effect in each case being due to the peculiarities of the site. This group of five will be discussed separately with the analyses from southwest England after the main group of analyses. The small set of fabrics from the Keith Water area will be first considered.

Keith Water area. A pilot study was made of fabrics from tills exposed in the Keith Water, an upper tributary of the River Tyne. This area was chosen because of the good exposures that exist, as described by Kendall and Bailey (1908).

The several tills of the Keith and Costerton area have been described in Chapter IV. There is such a variety of beds that the local stratigraphic sequence is not clear from these exposures even within one or two square miles. Ten fabrics were analysed from different tills to help establish and explain the stratigraphic sequence more fully (fig. 6.2).

The basal till along the Keith Water is the tough, dark grey deposit seen to be or assumed to be overlying bedrock (fig. 4.14). Till fabric analyses numbers 8, 9, 13, and 16 were carried out from this basal till; these fall into two pairs, the pairs being spaced almost a mile apart. Fabrics 8 and 9 are from adjacent right bank sections of the Keith Water. Fabric 8 shows a clear preferred orientation $N44^{\circ}E-S44^{\circ}W$, with the majority of particles dipping to the southwest, indicating ice movements from the southwest. The preferred orientation is moderately strong at $\chi^2 = 41$; there is no secondary orientation. Fabric 9 shows a lack of preferred orientation with $\chi^2 = 2.6$. The site of this analysis is an ideal one in consolidated unweathered material, and a random orientation of particles was unexpected. In this case, it is explained as a local variation in the fabric due to the presence of a large cobble which was revealed only when a half of the one hundred particles had been measured. This is thought to have affected the attitude of smaller particles nearby. Examination of the rose-diagram of fabric analysis 9 will show that there is a block of particles aligned east-northeast - west-southwest and dipping west-southwest, in a manner consistent with fabric 8, but this is not strong enough to register at a significant level.

Fabric 13 is from a river bank section, one meander down-stream of Red Scar. It shows a clear preferred orientation N54°E - S54°W, with a marked predominance of dips to the southwest, indicating ice movement from this direction. There is a suggestion of a secondary transverse orientation, more obvious in the southeast quadrant, and not quite at right angles in the northwest quadrant. Fabric 16 is from the basal till at the side of Red Scar (fig. 4.14), the same material as for fabric 13. The fabric gives an orientation east-west with no preferred dip. The orientation is weak, being significant at the 99th percentile, but not at the 99.5th percentile.

Taken together these fabrics show movement of ice from the southwest or west-southwest. Fabrics 8 and 13 agree in direction and in strength, and 9 shows a ghost fabric, obscured by local variation. Fabric 16 is anomalous and cannot be satisfactorily explained. The site is near the top of the basal till, below the gradation into bedded sands, and was not in a good state of preservation. This may be the explanation, the weak orientation obtained being the chance result of a random pattern.

A stone count from the site of fabric analysis 9 (Table 4.2; and fig. 4.18) indicates 39 per cent of Carboniferous lithologies and 21 per cent of Southern Upland material, which is consistent with a southwesterly origin. There is besides a considerable variety of other unnamed lithologies, forming 30 per cent of the total, as befits a relatively far-travelled basal till.

Fabric analyses 10, 17, and 69 are related to tills that seem to be in an intermediate position, being neither basal till by their stratigraphy nor the topmost till by their altitude. Fabric 10 is from the upper till exposed at Red Scar (fig. 4.14). It shows a very definite but not massive orientation N4°E - S4°W with a majority of dips to the south, indicating ice movement from this direction. Fabric 17 from the distinctive red till on the left bank of Keith Water shows a similar pattern, orientated N10°E-S10°W. In this case there is no dominant dip direction. From a site adjacent to this, fabric 69 in red till shows stronger orientation N22°E-S22°W, with the dips indicating ice movement from the south-southwest.

These three fabric analyses agree on orientation, (the direction of ice movement), and also on strength of orientation; the orientation is slightly weaker than for the basal till. Stone counts from fabric sites 10 and 69 are also broadly in agreement with the fabric results (Table 4.2 and fig. 4.18). The proportions of greywacke are much higher than at fabric site 9 in basal till, and support the indications of movement from the direction of the Southern Uplands as shown by the fabrics. Each stone count included only 6 per cent of unnamed lithologies.

The strong original colouring of the red till is thought to be due to movement of ice over the Old Red Sandstone outcrop immediately south of the Keith Water (see fig. 6.2). This outcrop is so local that contamination by Old Red Sandstone material must be limited to a narrow sector when ice passes over it from any particular quarter. This explains the red colouring of the till at fabric site 69 but the normal grey-brown colouring at site 10. In the red till, apart from the fine Old Red Sandstone material providing colouring, 13 per cent of the pebble erratics are also of Old Red Sandstone. This compares with only 1 per cent in the non-red middle till at Red Scar, which comes from a similar direction, but almost avoids contact with the Old Red Sandstone outcrop (fig. 6.2).

The remaining fabrics from the Keith Water are numbers 5, 7 and 70 from the top of the succession. As a group, these are difficult to interpret, and it may be that no one explanation suffices. Fabric 5 relates to the top capping till from the high section on Keith Water (fig. 4.15). The fabric diagram shows an orientation N68°W-S68°E with no preferred dip direction. The particles are on aggregate more flat-lying than usual. Fabric 7 from the same deposit at the top of Keith Bridge sand pit (fig 4.16) shows an orientation N80°W-S80°E with a preponderance of particles dipping to the east. The orientation is weak, being significant at the 99th but not the 99.5th percentile, and both dip and orientation are much more varied than in fabric 5.

There are two possible conclusions from this pair of fabrics. Firstly, as they agree to 12° on trend of orientation, they could indicate, regional trend of the ice depositing the capping till. On the other hand, there is in the case of fabric 5 a site factor that may have influenced the result. The section occurs at the northwest end of a high ridge of dissected glacio-fluvium. The top capping of till from which the fabric is taken cambers over the thick sand, the surface behind the section sloping to N60°W at 5°. This is in broad agreement with the orientation direction. Therefore the orientation in fabric 5 could possibly be the effect of slumping. This explanation could not he true of the other fabric, where the site is quite flat. This fabric is however the weaker of the two. These two possibilities will be held open until other evidence is described.

Fabric 70 was taken in the 2¾-foot layer of till on the east side of Keith Marischal sand pit (fig. 4.17). The bed of till consists of several sloping layers, separated by thin sand traces and so is unlike the homogeneous material of a normal subglacially-deposited till. In a section 10 feet wide, there were seen five sloping till layers, separated by four bands of sand, each up to half an inch thick. One of the till layers is of red till, the others of medium brown till. The till as a whole is sandy and contains large stones throughout; a stone count (Table 4.2 and fig. 4.18), shows a dominance of Carboniferous and 'other' lithologies, and a lower although not negligible proportion of Southern Upland greywackes than in other stone counts along the Keith Water. The fabric diagram shows an extreme random orientation. The dominant dip direction is to the north, which agrees with the slope of the individual till layers within the bed.

The internal structure and fabric pattern indicate that this till has an unusual origin. The sequence of deposits of which it is a part shows thick sand grading up into the till layer, which is in turn succeeded by alternating thin bands of till and sand; this suggests glacio-fluvial conditions with slumped ablation material from a glacier overlying this.

Being from sites at the same altitude O.D., fabrics 5, 7, and 70 were expected to provide a key to the thin-bedded sandy tills near the top of the Keith Water succession. This they fail to do, because the deposits are so varied. In particular, Keith Marischal sand pit shows ice-contact till deposits as well as thin-bedded shallow-water deposits (fig. 4.17). On the basis of the three sections the tentative conclusion is of ice readvancing locally into a shallow glacier-dammed lake. The direction of ice movement is not definitely established, two fabrics, both suspect showing trend west-northwest - east-southeast, and the third showing slumping to the north.

In summary, the total of ten fabric analyses in the Keith area, The area is essentially the drainage basins of the River Esk in Midlothian and the upper River Tyne in East Lothian. The geographical limits of other post-1950 researches in the region are shown in fig. 1.1, the work being conducted either by the Geological Survey of Great Britain or by a group from the Department of Geography of Edinburgh University. While the main concerns of the two bodies are drift geology and glacial geomorphology respectively, there has been some overlap of research interests which has led to valuable interchanges of ideas.

Apart from the absence of any other recent, accurate, published account, the area chosen for this thesis is attractive for geomorphological investigations for several reasons: in 1940 a so-called Upper Boulder Clay was described for the first time in Midlothian, overlying thick glacio-fluvial deposits in such a way as to suggest the till represented a glacial re-advance. This upper till has not previously been investigated with any thoroughness. A second favourable aspect is the long historical record of research in the district, providing an unusually large amount of accurate facts, while a practical factor is the exceptional number of helpful natural and man-made exposures in the drift.

Off-setting these incentives, it may be said that the morphological evidence is not at all distinct, particularly in the middle part of the Esk Basin. As an indication of the problem, the southern part of the Esk Basin was mapped by J. B. Sissons before 1960, but, owing to his dissatisfaction with his interpretation of this difficult area and the incompleteness of the evidence at this time, the material was not published (pers. comm., 1961).

Style of the investigation. The writer's interests in methods of augmented by stone counts, relate to three distinct phases of ice movement separated by two periods of glacio-fluvial or more probably glacio-lacustrine depositions. The first phase of ice movement was from southwest to northeast, depositing a thick ground moraine. Meltwater conditions succeeded the till deposition without a break, as shown by the gradation upwards at till fabric site 9.

The lower bedded sands must in some places have been eroded by ice or by their own water as the next till deposit, the middle till, sometimes rests discordantly directly on the lower till. The middle till, which is a distinctive red colour in places, indicates ice movement from the south, off the Southern Uplands. Then follows a phase of meltwater conditions, with sand deposits thicker than in the previous phase, and finally a third phase of glaciation, much less substantial than the previous two and of uncertain origin.

On the basis of the fabric analyses along Keith Water, the principal sections can be linked together. This is attempted in fig. 6.3. It will be noted that in spite of the great variation in type and thickness of drift materials, they can be grouped into not more than three depositional units. The vertical exaggeration necessary in fig. 6.3 gives an inadequate picture of the continuity of corresponding till layers.

<u>Esk Basin: basal till</u>. The fabric analyses from Keith Water have allowed substantial conclusions on the glacial phases in the upper Tyne, all the more satisfactory because the work is self-supporting, without the aid of morphological mapping. This scheme formed a very adequate pilot study for the main concentration of analyses in the Esk Basin, where other systematic investigations supplement the fabric analyses.

Almost all the till fabric analyses in the Esk Basin show a preferred orientation at a significant level and, by their dip patterns, also indicate the direction, as opposed to the mere trend, of ice movement. However, the fabrics do not fall into natural groupings according to orientation, and so it is necessary to associate them by linking the fabric sites stratigraphically as far as exposures make this possible.

The best-documented ice movement was that approximately west-east along the Firth of Forth, a movement deduced with great confidence from the crags and tails, fluted ridges, and striation pattern in and around Edinburgh city. No till fabric analyses need strictly to have been performed where the streamlined relief is so evident, but a small number were completed along the coastal belt in order to link the erosional forms with the corresponding till, and to decide on the order of glacial events.

It was assumed that the main west-east movement, powerful enough to override the Pentlands without being deflected substantially, was represented by the basal till. Fabric analyses numbers 11, 30, 37, 45, 48, 50, 53-55, 60-62 and 68 showed this to be the case (fig. 6.4); these will be described individually.

The area of the coastal strip is represented by fabrics 11, 30, 37, and 53-55, the first two of which are west of Edinburgh in the Almond Basin. Fabric 11 is from the hillslope above Dolphington Bridge, a temporary exposure relating to the Forth Road Bridge approach road. The exposure showed 5+ feet of till overlying bedrock. The till is a variegated, weathered deposit, containing much rotted material. It has a sandy texture and inclusions of grey and brown clayey till, more characteristic of the thicker unweathered till on lower ground in this district. In spite of a surface slope of 8° to the north from Dolphington Hill, the fabric diagram shows a clear orientation of moderate strength N75°W-S75°E along the slope, The slight preponderance of particles dipping west is not sufficiently marked to be conclusive.

Fabric 30 at Swineburn was taken from a temporary trench (open April 1962) on the south side of a large shallow drumlin. Stone orientation was expected to follow the alignment of the drumlinisation from just north of west to just south of east (Wright, 1957), but the fabric diagram gives no preferred orientation; this is presumed to be due to the very high proportion of boulders in the basal till, calculated to occupy a sixth of the total volume, which prevented the smaller particles from adopting an attitude related to ice movement (see Chapter V). The basal till is here the traditional bouldery clay, all the boulders being quite rounded and striated.

Fabric analysis 37 was made on the tail of Blackford Hill, which is one of the best-formed and most striking crag-and-tail formations in Britain (fig. 6.5A). The whole feature is about one mile long, with a precipitous western impact face and a horse-shoe shaped valley half encircling its base and extending eastwards as lateral grooves. A till fabric from such a site is of especial interest. The alignment of the crag-and-tail itself indicates the direction of movement of the ice-sheet, and so it can be found how closely the fabric pattern respects this movement, assuming the till is the product of the same ice movement. In this case, Blackford Hill crag-and-tail is aligned N85°W-S85°E, and fabric 37 produces an orientation of N77°W-S77°E, which represents a clear identity. The fabric also shows a majority of particles dipping to the west, the expected result in terms of the known direction of ice movement.

The lee slope of Blackford Hill is not composed of thick till, as the tail of a typical crag-and-tail feature is often described. There is a layer of 3-4 feet of till on the surface thickening to over 10 feet downslope but this rests on sand. The top part of the drift succession on the lee slope has been exposed very clearly in recent years by building foundations of University of Edinburgh extensions; sand underlies the surface till over most of the King's Buildings site. The thickness of the sand has not been established, the deepest foundation excavation being about six feet into the sand but not reaching its base. There is a record by Panton (1873) of 18 feet of sand in a pit on the tail of Blackford Hill in a position "428 yards from the cliff"; and Brown (1874), commenting on Panton's paper, wrote of sand pits, rather than a single pit. But these references may be to the extensive sand and gravel deposits that existed a hundred years ago along Braid Glen on the southern side of Blackford Hill, (Milne, 1840), deposits associated with the striated overhanging ledge made famous after a visit by Agassiz in 1840.

In the middle of the tail of Blackford Hill, the till overlies the sand with a graded junction: in one instance, the sand merged upward into till over a distance of 6 inches, passing through gravel, silty sand, and till with sandylenses (fig. 6.5B). Therefore the till does not seem to relate to a phase of glaciation separate from that which deposited the sand. The mode of formation of a crag-and-tail would seem to leave scope for sand and till deposition within one process: there may be a zone in the lee of the bedrock crag of reduced pressure and possible ice stagnation where freeze-thaw processes could be operative and running water would be available.

On a smaller scale, Carol has demonstrated a similar variation in pressure around bedrock knobs underneath a valley glacier (Carol, 1947).

It is possible that the bottom of the drift tail of Blackford Hill is occupied by another till deposited during the formation of the crag-and-tail, and that the till described above represents a second ice-movement from the same direction overriding the crag-and-tail; but there is no direct evidence for it. The surface till contains about 5 per cent by volume of sub-angular or angular boulders, some of which are very large. This gives the till the appearance of the Silverknowe and Prestonfield deposits, which are of basal till. Cockburn (1956) concluded from the lithologies of the boulders on the tail of Blackford Hill, that they are derived from the west. It is surprising that he did not mention any type of drift other than till over all this site.

Elsewhere along the coastal strip, the most interesting multiple-till section at Park Burn (fig. 4.11) has already been fully described. Fabric analyses were carried out as follows:-

T.f.a.	53	Basal till layer 3½-4 feet below top of till
	54A (1-50)	From 1½-foot till layer, in lid of gully
	54B (51-100)	From 1½-foot till layer, at side of gully
	55	From 4 inch band till layer.

The till has the same composition and appearance in the higher thin bands as in the basal layer. Although fabric 54 was carried out in two parts from layers separated by a trace of sand (see fig. 4.11), separate plotting of particles 1-50 and 51-100 showed no difference between the parts. The fabric is calculated and drawn as one unit. The fabric analyses give the following results:

	Direction of orientation	Strength χ^2	Dip direction
53	N63°E-S63°W	52.4	West-southwest
54	N61°E-S61°W	73.5	West-southwest
55	N63°E-S63°W	53.0	West-southwest

The three fabric analyses show exceptionally close agreement in orientation direction, dip, and strength. By comparison with the figures for the basal or middle tills at Keith, it can be seen that this result is much closer than would be expected from three fabrics taken from different sites of the same deposit. As the agreement between 53, 54, and 55 is as close as could ever be expected, the direct conclusion is that the till layers were deposited under identical conditions, by the same agency moving in exactly the same direction with the same momentum. It is extremely improbable that separate ice-sheets or tongues would readvance across ground in exactly the same direction or with the depositing mechanism developed to the same extent as the original ice-sheet depositing the basal till. The layers of till are therefore all regarded as part of a single till, the interstratified sand representing merely breaks in a single act of deposition.

Interpreted in this way, the layers of till correspond to beds (Virkkala, 1952) and the thin glacio-fluvial layers between are the bed limits. Virkkala also interprets this type of drift as showing interrupted lodgment deposition of till.

Stone counts from the two lowest layers of till (Table 4.1) agree exactly in confirming that the till is basal till with a westerly source. Both stone counts show a small proportion of local Carboniferous lithologies, some rocks from the northern part of the Pentlands, and hardly anything from the south. Three-quarters of the total material is derived from more widespread sources to the west.

Within the Esk Basin a scatter of other fabric sites within basal till provide orientations consistent with those for the coastal strip (fig. 6.4). The site of fabric 45 is the east bank of the River North Esk at stream level. Three feet of tough, dark brown till is truncated by 9 feet of coarse river alluvium, which forms a late river terrace within the bedrock Esk gorge. The fabric shows a strong preferred orientation almost east-west with no dominant dip direction. A similar river bank section is the site of fabric 48 on Dalhousie Burn below Shiel Bridge. In this case there is no bedrock gorge, the stream cutting deeply between thick drift. The fabric orientation is again nearly east-west with no dominant dip direction. A mile due east of this, fabric 68 was taken from the raw blocky till exposed in the diversionary cutting for the River South Esk at Kirkhill. The fabric orientation is N57°E-S57°W with a slight indication from the dips of movement from the west-southwest.

This group of analyses is completed by one from the basal till on Gilmerton Ridge and three between Penicuik and the Pentland Hills. On Gilmerton Ridge, the basal till in the temporary section on the west slope (fig. 4.8) is shown in fabric 50 to have an orientation N78°E-S78°W, with movement from the west. The ground surface slopes at this location to N60°W at 5°; this is about 40° away from the orientation direction and so the slope is considered not to have influenced the fabric pattern.

Fabric 60 from the lower of the two superposed tills at Cuiken Burn (fig.4.10) shows a strong orientation N81°W-S81°E with the dip direction indicating ice movement from the west. This analysis was completed in two sets of fifty particles, 12 feet apart at the same level, because the first few particles measured agreed so closely in orientation that some exceptional local factor was thought to be affecting them. However the sets of fifty particles produced identical results and have been plotted as one.

From the west bank of Silver Burn, a mile southwest of the Cuiken Burn site, fabrics 61 and 62 were completed, and the orientations in each case are very similar to those at Cuiken. Both fabrics show a strong orientation, within a few degrees of west-east with the dip direction indicating ice movement from the west. The section containing these two fabrics has certain similarities with the multiple till section at Park Burn. Above stream level is exposed 1½ feet of dark till (fabric 61), grading upwards over a foot into 4½+ feet of glacio-fluvium, comprising thin-bedded silt, sand and gravel. The section is then obscured but between 13 and 16 ft. above stream level, a further layer of till appears (fabric 62), slightly sandier and lighter in colour than the lower till. In both till layers, the strong orientation is apparent from visual inspection and is unrelated to any slumping with respect to the present valley side. The two till layers appear to be part of a single ice deposit, separated by an insignificant meltwater phase.

The total thickness of drift above stream level is over 50 feet. There are no exposures higher up but the vegetation and ground conditions suggest there is more till above the two exposed till layers, and till is exposed in the field immediately west of Silver Burn at a height well above stream level at the base of a deep kettle. It is probable that this higher till is analogous to the upper of the two tills at Cuiken Burn.

Of the thirteen fabrics discussed from the basal till of the Esk Basin and coastal strip, all except the bouldery clay at Swineburn show preferred orientation approximately west-east, the mean orientation of the twelve being N83°E-S83°W. The largest deviations from this mean are the fabrics sited furthest apart (fig. 6.4), numbers 11 at Dolphington and 68 at Kirkhill Cut. Eight of the twelve fabrics show a dominant dip of particles to the west; the remaining four show no preference. The movement of ice from west to east is therefore adequately reflected in the dip parameter of the particles measured. All fabrics apart from that at Dolphington were taken from unweathered till. The fabric strength (χ^2) of these eleven unweathered tills (excluding Swineburn and Dolphington) is quite varied, ranging from 17.6 to over 70, with a mean of 48.2.

Stone counts from the lower till layers at Park Burn have been mentioned briefly as being consistent with a westerly source for the basal till. Stone counts were made also in connection with fabrics 45, 48, 60, and 68 (Table 4.1), all sites east of the Pentlands. Three of the four show large proportions of Carboniferous, Pentland volcanic, and 'other' lithologies and a negligible proportion of Southern Upland greywacke; this suggests a westerly source, in agreement with the fabric results. The stone count from Dalhousie Burn is the exception, as it contains 48 per cent of greywacke. As the site and fabric analysis appear perfectly acceptable, the high proportion of greywacke can be explained only in terms of a movement of greywacke northwards off the Southern Uplands, followed by or at the same time as the main west-east movement in the Forth valley. Fabrics indicating movement of ice in directions other than along the valley will be discussed next.

<u>Esk Basin: intermediate till</u>. A considerable number of fabrics through-

out the Esk Basin show orientations more nearly north-south than east-west (fig. 6.6). Many of these are from sections originally thought to be in basal till. However, the fabric analyses show that the material is not basal till or, if it is, it is derived from an ice movement in quite a different direction to the main Firth of Forth flow.

Close under the east side of the Pentlands there are a number of fabrics with orientations parallel to the line of hills. Most of these fabrics are from tough, grey-black unweathered till.

At Boghall Burn (fabric sites 6 and 22), the top 3 feet of a till is exposed above stream level, separated by a very thin sand layer from the overlying 5 feet of Roslin Till and soil. This lower till is dark brown with a raw crumb structure similar to subsoil and some particle decomposition. Fabric 22 from the lower till shows a moderately strong orientation N35°E-S35°W without a dominant dip direction.

At the base of the Clippens sand pit, New Pentland, there occurs a skeletal till resting on bedrock (fig. 4.21B). Fabric 29 from this till shows a moderate orientation N8°E-S8°W with movement from the north. This fabric cannot be given normal weighting, whatever the result, because the till is such an exceptionally poor-developed layer. More than anything else, the fabric analysis helps to show that the basic material is in fact till.

Along Glencorse Burn, a line of three fabrics, numbers 32, 33, and 43, were taken at different distances from the Pentlands. These three sites are all in tough, dark, unweathered till near stream level. Fabrics 32 and 33 show moderately strong orientations N27°E-S27°W and N40°E-S40°W respectively, but differ in dip directions, one being predominantly south-quantitative investigation have meant that, although the glacial theme is pursued by both regional descriptions and systematic studies, the major contribution of original research is in the systematic aspects, while the conclusions are presented on a regional basis. In this, the thesis follows the tried framework of geography itself, whereby the systematic sometimes quantitative, investigation of geographical elements is followed by attempts at associating the elements and producing a qualitative conclusion which ideally finds causal relationships in an areal pattern.

The two systematic aspects which in method and approach may have some claim to originality are the analyses into the three-dimensional structure of till; and the heighting and correlating of river terraces. Each of these studies involves well-known established practices, but each is developed more fully here than in any previous known work.

The till fabric analyses represent a concentrated effort at finding regional directions of ice-sheet or ice-tongue movement from characteristics of the subglacial deposit, the till. The analyses are confined to featureless ground moraine; all other till fabric work on this scale has been related to specific drift forms such as drumlins and ice-pressed hummocks. The fabric analyses do provide the required patterns of regional ice-movement and besides, by their very number, allow some assessment of the pertinence of the method itself.

The examination of river terraces in sequence along the course of any major stream is a common practice, and here again any originality claimed for the investigation of the Esk river terraces lies in the detail of terrace mapping and height measurement attempted. The acquisition of height and plan position of over a thousand points located on over 140 southwest, the other northeast. Fabric 43 is from a site upstream of Flotterstone at the mouth of the Glencorse Reservoir valley. Eighteen feet of till is exposed above stream level grading upwards over two feet into about 90 feet of the typically coarse, varied beds of an esker. The esker is aligned N65°E, running down along the outer slope of the Pentlands, into the mouth of the valley, which it partly blocks. As the till at the base of the esker grades into the esker material, it might be expected to relate to the same period of deposition and the same source-origin. This proves to be the case; the fabric orientation is N49°E-S49°W, with the marked dip direction indicating ice movement from the southwest.

Several miles southwest of Glencorse Burn, fabric 44 was taken in a cutting of Braidwood Burn. Most of the 25-foot river bank is obscured but the vegetation and soil-moisture conditions suggest thick till beneath about 5 feet of coarse glacio-fluvium. A quarter mile downstream from this section, to the south of the A766 road, further sections show bedded sand under this same till, at a lower altitude than at fabric site 44. This suggests that the till exposed at fabric site 44, although thick, is not the basal till of the area. The fabric diagram shows a rather weak orientation N63°E-S63°W, with no preferred dip direction. The fabric pattern is asymmetrical in the quadrants transverse to the main orientation; a quarter of the total particle plots occurs in the northwest quadrant, mostly dipping steeply, while only a tenth of the particles occurs in the southeast quadrant, mostly flat-lying. Thus the secondary transverse orientation has a dominant dip direction to the northwest. The fabric would also show this by a preferred dip of the b-axis of tabular particles with the primary orientation.

The orientation of each of these six fabrics agrees closely with the direction of the Pentland edge at the point nearest to it. Of the particle dips, two suggest movement from the southwest, that at Milton Bank suggests movement from the northeast and two are inconclusive, while that at New Pentland is discounted. The general conclusion is of ice movement on the east side of the Pentlands from the southwest with its path directed by the line of the hills.

The stone counts at each of these six fabric sites along the Pentland edge generally support movement from the southwest. The proportion of greywacke decreases northwards from Braidwood Burn (28 per cent) to Boghall Burn (1 per cent) and New Pentland (0 per cent). The proportion of Pentland material varies with distance from these hills, with over-representation at Flotterstone. Rather surprising is the proportion of 'other' lithologies at Boghall Burn and New Pentland rather than of Carboniferous rocks; this suggests contamination from the basal till in this northern district.

In the Esk Basin further east away from the Pentlands, fabrics 46, 47, 66, and 67 also produce dominantly north-south orientations. Fabric 46 is from dark unweathered till with roughly horizontal fissile layers 3-6 inches thick. The site is near the top of the River North Esk gorge overlooking Dalmore Mill, where 10 feet of coarse glacio-fluvium forming a river terrace, overlies 60-75 feet of other drift. Most of this drift appears to be dark till as exposed at the top, but it is not possible to say whether it is all one unit. The junction between till and glacio-fluvium appears to be abrupt but is cambered, so that a natural graded junction could be concealed. Fabric 46 shows a strong orientation of particles almost due north-south with pronounced dip directions indicating ice movement from the south.

An almost identical fabric pattern representing ice movement from the south is shown in fabric 47 from Shiel Burn, Rosedale, two miles east of the Dalmore Mill site. About 15 feet of dark till is exposed above stream level, overlain by a foot of bedded sand and several feet of predominantly wind-blown material. The analysis was taken near the top of the till.

Fabric 66 is the most southerly recorded, from Fullarton Water at about 800 ft. O.D. Between the B6372 road and Edgelaw Reservoir, the Fullarton Water cuts through over 60 feet of drift but there are few fresh sections except in river alluvium. However, slumps and the vegetation pattern indicate a thickness of dark till in the centre of the drift succession with glacio-fluvium at the top surface and near bedrock. The lower bedded drift is silty in some places. The fabric site is halfway up the drift slope, and 5 feet below the top of the till, which shows as a sharp break succeeded by fine sand. The fabric shows a very strong orientation N40°E-S40°W with movement from the southwest.

On the east side of the Esk Basin, fabric 67 is taken from the top edge of the River South Esk gorge. The highest member of the drift succession here is a thick till, which produces the flat ground southwest to Aikendean and Carrington. The till is underlain by bedded sand of unknown thickness; the base of the succession is the till already described as the site of fabric 68.

Fabric 67 was completed in two parts 6 feet and 11 feet below ground surface. The orientations of the two parts agree exactly and so the fabric is calculated in the usual manner as one plot; there is a stong preferred orientation N14^{o}W-S14^{o}E. The dip measurements are not used to deduce direction of ice movement, although they are probably genuine; this is because the dip measurements of the first 36 particles are just possibly suspect due to slight slumping of one portion of the till.

These four fabrics 46, 47, 66, and 67, spread over several square miles of the southeastern part of the Esk Basin, all exhibit a north-south orientation and three of the four show the movement to have been from the south. All four locations have considerable thickness of drift beneath the actual fabric site so the tills investigated are quite probably not the respective basal till at these sites. In the case of fabric 67 at Kirkhill Bank, this can be demonstrated directly.

The stone counts at these four fabric sites again generally support the fabric analyses. The exceptionally high proportion of greywacke at Kirkhill Bank proves that the ice movement was from the south, a useful point of evidence since the direction of fabric analysis is suspect. The thickness of the top till here, the strength of orientation and the amount of greywacke all indicate that the last ice movement was a quite substantial one from the Southern Uplands. By contrast, the low proportion of greywacke at Fullarton Water is associated with an ice carry from the southwest, passing over only a small extension of greywacke bedrock. An additional stone count at R, on the side of the North Esk gorge at Roslin, indicates by the high greywacke content, that the till exposed is intermediate till, derived from the south.

There remains for consideration a number of fabrics in the neighbourhood of Penicuik (fig. 6.6) with approximately north-south orientation. Fabrics 35, 42, 56, 57, 59, 63, and 65 are all from within two miles of

Penicuik, but in spite of this density, or perhaps because of it, the small pattern they form is not at first sight internally consistent.

The upper till in the section on Cuiken Burn (fig. 4.9) shows a good orientation N11°E-S11°W with ice movement from the south (fabric 63). This is particularly satisfactory as the orientation is entirely different from the orientation in the lower till at this section, in fabric 60 already described. The orientation is not however parallel to the line of the Pentland edge. Such an orientation would be about N40°E at this point.

Two fabric analyses were made at the north side of Auchencorth Moss between 750 and 800 ft. O.D., along the course of Black Burn. The site of fabric 35 shows 3+ feet of dark brown, unweathered till, truncated by 2 feet of river alluvium. Bedrock is exposed within a few yards of the section, so the till is the basal till in this area. The fabric diagram shows a strong orientation N15°E-S15°W with movement from the south. Fabric 65 is from a section further upstream on Black Burn (fig. 4.12). At this point the full thickness of dark brown, unweathered till is preserved. The top of this till is 22½ ft. above stream level, 13½ ft. of till being exposed. The remaining 9 feet is slumped, but other nearby sections show that the same brown till continues downwards and rests directly on bedrock. Fabric analysis 65 was made 8½ ft. below the top of this till layer, and gives a very strong orientation and dip indicating ice movement from S39°W. As a spot check, a further 10 particles were measured 9 ft. above stream level, and show the beginning of what could be a similar orientation pattern. These two fabrics from Black Burn together indicate a basal till of about twenty feet thickness derived from ice moving from south-southwest. There is of course a higher till at one of these sections (fig. 4.12), and the fabric analysis from this is discussed later.

Sited roughly between the Cuiken Burn (63) and Black Burn (35 and 65) sites are four more fabric sites, numbers 42, 56, 57, and 59 (fig.6.7); the results here show movement from the southeast rather than the, by now characteristic, southwest. These are all satisfactory sites and the fabrics must therefore be accepted at their face value as giving an approximation to the true style of till movement.

Fabrics 42 and 56 are from similar river bank sites on Lead Burn between Howgate village and Halls Bridge, just below 750 ft. O.D. The till is rough and unweathered, and very dark grey-black in colour. Further downstream it is seen to be resting directly on bedrock. Both fabrics show orientations approximately northwest-southeast with prominent dip directions indicating movement from the southeast. Fabric 42 has a low nominal strength due to the number of transverse orientations, whereas fabric 56 is very strong.

Fabric 57 is from the top of the drift succession overlooking the Black Burn gorge just before it joins the North Esk. This is at about 700 ft. O.D. From the surface downwards is about 4 feet of weathered till grading into 30+ feet of unweathered dark brown till. Fabric analysis 57 at 7 ft. depth shows a strong pattern representing movement of ice from the south-southeast.

Finally in this group, fabric 59 is from the 3 feet of sandy till preserved between thick-bedded sand at Kirkhill, Penicuik (fig. 4.13). The fabric pattern is of orientation almost north-south, with dips indicating movement from the south.

The stone counts from the fabric sites around Penicuik support and re-emphasize the differing directions of ice movement that the above fabrics show. The two sites in basal till at Black Burn (35 and 65, Table 4.1) show similar proportions of rock types, although the more westerly source of ice shown by fabric 65 is underlined in the stone count by a greater proportion of Pentland rocks. Each site shows about a tenth of Southern Upland greywacke. Rocks of Highland origin were found more frequently by McCall and Goodlet (1952) than by the writer; otherwise the observations agree.

The stone count at Cuiken Burn is not exactly predictable, as it contains 40 per cent of 'other' lithologies, whereas a higher proportion of greywacke would be expected. In fact the stone count from site 63 differs only from that of site 60, the basal till in the same section (fig. 4.9), in that the basal till contains no greywacke at all.

Representative of those fabrics showing movement from the southeast is stone count 42 from Lead Burn, Howgate, which includes over 50 per cent of greywacke. The northern limit of greywacke is just half a mile from Lead Burn to the southeast. So not only does the stone count result agree with the fabric analysis, but also if the fabric had indicated movement from any other direction, for example the southwest, then the high proportion of greywacke would be surprising; in other directions but southeast, the northern boundary of Southern Upland rocks is much more distant.

A total of 16 fabrics from the Esk Basin showing movement approximately south to north have now been discussed. They have been grouped together in this way because their fabric results are similar, but it will be clear that they are not all necessarily the product of one movement. Unlike the first major group of fabric results showing movement west to east, which was associated with basal till, the second group is not obviously associated with any particular stratigraphic horizon. A number of the sites are in the topmost till, notably numbers 42, 44, 46, 56, 57, 63, and 67. On the other hand the till at Boghall Burn (22) is covered by Roslin Till; and the till at sites 35 and 65 at Black Burn is succeeded by a thinner grey till. The remainder occur somewhere within the drift succession, although those on Glencorse Burn are certainly near bedrock.

At Cuiken Burn and at Kirkhill there are two tills, the basal till in each case indicating movement from west to east (fabrics 60 and 68) and the upper till in each case indicating movement from south to north (fabrics 63 and 67). The movement from the direction of the Southern Uplands is therefore later than the movement from west to east in this area, a movement with which farther north are associated the major erosional features near Edinburgh. On aggregate, most of the second major group of fabric analyses can be associated with the upper tills at Cuiken Burn and Kirkhill. The intermediate or high position of the tills in the respective sections, the thickness of the till and the strength of orientation point to a substantial, later movement from the south.

The only fabrics that are particularly anomalous to this summary statement are those around Penicuik, and these must be examined further (fig. 6.7). The movement southwest to northeast recorded by fabrics 35 and 65 at Black Burn is in till directly overlying bedrock. In other words there is no earlier till representing the earlier movement west to east.

There are two possibilities by which these fabrics may be explained; the first is that the original basal till was not deposited or may have been deposited and then eroded by the later movement from the southwest. In favour of this explanation is the existence of a number of armoured till balls included within the lower till. These are roughly spherical lumps a few centimetres in diameter, composed of till, in some cases with a pebble as nucleus, but always with smaller fragments of rock as a surface protection. A few of these were found quite by chance in this section. They were not noticed anywhere else in the fieldwork area. The till balls are derived from a previous deposit, which can have been an earlier basal till or a lower part of the same till.

The second possibility is that the southern edge of the ice movement west to east did not extend as far as Auchencorth Moss, and that the movement from the southwest, the earliest movement represented here, was contemporary with the west-east movement on the lower ground. Against this are the facts of ice movement from the west at Cuiken only 100 ft. lower, and of reported east-west striations over the Pentlands, west of Auchencorth Moss at considerably greater elevation (Maclaren, 1849). The former possibility, that the original basal till is not now represented, seems the more likely for Auchencorth Moss, as it must also certainly be true for site 29 at New Pentland where a similar circumstance holds. There must be a southern limit to penetration of the west-east ice sheet along the north side of the Southern Uplands; but New Pentland and probably also Auchencorth Moss were submerged by this movement.

The till at Lead Burn is grey-black, whereas the lower till at Black Burn, which has been associated with it in the description above, is dark red-brown. A better match with the Lead Burn till is the upper till at Black Burn, the 3¾-foot, grey till shown in fig. 4.12. Also stone count 39 (Table 4.1) from this upper till, by its high proportion of greywacke, matches the stone count at Lead Burn better than the stone count in the subjacent lower till matches it. A fabric analysis from the upper till might be expected to agree with one of the other tills and so help further in associating them. However this is unfortunately not the case: fabric 39 from the upper till at Black Burn, a fabric analysis not previously described, is quite different from fabrics in both the other tills. The orientation is N67°E-S67°W with no preferred dip direction. The fabric has a low chi-square value, and contains a large asymmetrical transverse population, dipping north. Such an orientation in a thin top till does not occur in any other fabric recorded. The presence of 40 per cent of greywacke suggests a southerly source for the till rather than a roughly easterly or westerly source as indicated by the fabric.

There is a suggestion that this fabric result is an exceptional one, not proving one direction of ice movement. The stone orientations were taken between 2 and 3 feet depth in the thin upper till, which includes a thin sand horizon at 2½ feet depth. The orientations vary slightly with depth, being more southwest - northeast near the base and west-east higher up. Although an extra 50 particles were measured at a later date when the original plot of 100 gave an inconclusive result, the final plot of 150 particles still does not provide a strong peak. However it was argued in Chapter IV that the particular style of deposits at Black Burn indicates two units of deposition, and it is still considered that the thin upper till represents a later readvance over the red-brown till.

terrace-remnants has enabled confidence in conclusions about these features that would not have been possible with less rigorous methods.

Fieldwork for this research started in 1961 and was completed in 1965, with the minor exception of some height measurements on river terraces completed at a very late stage. During the first and second summers, the major emphasis was on becoming familiar with the region and in making till fabric analyses. These first analyses involved much experimentation and so were completed very slowly; more analyses were completed in 1963 than in either of the previous summers. Fabric analyses usually involve extremely awkward field conditions, with up to five hours spent against the same till face, and this aspect of the work never proceeded as rapidly as was hoped.

The glacial landforms of the Esk Basin were mapped mostly during 1962 and 1963 on days when conditions were unsuitable for fabric investigations. The official six-inch Drift Geology sheets were used as the base for all field mapping. These sheets proved to be extremely reliable: none of the drift formation that could be checked was faulted except on very minor details.

The field mapping brought into focus the great extent of the outwash and river terraces of the Esk, and thus their importance towards interpreting the deglacial and post-glacial sequence of events. The terraces were mapped as part of the general landform mapping and height measurements were made on them later, during 1963-65. The height data also took longer to obtain than had been hoped, particularly because of the vertical height ranges to be covered within the Esk gorge. The work was in any case not rapid because it had been decided, firstly, to carry out the work accurately

Rather as an appendage, two further fabrics from the middle Esk Basin remain to be described. Fabric 64 is from within the bedrock gorge of the River North Esk at New Saughton Hall. About 20 feet of very compact mid-brown till is overlain by rhythmites (fig. 4.22). The fabric was taken from mid-way down the exposed face of till to the north of a small tunnel. At this depth in the gorge, in a position similar to the site of fabric 45 at Auchendinny, the till is probably true basal till. The fabric pattern shows orientation N48^{o}E–S48^{o}W with movement from the southwest. The direction of movement is therefore midway between the west-east of the basal till and the south-north of the intermediate till and, in the absence of a full stone count, cannot be conclusively grouped with either. But a limited count of 50 stones did not reveal a single greywacke, and on the basis of this, the fabric is included in fig. 6.4 with the basal fabrics.

Similarly there is no indication from fabric 23 of the direction of ice movement responsible for the till overlying Carboniferous Limestone at North Middleton Quarry. The quarry is a well-known excavation, described by Walton in Mitchell, Walton and Grant (1960, p.117). As exposed in 1962, the southwest end of the quarry showed a wedge of unweathered, dark brown till, flat-topped but varying in thickness from 3 to 12 feet to accommodate the limestone dipping at 12^{o} to the northwest (fig. 6.8). The till grades up into 18 feet of glacio-fluvium which becomes coarser upwards and is locally succeeded by colluvium (Table 4.3; sample 105). The fabric pattern is of randomly orientated and randomly dipping particles. The till contains many cobbles and boulders of the local North Greens Limestone, which may have precluded the orientation of interstitial material, as in the case of fabric 30 at Swineburn. The fabric is tentatively located in fig. 6.6 with the fabrics from the intermediate till.

Esk Basin: Roslin Tills and related tills. The remaining fabric analyses from the Esk Basin were all taken from the area around the north end of the Pentlands, a critical area at the junction of the Midlothian coastal district and the enclosed Esk Basin (fig. 6.9). The northern and southern parts of this area have different drift successions. The southern end is underlain by thick glacio-fluvial or glacio-lacustrine sand terminating in a zone roughly east-west from Hillend to Eskbank. North of this is a district of broken relief around Edinburgh, the till-covered low ground being interrupted by the Gilmerton Ridge, the Braid Hills, and Blackford Hill.

The majority of fabric analyses were taken from the Roslin Till, within the area of Roslin Till described by Mitchell and Mykura (1962). The remainder were derived from weathered top till of a very similar appearance from sites further north nearer Edinburgh.

Fabrics 1, 2, 3, and 12 were among the first fabrics taken in connection with the entire research programme, as the numbering suggests. They all relate to the same site at Bilston sand pit, opposite Langhill Farm on the B7006 road. The sand pit was formerly much more extensive; the ground for several acres around the present pit has now been returned to agriculture leaving the surface lower than before but deceptively natural in appearance. The fabric analyses were made along a local rise in the ground, the last part of the sand pit to be worked. Roslin Till, 4-6 feet thick, overlies about 30 feet of current-bedded glacio-fluvial sand, the till being removed as overburden in the sand pit workings.

The four fabric analyses would be expected to give the same result, and, assuming no variation in personal error, the amount they differ is an indication of the possible true variation in the till fabric. In this case, fabrics 1, 3, and 12 agree quite well, but are not identical. The orientations are respectively 16°, 41°, and 20° east of north, a spread in orientation of 25°. Fabrics 1 and 3 show no preferred dip direction; fabric 12, which was carried out in the laboratory, shows a preferred dip to the northeast. In strength of orientation, there is reasonable agreement, χ^2 varying from 49.5 to 33. Tills at the surface, like the Roslin Till, which are leached and show particle decomposition, worm casts, and hair roots, are very much more difficult to work with than the unweathered tills which have been discussed up to this point. In the circumstances, the fabric results appear quite satisfactory.

Fabric 2 exhibits a markedly random orientation pattern. Although the site appeared natural when the analysis was made, the fabric pattern is so unlikely for a natural till, that the site was revisited, and definite signs of disturbance were found. These included nearby tile drainage, household rubbish and unusual vertical structuring. Therefore the fabric was discounted; it is included here for purposes of comparison.

A mile to the south of Bilston, fabrics 4 and 24 were taken from Roslin Till in the sand pits at Oatslie, overlooking the River North Esk. Each fabric shows a moderately strong orientation northeast-southwest. Dip measurements were not taken for fabric 4; fabric 24 shows no preferred dip direction.

Six further fabrics, numbers 6, 19-21, 34, and 41, have been recorded from the Roslin Till, all further north than Bilston and Oatslie. Fabric 6 from Boghall Burn is from the upper till at this site and shows an orientation N35°E-S35°W, much stronger than the orientation in the subjacent lower till, and with a dominant dip showing movement from the southwest.

Fabrics 19 and 20 are from sites 130 feet apart in the Roslin Till which forms the overburden at Clippens sand pit (fig. 4.21A), Being from adjacent sites, these fabrics should therefore also agree. The orientation directions are respectively 17° and 9° west of north. Each orientation is quite strong, but only fabric 20 shows a dip direction. This indicates ice movement from the north. By contrast, fabric 21 from the very thin till overlying the 25 feet of sand at Burghlee sand pit shows as strong and orientation but with movement from S25°E. And a fabric analysis at New Pentland, at the site of the vegetation remains described in Chapter IV (figs. 4.6A, 4.25), shows a weak orientation approximately north-south with movement from the south.

The final fabric within the area of Roslin Till, fabric 34, is from the thin till overlying the thick bedded sand at Haveral Wood (fig. 4.3). The sand pit, opened in November 1961, has expanded (1965) to destroy the actual fabric site. The glacial drift in this district is interrupted by meltwater channels and river terraces, so that the till capping cannot be traced directly into Roslin Till further southwest. However, the thin till is visually identical to the Roslin Till, showing sandy pockets, and the whole being gleyed with vertical cracks. The fabric shows a strong orientation almost north-south with the dip direction indicating movement from the north.

These eleven fabrics, excluding fabric 2 from Bilston, display a considerable range of orientation, from N48°E to N25°W, which might suggest that they are from different tills; but this is not the case as, except for Haveral Wood, the Roslin Till can be traced directly from one site to the next. Fig. 6.9 shows that the orientations do in fact form a single pattern, from northeast-southwest at Oatslie veering through north-south to north-northwest-south-southeast at Old Pentland. This pattern is parallel to the edge of the Pentland Hills, which suggests that the local relief controlled the direction of movement of this particular glacier. Of the dip directions, three suggest movement to have been from the south, that at Haveral Wood and one each from Bilston and Clippens point to movement from the north, and the remaining five show no preferred dip directions. This line of evidence is therefore quite inconclusive. The eleven fabrics all show a fairly strong orientation, except for the site with vegetation remains at New Pentland. The much weaker orientation here can be explained as due to modification of the fabric by root action.

Because the dip measurements in the Roslin Till are not conclusive on the direction of ice movement, the five sets of stone counts (Table 4.1, Chapter IV) assume an added significance. At Bilston, Oatslie, Boghall Burn, and Clippens/New Pentland, the stone counts give similar results (fig. 4.18) each with about a third of Carboniferous and 'other' lithologies, and a fifth of Pentland volcanics. By contrast, Haveral Wood, further east, shows 70 per cent of 'other' lithologies. This very high proportion of non-local material is matched only in the skeletal basal till at New Pentland (fig. 4.21B) and the basal tills at Park Burn (fig. 4.11), and at Silverknowe, which suggests that the Haveral Wood deposit has a northerly rather than a southerly source. The dip measurements in fabric analysis 34 support this.

The fabrics show a trend approximately north-south; if the movement were from the south, then a higher proportion of Southern Upland greywacke might be expected than is present. Greywacke is uncommon (0-4 per cent) and in any case might have been derived from the Pentlands (Anderson, 1940). On the other hand, the proportion of greywacke carried in a glacier from the south might be somewhat reduced by the distance from the Southern Uplands, as is seen by the very variable proportion of greywacke in the intermediate till of the Esk Basin. However, the stone counts in the Roslin Till do not confirm the southerly source for the Roslin Till postulated by McCall and Goodlet (1952) and Mykura (in Mitchell and Mykura, 1962).

The remaining fabrics were taken from the Liberton-Craigmillar Ridge and the Gilmerton Ridge. Fabric 36 is from the weathered till on the Liberton-Craigmillar Ridge, an ideal site on flat ground that gradually drops away in all directions. The section used was on a building plot fronting onto the Lasswade Road opposite Liberton Hospital; the site has since been completely built over. A thickness of 4 feet of till was revealed, with bedrock at an unknown depth. The till is leached with hair-roots and worm-casts throughout. The fabric analysis shows a strong orientation N34°W-S34°E with the predominant dip direction signifying movement from the northwest.

On the Gilmerton Ridge, till fabric sites were established on both the northwest and the southeast flanks; the sections have already been described in detail because they show superposed tills (figs. 4.8 and 4.9).

All four fabrics from Gilmerton Ridge are from sloping sites, so that the slope is a possible factor affecting the result. On the northwest flank, a fabric from the lower or basal till (fabric 50) has already been seen to be unaffected by the slope, the result indicating ice movement approximately from the west. Fabric 49 from the upper till at the same site (fig. 4.8) is quite different to fabric 50, and also quite unlike most till fabrics in particle arrangement. The fabric is open to several interpretations. Examination of the particle plot will show there are two maxima, not at right angles. The larger grouping is approximately northwest-southeast, which may indicate some slump movement. The slope at the surface is here down to N60°W at about 5°. It does not follow that because the lower till at this site is unaffected by slope, the upper till is also immune; the upper till is weathered, and by its position is more liable to surface movements. On the other hand, an orientation northwest-southeast forms part of the regular trend of upper tills around the northeast part of the Pentlands, as fig. 6.9 shows. The secondary peak is approximately north-northeast - south-southwest, being more evident in the northern quadrant. This grouping could have occurred by chance, although this is statistically improbable, or, if the main grouping were due to the slope, the secondary peak could relate to a genuine ice-movement. This fabric seems to be a case where one hundred measurements are not sufficient to give an adequate pattern. The chi-square test for calculating the orientation produces an answer of N24°W-S24°E, the lesser grouping pulling the answer off the centre of the greater grouping.

On the southeast flank of the Gilmerton Ridge, fabrics 14 and 15 again have unusual patterns. From the section illustrated in fig 4.9, fabric 14 shows two peaks with directions very similar to those in fabric 49, but in this case so evenly balanced that the chi-square test is not able to produce a preferred orientation. The two orientation peaks relate to two different depths in the till (fig. 6.10); particles 1-50 relate to a working depth below ground level of 3 ft. 6 in. to 3 ft. 10 in., and are responsible for the northwest-southeast orientation; particles 51-100 were taken after a further 2 inches of till were removed, at a depth of 4 ft. to 4 ft. 3 in. The second fifty are responsible for the north-northeast - south-southwest orientation. It does not appear from the section that there are different till layers at these depths (fig. 6.10), but the two orientations are consistent with other postulated directions of ice movement, an earlier one south-north in the Esk Basin, and another one around the northeast part of the Pentlands. As in the case of fabric 49, the fabric may be the result either of the slope or of regional movements, or a combination of both. Such variation has not been found anywhere else in such small vertical extent. The fabric of a till may become reorientated by overriding glaciers (MacClintock and Dreimanis, 1964), and presumably also by secondary movements of the surface layer down slope, but some defomration or structural break at the horizon of reorientation would be expected.

Fabric 15 was obtained 140 yards northeast of fabric 14 in a similar site. Being taken 3½-4 feet down in 7 feet of brown till with no apparent variation, the fabric shows a moderate orientation N34°W-S34°E. With the ground sloping S20°E at 5°, this fabric may again represent either a secondary slope movement or an original regional movement.

The fabric analyses from the Roslin Till and related tills allow far less firm conclusions than do the analyses from the basal and intermediate tills. Assuming that these tills all relate to one ice movement, the orientation pattern suggests movement around the base of the Pentlands, but the particle dips do not indicate whether the movement was from the northwest or from the south. Stone counts also are not conclusive. The trend of the more northerly located of these fabrics suggests movement from the northwest into the Esk Basin rather than the other way, as a glacier descending through the Esk Basin is more likely to have continued downslope toward the sea than have veered northwestwards up over higher ground at Liberton. The morphological evidence to be presented in the next chapter also favours this alternative.

Tyne Basin. The eight fabric analyses scattered in the Tyne Basin are the last to be described and complete the regional coverage. These fabrics relate to 5 localities, and generally substantiate results already obtained in the Keith Water area.

Fabrics 38 and 51 are from basal till and each shows an orientation approximately east-west, with no specified direction of ice movement (fig. 6.4). Fabric 51 is the more satisfactory, showing a strong orientation in a direction that matches the moulding of the till plain in East Lothian. This is from fresh unweathered till; fabric 38 is from an old section, and the extremely low orientation strength may be due to the greater difficulty in working an older desiccated section (fig. 4.1).

The movement from the Southern Uplands represented at Keith Water by the middle till is brought out by fabrics 18, 52, and 72 from widely spaced sites (fig. 6.6). Fabric 18 is from East Water, an upper tributary of Keith Water. The section does not show the multiple tills as seen in the Keith Water sections, but just 9 feet of dark brown till truncated by 2 feet of river alluvium. There is thus no direct stratigraphic correlation with the Keith sections. Fabric analysis shows an orientation N38°W-S38°E, with ice movement from the southeast. The orientation is exactly normal to the Southern Upland faultline scarp of Soutra Hill. No full stone count was made from the till, but of the small number of stones examined, greywacke was more abundant than Carboniferous or Old Red Sandstone, unlike the overlying alluvium in which Old Red Sandstone is dominant. Orientation direction, dip direction, and lithology all agree on a Southern Upland source for this material, and so the fabric may be grouped with numbers 10, 17, and 69 at Keith. It agrees with these fabrics in orientation strength.

From the west bank of Birns Water above Milton Bridge, fabric 52 shows a moderately strong orientation indicating movement of ice from about due south, a result which contrasts with the basal fabric nearby (51); the results of fabric orientations 51 and 52 along Birns Water once again completely substantiate the accompanying stone counts.

There is a further point of interest connected with the site of fabric 52. The middle till as exposed appears to be formed of three superposed parts: at the base 4+ feet of moderately compacted red-brown till, followed after a sharp break by 4 feet of very compacted dark grey till, which in turn grades up into 4+ feet of compact grey-brown till. Fifty fabric particles were measured in each of the two lower parts; the results are identical and so they are presented as one fabric. Also, separate stone counts, 52A and 52B, were made in each of the two lower with level and staff, and secondly, that each levelling traverse should run from a bench mark of known height and should close satisfactorily. Although some of the heights would have been obtained more rapidly by a number of other methods, such as working from spot heights, or using other equipment, it was considered that heights so determined would not necessarily be sufficiently accurate.

Levelling assistance was provided by about a dozen individuals, none working for more than a few days. Some of these were research students who gave their services on a reciprocal basis or in exchange for coaching in surveying.

Organisation of the thesis. The organisation of the thesis follows a straightforward pattern. Following this introductory chapter, Chapter II represents the physical milieu and Chapter III summarizes the quite considerable amount of earlier work carried out in the Edinburgh area. This summary mentions many papers whose results are incorporated into descriptions and discussions at later points in the text. The account of the field work starts at Chapter IV with a lengthy treatment of the superficial deposits forming the drift cover. The deposits are described approximately in chronological order, beginning with the basal till in this area and concluding with periglacial effects and post-glacial vegetation remains.

Any investigation of the drift cover involves the correlation of like deposits over widely scattered locations, at first based on visual inspection, and later re-assessed with the aid of systematic tests. The conclusions with respect to the till deposits are deliberately presented sequentially, as the evidence is described: at the start of Chapter IV, parts: Table 4.2 shows that they are similar except in the proportion of greywacke at 25 and 15 per cent. Therefore, the superposed layers of till are thought to have the same origin as the middle till along Keith Water where the red or grey colouring depends on whether ice traversed or missed the local outcrops of Old Red Sandstone. The same succession of red and grey superposed tills is present further downstream at a bend of Birns Water near Milton Farm.

The fabric orientation in the weathered surface till at Cotty Burn (72) again might have been correctly predicted from the corresponding stone count. The stone count includes a significant proportion of greywacke, and fabric 72 indicates movement from S16°E.

The final three fabrics, 25-27, from an ideal site adjacent to the A1 road east of Gladsmuir, cannot be explained satisfactorily, as they are neither mutually consistent, nor in agreement with any suspected ice movement. But the material and the conditions under which it was worked are also unusual. The fabrics are all the result of laboratory measurements on blocks of till taken from a temporary trench, in which washed till (Macmerry-type; see Chapter IV) occupied the top 2-3 feet. The till used is thought to be from the top of the (Winton-type) unwashed clayey till beneath the washed till, although the junction was often very indistinct. Both washed and unwashed tills are leached, but the Winton-type till contains many more undecomposed particles.

Fabrics 25-27 show three very different results, respectively a weak orientation northwest-southeast, a moderate orientation with movement from north-northwest, and a non-preferred orientation showing a concentration northeast. There is no morphological evidence and no other fabric evidence for a movement from the northwest, such as fabrics 25 and 26 might suggest; if the Winton-type till is basal till then an east-west orientation would be expected. The north-south orientation of fabric 26 might indicate the middle till, but the dip direction does not support this. An alternative explanation for the three fabrics is that they are from an ablation till, the meltwater product of stagnating ice on this quite flat site, and so do not show any regional movement.

Summary of fabric evidence in Esk and Tyne Basins. The individual till fabric analyses have now been examined at some length. They have been grouped largely in a stratigraphic context: the fabrics from the bottommost till or basal till, separated from the fabrics of tills in the middle of the stratigraphic succession, and further separated from the topmost tills. This grouping has broken down in a few cases where the three tills are not present or where the stratigraphic position of a particular till was not clear; in these cases the fabric has been grouped according to its orientation. The maximum development of multiple tills is in the middle parts of the Esk and Tyne Basins; further south the intermediate till rests directly on bedrock in places, while further north the basal and intermediate tills cannot be identified as such.

In one respect the fabrics have led to a modification of the stratigraphic sequence as previously understood. The so-called "tough argillaceous basal till, which was deposited by ice from the Highlands" (Mitchell and Mykura, 1962, p.111) is seen on the basis of the fabric results to be two tills, one deposited by movement from the west, the second by movement from the southwest. As the two tills have similar physical appearance, it is easy to confuse them; but where a full sequence of deposits is preserved, they are seen to be separated by thick glacio-fluvium.

The fabric results show that the sequence of glacial movements is the same in the Esk as in the Upper Tyne Basin, and there is no need to postulate different case histories. In each case, the earliest movement of ice is recorded by the basal till with fabric orientations indicating movement from the west or southwest. In the immediate lee of the Pentlands the direction is true west-east, but further east the direction is more nearly southwest-northeast, as the ice sheet moving down the Firth of Forth is more influenced and deflected by the high ground of the Southern Uplands. The striation pattern on small-scale glacial maps of Scotland shows a similar deflected flow.

The full drift successions at Kirkhill and Costerton indicate a period of meltwater conditions before the next main ice movement, from the southwest. This movement is very well recorded throughout the district (fig. 6.6), particularly by the many fabric sites adjacent to the Pentlands. There is more variation in the apparent directions of movement than with the earlier glacier-flow. The unusual fabric orientation pattern south of Penicuik has been described as a somewhat later phase of ice movement from the south; other variations of this glacier flow may have been caused by local relief. The easterly component in fabric 67 on the South Esk may be due to its position against the southwesterly part of Roman Camp Ridge, while the movements on East Water (fabric 18) and on Keith Water are directly away from the line of the Southern Uplands scarp. In fact, the movement from the southwest, represented by the intermediate till, is everywhere related to the relief of the district and in this respect differs from the earlier glacier-flow which transgressed the relief.

The northern limit of the intermediate till is not marked by any morphological feature, and on the coastal plain of East Lothian, the equivalent of the basal and intermediate tills of the middle basin area has not been found. It appears likely that the glacier from the southwest continued northeastwards and eastwards either joining or succeeding the Firth of Forth west-east movement, all producing a single direction of ice movement and therefore a single till orientation along the coastal plain.

The final movement in both the Esk and Middle Tyne Basins is of a more local nature. The associated till has been traced over limited areas only. From the stratigraphic succession, the till examined by fabrics 5 and 7 in the Tyne corresponds to the Roslin Till in the Esk. But in these more weathered layers, the fabric analyses do not satisfactorily illustrate the local direction of ice movement. In the Esk, the trend of ice-movement is clearly seen: in the Tyne Basin the top till is in an advanced state of erosion and insufficient samples were found to allow any real conclusion; the rather dubious orientations west-northwest - east-southeast do not necessarily correspond with anything in the Esk.

<u>Significance of interstratified deposits</u>. In Chapter IV were introduced many examples of superposed tills and interstratified tills and sands. Many of the fabrics described previously in this chapter are taken from the tills of these multiple-unit deposits, and so it remains only to comment on the general significance of the multiple units in the light of the fabric results.

There have been a number of earlier observations on the multiple till sections. Following upon one of the original descriptions of till-sand layering by Croll in 1870, Somervail (1877) interpreted the interstratified beds as related to an oscillating ice-front. Somervail also considered that another theory, that of alternating glacial and interglacial periods, had no validity. From their examination of the Keith Water sections, particularly the big section at Red Scar (fig. 4.14), Kendall and Bailey (1908) concluded that an oscillating ice-front was in fact responsible. They supposed that a residual ice-sheet covered the low ground to the north, and ponded up lakes between the ice-front and the ice-free Southern Uplands. In these lakes, thick beds of sand were deposited and then the lowland ice re-advanced southwards over these sands, depositing the intermediate till. In the words of Kendall and Bailey, the lowland glacier "was not melting away as an inert mass of ice, but ..... was ready, when climatic conditions favoured, to re-advance on to the floor of the temporary lake which spread out before it, and there deposit a covering of boulder clay upon the sands and silts which has previously been collecting. ..... the oscillation recorded here seems to have been of considerable magnitude" (1908, p.17).

The same evidence was quoted in a wider setting by Charlesworth (1926), who thought that the interstratifications probably implied oscillations, although he was aware that Kendall and Bailey's interpretation had not been proved. Other lines of evidence for oscillatory movement of the ice-margin in East Lothian were examined by Sissons (1958a) and were found wanting.

Almost all the interstratified deposits described in this study have been interpreted as representing two or more distinct depositional units. In the case of Red Scar, fabric analyses and stone counts confirm that the intermediate till is derived from the direction of the Southern Uplands and not from a re-energised northern ice-sheet. There is no indication of transgressive or oscillatory ice movements. Similarly in the cases along Birns Water, Black Burn, and other multiple-till localities, the fabrics show the depositional units to have quite independent origins.

There are one or two cases where the theory of ice-margin oscillation is more plausible to explain interstratification: the strikingly regular alternation of till and sand in the Park Burn section (fig. 4.11) might be considered from its appearance as being formed by an oscillatory advance-retreat type of movement. But the section has already been interpreted as being a single depositional unit, and the fabric results from the separate till bands are so similar that not even oscillation seems appropriate. This is regarded as a case where the glacier depositing the till is a wet-base glacier (Carey and Ahmad, 1961) with basal meltwaters and glacial deposition fluctuating; there is no evidence to suggest a reason for the fluctuation. The alternating thin beds of red till and sand in the sand pit at Keith Marischal (fig. 4.17) are likewise too regular and undeformed to illustrate the unstable conditions at an oscillating ice-cliff; they are also interpreted as subglacial deposits with temperature fluctuation causing differential basal melting.

<u>Local and secondary movements of till</u>. This chapter is concluded by a discussion of some till fabric non-regional results and an appraisal of the adequacy of fabric methods, before the regional story is taken up again in Chapter VII.

Non-regional movements of till, either original local movement due to the topography, or secondary movements due to slumping or climatic action, are not always easy to distinguish. One or two fabrics have already been described where, due to their hill-slope site, there is some possibility of a non-regional result. The five till fabrics described below all show an orientation resulting from local movements.

To assist identification of such fabrics, two fabric analyses were completed froma head deposit outside the fieldwork area, in South Devon. The process of solifluction responsible for a head deposit is not necessarily the same as that as slumping or mass movement, but in each case the parent material is broken up and particles are moved downslope by processes of which gravity and water-lubrication are common to both. The fabric of the resulting stabilized deposits should therefore be similar.

The two head fabric analyses were carried out in thick head overlying raised beach deposits at Wembury on the South Devon coast. The morphology of this coastal strip has been examined by Orme (1960). The head material is derived from slate and limestone bedrocks, providing many blade- and rod-shaped particles suitable for orientation measurements. In vertical section the particles show visible alignment as well as a flow arrangement around and over larger stones. Both head fabrics were taken from near the base of thick head, in one case the line of section being parallel to the regional slope of the ground, in the other case being normal to it. The fabric results, H1 and H2, (Table 6.2), show very strong orientations, about 90 per cent of the particles being grouped in the primary orientations and only 10 per cent being scattered elsewhere in the fabric plots; there are very small transverse peaks. Neither fabric shows a dominant dip direction, the majority of particles lying near horizontal. The orientation direction in each case is close to the overall slope of the ground. The orientation strengths, as given by the chi-square values, are greater than any values recorded in till. These two tendencies, for the orientation and ground slope directions to agree exactly, and for a high orientation strength, may be considered diagnostic of well-developed head fabrics generally.

Orme (1960) mentioned that the large fragments of bedrock had their long axes aligned downslope, but he did no quantitative work on the South Devon head deposits. Also Lundquist (1949) has recorded orientation patterns of the coarser material in certain forms of patterned ground in Scandinavia; Hoppe (1952) has published the result of an orientation analysis in loose scree; and Ragg and Bibby (in press) have produced solifluction fabrics from the Southern Uplands of Scotland. But there is little other work recorded on this branch of fabric study.

The five till fabric analyses described below are also characterized by an orientation directly down the slope and, with one exception, a very high orientation strength (Table 6.2). Fabrics 31 and 58 represent sites where the surface layers of till have cambered over the unweathered till below, due to undercutting of river banks, producing an orientation normal to the exposed face. This can be demonstrated satisfactorily at each of the sites because there are fabrics from adjacent unmoved till for comparison. Fabric 31 is from the intermediate till exposed near Flotterstone along Glencorse Burn; fabrics 32, 33, and 43 give the regional ice-movement in this vicinity, which is from the southwest. The Flotterstone fabric was taken 5 feet down and 2 feet back from the steeply sloping till surface; this was apparently not quite enough to escape the cambering, as the fabric still shows a weak orientation directly downslope.

From fig. 6.11 it can be seen how the particles at 3 feet depth in the thick till at Pomathorn are aligned downslope, while at 7 feet depth the same till, less weathered, has an orientation which relates to other fabrics in the district. The dominant dip of fabric 58 is upslope, relating to a rotational slump movement.

Movement of till downslope at some date subsequent to its deposition is demonstrated by fabrics 40 and 71 from Esperston and Partridge Burn respectively, both on the foothills of the Southern Uplands. The large majority of particles dip upslope at Esperston, denoting a slump rotation. The fabric at Partridge Burn was taken at depth and does not appear to have suffered any secondary movement. But the fabric orientation is directly downslope (fig. 6.2) and has a very high chi-square value; furthermore a stone count from the till (Table 4.2) gives proportions normally associated with basal till derived from the west rather than the Southern Uplands to the south. The till is probably basal till reorientated downslope. The unusual features of the section illustrated in fig. 6.12 from Haveral Wood are due to a combination of recent slumping and subsidence due to coal-mining. Till grades downslope through washed till into coarse glacio-fluvium, and is truncated on the upper side by a fault due to subsidence. A uniformly fine sand has washed down over this till subsequent to the recent faulting. The orientation peak is directly downslope, with the dips following the slope of the till layer itself.

Appraisal of till fabric analysis procedures. From the lengthy descriptions of the till fabrics in the Lothians, it will be apparent that they are a very effective indicator of regional ice movements.

Fabric analysis results have proved far more useful than striation evidence in this area; striation evidence is poorly preserved and in any case limited to a few isolated areas of upstanding ground. Where sections exist, fabric evidence is possible over all the low ground and has the supreme advantage that it can be used on different tills to formulate a succession of events, whereas striations commonly register the direction of a single ice movement, the bedrock often being protected by one till from the action of glaciers depositing later tills.

Both fabrics and striations have an advantage over stone counts as an indicator of ice movement, as they indicate the trend of movement precisely to within a few degrees, and often illustrate the direction of movement as well. Stone counts are usually much less decisive, providing only a braad indication of direction of carry, particularly as with multiple tills the carry of erratics from source to final position is likely to have been by a series of legs in different directions. The stone counts in this study have supplemented the fabric analyses, confirming the direction of ice movement in some cases where the fabric analyses left doubt. An accurate stone count remains to be done, but in view of the work involved and the limited conclusions likely to result, fabric analysis seems the more worth-while alternative. Simpson (1960) described counting over 13,000 erratics from till and glacio-fluvium in the Manchester area. The conclusion even from this large number was not very satisfactory.

The main disadvantages of till fabric analyses are the time necessary to take measurements, often under awkward field conditions, and the practice necessary to achieve reliable results. Although the measurement only two different tills are identified, a basal till and a till described in this thesis as the Roslin Till, these being the two tills identified in previous writings. The results of stone counts given later in Chapter IV suggest that more than two tills may be present. This is confirmed in Chapter VI where fabric analyses show there is quite definitely a third till, intermediate in position between the basal and Roslin tills.

Chapters V and VI consider respectively the theoretical background and the fieldwork results of till fabric analysis, this technique being the major method of investigating the till. No other appraisal of till fabric analysis procedures as comprehensive as that of Chapter V is know in published form. This chapter also includes a description of the pioneering till fabric work carried out around Edinburgh in the nineteenth century.

Each example of till as exposed in a section has to be related to one or other particular ground moraine. The final decision on how to label each example of till has depended on the results of fabric analyses; the tills are distinguished from each other on a 'best-fit' principle by considering together stratigraphic position and fabric result, with erratic stone counts used as a secondary guide. Therefore the descriptions of the fabric analyses in Chapter VI are grouped by tills, each of the three tills in the Esk Basin, for example, being considered as forming a separate ground moraine.

The glacial morphology of the Esk Basin is presented essentially by maps; the main features of these maps are discussed in Chapter VII. The more detailed study of the extensive glacial outwash and terrace system of the Rivery North Esk forms Chapter VIII. This chapter carries the historical sequence of events from the glacial into the post-glacial.

of each particle must be very careful, the number of particles must be sensibly related to the object of the analysis. Taking into account time for travelling and preparing the site, one hundred measurements take only about 40 per cent more time than fifty measurements. For a reconnaissance regional study of glacial drift, where there are many sites available, a larger number of approximate results plotted to 10° would be more satisfactory than a smaller number of accurate results (Dreimanis, 1959a). Where the number of sites is limited and it is necessary to extract maximum information from each site, one hundred or more measurements would be desirable, perhaps followed by some statistical test.

In this study, the second course has been followed. A total of one hundred measurements was adequate at all except a handful of sites where a double peak or a weak preferred orientation occurred. More measurements would allow greater confidence on these results. By contrast, there are a number of cases where the orientation is so strong that fifty measurements would have been sufficient; this is especially so of the non-regional results discussed above. However, the time saved would have been at the expense of the statistical chi-square test which is invalid for less than a hundred particles with the chosen grouping range. In a reconnaissance study, fifty or even twenty-five particles for the very strong fabrics would be justified.

Individual fabric results are of little weight, but where a number of fabrics from the same till layer show the same regional result then the combined weighting is very substantial. There is no means of estimating just how likely is a single fabric to record regional movement, as no-one has yet published the result of tests on the variation in fabric patterns within a small volume of till; however a crude reliability factor of about 0.7 can be estimated from the fabric results in this study, taking unity as absolute reliability.

For a group of fabrics, the weighting can be calculated only if they are all known on other evidence to relate to a single ice movement, when they produce a feasible pattern. In this study, the fabric sites are so dispersed that there is room for considerable deviation between orientation anyway, as the glacier locally changed direction. The only theoretical way to calculate the adequacy of the group of fabrics would be to assume a simple glacier trend, either a straight line or a smooth curve if there is some local topographic control, and register deviations from this trend. In practice this does not work as there is no means of checking the accuracy of the assumed simple trend.

Within the same till, variation in orientation strength and dip pattern could be either a measure of the accuracy of working or an inbuilt characteristic. Assuming that the fair working accuracy shown at Bilston, Oatslie, and particularly Park Burn has been maintained throughout, then it is seen that genuine variations in orientation strength and dip pattern do occur. An attempt has been made to see whether each till is characterised by a particular fabric strength. Calculating the standard error of the difference and applying Student's Test for each group, it was found that the strengths of the slump fabrics are significantly greater than the strengths of the basal till or Roslin Till, but that the strengths of the basal till and Roslin Till differed only between the 25 per cent and 10 per cent levels of probability, which is not significant. The fabrics of the intermediate till show a range of strengths and are not distinctive as a group. Further details of the test applied and a worked example are given as Appendix C.

As an estimate of the consistency of the dip pattern, in the basal till eight out of twelve fabrics show a marked dip towards the source of ice movement, and four show no preference. In the intermediate till, thirteen out of eighteen fabrics show a marked dip towards the source of ice movement, four show no preferred orientation and one shows an opposed dip. Thus, combining the two sets, twenty-one out of thirty (70 per cent) show a dip upflow and only one is opposed to this.

The reliability of the dip pattern in indicating direction of ice movement is much less in the weathered surface tills. The twelve fabrics from the Roslin Till show about equal proportions dipping north, dipping south, and without dominant dip. This result agrees with some earlier fabric work attempted by the writer (Kirby, 1960) where only the fabrics from relatively unweathered compact till produced dip pattern upflow, and the remainder showed a variety of patterns. It is concluded that the dip of the a-axis parameter is a helpful and reliable indicator of direction of ice flow, when measured in unweathered ground moraine at suitable sites.

Fabric patterns almost certainly vary according to particle size and shape. No systematic attempt was made to relate the attitude of individual particles to the size and shape, as it would be difficult to improve here on the work of Holmes (1941). However, as has been demonstrated, the till fabric orientation is best recorded by the largest or dominant particles, and may be absent in the coarser particles of the matrix (for example, fabric 30). In fig. 5.6 the set of particles of greatest size (fabric 53) produces the highest orientation strength; further measurements would show whether this result is generally applicable. But even if it is, there are inevitably other factors, such as till compaction and grain size proportions, affecting the result at the same time. As another example of a possible factor affecting the fabric, in some fabrics associated with sandy till (for example, fabrics 54 and 62) a higher than usual number of particles have attitudes with very low dips. It is possible that a flat-lying attitude of particles is characteristic of the 'wet' conditions of till deposition that are thought to have occurred at Park Burn and Silver Burn, the sites of these fabrics.

A secondary peak or transverse concentration of particles at right angles to the principal orientation was exhibited by 55 from the total of 65 till fabrics showing any preferred orientation, and appears both in undisturbed and modified deposits. A transverse peak is seen as a normal component of macroscopic till fabrics and any theory of till deposition has to take into account possible processes that will produce this peak. Harrison's (1957b) theory is not entirely adequate. The size of the transverse peak varies, with up to 25 per cent of the particles included in it in fabric 42. In no case was a transverse peak found exceeding the parallel peak in magnitude as Glen, Donner and West (1957) described. With a transverse peak containing as many as 25 particles, the primary peak is correspondingly reduced, and shows only a low strength value, as calculated by the chi-square test; this therefore gives rather a misleading impression of the good shape of the fabric pattern as a whole. Ten per cent is a more typical proportion of particles to be found in the transverse peak (for example, fabrics 43, 51) and often the transverse peak is only a slight concentration in a complete girdle of particles around the fabric diagram (for example, fabrics 54, 65).

The head fabrics and the slumped till fabrics all show small transverse peaks, the most distinctive being also the smallest: the strongest fabric recorded, fabric 40 at Esperston, has 98 particles forming the primary peak and the remaining 2 exactly at right angles to this.

The size and nature of the transverse peaks are not exceptional, being those found by other workers. No distinction was made between the orientation attitude of discs, blades, and rods, so that although the origin of transverse peaks is at least partly explicable in terms of particle shape, no further evidence can be given. Glen, Donner and West (1957) mentioned that a transverse peak is particularly noticeable in narrow band tills. If the thin tills at Black Burn (fabric 39), at Park Burn (fabrics 54, 55), and at Kirkhill, Penicuik (fabric 59) are regarded as band tills, then their observation is not supported, as the above fabrics do not have a transverse peak that is in any way unusual.

CHAPTER VII

GLACIAL LANDFORMS

> "On the east side of the Dalkeith and Edinburgh road, some remarkable ridges of gravel make their appearance. They there go by the name of Kaims, and are thought by many to be artificial. They run for about a mile, and make a considerable bend in their course."
> Mr. Milne, on the Midlothian and East-Lothian Coalfields, 1840.

As the Esk Basin is so easily accessible from Edinburgh, the reconnaissance stage of landform mapping was carried out as much on the ground as from aerial photographs. The whole basin was first covered rapidly on foot, and promising locations were examined on stereoscopic pairs of aerial photographs at 1:10,000 (Kirby, 1964). Field mapping was carried out entirely on 6-inch Drift Geology sheets, overlain with Ethulon. The symbols used for the landforms are basically those used in similar studies by other British workers and need no special comment.

The drawings at 6-inch scale were later replotted directly onto 2½-inch topographical sheets. The scale change was accomplished on a Zeiss Aero-Sketchmaster, working with a small piece of map at a time. The details from eighteen 6-inch Geology sheets were thus reduced onto seven 2½-inch sheets, which could be joined together and viewed as a whole.

A further-reduced and much simplified picture of the glacial landforms of the Esk Basin is shown in fig. 7.1. Although much more generalized than the 2½-inch maps which form the basis of the main part of this chapter, it will be clear from fig. 7.1 that different types of glacial landforms predominate in different parts of the basin; and this provides a convenient framework for the subsequent descriptions.

Although almost all of the low ground is mantled with drift of some type and often very thick drift (see Chapter II), there are only limited areas where hummocky till or glacio-fluvial forms are well developed. The district presenting the best developed forms is that west of the River North Esk between Walstone and the built-up outskirts of Edinburgh. Here glacio-fluvium predominates. East of the North Esk, there are fewer major glacio-fluvial deposits, although those at Howgate, Rosewell, and Lasswade must be mentioned. Between the rivers North and South Esk and extending across the southern edge of the basin from Carlops to Borthwick, the most evident features are glacial drainage channels, some of which are of large dimensions. Running through the centre of the basin, the River North Esk itself has associated with it extensive areas of outwash sand and several series of river terraces.

This chapter considers these glacial landforms, taking what appear to be natural blocks of landforms, one block at a time, beginning at the southwest and continuing northwards and eastwards to the Firth of Forth. The outwash surfaces and terraces of the North Esk are discussed in a separate chapter, following the present one.

Each district provides a fairly unified set of glacial morphological features, from which some part of the glacial history may be reconstructed;

no attempt is made until Chapter IX to fully reconcile the different districts.

It is not the aim to describe each morphological feature in detail and draw a conclusion as to its origin. The amount of research into glacial morphologies, particularly in Scandinavia and Canada, whereby certain forms and types of deposits can be logically grouped together as a suite and attributed to certain processes of formation, now means that particular features can be generally regarded as of subglacial, sub-lateral, sub-marginal, ice-contact, or proglacial origin. This is not to suggest that unusual forms for a particular process of formation do not occur - for example, in the Esk basin there are isolated features that cannot satisfactorily be explained - but that in general, the association between form and process is fairly well agreed upon.

<u>District from Walstone to Lawhead</u>. The district between Walstone and Lawhead in the southwestern corner of the Esk Basin shows well developed deposits and meltwater channels characteristic of deglacial conditions (fig. 7.2). It has already been shown that there is a multiple drift cover in this district; the surface forms relate to different layers of this drift cover, being partly in till and partly in glacio-fluvium.

The basal till so clearly demonstrated by the west-east orientations at Silverburn and Cuiken does not produce any topographic forms, and most of the deglacial features are thought to relate to the later ice movement marked by the intermediate till. At the Braidwood Burn site, this ice movement was found to have been from the southwest. The intermediate till occurs at the surface from south of Walstone to beyond Braidwood, but northeast of this it is covered by increasing thicknesses of meltwater deposits.

Apart from the stratigraphic succession, there are clear morphological indications that the surface forms are composed of drift derived from the southwest. On the hill slope below Braid Law there is a strong glacial moulding of till (1, fig. 7.2), a tail that is aligned to the northeast and slightly deflects the course of Eight Mile Burn. In the same locality a striation southwest - northeast was recorded by Peach et al (1910), but this has not been rediscovered by the writer.

On the lower flanks of the Pentland Hills between about 1000 and 1200 ft. are small series of sublateral meltwater channels (2 and 3). Other series occur nearer Carlops in a similar position. The slope of all these channels to the northeast reflects the overall slope of the melting ice-sheet and therefore suggests a greater thickness and source to the southwest. The lowest of the sublateral meltwater channels at Walstone feeds into a low esker 1000 yards long (4). The trend of this and other smaller eskers and the trend of the shallow meltwater channels on the flatter ground below about 1000 ft., with which the eskers are associated, suggest that meltwater flowed northeastwards along the line of former ice-movement.

Between Silverburn and Carsewell, the subglacial drainage turned abruptly southeast towards the trunk drainage line of the North Esk, while east of the Esk at Ravensneuk, the alignment of kames almost east-west suggests further directional change and subglacial control of water movement at a time before the present route down the River Esk was available. To the south of the kames at Ravensneuk is a deep glacial drainage channel (92) which by its size and position seems anomolous to the general pattern in this district (photo. 22). Its higher end is on flat ground to the east; it then descends westwards with a shallow gradient of about 50 feet in ¾-mile towards the gorge of the North Esk, and can be recognized to cut into the edge of the gorge to about a half of its depth. The main glacial drainage pattern both east and west of this channel can be shown to be to the east. If this channel links the drainage systems to west and to east, as its position suggests it might, then it has a reverse gradient and must have been cut by water flowing uphill under hydrostatic pressure, which in turn suggests a thickness of ice of some hundreds of feet. An alternative explanation for this channel is that it is an isolated feature of a later date, not part of the west-east meltwater drainage. If this is so and meltwater flowed down the channel rather than up, then the crescentic gully halfway to the bottom of the present valley (5) could represent its lower course. A more important consideration is that, if channel 92 did act as a drain for water from Auchencorth Moss, then the direct route for water downslope to the northeast must have been blocked by an ice-cover to the north.

This latter explanation that channel 92 is a normal downslope drainage channel is favoured by Mykura (in Mitchell and Mykura, 1962) although he considered that the ice which blocked the drainage from Auchencorth Moss was the same as provided the intermediate till and the glacio-fluvium in this district, derived from the Southern Uplands. It is difficult to see how the Southern Upland ice could have achieved this blockage, even when considering Mykura's suggestion that the melting ice may have separated into a number of more or less isolated ice-masses in valleys and depressions. It is more likely that the blocking ice was lying mainly to the north and was derived from the north.

THE GLACIAL GEOMORPHOLOGY OF THE ESK BASIN, MIDLOTHIAN

by

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Chapter IX attempts to bring together the conclusions of earlier chapters in a discussion of the succession of events during the last glaciation, ending with the present landforms. Some aspects of the glaciation are shown to be quite well documented, but relative weaknesses in the story are pointed out.

Conventions. A brief comment is necessary on the use in the text of certain words not of commonly-agreed meaning. The term 'preglacial' is used to describe features or events prior to the deposition of the basal till in this area; therefore it means earlier than the last full glaciation but not necessarily earlier than the whole of Pleistocene glaciation, whatever that may prove to be in Scotland. The terms 'interglacial' and 'interstadial' are used as defined by West (1963). It will already be clear that the older Scots term 'till' is used in preference to 'boulder clay' although the latter term is still used in much contemporary British literature. In some publications the two terms are used interchangeably (for example, in Mitchell and Mykura, 1962). In this text 'till' is used except in reference to some deposit already labelled by other workers as a specific boulder clay. One new term is introduced: 'glacio-fluvium' is used in the meaning of 'glacio-fluvial deposit', the two terms being analogous to other accepted pairs such as 'alluvium' and 'alluvial deposit'. Finally, for convenience of reading, 'feet' is used for a specific thickness, as of a bed of sand, and 'ft.' for a local altitude or a height above sea level (O.D.). This practice is not followed on the diagrams, to agree with cartographic convention.

Many of the diagrams required to illustrate the thesis are of large format. For this reason, all the diagrams are contained in a separate

There is specific evidence from the glacio-fluvial deposits for such a blocking effect by an ice-mass on the north side: the spread of sand south of Lawhead is restricted to ground above about 750 ft. O.D. and is bounded on the north-east side by a striking ice-contact slope (6) about 750 yards long.

Although the main spread of sand is derived from the southwest, the northern part of the glacio-fluvium near Lawhead appears to have been derived largely from the lower Pentland slopes. A large chute (7) on Lawhead Hill feeds south onto hummocky glacio-fluvium, while further to the southwest a small esker leads down from a mass of sand in the position of a kame terrace (8).

The kettles interspersed in the thick sand of this district are sometimes very deep. The large kettle (9) near Braidwood apparently in intermediate till is either the result of dead ice melting away and creating a hollow on the surface of the till or, as is more likely, implies that there was ice imbedded in the sand known to exist beneath the intermediate till, the ice subsequently melting out and collapsing the till from beneath, a mechanism demonstrated by Thwaites (1956, p.48).

The glacial gorge of the River North Esk itself completely dominates this district (photo. 23). The gorge is here over 100 feet deep, and of a different scale from the features described above from its flanks. The more complex part of this gorge in the district around Carlops immediately to the southwest has already been mapped in detail and explained by Sissons (1963). Sissons considered the size of the gorge is due to the concentration of meltwater from the thick ice-sheet which covered the entire region. He argued that the ice front eventually retreated towards the southwest, where the ice was thickest. The last glacial meltwater to pass down the section of the gorge shown in fig. 7.2. would therefore be proglacial to the retreating ice-sheet, which explains the lack of integration of the gorge with the local deglacial features. No glacial deposits have been discovered in the gorge, although deposits may have been obliterated by landslipping, which has considerably modified the sides of the gorge.

<u>District from Ravensneuk to Mount Lothian</u>. Part of this southern district is adjacent to the Eddleston Valley in Peeblesshire, which forms part of the Tweed drainage southwards. The glacial geomorphology of the Eddleston Valley has been described and interpreted by Sissons (1958b) and as the watershed between the two districts is a very imprecise feature, the interpretation for the upper Eddleston Valley is extremely relevant for the district to the north. Leadburn is located on flat ground, approximately on the watershed.

Both districts show mainly deglacial features but whereas meltwater drained through the upper Eddleston Valley in a northeast direction, the glacial drainage further north is dominated by the Howgate esker system (E-E; fig. 7.3) and a major meltwater channel (25) which run east-west across the regional slope. And while the upper Eddleston Valley is the northern limit of a large area extending into the Southern Uplands showing a consistent pattern of drainage to the north and northeast, the Howgate system is the southern limit of a major pattern of drainage to the east. The district now being considered is therefore at the junction of the two distinct glacial drainage systems. The vague watershed area around Leadburn between the Esk and Tweed basins shows few distinct glacial morphological features of any sort.

In the upper Eddleston Valley mapping of about 150 meltwater channels indicates a flow of meltwater from south to north (Sissons, 1958b). The pattern of channels also indicates that the ice margin sloped down to the northeast, which in turn strongly suggests that the last glacier ice to occupy the district came from the Southern Uplands.

The geographical position of the upper Eddleston Valley draining into the Southern Uplands is such as might provide a possible site for an ice-dammed lake, but to the contrary, Sissons has demonstrated extensive sub-glacial deposition and drainage with kettles, kames, and kame-terraces. Two main altitudes of kame-terraces are recognized, being 850-860 ft. and 880-900 ft. O.D. With these, Sissons has associated two shallow cols as escape routes for meltwater draining northeastwards across the watershed. It is suggested that these were operative until further ice-melting allowed the re-establishment of normal drainage to the south.

Although from the pattern of meltwater channels in the Eddleston Valley, there would appear to be no alternative to water escaping to the northeast, neither of the two cols proposed as escape routes seems to have carried substantial quantities of water. The more southerly one, at 865 ft., is slightly the more impressive feature, as it is succeeded by a long esker, extensive glacio-fluvial deposits, and the larger meltwater channels northwest of Gladhouse Reservoir. The more northerly col, which is shown on fig. 7.3 as a channel at N.T. 25 55, is an insignificant feature, being merely the shallow depression between existing watercourses. East of Leadburn are several small channels (16 and 17) aligned diagonally down the south side of Kingside Edge, and the more northerly col described by Sissons is regarded as being the lowest of this set.

The direct evidence of drainage from the Eddleston area to the northeast is provided by the Lead Burn (20), a broad shallow course too large to have been cut by the existing stream and with several meltwater feeding channels at its southern end; another detail in evidence is an isolated section of esker aligned northeast-southwest on the east side of Kingside Edge.

Apart from these small features, there is an absence of any type of glacial retreat features along the line of the watershed from Auchencorth Moss eastwards to Mount Lothian Moss.

To the north of the watershed, the Howgate drainage system is the most southerly major indication of a large west-east glacial drainage pattern. The Howgate system consists of two parts: in the west is a broad belt of glacio-fluvium in the form of kames, kettles, and short sections of esker (E-E). The esker begins as the ridge on which Lockhart Halls Farm is situated, and continues eastwards to pass north of Howgate village. After this point, the amount of glacio-fluvium decreases, and its area is concentrated within the funnel-opening of a large glacial drainage channel (25), which is the eastern part of the drainage system. A tributary channel (25a) joins the main channel from the north.

The transition from glacio-fluvial deposits to channel 25 occurs on the line of a minor height of ground in this part of the upper Esk Basin, called by Mykura the Kingside-Rosewell Ridge. This ridge is the topographical expression of the Herbertshaw (Herbershaw) Anticline, with Ordovician greywacke cropping out in the south and Limestone Coal Group further north. Although not a significant relief feature during active glaciation, it is clear that during deglaciation meltwater moved eastwards across the ridge, and the position of meltwater channels is controlled by it. Apart from channels 25 and 25a, whose intakes are on the Kingside-Rosewell Ridge, there is another smaller channel just to the south of Herbertshaw (18) with its intake on the same ridge at 935 ft, This channel represents a higher level of water movement from west to east.

The western, depositional, part of the Howgate system consists of thick sand in the form of kames and deep kettles with steep ice-contact sides. These are essentially dead-ice features showing no accordant summit-level. The Howgate esker extends on the south side of the kames and kettles. The summit heights of its sections rise from just over 800 ft. at Lockhart Halls Farm to 850 ft. east of Howgate. Whereas the mass of kamiform sand forms the north wall of channel 25 at its western end, the esker enters the channel and follows its floor for 700 yards, and was therefore formed after the channel itself. There is nowhere exposed in the esker any bedding which might show by its dip the direction the meltwater was flowing, and it is from the general pattern of the features that an eastward flowage is proposed. Channel 25 has a reverse gradient at its entrance but the gradient becomes eastwards to the east of Kingside-Rosewell Ridge and then continues to be eastwards for several miles, the channel forming part of a larger system of meltwater drainage.

The meltwater responsible for the Howgate system drained eastwards because it was prevented by an ice-cover from draining northeastwards down to the sea. Considering again the drainage out of the Eddleston Valley, if the Howgate system represents the main trunk system of water from Eddleston, it would be natural to expect feeders into it from the south side. Lead Burn is the only reasonably developed feeder channel. The contemporary stream course is diverted westwards by the esker system until it intersects the Black Burn, the two streams uniting to pass around the western end of the esker in a deep channel. But the glacial course of Lead Burn may have swung eastwards to link with channel 25.

Although it is possible that the northeast meltwater drainage from Eddleston is part of the same system as the eastward drainage at Howgate, the local watershed acting on the overlying ice-sheet in such a way as to deflect the meltwaters in a different direction, there is also some evidence at Ravensneuk, Ravelsyke, and around Mount Lothian for more than one glacial drainage pattern. The details of this evidence are given below; they relate to several localities, and the general conclusion is that they are pene-contemporaneous, relating to the same ice-sheet.

At Revensneuk, the east-west alignment of kames is interrupted both by channel 92, which has cut into a kame on its southern side, and by channel 92a which drains northeastwards and also cuts across an east-west ridge of sand.

At Ravelsyke, there is a group of four drift hummocks, aligned more or less east-west (23). The hummocks differ in composition: two out of four are of sand, one is of till, and one is partly sand and partly till. Those composed of sand have fresh ice-contact slopes, but those of till are more shallow-sided. The most westerly of the four hummocks partially blocks the Lead Burn, here in its glacial course, and therefore the hummocks are of later origin than the channel.

There are several other hummocks composed of till on the north side of the esker (T,T). They are not streamlined in any direction to suggest they were moulded by moving ice, but are rather of a form and in a position that suggest their origin is linked with that of the Howgate system itself. Till hummocks 23 and T, T may have been formed by pressure beneath the ice-sheet along crevasse- or drainage-lines during the deglacial phase. Such till forms due to pressure in the vicinity of dead ice have been demonstrated by Hoppe (1952), Stalker (1960), and other workers.

A third locality showing more than one drainage pattern is around Mount Lothian and just further north on both sides of channel 25. On the north side of the channel, several ridges composed of sand trending northwest-southeast are cut across and therefore postdated by channel 25. South of this channel, channel 18, previously described, and channel 18a, a slighter up-and-down channel in the same sequence east of the Kingside-Rosewell Ridge, are each continued eastwards by low eskers. The eskers coalesce near Mount Lothian and can be traced on for 2½ miles, although the morphology is indistinct in places. Its course east of Mount Lothian is composed of dog-legs southeast and northeast, basically the two directions of meltwater drainage being compared. This esker is cut across by channel 31a, a channel which starts in the direction of the sand and gravel spreading northeastwards from Eddleston. Channel 31a turns eastwards and eventually becomes much larger; this channel clearly had the function of directing meltwater from the upper Eddleston Valley northwards across the present watershed and then eastwards towards Borthwick (see also fig. 7.4). Both esker and channel 31a are in turn cut across by the valley of Fullarton Water, which must have started as a meltwater stream, but is now occupied by a normal river.

Summarizing the evidence in this district, the deglacial features along the watershed point to ice movement from the southwest. The stratigraphic evidence from Black Burn as well as stone orientations confirm this movement from the southwest. North of the watershed, although the stone orientations show the same direction of ice advance, the meltwater has been deflected eastwards. Also between Ravensneuk and Mount Lothian there is evidence of two drainage patterns. The freshness of the esker ridges, kames, and ice-pressed till hummocks of the Howgate system indicates that the system was developed under the last ice-sheet to cover the area, the subglacial drainage being at a time when there was still a thick ice-cover blocking drainage towards the sea.

If pressure-moulding of the till did take place during deglaciation in the vicinity of the Howgate system, the stone orientations completed here require re-examination. The two fabrics concerned, 42 and 56, both show a normal type of particle plot distribution, but the resulting orientations are southeast-northwest. This unusual trend has been discussed in detail already, and no definite interpretation was reached. Although a local orientation effect due to pressure-moulding would be attractive, it can be recorded only as a possibility. As the till concerned is covered by glacio-fluvium and does not have any surface form of its own, it is not possible to make the type of deductions used by Hoppe (1952) in respect of ice-pressed forms.

<u>District between Mount Lothian, Borthwick and Lasswade</u>. This triangular-shaped district (fig. 7.4) continues eastwards and northwords the features described in the last district. Some parts of this district have already been mentioned in published literature; the Borthwick area by Peach et al

(1910), and by Cossar (1911-12); and an area of 20 sq. km. east of Rosewell by Sissons (1960-61). Also the account of the whole district by Mykura (in Mitchell and Mykura, 1962) contains little with which the writer has cause to disagree. The remarks below are mostly confined to amplification of the earlier accounts with emphasis on the points of disagreement, the remarks being based on the writer's remapping.

The southern part of the district sees the eastward continuation of the Howgate system. The line of glacial drainage is continued by an extension of channel 25, which follows a winding course for one mile towards the complex area of meltwater channels between Edgelaw and Arniston. Channel 25 continues to be aligned approximately across the regional slope, and is partially blocked by drift in two places, north of Mount Lothian, and between Cauldhall and Edgelaw.

Although there are no other esker systems like that at Howgate, its erosional counterpart, channel 25, is only one of a series of channels extending eastwards in roughly parallel fashion from the line of the Kingside-Rosewell Ridge. Apart from channels 18 and 25, there are five other substantial channels (24, 26-28, and 33) cut in both drift and bedrock. They vary in size but are locally up to 50 feet deep and 200 yards wide. In two cases the lower end of a channel turns downslope and is truncated by the next channel to the north, suggesting a sequence of drainage with the southerly channels being the first formed and first abandoned. This entails drainage in relation to an ice mass thickest to the north and with its decayed zone retreating northwards. In spite of the parallelism of this set of channels, their regular spacing of about 1000 yards, and their position across the regional slope, several channels have upslope intakes, and the writer agrees with Mykura that there are altogether substantial reasons for regarding them as of subglacial origin.

Mention has already been made of the minor channels and eskers (29-32) south of channel 25, combinations of features that also imply subglacial drainage. On the other hand, channel 28 has an intake at Kirkettle which could be ice-marginal, with water flowing down the Esk gorge being blocked by ice to the north and diverted eastwards; a glacial outwash terrace built up to the intake of channel 28 would prove it to be ice-marginal. Also the channels and ice-contact deposits east of Rosewell are thought to be of ice-marginal origin (Sissons, 1960-61). Therefore the sequence of deposits and channel-type from channel 18 northeastwards along the Kingside-Rosewell Ridge to Rosewell suggests that the earlier drainage at the southern end was subglacial and, as the ice thinned and an ice-front developed as the southern edge of the residual ice, the drainage became more sub-marginal.

The belt of glacio-fluvial drift east of Rosewell consists of sand with some gravel, all rather coarsely bedded. The sand and gravel thickens downslope to over 50 feet and has a steep ice-contact face to the northeast. Both Sissons (1960-61) and Mykura (in Mitchell and Mykura, 1962) consider that the channels cut into the spread of sand are related to the decayed southern limit of a residual ice-block. To quote Mykura:

> "..... the southern margin of the ice became so broken that it ceased to be a positive barrier to glacial meltwater. Its line is now marked by a belt of gently undulating sand and gravel which extends east and west of Rosewell and is cut by a number of small meltwater channels (45-49) running for at least part of their course directly downhill. This suggests that meltwater flowed northeastwards over the ice, first spreading over its entire surface and depositing sand and gravel, and later,

volume. Although this means that two volumes must be consulted together, this is considered preferable to the over-reduction of drawings necessary to fit the standard format.

> as it became channelled along depressions, forming several streams which eroded the gravel and residual ice, locally cutting into the underlying boulder clay". (Mitchell and Mykura, 1962, pp.117-18).

There are a number of kettles in the sand, suggesting that sand was spread over residual ice, as Mykura stated, but most of the sand occurs as flat spreads rather than undulations. As another point of detail, it seems unlikely that meltwater would have flowed over decaying ice for any distance; and the alternative explanation, by Sissons, is preferred, that the channels are shallow chutes, the decayed ice allowing the water to run underneath it directly downslope.

The outlets ends of the more northerly channels (north of channel 28) link northwards with the glacial drainage of the glacial river South Esk. The more southerly channels pass eastwards and are provided with a drainage outlet around the south end of Roman Camp Ridge and Borthwick. Between Cauldhall and Borthwick the meltwater channels do not occur in an easily explained pattern. Between Cauldhall and Arniston, the general impression is of several superimposed elements: the latest element is provided by the large meltwater channels, often 100 feet deep in rock-cut gorges, extending northeastwards as active tributaries of the River South Esk; the outlets of channels 25, 26, and 28 join these larger channels, but their former course is indicated by channels 29a and 34 which extend on to Borthwick. Another element of the glacial drainage is a number of smaller subglacial channels such as 37, 38, 38a, 40, and 41, which represent lesser concentrations of meltwater draining eastwards. Finally, this area has seen extensive opencast coal mining, and the drillings have revealed short sections of at least five buried valleys (fig. 7.4). These buried sections, all containing over 100 feet of drift, cannot be integrated into a complete pre-glacial or glacial drainage pattern; their various trends suggest that they are not necessarily related to one another at all.

The complexity of the drainage pattern between Cauldhall and Arniston has been partially explained by Mykura by postulating a submarginal drainage pattern in dead ice; but this must be a simplification of the actual deglacial history. The buried channel extending north-south through Arniston and the pre-existing depression now occupied by Rosebery Reservoir across which a west-east meltwater channel is deflected, both indicate pre-glacial or early glacial drainage to the north. Following the west-east meltwater phase, drainage to the north was re-established, the tributaries of the River South Esk sometimes occupying meltwater channels, but being independent of the elements of the underlying buried system so far discovered.

Between Arniston and Borthwick, the area between channels 34 and 42 consists of thick glacio-fluvium with the central hill of Halk Law covered only by till. The glacio-fluvium is of a hummocky nature with kettles indicating dead-ice deposition although south of Middleton, the sand is terraced by the former glacial meltwater stream of channel 42.

The drainage derangement around Borthwick has been noted for many years. Both Peach et al (1910) and Cossar (1911-12) described how the Middleton North and South Burns are deflected from a former course down the Tyne Water to a new course northeastwards down the Gore Water tributary of the South Esk. Peach et al did not regard this as anything other than straightforward river capture, but Cossar did at least envisage some control by an ice-sheet on the low ground diverting the Midlothian drainage. In fact there appear to be two stages of glacial drainage associated with the main Borthwick channel 43. The channel is a large feature, locally over 100 feet deep and over 400 yards wide. The line of this channel continues northwest as a buried channel around the end of Roman Camp Ridge, with 144 feet of drift proved at one point. The present glacial entry to channel 43 is the much smaller channel 34, the more northerly of the channels carrying the west-east meltwater. Channels 34 and 42 are not only much smaller than the original Borthwick channel, but they enter its sides discordantly. Immediately east of Borthwick Mains, a thick mound of sand and gravel almost blocking the valley suggests an ice cover later than that associated with the cutting of the main channel, and responsible for the eastward deflection of Middleton North and South Burns.

Only limited attention has been paid to the deglacial channel systems feeding to Borthwith and to the South Esk. Particularly when more borehole data becomes available, a fuller story will emerge. But in summary, it is clear that the west-east drainage pattern is well authenticated, and indicates a dominance of ice to the north, with the ice-front receding in this direction. There is also evidence for an earlier glacial drainage system, as seen in many dissociated features. The few fabric analyses carried out in this district have indicated that there were at least two ice covers, the former from the west-southwest, the latter from the south-southwest; and as the basis for further investigation, it is possible to consider combining the two glacial and the two deglacial phases in alternating succession.

District from Lawhead to Straiton. The district adjacent to the northeast side of the Pentland Hills (fig. 7.5) is one in which three distinct till have been recognised. The landforms may therefore be expected to show the results of several separate glacial and deglacial episodes. As in the district southwest of Lawhead, the basal till does not produce any landforms, but the intermediate till and its deglacial equivalent, derived from the southwest, do provide some of the surface cover material. The rather featureless slope between Cornbank and Glencorse (aerial photograph A), with a broad bench between Cornbank (735 ft. O.D.) and Cuiken (675 ft.) as the only positive feature, is underlain by this intermediate till, as fabrics and stone counts have illustrated. Further north, the intermediate till becomes increasingly covered by both glacio-fluvial sand and by the Roslin Till. The Roslin Till is itself too thin a formation to give rise to any morphologies. But due to its thinness, it is difficult to determine whether glacio-fluvial deposits are protruding through Roslin Till, and therefore belong to an earlier sequence of events, or are overlying it.

Glencorse Burn approximately delimits the southern edge of the thick glacio-fluvium in this district. North of Glencorse Burn as far as Straiton, exposures show thick beds of sand. From sections already described it has been concluded that the landform resulting from these sand deposits was a shallow deltaic or braided outwash plain. This plain is pitted by a small kettle at Bush and larger kettles further north near Pentland Mains. Small kames occur in isolated fashion on flat ground at Bush and near Bilston. The outline of all these features is very blurred because the kettles are lined with Roslin Till and the kames are covered by it.

The presence of the kettle does in fact demand a particular mode of formation. As the ice responsible for the Roslin Till is known to have truncated some of the bedding in the glacio-fluvium beneath, and as the kames have been partially obliterated, any pre-existing kettles might equally have been filled in. It is theoretically unlikely that blocks of ice melted down through the Roslin Till to form depression deep in a lower drift; it is much more probable that the kettles were formed by the melting of buried ice-masses from the Southern Uplands ice-movement, the melting occurring after the Roslin Till was laid down. Although this might suggest that only a short period of time elapsed between the melting of Southern Upland ice and the re-covering of the ground by the ice depositing the Roslin Till, it is known that the ground was exposed long enough for the formation of frost wedges.

The northern limit of the glacio-fluvium occurs as an ice-contact slope east-west through Straiton; other parts of the same morphological feature occur to the east on each side of the River North Esk at Melville Mains and Lasswade golf course. A north-facing ice-contact slope is well developed at each of these localities (photo.24). At Straiton there is a deep kettle and some isolated low mounds of sand outlying from the main deposit (aerial photographs B).

There are two morphological features which suggest that the deposition of the glacio-fluvium to Straiton was subglacial, rather than against an open ice-mass to the north. The surface of the glacio-fluvium at Straiton is at 455 ft. O.D. Meltwater channel 53 across Gilmerton Ridge has an intake at 450 ft., and it is suggested that it formerly fed water from Straiton east and then northeast. The intake of channel 53 is upslope, requiring a subglacial mode of formation.

A second feature which suggests subglacial deposition of the glaciofluvium at Straiton is the position of Cameron Wood esker (aerial photographs B). This is a wooded ridge extending almost continuously for about a mile from the area of kame and kettle at Pentland Mains down across the ice-contact face into the flat-bottomed basin of Straiton Moss to the north. No bedding is exposed in this esker, and its origin is presumed from its form and the coarseness of its constituent material, the sand, cobbles, and boulders being exceptional for the area. The higher southern end of the esker stands on level ground in association with the kame andkettle area, while the northern end is a hundred feet lower and finishes in beaded portions on the middle of Straiton Moss. It is clear that if the esker is to be associated with the other dead-ice features, as the evidence points, then all must have been deposited subglacially.

The fact that Roslin Till does not overlie the esker might suggest that the esker overlies Roslin Till and is therefore of a later date than other features in the vicinity. If the esker is later, it is an isolated feature without any other forms to explain its raison d'etre. Augering has not proved that Roslin Till underlies it (the auger continually being obstructed by stones) and, on the contrary, at the most northerly bead of the esker, 3 feet of sandy till, which may be the Roslin Till, overlies the esker sand.

The basin of Straiton Moss is a natural depression between the Braid Hills and northern Pentlands to the west and a small outcrop of Carboniferous Sandstone to the east. The depression must have extended further south before the incursion of thick glacio-fluvium. The section to bedrock at Clippens sand pit (figs. 4.21A and B) and various trenchings and borehole evidence show little till in this basin, but do show a lining of grey silt (mechanical analysis, Table 4.3). The silt has the grain-size characteristics of an aeolian deposit, but there also occur many rounded pebbles, so that the total deposit could be of wind-blown and ice-rafted material such as occurs in a late-glacial lake adjacent to expanses of sand. The two belts of sand (53a and 53b) which lead into the present depression have a hummocky form suggestive of subglacial deposition, with local meltwater flowing down from higher ground to the west and northwest. If this is so, this sand would have been deposited with the Straiton glacio-fluvium before the temporary glacial lake existed.

There remain for consideration in this district the numerous small deposits marginal to the Pentlands. The most southerly of these consists of an esker and associated spreads of sand on the southern slope of Glencorse. From the account in Chapter VI, it will be seen that the esker is derived from Southern Upland ice, with meltwater flowing northeast down the slope. Further north, short meltwater channels 4, 7, and 13 fall in height to the south, while between Glencorse and Hillend there is a series of kames with steep ice-contact slopes. The feature north of Bush is flat-topped and resembles a kame-terrace in a position marginal to the Roslin Till readvance ice, but a similar feature west of Bush is covered by Roslin Till. The position and form of these features suggest they are the product of meltwater from the adjacent Pentlands rather than from any distant source.

<u>The coastal district</u>. The glacial morphological forms in this last

district to be discussed, the lower Esk Basin bordering the Firth of Forth, are more fragmentary than in the districts further inland (fig. 7.6). There is a significant difference in the glacial sequence also, as only one ice movement, from west to east, has been recognised, and only one period of deglaciation, with ice thinning northwards.

The principal indications of ice movement are the crag-and-tail formations, which have been described many times since they were first recognized by Hall in 1812. Many of the tails of the streamlined forms are not of till, as is commonly assumed: the tail of the small feature of Corbie's Craig, for example, situated on the larger crag-and-tail of Blackford Hill, is of bedrock (fig. 6.5; photo. 25). The tail of Blackford Hill itself shows a variety of drift types, as previously described.

Associated with the streamlined forms within the city of Edinburgh are numerous ice-gorged depressions, which were occupied by late-glacial lakes, almost all of which have now been drained. The several accounts of these lochs are listed by Mitchell and Mykura (1962).

The best integrated sequence of deglacial features occurs around Gilmerton Ridge. The meltwater channel 53, discussed above, is the highest of a series of channels (fig. 7.7) which for the most part begin at the ridge crest and descend to near the base of the east side of the ridge. The channels have successively lower intakes from 450 ft. (channel 53) to 180 ft. (channel 58). These two channels, the first and last in the series, have slight upslope intakes, while at Hilltown, there is a channel descending 30 feet on the west side of the ridge that may represent an upslope intake to the larger channel 56 with which it is aligned.

Figure 7.7 shows also that most of the hummocky glacio-fluvium on the lower eastern slope of Gilmerton Ridge is deposited near the lower ends of the meltwater channels. The most distinctive part of the glacio-fluvium is the Sheriffhall esker, a ridge about a mile long, composed of coarse sand, gravel, and cobbles. This esker is described by Milne (1840) in the passage given as the introductory quotation to this chapter. It has two different elements: the northern part consists of hummocky spreads of kettled sand without any directional trend (fig. 7.6). An isolated kame with steep ice-contact slopes stands up within this part, and the identifiable ridge starts at the base of this kame, and forms the southern part, or esker proper. The top of the isolated kame is at 232 ft. O.D. (fig. 7.8), which is the same height as the terminal end of the adjacent meltwater channel 53. Between the isolated kame and Campend, the esker follows the contour of the underlying till-covered slope, so that its base on the easterly (downslope) side is 15-20 feet lower than the base on the northerly (upslope) side (fig. 7.8). At Campend, the crest of the esker reaches its greatest height, but the esker turns downslope at this point, and its crest-line falls steadily towards Sheriffhall.

At Sheriffhall, the esker deposits are succeeded by the extensive spreads of glacio-fluvium associated with the glacial course of the River North Esk. The exact junction between the esker and the outwash spread is obscured by earthworks, a railway, roads, and tree plantations (aerial photographs C). But height measurements have shown that there is no direct continuity between the crest of the esker and its projection onto the outwash surfaces at this point. However the highest outwash surface (terraces 225, 226, and 227, which includes parts of Dobbie's Nurseries and Dalkeith Park) has a range of heights from 240 ft. to 200 ft. (fig. 7.8) and as the limit to this outwash surface at one point is an ice-contact slope, it is possible that the esker and the highest terrace surface have a common subglacial or submarginal origin.

The series of meltwater channels and deposits on Gilmerton Ridge indicates subglacial meltwaters moving eastwards into the channel of the glacial Esk. The upslope intake of at least two channels, the incised course of channel 54 and the probable link between channel and subglacial esker deposit all indicate a subglacial mode of formation. The writer has not found any direct evidence for Mykura's suggestion that Gilmerton Ridge separated stagnant ice in the Esk valley from ice occupying the Forth valley and still moving eastwards at this time.

On the east side of Roman Camp Ridge is a group of meltwater channels (fig. 7.1) at a height which suggests they were formed earlier than the channels on Gilmerton Ridge. These were formed by meltwater from the Esk in the period intermediate between drainage eastwards to Borthwick and free drainage northwards directly towards the Forth. The main channel starts as a bench at 440 ft. and cuts eastwards through the ridge to integrate with the glacial drainage scheme in the Tyne Basin (Sissons, 1958a). The lowest meltwater channel in the Esk Basin is on the north end of Roman Camp Ridge between 160 and 120 ft. O.D., and marks an even later stage in the ice retreat southwards from the Esk Basin.

The limited morphological evidence within the city of Edinburgh is effectively summarised by Mykura. The only features that can be linked directly one with another include the small channels between Swanston and Morningside, together with the Comiston sand-mass described originally by

CHAPTER II

THE PHYSICAL SETTING

"Wretched is the man who lives in
a gravel pit." Proverb quoted
by John Ray, 1678.

The main area of this study coincides with the drainage basin of the rivers North and South Esk to the southeast of Edinburgh within the county of Midlothian (fig. 2.1). Watershed boundaries would have been sufficient had the study been of post-glacial processes; but ice divides and watersheds seldom correspond and in this study of glaciation it has been convenient to provide some comparative evidence from adjacent areas. A pilot study was made of an area on the upper tributaries of the River Tyne in East Lothian. Small investigations were also made along the coastal plain near Kirkliston to the west of Edinburgh, and along the edge of the Southern Uplands Fault which forms a distinctive southern boundary to the area. However, the ultimate conclusions are concerned entirely with the Esk and upper Tyne Basins.

Topography and geology. The dominant physical feature of the district is the line of summits formed by the Pentland Hills, which extend from the outskirts of Edinburgh in a southwesterly direction through Midlothian into the adjoining counties of Peeblesshire and Lanarkshire.

Campbell and Anderson (1909). The controlling water-level of 550 ft. at Hunter's Tryst, Fairmilehead, is too high for an ice-margin here to be related to any features in the lower Esk Basin adjacent.

Although the morphological features of the different districts of the Esk Basin show more dissimilarities than likenesses, one commonly recurring theme has been that of ice retreat phases, with glacio-fluvium carried from the south or from the Pentlands being held up against or under a melting ice-sheet which was thickest to the north. The phases of ice retreat are described in the next chapter in terms of the River North Esk glacio-fluvial spreads and alluvial terraces.

CHAPTER VIII

TERRACES OF THE RIVER ESK

> "In every thyng, I woot, there
> lith mesure." Geoffrey Chaucer,
> Troilus and Criseyde, 1375.

Particular attention has been given to the morphological mapping of terraces of the River Esk. These terraces have been shown in generalized fashion in fig. 7.1. In this text, the term 'terrace' is used for convenience as a baggage term to include both glacial outwash surfaces and river terrace remnants. The former are of course surfaces due to deposition, while the terrace remnants are erosional, being the surviving parts of a formerly continuous valley floor that has suffered both horizontal and vertical corrasion (the definition of Cotton, 1940). A set of terrace fragments correlated as a single feature is here called a 'Terrace', and is labelled by letters; and the individual fragments of terrace or outwash are not referred to with a capital letter and are numbered.

The terraces are important among the morphological features of the Esk Basin for two reasons. Firstly, they have considerable physical dimensions and extent. There are several individual terrace remnants over half a mile in downstream length and the three largest are each over a mile long; the terrace remnants as a whole form an almost unbroken sequence from the vicinity of Penicuik to the river mouth. Secondly, the terraces are important in that they provide a possible interpretation of the late-glacial and immediate post-glacial development of the basin by morphological means. The highest surfaces are underlain by material originally deposited as proglacial, ice-contact, or subglacial spreads, and in some cases the terraces may be directly related to glacial melt-water channels. Following the deposition of this glacio-fluvium, its subsequenct dissection within the valley of the Esk as presently located has produced flights of river terraces in some cases at five or six separate levels. By arranging these terraces diagrammatically, it can be seen whether or not they fall into significant altitudinal groups, and therefore whether or not they represent intermittent falls in base level or a more or less steady fall in base level.

Little attention has previously been paid to the terraces of the Esk, although the larger ones are recorded on 6-inch Geology sheets. Mitchell and Mykura (1962) noted that five well-defined terraces occur between Dalkeith and Musselburgh and that, as the lower terraces are cut in raised beach deposits, some of the higher terraces may be contemporaneous with the raised beaches.

Terrace mapping and height measurement. The terraces were mapped on 6-inch drift Geology sheets in the same way as for other morphological features. A central line down the length of each terrace was decided upon, and the heights of points at intervals along this line was established. The usual interval between heighted points is 50 yards. In the case of large terraces, one or more transverse lines of points were heighted, and occasionally on broad terraces two parallel lines of heighted points were established along the terrace lengths.

Height measurements of the terraces were carried out entirely in the field by level and staff, using an Autoset Level and an Autoset Level 1 (Hilger and Watts), with a 14-foot staff. The work was done at periods over three years, depending partly on crop conditions.

Details from the individual 6-inch sheets were transferred to a single map (fig. 8.1), and a reference base-line was drawn southwest - northeast, parallel to the general line of the present River North Esk. The locations of all heighted points were then projected at right angles onto the base-line, and heights plotted against distance on a second diagram, (fig. 8.2).

Figure 8.2 therefore summarises the height information for 142 terrace remnants and outwash surfaces, and forms the principal evidence on which the history of terrace development will be argued. It will be apparent from above that there is a considerable list of operations involved in the production of fig. 8.2, and therefore a large number of factors influencing the accuracy of the final diagrammatic plot. In order to understand what reliance may reasonably be placed on fig. 8.2, it is therefore necessary to consider the main possible sources of error and misrepresentation. The sources of error are considered in the order in which they might have been encountered. They are:

(i) Errors in instrumental height measurements

(ii) Errors in locating heighted points

(iii) Choice of points to height

(iv) Choice of base-line for projection

(v) Scale of plotting

(i) Errors in instrumental height measurements. All levelling was carried out between Bench Marks of known height (marked on fig. 8.1), and the measured height of any point is correct to ±0.5 ft. A maximum closing error of 0.5 ft. was permitted for short levelling traverses and 1.0 ft. for long traverses. In practice the mean closing error for the first 38 traverse completed is 0.15 ft., and most points are correctly heighted to 0.2 ft.

This accuracy is slightly greater than the nature of the terraces justifies and is also greater than can be used for plotting, but it is not possible to use another surveying method that will produce results to the necessary accuracy of 0.5 - 1.0 ft. with comparable speed. In fact the use of a modern self-levelling instrument with superior telescope magnification is quite economical in time.

During one level traverse, a Bench Mark error of -2.8 ft. was discovered (at Grid Ref. NT 2982 6494). This may be attributed to local mining subsidence, which occurs commonly in Midlothian to the order of a few feet. Up to 10 feet of subsidence has been recorded in certain zones. There is no factor that can be used to correct the errors that subsidence produces on terrace heights.

(ii) Errors in locating heighted points. Positions of the points being heighted were recorded on the 6-inch sheets as the levelling proceeded. The interval between points was standardized at 50 yards wherever the ground allowed. The distance was measured by pacing, the staffman having previously checked his pacing against a tape-distance. Errors in location of the heighted points are negligible at the plotting scale. The complete list of heighted points, totalling 1224 in all, is given as Appendix D.

(iii) Choice of points to height. For each terrace, one central line of points was run, supplemented on occasions by a transverse line or a second line lengthways.

Some attention was paid to a scheme of river terrace mapping developed by Brown (1952). This involves finding the heights of the four corner positions of each valley-bench as well as measuring the length of the bench. These measurements allow the surfaces to be represented on a diagram as areas, which lend themselves to visual comparison.

For a number of reasons, this scheme was not used in the present work; the terraces had already been mapped independently of the heighting process, so that their lengths were known; there is a vast range of size from the largest to the smallest terrace, which would make a diagrammatic comparison of area impossible; there is often little or no transverse slope and therefore no range of height from rear edge to leading edge; and finally, many terraces are not rectangular or of any well-defined shape. The scheme that was employed of making height measurements at intervals down the length of the terrace avoids the difficulties of using the rear edge of the terrace, which may show a backswamp depression or a talus infilling, and avoids the front edge of the terrace, which is usually cambered, factors which have also been commented upon by Frye and Leonard (1954). The scheme also shows the gradient at intervals down the terrace and the regularity of the overall gradient.

(iv) Choice of base-line for projection. The base-line onto which the heighted locations are projected is a straight line southwest - northeast, being the direction which best fits the present river course. A consequence of this is that unless the line of levelling on a particular terrace is exactly southwest - northeast, the projected locations will give a series of points on fig. 8.2 for which the line of best fit has a gradient steeper than it should be. Fig. 8.3 illustrates this by reference to a simple example. Where the line of levelling is parallel to the projection base line, the slope as plotted in section is the true slope (fig. 8.3A). In other cases, the apparent slope of the terrace will be steeper than the actual slope by a factor of $(1 - \mathrm{Sec}\ \theta)$, where θ is the difference in bearing between the line of levelling and southwest - northeast. For small differences in direction, this projection error does not alter the appearance of the slope. For a 30° deviation, representing a line of levelling N75°E-S75°W, as in fig. 8.3B, the projected slope angle would be increased by about 1/7th. For greater deviations, the slope angle increases more rapidly.

Choosing the projection base-line as a straight line also has the effect of compressing the extent of each terrace and their spacing one to the next. In theory, the projection line should be curved to fit the curves of the stream, or rather, there should be a separate projection base-line fitting the course of the stream occupied during the formation of each associated group of terraces. In practice this is not possible as the former stream courses cannot be reconstructed, while the present stream course fits only the contemporary flood-plain, a very small proportion of the total area.

The projection line used in fig. 8.2 might be expected to fit the higher terraces better than the lower ones, as the higher terraces were formed by water moving in a fairly direct course to the northeast over open ground, while the lower terraces were formed within a valley when the water was channelled in a meandering stream.

The only concession made to deviation in the course of the River Esk is for the area between Dalkeith and Musselburgh at the junction of the North Esk and South Esk. The general alignment of the rivers and terraces over a distance of two miles here is more south-southwest - north-northeast, and a supplementary projection base-line was drawn at N25°E-S25°W to accommodate them (fig. 8.1), a swing of 20°. The terraces replotted against this supplementary base-line are shown as the inset to fig. 8.2.

Comparison of the two plottings of the terraces between Dalkeith and Castle Steads shows how the choice of the projection base-line influences the appearance of the terraces as plotted. In each case, terrace fragments have been associated by position in height sequence, by projecting the line of terrace up and down slope, and by natural height breaks. Although there are differences in detail, the same basic correlation of fragments emerges from each plot. But the representation as part of the main plot gives a better impression of the higher terraces, that is, those that extend continuously over distances of ¼-1 mile. The inset plot gives a better representation of the lower terraces, particularly the lowest two sets, which become more naturally separated, and conversely, it shows the higher terraces less well. In the inset plot, terrace 227 appears to have a reverse slope, due to the direction of the base-line chosen, while the actual uniformity of terraces 228 and 230, which are demonstrably part of one feature on the ground, appears broken.

(v) Scale of plotting. A final cause of misrepresentation in fig. 8.2 is the vertical exaggeration of between x17 and x18 necessary to present the height plottings clearly and at a feasible scale. The effect of this is to increase the apparent slope of all terraces greatly, besides increasing the apparent irregularity of terrace surfaces.

Of the five sources of error in fig. 8.2 that have been discussed, some are much more serious than others. But it is not possible to allocate specific weight to any error. The initial choice of points on the ground is subjective; but once the choice has been made, the errors in locating these points and finding their height is negligible at the plotting scale. The only significant error occurs in plotting against the chosen projection base-line, but again it is not thought likely that any terrace plotting gives too misleading an impression because of this. The last factor, the plotting scale, is also adequate to represent and connect terraces without confusion.

Details of individual terraces. One of the features that cannot be fully brought out by these methods of heighting and plotting is the irregularity of individual terrace surfaces. In fact, to allow a truer appraisal of the character of each surface, a tacheometric survey would be needed, providing many more heighted points located in plan all over the surface. The existing linear pattern must in practice be taken as representative of an areal pattern and although the lines of levelling have been located in optimum positions, it is still possible to encounter irregularities. These include kettle-holes on the glacial outwash surfaces and vague water-course depressions and banks.

The strength of each levelled line of points lies in the line as a whole, representing the average form, rather than in the eccentricities of individual points. A straight line of best fit through the plotted points is the most accurate summary of the height range and slope of the terrace that the measurements justify. Usually the last heighted point on a terrace surface shows the effect of cambering. Examples from fig. 8.2 where the cambered point has been retained in the plotting are terraces 121 and 209.

The deposits underlying the terraces are in most cases what would be expected from the landforms. The glacial outwash surfaces are underlain by sands, gravels and occasionally coarser material. Besides this there is a thickness of Roslin Till overlying certain of the glacial outwash surfaces; this is a special circumstance, as will be seen below. The river terraces are normally composed of coarse river alluvium, a mixture of sand, gravel, and cobbles, all water-worked and rounded. But in contrast to these terraces there are a number of flat areas bordering the River North Esk resembling normal river terraces but underlain by till. These areas were mapped and levelled in the same way as outwash and terrace fragments; this has shown them to have exactly the same morphological characteristics as terraces, and has allowed them to be integrated by height and position in sequence with other terraces. Because of this, the features are regarded as glacio-fluvial and fluvial erosional surfaces where water has planed the till cover to a uniform slope and no alluvium or glacio-fluvium has been deposited. In spite of the compactness of the unweathered till locally, it does not appear to have inhibited terrace development as bedrock does for a rock-defended terrace (Cotton, 1940). The major examples of these terraces are T118, T142 at Kirkettle, and T223A at Eskbank (fig. 8.1).

Apart from till-based terraces, there are at least two cases where

The Pentland Hills are separated from the Southern Uplands by the valleys of the rivers Medwin and Clyde around Biggar. They comprise a broad anticlinal fold with the axis in a northeasterly direction. The western limb of this anticline shows gentle undulations for many miles, but the eastern limb was fractured along the line of the Pentland Fault, which runs through Portobello and Carlops. The entire region was once covered by the Carboniferous system but as a result of very considerable erosion, the Carboniferous rocks were completely stripped off the crest of the Pentland anticline, exposing the long-buried Old Red Sandstone and Silurian formations. To the west, undulating strata of the Carboniferous Calciferous Sandstone Series were laid bare as far as the Bo'ness - Bathgate area, beyond which Coal Measures are preserved in the downfolded basin of the Central Coalfield. To the east of the Pentland anticline a second but much smaller anticline was formed along a parallel axis, the remains of which now form the Roman Camp Ridge. Between these two anticlines lies a comparatively sharp syncline forming the Esk Basin, the strata dipping more steeply in the western than in the eastern limb. The basin preserves an isolated stratum of Coal Measures which, together with the Carboniferous Limestone Coal Group, form the Midlothian Coalfield. In East Lothian the upper series of the Carboniferous were removed and the bevelled edges of the strata of the Limestone Coal Group at the top of the Carboniferous Limestone Series were laid bare. This is succeeded eastwards by older Carboniferous rocks.

During the Old Red Sandstone and Carboniferous sedimentations, there was considerable volcanic activity. This was confined, however, to the area north and west of the Pentland axis; there is no evidence of it the material underlying river terraces appeared at first sight to change in an upstream direction from alluvium to till (fig. 8.2; T121 and T144). However levelling has shown that the change in type of deposit corresponds with a sharp break in the surface slope. The break of slope indicates the highest point of the true washed terrace surface, the steeper slope above this being the original slope of the till mantle.

Method of correlating terraces. At any one point across the River North Esk, there may be up to a dozen fragments of outwash surface or terrace remnant, and the correlation of these with other fragments along the river is not at all straightforward.

The two main criteria for correlation are continuity along the valley, and similar relative elevation above the present river. Continuity between fragments can sometimes be seen immediately from the diagram (fig. 8.2) by extrapolation. But there is no objectively-derived limit to the gap that can be jumped between fragments and each case must be examined individually. A linear regression curve is not appropriate because some individual heighted points are themselves not typical of the surface, and because the full terrace profile is anyway not linear but a smooth curve of an unknown form. In criticism of fig. 8.2 it may be said that there often appears to be a more obvious correlation by eye in the field than on the plotted diagram.

Similar relative elevation is likewise an uncertain method of correlating terrace fragments. Correlation of the corresponding members of, say, three terraces in one part of a river with three terraces in another part might be in order but, as Leopold, Wolman and Miller (1964) have pointed out, there is considerable danger in doing this where many fragments occur within a limited height range, as is the case in the Esk valley.

Correlation of terrace remnants across the valley is easier than correlation along its length for, if the projection base line is correctly orientated, plots of left bank and right bank terraces at the same height will be superimposed.

There are two cases where surface remnants match across a valley. In the case of glacio-fluvial outwash material, paired fragments indicate an original depositional surface predating the excavation of the valley. In the case of true river terraces within the valley, paired fragments indicate halts in the process of river downcutting. In both cases, paired fragments are likely to indicate fairly major events, and so be distinctive in size. This is true of the River North Esk, where the paired terraces include almost all the larger units and are at quite distinctive elevations.

Unpaired terraces occur in the normal downcutting of a river into its valley and represent the swing of the valley floor from side to side. Slip-off slope terraces (Cotton, 1940) are also typical of normal continuous downcutting. In the Esk valley, many of the smaller terraces are unpaired or are of the steep, slip-off type. The total impression in the Esk is therefore of flights of terraces, some of which appear to match and some of which alternate, pointing to a composite origin, some having been cut during halts and others during continuous downcutting.

<u>History of terrace development: Terrace A</u>. With the above points in mind, the writer has analysed the terrace fragments shown on fig. 8.1 and grouped them into 12 sets, labelled as A to L. The highest terraces

on the main North Esk are T101-105 and T110-111. These are shown on fig. 7.2, occurring just south of Penicuik.

Terrace 101 is a large feature, apparently flat to the eye. Its major dimension is transverse to the Esk, the terrace being about 500 yards broad and at its greatest about 300 yards in the downstream direction. From the lines of heighted points parallel and transverse to the Esk (fig. 8.1) it may be seen that the surface is almost horizontal. The range of height values is from 738 ft. to 743 ft. O.D. There is no systematic change in height along any of the profile lines.

Terrace 102 adjacent to T101 is to be associated with it directly as it is only about 6 ft lower. It is roughly square with sides about 200 yards long, and with no measurable slope in any direction. There is a kettle-like depression 7 ft. deep towards the rear of the terrace.

Terraces 101 and 102 are both terminated on the northeast side by a 50-foot high ice-contact slope overlooking Penicuik. The eastern and southern parts of the terraces are limited by the glacial gorge of the Esk, and on the west at approximately the same altitude as the terrace surfaces there occur extensive glacio-fluvial dead ice features with flat-topped kames being predominant. The lack of alignment of T101-102 with the Esk valley, the lack of surface gradient, the ice-contact termination to the northeast and the assembly of dead-ice features to the southwest together indicate that the terraces are a glacial outwash feature (Terrace A), the outwash material being derived from the south and deposited in contact with residual ice occupying the Penicuik area.

Forming part of the same system as T101-102, but about 10-15 ft. lower are terraces 103 and 104. These are each about 100 yards long and together slope down to the northeast within the height range 730-720 ft. O.D. Also at about 720 ft. occurs T110, a larger terrace on the other side of the Esk, as fig. 8.2 shows. Terrace 110 like T101 has its longest axis transverse to the Esk valley and has no slope downstream. A series of six levelled points at 50 yd. intervals downstream over this terrace surface approximately parallel to the Esk give the following values:

719.9
718.3
719.8
721.7
721.0
719.8

Terrace 110 is also just adjacent to the kame deposits at Ravensneuk which here trend east-west.

Terraces 104, 105 and 110 are the remnants of a glacial outwash feature similar to that represented by T101-102, the slightly lower level being due either to glacio-fluvial erosion of the higher surface or by a change in the condition of the bounding ice on the north. It is assumed that T110 was also bounded by an ice-contact front to the northeast; this is not now distinguishable because of the courses of the River North Esk and the Black Burn. Terrace A is therefore extended to include the terraces 101-104 and 110.

Terrace A is a complete unit in itself. There are no other corresponding terraces at this altitude either upstream or downstream. The Terrace seems to have been formed in intimate contact with melting ice-sheets both to the southwest and northeast, the one indicated by the glacio-fluvial morphologies associated with the melting of Southern Upland ice around Ravensneuk, Carsewell and Braidwood, and the other indicated by the ice-contact slopes.

The northward flowing meltwater ponded up at the position of Terrace A must have escaped laterally. The only escape routes open to it, other than the later one down the Esk, are to the west, along the side of the Pentlands, and eastwards out of the Esk valley. There is some evidence for each of these possibilities. The broad hillside bench mantled in thick till between Cornbank and Cuiken west of Penicuik slopes northeastwards from 740 ft. to 670 ft. O.D., the upper value being the height of T101. However there is no indication of fluvial erosion anywhere on this bench and in spite of many sections examined during housing development, no alluvial deposits have been found. The second possibility seems the more likely one. There are two possible eastward routes. Upstream of Terrace A a large meltwater channel ascends eastwards from the Esk towards Black Burn. This is channel 92 (fig. 7.2), previously discussed in some detail in connection with the Howgate esker system. The lower end of channel 92 is at about 740 ft. O.D. If this channel does provide the upslope escape route for the water backing up from Terrace A, then this whole deglacial meltwater sequence must have been subglacial. Alternatively, channel 27 on the Kingside-Rosewell Ridge has its highest intake at about 740 ft. O.D. If this last alternative were the correct one, the style of meltwater drainage would be identical to that of other Terrace-channel systems to be described below.

Near the western end of channel 92 occur the next group of terraces, T106-109, located on the Black Burn and Lead Burn tributaries of the North Esk. These terraces, the highest of any terraces mapped, can be divided into two pairs by altitude: T108 and T109 are at about 775-781 ft., and T106 and 107 at about 765 ft. The higher pair are at the level of the upper end of channel 92 and it might be argued that the terraces represent a further subglacial depositional phase. But the surface slope of T108 is at a regular rate towards channel 92 rather than away from it. Also, in spite of the difference in height T108 is backed to the southwest by glacial dead-ice deposits similar to those behind T101. It is concluded that the terraces on these tributaries of the Esk have a similar origin to those of Terrace A. The lower pair on Lead Burn, T106 and 107, represent one surface interrupted by the post-glacial stream cutting.

Terrace B. The site of the present town of Penicuik is a large basin, the meeting of several valleys, and an area which appears to be of unusual significance in this context. The controlling bedrock morphologies are, to the west, a gently rising till-covered slope incorporating the Cornbank-Cuiken bench and, on the east, the ground rising to the Kingside-Rosewell Ridge. On the south side are the thick drift deposits underlying Terrace A, as has been described. On the north side at Kirkhill, the centre of the broad depression is occupied by a high area of thick sand and gravel with some till (fig. 7.5). This mass of drift is surrounded by lower ground on all sides, notably by the Esk gorge to the east and by lower kamiform deposits to the north.

The surface of the Kirkhill drift area consists of two terraces, 113 and 114. These can be correlated with other terraces nearby, and evidence is presented below to show that the area of drift at Kirkhill in which T113-114 are cut is a residual core that has been dissected by glacial meltwaters.

The higher terrace at Kirkhill, T113, is about 500 yards wide and 250 yards long. Part of it is now built up but heights have been derived from the rest of T113 and are found to vary eratically from 674 ft. to 670 ft. without an obvious slope in any direction. At the same height as T113 is T121, one of the higher right bank terraces of the Esk. Terrace 121 is about 650 yards long but only 100 yards wide. It slopes downstream at about 1:290. Also to be associated with T113 are the smaller fragments T105 and T111, located south of Penicuik in the same belt as Terrace A. These are too small for their slopes to be measured.

These four terraces are regarded as one major unit (Terrace B) because they fit together accordantly with an overall slope to the north-east, and are of a height quite distinctly different from any other Terrace (fig. 8.2). The origin of Terrace B is considered to be the same as that of Terrace A. In this second case of deposition in contact with wasting ice, there appears to have been greater scope for terrace development longitudinally. The small fragments upstream, T105 and T111, are against the inner side of the earlier Terrace A in the way that is also characteristic of true river terraces, and in this case have been carved out of the parts of Terrace A.

Terrace B is underlain by glacio-fluvium deposited by water pounded up to a height of about 670 ft. An escape route for water at this height is provided by glacial meltwater channel 27 on the Kingside-Rosewell Ridge. This channel has an uphill intake about on the 700-foot contour line, and a second intake along the slope at about 670 ft. Overflow water from the Terrace B stage is therefore thought to have drained eastwards subglacially.

The large depression northwest of the Penicuik basin between the bedrock slope and the Kirkhill block of drift is occupied by an insignificant stream far too small to have created it. The depression may have been occupied by stagnant ice at the time Terrace B was being formed but, from the location of the parts of Terrace B, it seems more reasonably to suppose that the entire Penicuik depression was filled with drift which has been re-excavated by glacial meltwaters, derived from the southwest and from the adjacent low flanks of the Pentlands and draining northeastwards along the route of the present main road A701 before the Esk valley was available.

Terrace C. This comprises a set of features similar to those forming Terrace B, and a similar explanation is presented for them. Terrace C is made up of the individual terrace fragments 114, 122, and 123. These are of accordant height with a slope northeastwards of about 1:180, and they occur at a height quite distinctly different from that of any other terraces (fig. 8.2). On both sides of the Esk the terraces are carved out of the downstream ends of parts of Terrace B. The right bank fragments, T122 and T123, are the same surface interrupted by a post-glacial stream.

There is a high ice-contact slope at the downstream end of T114. For T123, the eastern bedrock-slope side ends as one wall of a meltwater channel. This is first recognisable at about the height of Terrace C, which is at 630 ft. O.D. at this point, and can then be traced as Channel 28 (fig. 7.4), the Kirkettle channel, which follows the contour of the bedrock slope at about 620 ft. before turning eastwards. Channel 28 has the appearance of a marginal channel at its intake end, but its form further eastwards is more like that of a subglacial channel (see Chapter VII).

On the basis of the above characteristics, Terrace C is regarded as another discrete depositional phase, later than Terrace B, with glacial meltwater coming down the Esk valley being efficiently blocked on the north side and finding an escape route eastwards across a minor height of land, the Kingside-Rosewell Ridge.

Both Terraces B and C are of very similar form, the shape of the individual outwash surfaces being largely controlled by the bounding bedrock slopes. There is only limited room for development of right bank terraces against the bedrock slopes in the upper part of the Esk Basin. These terraces are alwasy narrow and tend to have surface slopes steeper than those of other terraces. The left bank terraces are seldom so restricted and as a result tend to be of more varied shape, generally broader with a less pronounced surface slope.

<u>Terrace D</u>. Each of the Terraces A, B, and C contains only a very small number of fragments, and there is thus little problem in associating them. From Terrace D downstream, there are many more fragments on both sides of the Esk and they are concentrated within more limited height ranges. The result is that there is greater difficulty in sorting them into definite Terraces. But fairly successful results are obtained by projecting upstream from an obvious large terrace fragment. Terrace D is like most of the other Terraces along the central part of the Esk in having a large terrace remnant at its downstream end which serves as a useful starting point.

Terrace D forms the topmost flat surface in the vicinity of

Auchendinny and Oatslie (fig. 8.2). It comprises the original glacial outwash surface extending back from the present river, particularly on the west side. The Terrace is now represented by the fragments T124, 144, 160, and 170, which are typical narrow right bank terraces, and by T152 on the left bank. T152 is the major remaining fragment of Terrace D; although much of it has been destroyed by working for sand at Oatslie, it is still about 1000 yards long and 400 yards wide.

The upper part of T152 plots in an anomalous manner on fig. 8.2 due to the location of the levelling traverse for this part, which was almost normal to the projection base-line, or at right angles to the present river valley. This part shows T152 rising slightly away from the river.

Another anomaly in Terrace D shown in fig. 8.2 is an apparent break in altitude between the right bank projection downstream (T144) and the left bank projection upstream (T152). If a comparison were made of projections to the same point on the base line, a 15-foot difference would be observed. But this can be eliminated by using a different projection base line - by changing from N45°E-S45°W to N70°E-S70°W, agreeing more closely with the general alignment of the belt of terraces at this point. This adjustment is valid for the top surface, which is outwash unchannelled to a particular course, whereas it would not be valid for true terrace fragments, derived from the river cutting into its particular confined channel thereafter.

The overall slope of Terrace D is 1:220, using the main projection base line. The highest part of the Terrace is a well-developed feature T124 cut on the inside lower edge of T123 (Terrace C). A small glacial drainage channel cuts across T124, accounting for the irregularity of its between the Pentlands and the Roman Camp Ridge. Contemporaneous vent lavas and tuffs were intermingled with the Old Red Sandstone sediments, and the northern part of the Pentlands is formed mostly of these rather than of sedimentaries. Intrusive sills and dykes, mainly of Lower Carboniferous age have subsequently been eroded out and, forming small but arresting hills, are the dominant element in the coastal landscape north of the Pentlands.

The Upper Palaeozoic rock-groups are truncated southwards by the Southern Upland Fault, a major line of crustal fracture aligned southwest - northeast. This marks the edge of the great region of southern Scotland occupied by Ordovician and Silurian greywackes, usually hard blue-grey grits and slates, and marks also the end of a topographic region, the high rolling Southern Upland Hills. The Moorfoot Hills are that part of the Southern Uplands facing northwestwards onto the Esk Basin.

Topography and scenery. In summary then, the elevated mass of resistant rocks forming the Pentland Hills is bordered on the east, north, and west sides by a gently undulating plain of weaker rocks, which slopes gradually from the base of the hills to the shores of the Forth, but has its outline frequently interrupted in the north and west by the craggy igneous remnants. To the east and south, the low ground is broken by the Roman Camp Ridge but then continues with increasing altitude to the sharp fronts of the Lammermuir and Moorfoot Hills (fig. 2.2A).

The ancient resistant sandstones, conglomerates, lavas and tuffs, forming the Pentland Hills, are much deformed and faulted, and have been eroded by glacial and extra-glacial processes to domes and broad-shouldered spurs of moderate relief. The hills extend south-westwards for about profile. The lower end of Terrace D is rather indeterminate. The largest part (T152) falls away gradually downstream to merge with a lower surface underlying the village of Roslin. The lowest right bank terraces are merely isolated outliers that have largely lost their original form.

There is no distinctive terminal front to Terrace D and it is possible that this originally occurred downstream at somewhat lower altitude than the limit of the present feature. But if Terrace D did terminate where the present fragments end at about 515-525 ft. O.D., then an appropriate glacial meltwater escape route to the east is provided by channel 33 (fig. 7.4). This channel has an intake at about 500 ft.; the exact height cannot be given with any certainty as channel 33 is now occupied by a small post-glacial stream flowing out at the glacial meltwater intake end.

Terrace E. At an average of about 25 feet lower than Terrace D but otherwise with very similar characteristics are a number of terrace fragments which have been grouped together as Terrace E. The largest components of this Terrace are T162 at Roslin and T169 and T171 at Rosewell. The right bank terrace is the most impressive feature, the combined length of T169 with its now detached parts T161 and T160A being about one mile and the width 400 yards. The slope of the right bank terrace parallel to the projection base line is 1:240. A line of levelled points on T169 at right angles to the base line (given in Appendix D; not shown in fig. 8.2) illustrates that there is no transverse slope.

The left bank terrace T162 could not be heighted by levelling because it underlies Roslin village, but from bench mark heights and the general form of the ground it is clear that the surface exactly matches T169 across the river. The downslope end of both terraces is marked by ice-contact features: the terrace at Roslin by irregular kamiform deposits at a slightly lower altitude than the terrace, the right hand terrace by a distinctive ice-contact face. This latter terrace is part of a belt of thick glacio-fluvium extending eastwards from Rosewell for almost two miles, which has been previously described in Chapter VII as marking a deglacial phase with an ice cover retreating northwards. There are several terraces (T171-178) cut on the surface of this glacio-fluvial depositional zone, all at lower altitudes than T169. The heights of the terraces are thought to relate to progressive lowering of the glacio-fluvial depositional surface as the bounding ice-front became less competent; they have not been heighted by levelling.

Upstream of the main terminal units of Terrace E, the small features T123A, 124A and 124B, 128 and 137 are regarded as being part of the same Terrace. The largest of these upper fragments is T137 underlying Auchendinny Farm. Just upstream of this and also on the left bank, T128 is now the site of Glencorse Barracks; the heights recorded for this terrace are only approximate as they relate to ground artificially flattened off.

The overall slope of Terrace E is about 1:190, using the main projection base line. The slope is therefore steeper in the upper part than in the lower part, as the slope of the major right bank terminal terrace T169 is 1:240.

There are two evident meltwater routes leading from the zone of ice-contact glacio-fluvial deposition at Roslin-Rosewell. The height of the lowest point on Terrace E is about 487 ft. O.D. (T169). There is a moderate sized meltwater channel cut into bedrock on the west side of Roman Camp Ridge with an intake along the contour at about 475 ft. O.D. (fig. 7.6; channel 44a). This channel joins a lower parallel channel whose intake is at about 435 ft. and then a further channel at about 330 ft. O.D. The unified channel system continues as a large dry valley across Roman Camp Ridge to join the Tyne Water. The possibility that this route is the outlet of water from the Roslin-Rosewell area might be considered less conclusive than is the case with other channels and other terraces already described simply because the distance between Rosewell and channel 44a is 4½ miles; for the meltwater from Terrace E to escape by this channel requires a uniform englacial water-table over this distance. However such relationships are recognised over considerably greater distances in Norway (Gjessing, 1966, pers. comm.).

The fact that meltwater continued to flow over the belt of outwash material at Rosewell but did not continue to escape from the district at a height of 480 ft. is clear from the second meltwater route leading from the ice-contact area. The belt of glacio-fluvium is dissected by drainage channels; meltwater evidently passed down under the ice and found an exit from the area down the regional slope towards the sea at a time when the ice was becoming decayed and unable to withstand penetration of ground water. These channels formed late in the history of Terrace E are numbers 45-49 (fig. 7.4), as previously described.

The small remnant terraces T117-120 near Glencorse should be mentioned for completeness. They are irregular fragments separated by glacial meltwater depressions. The small flat tops of these terraces may not be the original depositional surfaces. Heighting was carried out by aneroid barometer, and this only allows the conclusion that they belong either to Terrace D or Terrace E.

Terraces F and G. Each of these Terraces consists of a full set of terrace fragments, the one set about 30 feet higher than the other. But as the Terraces have similar forms and neither has a glacial meltwater escape channel that can be exactly related to it, they may be conveniently considered together.

Both Terrace F and Terrace G are represented by large remnants at their terminal ends and by smaller remnants upstream. Terrace F consists of 4 left bank terraces 129A, 152B, 164 and 165, and 6 right bank terraces 125A, 127, 142, 154, 179, and 187. The lowest terraces on both sides of the Esk are of identical heights. Terrace F as a whole drops in altitude downstream from 532 ft. to 464 ft. O.D., an average slope of about 1:290.

Terrace G consists of 5 left bank terraces 130, 138, 163A, 166 and 167, and 5 right bank terraces 142A, 155, 168, 179A and 189. Of these 167 and 168, and 166 and 179A can be paired by height across the Esk. The whole Terrace has an average slope of about 1:230, the height range being from 504 ft. to 423 ft. O.D.

The last fragment of Terrace G (T189) terminates in an ice-contact slope at Polton Farm. The higher Terrace F has no ice-contact slope associated with it but there is a solitary Terrace T201A for which the most likely interpretation is that it is an outlying remnant of Terrace F. This remnant T201A has until recently formed the top surface of the Haveral Wood sand-pit site but has now (1965) been largely worked away. The remnant is downstream of T189 on the other side of the river, yet its top at 430 ft. is the higher by about 7 feet. Therefore T201A must more naturally be associated with Terrace F although it is too low to fit the downstream projection of Terrace F exactly.

The glacial drainage channel on Roman Camp Ridge with an intake at 435 ft. O.D. may provide a suitable escape route for water from the Terrace F ice-contact zone, but the relationship cannot be shown precisely because of the lack of a true terminal height for the deposit.

There are a number of terraces shown on fig. 8.2 lower than Terrace E and higher than F and G that have not yet been mentioned. Terraces 125, 126, 129, 139 and 143 cannot be reconciled immediately with any other main sets discussed above. They are at irregular heights; they occur on both sides of the river but are not paired; and the slope of the largest terrace (T143) is 1:110, steeper than the slope of any other substantial fragment. It is concluded that these terraces were formed in the process of downcutting and do not represent a state of temporary grade in the outwash stream regime.

There is a complicating factor where these terraces occur: Glencorse Burn joins the North Esk at this point, cutting its own terraces and also dissecting those along the main valley. Terrace 129 in particular has a slope suggesting it is more related to the Glencorse Burn than to the North Esk.

<u>Roslin Till coverage of Terraces</u>. As described so far, the main Terraces A, B, C, D, E, F, and G are all similar in terms both of their genesis and their form. Each Terrace is underlain by glacial outwash material derived from the southwest and deposited against ice on the north side. The glacial meltwater then passes eastwards by a series of channels at successively lower levels. The upstream ends of each Terrace are

carved from the next older, slightly higher, Terrace. The average difference in height between Terraces is of the order of 50 feet. The Terraces also show approximately the same characteristics of continuity across and along the Esk, and of downstream slope.

It must now be revealed that Terraces D, E, F, and possibly G are covered by the Roslin Till, the deposits typically 3-5 feet thick which has been described at length in previous chapters. The Roslin Till provides a coating of quite different material over the glacio-fluvial outwash. The typical characteristics of the Terraces mentioned above - their continuity, form and slopes - are therefore held to be true characteristics in spite of the covering of a later deposit. The correlation of terrace remnants and the proposals as to their origin have not required modification in spite of what must clearly be a further complexity in the deglacial morphogenesis.

The Roslin Till may be up to 7 feet thick, but this varies greatly. For example, it forms the surface cover of T165 but is absent from T164, an adjacent terrace at the same height. To correct the levelled height values over the outwash surfaces for the presence of Roslin Till, a first adjustment should be to subtract an average of say 4 feet from the absolute heights. This has not been done, but if it were done it would still not significantly alter the correlation between fragments of any one Terrace or the separation between Terraces which are an average of 30 feet apart. It has been seen in Chapter IV that the Roslin Till is not thick enough to conceal the form of underlying dead-ice deposits. This is true also of the glacio-fluvial outwash surfaces.

A second adjustment that can only be mentioned in theory is to add a value in feet for the amount of glacio-fluvium eroded from the top of the outwash by the re-advancing glacier responsible for the Roslin Till. This cannot even be attempted in practice. But any areas of erosion must have been discontinuous because of the presence of undisturbed frozen-ground phenomena such as frost-wedges. In summary, at the scale of plotting heights on fig. 8.2, the raising or lowering of absolute height values by up to 5 feet by the addition or removal of drift makes little or no difference.

Roslin Till overlies certain parts of Terraces D, E, F, and possibly G, but not all parts. It is best represented on the larger left bank terraces 128, 137, 152, 162 and 165, where it forms a complete mantle, but may also be seen on the smaller right bank terraces 144, 154, 155 and 160. Most of the terraces covered are near or at the original outwash surfaces; only minor terraces covered with Roslin Till are found within the gorge and the evidence for including these at all is less substantial.

The exact significance of the Roslin Till overlying a number of well-developed glacio-fluvial outwash surfaces, themselves indicative of ice-wasting conditions, can be best considered in the final chapter when all the previous evidence can be incorporated into the argument. It is sufficient to record at this point that the two more probable alternatives to explain the Roslin Till are that it is an ablation material related to the decaying ice responsible for the glacio-fluvial forms, or that it represents a later readvance of active ice. It will have been noted that the latter alternative has been assumed in the text so far.

The presence of the Roslin Till, although a considerable complicating factor in the total glacial history, does assist in correlating the morphologies of two parts of the middle Esk Basin. Roslin Till overlies T162, the left bank terminal fragment of Terrace E, which ends at about 485 ft. O.D. Roslin Till also overlies the thick glacio-fluvial sands at Straiton east of Gilmerton Ridge, as illustrated at Clippens sand pit (fig. 4.21A). Where it is best developed, the ice-contact front at Straiton, buried by the Roslin Till, has its upper edge at 475-490 ft. O.D. Even if the close agreement between the heights is coincidental, the circumstance of Roslin Till overlying two genetically identical glacio-fluvial forms indicates the forms are pene-contemporaneous. The glacio-fluvial deposits at Straiton can be associated with at least the middle block of Esk Terraces D, E, and F.

Terrace H. Continuing the sequence along the Esk, the next lower Terrace in height is H. No part of this is covered by Roslin Till.

Terrace H is characterized by very considerable terminal fragments on each side of the Esk, and by the ice-contact fronts which are the largest of any such features along the Esk. The overall downstream length of Terrace H, about 5 miles, is also exceptional.

The terminal terraces 202, 202A, and 209 are known from commercial excavations to be underlain by bedded sand over fifty feet thick. The material at Melville Mains sand pit has been described and illustrated by photographs (Chapter IV); the surface above this sand pit is part of T202. The terraces are of identical altitude on each side of the river, and the ice-contact fronts are each about 40 feet high and retain much of of their original steepness. The line of levelling on T209 was continued northeastwards at 50-yard intervals down over the ice-contact slope on to the till plain beyond. The figures given in Appendix D for this terrace illustrate the steepness and height of the ice-contact edge.

Terrace H is represented upstream by T201, a well-preserved but detached portion of T202, and by the smaller remnants T135, 152A, 153, 167A, 180, and 187A. The slope of the lower part of Terrace H, represented by T201-202-209, is 1:215, while the overall slope is about 1:166, which emphasises the increased gradient further upstream.

As befits such an impressive outwash deposit, the main meltwater escape channel from Terrace H is also a relatively large feature. The terminal height of the terraces on both sides of the Esk is about 338 ft. O.D. Channel 44c crossing Roman Camp Ridge has an intake at 330-340 ft., and continues eastwards to join the Tyne system (fig. 7.6). This channel receives higher channels near its intake end, and the combined channel is a broad valley utilizing a pre-existing depression across Roman Camp Ridge, but still apparently cut deeply into bedrock at the eastern end.

Apart from this main channel which removed water from the Esk Basin completely, there are smaller local glacial meltwater channels cut into the surface of T209 and descending the front edge. Also the separation between T201 and 202 and between T202 and 202A is achieved by channels cutting deeply into the sand. It appears that the late drainage from this zone was by penetratinn of the meltwaters under the ice northeastwards down the regional slope.

Terraces I and J. The measured parts of Terrace I consist only of T224-227 and 227A, which form one large unit 1½ miles in total downstream length, and the small fragment T203. The right bank terrace 223A, which is developed in till, could not be heighted by levelling, but bench mark heights and spot heights show it to be equivalent to T225-226 on the opposite side of the Esk.

The overall slope of Terrace I is steeper than 1:100, but this figure is misleading as there are minor falls in the terrace surface separating areas of more gentle gradient. The main section T224-227 is regarded as of composite form. There is a steeper river terrace bank separating T227 from the next lower Terrace level.

It is Terrace I that the Sheriffhall esker meets in the vicinity of T227-227A (fig. 7.8). There is agreement in height to within 10 feet between the top of the esker and the highest outwash surface that extends across in front of it. It is not possible to be more specific than this because of numerous disturbances and artificial structures at the point of union.

Terrace J is about 25 feet below Terrace I and is a well-preserved outwash feature, notable for its great breadth. A further physical feature is introduced with this stage: the River South Esk unites with the North Esk near the lower end of the Terrace, and the original surface is preserved in three areas, the outer sides of both rivers and the common ground between them. This is clearly illustrated in fig. 8.1. The heights of all three areas agree exactly when projected against the supplementary base line (fig. 8.2 - inset). The slopes across the three areas are also in reasonable agreement:

T228	Slope 1:160
T237	1:190
T250	1:180

The presence of the three identical units confirms that the South Esk, like the North Esk, has found its present course by cutting into the glacio-sixteen miles and vary in breadth from three to eight miles, gradually narrowing towards their northern end. The northwesterly slopes out onto the plain of West Lothian are quite moderate; the slopes to the south-east are somewhat steeper, and the slopes at the truncated northern end represent a very bold steep face towards the city of Edinburgh, from Allermuir Hill (1617 ft.) down to Swanston (600 ft.). The Pentland Hills nowhere top two thousand feet, the maximum elevation being Scald Law (1898 ft.) with Carnethy Hill a few feet lower, but there are more than 60 square miles over one thousand feet in height and, viewed from the south, the Pentlands have all the remoteness of the Grampians (Finlay, 1960).

Between the chief summits of the hills, there is comparatively little difference in height, a fact first remarked on by Cossar (1911-12), in an admirable paper on the physical geography of the district. There are sixteen principal summits between 1600 and 1900 ft. Ogilvie (1930) considered these as indicative of a high peneplane surface, and also pointed out another marked surface at 1300 ft. However, a large part of the Pentlands is characterised more by convex rounded summits than by recognizably flat areas.

The hills are dissected to a much greater extent towards their northern end, and here several of the valleys which run across the belt of hills are out of all proportion to the streams which at present occupy them. The major through valley from Bavelaw to Flotterstone, drained by the Glencorse and Logan Burns, has been deepened and modified by glacial meltwaters. A description and interpretation of this glacial action has been provided by Mykura (in Mitchell, Walton and Grant, 1960). Other fluvial outwash surface and is a post-glacial development.

Upper fragments of Terrace J are found on the North Esk in T219 and 220. No fragments have been mapped on the South Esk.

Terrace 230 terminates in an ice-contact slope at about 158 ft. O.D.; T237 terminates in a steep bluff, possibly ice-contact, at 155 ft.; and T250 falls gradually to lower ground, the lowest height in the projection along the terrace being about 151 ft. Terrace J therefore appears to end at about 150 ft. and, considering the amount of deposition, the meltwater must be expected to have a definite escape route before the confining ice decayed sufficiently to allow the water underneath. The channel at the north end of Roman Camp Ridge is the obvious escape route by height correlation. It has its intake along the contour at 150 ft. O.D. and descends northeastwards towards Tranent to about 120 ft.

Terrace K. The last major retreat stage of ice is indicated by Terrace K. The evidence for this consists of T229, 231 and 241 west of the combined North and South Esk (fig. 8.1), T238 between the rivers, and T242 east of the rivers. Terrace 242 is the largest of these terraces, being over a mile in downstream length, and falling from 139 ft. to 101 ft. O.D. Terrace 218 is a possible upstream extension of the same set.

The five large remnants of Terrace K are not entirely consistent in height (fig. 8.2 - inset). In particular T241 can be seen to be about 15 feet lower than T231 and separated from it by a definite river terrace bank. The nearest height-projection association of T241 is with T242. But T242 in its higher parts can be seen by inspection to be equivalent to T238 and T229; and T229 continues as T231 with no break in altitude. This apparent lack of agreement may be resolved by considering the nature of the terminal zones of the terraces each side of the combined rivers. On the west side, the surface of T231 becomes undulating northwards with several shallow hummocks and depressions. The terrace ends at Craighall in an ice-contact zone marked by kames and deep fresh-looking kettle-holes. The 100-foot contour line follows the top edge of the surface. On the east side, there is a distinct bench extending northeast from Sweethope for over a mile to north of Wallyford. This bench has been heighted by levelling (by J. B. Sissons); it slopes from about 94 ft. O.D. at Sweethope to about 82 ft. at Wallyford. It is suggested that T231, the highest part of the Terrace front, illustrates ice-margin conditions as the outwash was being deposited, and that the lower terraces result from a slightly later phase with meltwater flowing away northeastwards parallel to the ice-margin and slightly cutting into these terraces.

A summary for Terraces A-K is given in Table 8.1. The similarity of surface gradient, the common method of downstream termination, the association in eight and possibly nine out of eleven cases of a demonstrable meltwater escape channel with the terminal terrace height all point to the common origin of these features. But the presence of the Roslin Till over a number of the middle Terraces indicates that the succession of Terrace development A to K was not necessarily an unbroken one.

<u>Terrace L</u>. The ice-contact front and the water-cut bench at about 100 ft. O.D. mark the lowest limit of glacio-fluvial outwash surfaces recognisable in the Esk Basin. Below this there are three further sets of terraces along the combined Esk which illustrate the further downcutting

TABLE 8.1

SUMMARY OF TERRACES A - K

Terrace	Downstream termination	Gradient	Terminal height	Escape channel
A	ice-contact	not measure-able	735 ft.	740 ft.
B	ice-contact	1:290	670	670-700
C	ice-contact	1:180	625	620
D	no form	1:220	515-525	500
E	ice-contact	1:190	485	475
F	no form	1:290	464-430 ?	435
G	ice-contact	1:230	423	---
H	ice-contact	1:166	338	330-340
I	river terrace bank	not measure-able	204	---
J	ice-contact	1:180	150	150
K	ice-contact	1:200	100	94

of the rivers to present sea level. These are combined together as Terrace L, the post-glacial stages. The post-glacial terraces are regarded as representing still-stands in base level conditions because they occur at distinct levels in paired sequences, and occur the same distance upstream of the confluence of both North and South Esk (fig. 8.2 - inset).

The exaggerated slope for the post-glacial terraces shown in fig. 8.2 is due to the projection of the heighted points against a conventional straight base line rather than against a base line derived from the longer curving course of the present rivers. Further levelling might enable the low river terraces upstream of Dalkeith to be associated with those near the confluence of the North and South Esk. There are as yet no specific proposals for associating raised beach heights at the mouth of the Esk, based on work along the Firth of Forth, with these post-glacial terraces on the Esk, but such proposals may be anticipated shortly.

Former course of River North Esk. It will now be evident that the majority of the higher so-called terraces along the River North Esk can be reasonably interpreted as being formed of glacio-fluvial outwash successively dissected by meltwater working to lower base levels. By contrast, the terraces nearer the present river level represent the post-glacial cutting of the river into drift and bedrock. These more recent terrace fragments cannot be correlated with confidence because of the increasing influence of bedrock in producing local nick-points and because of the grouped nature of the terraces between stretches of rock-walled gorges. But it is clear that as far upstream as Rosewell, the terrace remnants even up to 30 feet above present river level are of post-glacial age. The two biggest stretches of the North Esk confined in rock-walled gorge are upstream of Penicuik, where the glacial nature of the gorge has been reasonably proved, and between Roslin and Polton.

The elaborate meander south of Polton shows the valley of the Esk in its two aspects. The river cuts partly into basal till exposed near present stream level, and partly into the friable Roslin sandstone. As the lower terraces upstream of Polton are of post-glacial origin, the meanders at Polton must have been entrenched to their present depth also in the post-glacial period.

The valley of the North Esk must be preglacial over at least part of its length, as proved by the presence of basal till at stream level at Auchendinny, Polton and Roslin. After the known succession of glacial drift had filled the valley, the drift was progressively scoured out again, first by the meltwaters from the southwest and then by the post-glacial river. The present course of the North Esk represents at least in part the earlier pre-glacial channel re-occupied. The buried channel northwest of Roslin where over 180 feet of drift has been proved seems more likely to indicate an earlier course of Glencorse Burn than of the main river, as the 114 feet of drift at Kirkettle suggests the pre-glacial Esk followed a course similar to the present one in this vicinity.

CHAPTER IX

GLACIAL HISTORY OF THE ESK BASIN

> "..... and I trust that the present attempt to investigate these (glacial) phenomena, if not attended by any direct benefit to science, will have, at all events, the effect of stimulating other geologists of greater experience and more leisure, to confirm or correct the descriptions I have given and the opinions I have ventured to express." Mr. Milne, on the Mid-Lothian and East-Lothian Coalfields, 1840.

In the preceding chapters, the glacial geomorphology of the Esk and Upper Tyne Basins has been described under systematic headings of drift geology and landforms. But interpretations of the glacial features have generally been limited to statements as to genesis and immediately local significance. The theme central to much of the considerable amount of earlier research in this part of Scotland has been the interplay of ice-sheets derived from the Highlands and the Southern Uplands. In this thesis, several lines of evidence have been examined that contribute to a fuller appreciation of the overall glacial succession - in particular, the variety and stratigraphic relationships of different types of glacial deposit; the direction of ice-movements by till fabric analysis; the study of erratic stones in till; and landscape mapping and morphometry. Following a brief restatement of the main conclusions from earlier chapters, these different lines of evidence are now analysed together in an attempt at a chronological sequence of events in the local regional setting.

Summary of main systematic conclusions. One of the chief barriers to understanding the relative influence of Highland and Southern Upland ice in east-central Scotland has been the assumption that the product of one glaciation includes a ground moraine of fairly uniform physical characteristics. It has not always been appreciated how radically any moraine can alter in appearance and content. In the absence of any method for absolute dating of fossil-free till directly, knowledge of the source of the ice and directions of ice movement must continue to be based on stratigraphic considerations of superposition, possibly linked with closely spaced erratic and fabric analyses. In the Esk Basin, the full stratigraphic succession is not exposed at any one site, nor is there yet a satisfactory picture available from bore-hole or other secondary sources. Based simply on appearance, only two tills have been recognised in the past, a lower till and the Roslin Till, often separated by thick beds of sand. Where this sand does not occur, the upper and lower tills have not been recognised as different deposits. The lower till has traditionally been regarded as the product of Highland glaciation. It is often described as the 'basal boulder clay' (Mitchell and Mykura, 1962). The upper or Roslin Till has likewise been regarded as the product of a Southern Upland readvance.

By a number of field tests at many different till sections, it has been possible to distinguish three tills rather than two. The till fabric results give the strongest indication of a threefold division.

By the method of fabric analysis, a dominant particle orientation is found in till, and an ice-movement direction is inferred from this. In the Esk Basin, the fabric orientations from the so-called lower or basal till occur in two contrasting sets, the one set east-west and the second set north-south. Simple stratigraphic considerations show that the east-west pattern is the earlier of the two, and the dip measurements in the fabric analyses indicate a westerly source for the older and a southerly source for the younger till. On the basis of the fabric results, the deposit traditionally recognised as basal till has been relabelled as two tills - basal and intermediate.

The fact that these two tills are separated by thick sand in certain sections is used to suggest that the tills represent distinct ice-movements with possibly a period of local ice-free conditions between them. In many sections a depositional unit has been identified, this being a till grading upwards without a break into glacio-fluvium. Both the basal till and the intermediate till occur in such depositional units, reinforcing the view of two periods of glaciation.

The Roslin Till must therefore be considered as the third in sequence. These three tills must represent a minimum for the Esk Basin. In Midlothian and East Lothian together, the Soil Survey officers have noted about six tills of fairly local origin, distinguishing them by colour and large-stone content. These tills are of restricted areal extent, and their horizontal limits are not clear-cut. Such local tills are to be expected from a careful study of drift deposits through an area of such heterogeneous bedrock lithologies. But ultimately they would be expected to group into sets representing a few major ice-movements.

Field studies of till colour, large-stone content and till fabric are all disassociative techniques when used in a lowland area such as the Lothians, reflecting all local variations and not allowing much extrapolation back towards the ultimate ice sources.

Continuing the present writer's results, the stone counts and mechanical analyses from the basal and intermediate tills now defined in the Esk Basin give moderate support to the till fabric conclusions. With only rare exceptions, till thought by fabric analysis to be derived from the west shows a mixed lithology with more westerly material predominant; and till thought to be derived from the south shows a moderate or high proportion of greywacke. Mechanical analysis shows close similarity in the sand, silt and clay content of all three tills. The Roslin Till has a slightly greater proportion of silt than the other two tills; this difference is not sufficient to be a diagnostic characteristic on the number of samples analysed.

It was the presence of the Roslin Till that gave point to the original investigations by the writer. But in spite of the work on it, its nature still requires careful consideration. The Roslin Till has so far been assumed to be a readvance moraine, although not necessarily part of a Southern Upland readvance, as described by previous writers. To justify it as a readvance deposit, a summary of all the information about it is presented here again.

There are some considerations suggesting that the till forms an ablation moraine: in particular, its very limited occurrence areally; and its abrupt variation in thickness from nothing upwards. But there are rather more factors suggesting that it forms a readvance moraine:

(i) The till fabric analyses give a consistent if weak set of orientations. These are approximately north-south but follow the flank of the Pentlands. If the deposit were formed by ablation, then, according to a lodgment theory of till deposition, there should be no preferred orientation. If the deposit were a solifluction deposit, it would have an orientation pattern radiating from the Pentlands.

(ii) The mechanical analyses give a texture similar to that of other tills in the Esk Basin. An ablation moraine is generally regarded as being more water-washed and therefore coarser-grained. Indeed, ablation moraine often consists only of scattered large boulders and not a continuous 'bouldery clay'.

(iii) The erratic stone counts are distinctive. Although the stone counts cannot be considered conclusive, as the total number of stones examined from several sites was only 750 (Table 4.1), the proportions of particular lithologies are quite different from those in the intermediate till beneath. If the Roslin Till were the ablation till of the Southern Upland ice, it would be expected to show similar stone counts to the intermediate till, with greywacke forming a high rather than a negligible proportion.

(iv) The areal occurrence of the Roslin Till in relation to other glacial features indicates a readvance rather than ablation deposition. The till is not known to occur on the coastal plain, or inland much south of Glencorse. It has been located east of the River North Esk in a very few places, but does not obscure the meltwater channels on the Kingside-Rosewell Ridge. It covers several of the Terraces in the middle part of the Esk; if these Terraces were formed subaerially, as has been suggested glacial or glacially-modified valleys occur in small numbers around all sides of the Pentlands, often as small notches. The large system of glacial meltwater channels on the southeast side of the hills at Carlops has been described and interpreted by Sissons (1963a).

Occasionally in the Pentlands there are precipitous scree-covered slopes, particularly forming the backwalls of what may be called small, incipient corries. Much of the higher land is peat-covered or otherwise ill-drained, and given over to sheep. Reservoirs have been constructed in several of the larger valleys, and the hills have considerable amenity value for walkers from Edinburgh.

Eastwards from the Pentland Hills, the Esk Basin is a gently undulating plain, traversed by the well-wooded valleys of the rivers North and South Esk and falling with slight gradient from the south down to the Forth (fig. 2.2B). The section-line from Gladhouse northwards through Dalkeith to the coast shows a drop of 900 feet in 12 miles. Except where this line is crossed by the River North Esk, there is a remarkedly uniform slope. This plain was recognized as part of a peneplane surface (Ogilvie, 1930) and a photograph and brief supporting statement were provided by Linton (1951). Ogilvie described the higher Lowland peneplane as having its greater area between 500 and 750 ft., but in places near the east coast it may be less than 400 ft., and around the hills slightly over 1000 ft. Ogilvie also tentatively recognized a lower Lowland peneplane between 100 and 500 ft. This comprehensive height range certainly includes the Esk Basin but it can not now be called a peneplane in any generic sense. The smooth appearance is largely due to glacial deposits filling in a very irregular bedrock surface.

above, then the Roslin Till cannot be an ablation till of the same ice sheet.

The balance of evidence supports a readvance origin for the Roslin Till, and this is accepted by the writer. In its thickness and variability, it is very similar to Wisconsin readvance till sheets described by White (1952).

It will have been noticed that the presence of frost wedges at the top of the sand below the Roslin Till has not been used in evidence. The frost wedges probably indicate that the sand was exposed to the atmosphere for a period before the Roslin Till was deposited, and therefore that a readvance did occur, but there is some current opinion (1966) that frost wedges can be formed in sand beneath such a thickness of till. The writer cannot add any weight to this argument, except to mention that the details of the contact between sand and till suggest that in this case, the frost wedging was produced subaerially.

It now remains to decide the source-direction of the readvance ice sheet that lay down the Roslin Till. The two alternatives are clear from the fabric evidence: north-south or south-north. The dip pattern of the fabric analyses does not particularly favour either direction, but the pattern of orientations themselves suggests the movement was north to south, the ice extending around the northeast flank of the Pentlands and southwards as a salient into the basin. Ice moving in the opposite direction from the south would hardly have followed the flank of the Pentlands northwestwards around up on to slightly higher ground, but would have continued northeastwards downslope in the direction of Dalkeith.

Certain deglacial morphologies in the upper Esk also suggest the movement was north to south. Neither the east-west Howgate esker system nor the highest Esk Terraces near Penicuik appear to have been modified by an ice readvance over them. The ice-contact slopes associated with these features are all fresh and steep-sided.

The erratic stones in the Roslin Till give some further assistance. In the original description of the Roslin Till by Anderson (1940), it is stated:

> "..... the vast majority (of boulders in the overlying boulder clay) are igneous rocks, many of types common in the neighbouring Pentland Hills, and Devonian and Carboniferous sedimentary rocks, along with a small number of stones of Highland origin. Southern Upland greywackes are rare (1%) and the few present might well have been derived from the Pentland Hills." (Anderson, 1940, p.471).

Anderson regarded the Roslin Till as forming a readvance moraine, but did not offer an opinion as to its source. It was the opinion of McCall and Goodlet (1952) that the Roslin Till represented the Southern Upland readvance moraine, the proof of a movement from the Southern Uplands via Dolphinton, West Linton and Auchencorth Moss, with a subsequent retreat through West Linton and Dunsyre. The case for this substantial advance and retreat was based in the Roslin area solely on an examination of 25 felsites. Almost all of these felsites were referred to Tinto Hill, which is at the south end of the Pentlands. The lack of greywacke was not commented on.

The small size of the felsite sample does not give great confidence in this result. Also felsite is difficult to refer to Tinto Hill uniquely, even in thin section; there may be other felsite bedrock of the Tinto type in other localites now buried by drift. And even if the felsites examined were derived ultimately from Tinto Hill, they may have been derived in the meantime from other drift deposits and have reached Roslin by an indirect route via the west side of the Pentlands.

It is concluded that the Roslin Till is the product of an ice readvance from the north, and that the published evidence to the contrary requires to be re-assessed.

Post-depositional glacial disturbance of either a till or a glacio-fluvial deposit has been noted only in isolated cases. At Kirkhill on the River South Esk, the basal till along one section of 80 yards contains faulting and minor folding over the full height of the section exposed, about 15 feet. Sand overlying the till has been caught up in the contortions. This section has been visited by a number of experienced glacial geomorphologists who agree that this appears to be an example of glacial tectonics, the basal till and overlying sand being crumpled by the movement of an ice-sheet over-riding the deposit. As the intermediate till occurs in this section at a higher level, the necessary second ice-sheet would appear to have been that from the south.

Observations on the periglacial features in the glacial drift have added little to the reports of earlier workers. Frost-wedges and similar phenomena have only been seen at the contact between the Roslin Till and the underlying sand, an occurrence which suggested an interstadial interval to Galloway (1958). No vegetation remains or even pollen grains have been located in a stratigraphic position earlier than the latest till. Vegetation remains at one site beneath Roslin Till have proved to be of Zone VIIb age.

The cumulative impression from this study of the glacial drift evidence is of a succession of ice movements, with ice-sheets invading the

Lothians from different directions. The landforms show little of this multiple glacial activity. Neither the erosional nor the depositional morphologies show much more than one glacial event in any one district. The treatment of these landforms in Chapters VII and VIII is by districts, each district showing one particular suite of glacial morphologies. A summary of each of these districts would involve a restatement of almost all that has been written before, as the districts have little in common. Inland most of the mappable forms relate to deglacial events; it is only along the Firth of Forth coastal plain that active glaciation is represented, by the crag-and-tails and the ice-moulded till plain itself. The next section reconciles these different districts in a proposal for the complete glacial history.

Regional glacial history. The till overlying rockhead on most of the lower ground in the Esk and Upper Tyne Basins is taken to be of Würm age. It was deposited by ice from the Scottish Highlands moving eastwards through the Lothians, unaffected in direction by the Pentland Hills aligned obliquely across its path but deflected east-northeast by the northern edge of the Southern Uplands, particularly in East Lothian. The till filled up many low-lying depressions, for example, the valley bottom of the River North Esk.

Following this west-east movement, there was a substantial ice movement through the area from south to north. Although the direction of movement within the Esk and Upper Tyne Basins is known, and the stone count indicates a carry over some part of the Southern Uplands, the ultimate source of this second ice sheet is not known. The most likely source is the west-central part of the Southern Uplands, the ice taking a fairly straight course to the Lothians. From the thick sand between the basal and intermediate tills at Red Scar, Keith Water, and elsewhere, and the glacier tectonics at Kirkhill, it is inferred that the Southern Upland ice movement was not contemporaneous with the Highland ice movement, at least in the southern parts of the basins.

The magnitude of the glacial episodes indicated by the two tills is difficult to estimate. To represent glacial episodes of interstadial proportions, the two tills should cover a much larger area than the Esk and Tyne Basins. But in fact the two ground moraines are not even found throughout this relatively small area. The basal till is best developed along the coastal belt and in the central part of the basins below 750 ft. O.D. The intermediate till is best developed at the southern end of the basin on higher ground, and appears to be absent as an independent unit near the coast. The only indications of more than one depositional unit found near the coast are on the tail of Blackford Hill, where till overlies sand, and at Park Burn, Dalkeith Park, where there is a multiple till section (fig. 4.11). But both cases have been taken to indicate subglacial temperature and pressure fluctuations rather than separate glacial phases.

Although this part of the history will unquestionably be refined as more drift observations and records are incorporated, the existing evidence suggests that at first the Highland ice moved across the area, extending at least to the Southern Upland scarp. Ice with a source in the Southern Uplands then thickened sufficiently to repel the Highland ice and establish a south-north movement across Midlothian and East Lothian, joining with the Highland ice and moving eastwards along the Firth of

Forth. The effect of this would be to have Southern Upland ice apparently becoming thicker northwards on lower ground.

Morphological evidence effectively begins with the thick bedded sands of the Esk and Upper Tyne overlying the intermediate till. Through the central part of the Esk Basin, the sand forms a series of eleven glacial outwash zones. It has been shown in Chapter VIII that these represent halts in the recession of an ice-front northwards down the slight regional slope to the Firth of Forth. The outwash material consists mainly of shallow-bedded sands, with gravels confined to the upper parts of each section. Ice-contact slumping of the beds is uncommon; by contrast two of the larger sand-pits show excellent deltaic bedding with foreset bedding at a moderate angle and about three feet of top-set deposit. So whereas the frontal form appears to be ice-contact, the sediments are deltaic, a fact noted by both G. Hoppe and J. Gjessing during personal visits to these exposures. One possible explanation is that the outwash material was often deposited in water ponded up behind the ice-front rather than subaerially against the ice itself.

Associated with at least eight of the outwash zones or Terraces are glacial drainage channels that carried water away eastwards. The three highest of these channels (Table 8.1) drained water eastwards from the Kingside-Rosewell Ridge towards Borthwick at the south side of Roman Camp Ridge, and so into the Tyne system. The lower channels drained from the Kingside-Rosewell or across Roman Camp Ridge at its lower northern end. Altogether the channels across the two ridges form a sequence for eastward draining meltwater from 940 ft. to 150 ft. O.D.

The form and combined character of the outwash zones and meltwater channel allows fairly specific comment on the environment of their formation, subglacial or subaerial. All the channels on the Kingside-Rosewell Ridge are regarded as of subglacial origin. This includes channel 18 at the south end, the large Howgate system of esker and channel, and the further channels as far north as Rosewell.

Terraces A-D are associated with some of the channels in this group. Nothing in the form of the Terraces absolutely contradicts their formation subglacially, but the ice-contact margins and the general evenness of the surfaces with only occasional kettle-holes suggests a subaerial environment. Terrace A, the highest depositional zone at 735 ft. O.D., would require to be formed subglacially if one of the stated possible outlets for its meltwaters, channel 92, were the correct outlet. But an alternative possibility, the use of channel 27, does not require that Terrace A should be formed subglacially, and it does not seem necessary to make an exception for the formation of this one Terrace. Correlating channel 27 with Terrace A leaves channels 18, and 24-26 without corresponding depositional zones. These channels must have been formed immediately prior to Terrace A and channel 27 before the ice-sheet thinned down to the ground and the northward retreat of the ice-margin took place.

Although the higher meltwater channels were cut subglacially, it is not necessary that they should have been formed far under the ice. The situation envisaged is of meltwater running laterally through the decaying margin of the ice-sheet, being held in this zone by the regional slope and by the relative competence of the thicker ice on the north side further from its margin.

For the lower Terraces E-K along the Esk, the outwash surfaces in each case were formed subaerially, and the associated channels were marginal or sub-marginal features. From a comparison of figs. 7.4 and 7.6 with fig. 8.1, it will be noticed that every outwash terminal zone A-K along the Esk is located upstream of the meltwater channel associated with it. It appears that the outwash material was deposited against the ice-front, sometimes in shallow temporary lakes, and that excess water drained englacially or subglacially slightly forward into the decaying ice before being diverted northeastwards.

The lowest meltwater channels have the appearance of being sub-marginal, but only the small sections cut in bedrock on Roman Camp Ridge are preserved, and it still requires an englacial water table to bridge the gap between the terminal depositional zone and the present channel remnant.

It is noticeable that all meltwater drainage is to the east or northeast, and none is northwestwards along the eastern flank of the Pentlands. This must reflect the original slope of the ice, the retreating ice-front being aligned west-southwest - east-northeast, rather than, for example, northwest-southeast.

The source of water responsible for the ice-front depositional zones of sand down the Esk valley and the meltwater channels eastwards is, first, the meltwater from the Carlops system and beyond to the southwest, and second, the melting local ice-sheet itself. The Carlops system is a regional trunk glacial drainage channel that poured large quantities of water into the upper end of the Esk Basin. Some of this appears to have been deflected eastwards via Borthwith subglacially and the remainder by lower channels northeastwards as the ice-front retreated.

Beyond the southern limit of the Esk Basin, the pattern of deglaciation in the Upper Eddleston Valley and the West Linton Basin would have brought meltwater into the Esk for a period of time, but the direction of final ice-retreat in these basins was to the south. Assuming that the southward retreating ice-front in the Eddleston Valley and the northward retreating ice-front in the Esk represented the decay of the same ice-sheet, then it is necessary to postulate a split of the ice-cover in the vicinity of the present watershed near Leadburn, and an increasing gap as the ice-fronts moved apart downhill to the north and south respectively. Critical conditions of the slope of the ice-surface compared to the slope of the ground surface are necessary, but the mechanism is similar to that described for central Norway (Strøm, 1956; Gjessing, 1960). It has the merit that, not only would the two parts of the ice-sheet be in the correct geographical position to produce the meltwater forms, but the ice wasting southwards towards the Southern Uplands would provide the meltwater flowing into the south end of the Esk Basin. To explain the full suite of Terraces on the Esk, the ice to the south must have continued to supply meltwater northwards until the northern part of the ice-sheet has wasted down and back a considerable way towards sea level, suggesting that the southern part of the ice-sheet wasted away rather more slowly.

There is a second possibility that broadly conforms with the morphological evidence of backwasting in the Esk Basin. The deglacial halt stages down the Esk were controlled by a mass of ice on the north side, presumably thicker northwards than at its southern edge. An ice-sheet thicker on the north side might well have been derived from the north.

It could have originated as a resurgence of Highland ice pushing in a tongue up the Esk Basin and then retreating back down the basin.

Such a readvance from the north would have widespread implications in respect of morphology and of stratigraphy. The evidence supporting the concept of a northward retreat of an ice sheet partly derived from the Southern Uplands has been given above. However, it has been argued earlier in this chapter that the Roslin Till, the uppermost deposit of all, indicates a readvance of Highland ice into the Esk Basin. Its occurrence is therefore of the greatest significance, and it is now necessary to consider whether the deglacial morphologies need to be reinterpreted in the light of this.

Apart from producing the ground moraine itself, a tongue of Highland ice might have created proglacial deposits as it advanced; these deposits would subsequently be covered by the advancing ice. Highland ice might also have created terminal and lateral moraines to mark its maximum extent; and it might further have left till or glacio-fluvial deposits to mark its retreat stages. In fact no positive features composed of till have been recognised, and the only possible marginal features are the group of kames with steep ice-contact slopes between Glencorse and Hillend (fig. 7.5) between 625 and 675 ft. O.D.

The case for certain of the lower glacio-fluvial spreads of sand being formed by the readvance is much stronger. Of the outwash ice-contact stages on the Esk, at least Terraces A-F were formed in order downslope. This is clear from the pattern of the meltwater channels draining from them and also from the structure of the Terraces themselves, each Terrace being carved out of the next higher Terrace. If these

At only two places does bedrock obtrude through the varied drift cover of the Esk Basin to produce local bedrock relief. Between Straiton and Edmonstone, the steeply dipping western edge of the Carboniferous Limestone Series forms a ridge about a third of a mile wide. This ridge falls in height over its three mile length from 450 ft. at Straiton to 250 ft. at Edmonstone. It is referred to in this text as the Gilmerton Ridge after the district of Gilmerton, which also gives its name to the local member of the Lower Limestone Group.

The Gilmerton Ridge is cut across by several glacial drainage channels. These have been discussed by Mykura (in Mitchell and Mykura, 1962).

The second obtrusion of bedrock in the Esk Basin is the Roman Camp Ridge, previously referred to, which separates the Esk Basin from the upper Tyne valley to the east. The Roman Camp Ridge like the Gilmerton Ridge consists of the lower members of the Carboniferous Limestone Series and its crest line similarly slopes down from the south, from 750 ft. west of Gorebridge to 250 ft. seven miles north-northeast at Falside Hill near the coast at Prestonpans. Its southern end is cut off from the Moorfoot Hills by the valley of the Gore Water, in an area where the drainage is considerably modified by glacial meltwaters (see Chapter VII).

The physical appearance of the Esk Basin is much affected by the mineral workings. There are many coal mines and spoil-heaps, particularly at Loanhead, Rosewell, Newtongrange and Bonnyrigg. Two large new collieries have been recently opened at Bilston Glen near Loanhead and at Monkton Hall north of Dalkeith. There has formerly been much open-cast mining at the south end of Roman Camp Ridge and in adjacent areas. The depositional zones were formed proglacially to the advancing ice, they would not be constructed in this manner. The same argument cannot be applied for the thick deposits of sand nearer the Pentlands at Straiton and Bilston. There is a height correlation at 485 ft. O.D. between the terminal zone at Straiton and Terrace E, but the deposits at Bilston in particular could have been formed proglacially to the Highland readvance.

Because Terraces D-F are covered by Roslin Till, it is not possible that they were formed during the retreat of the Highland readvance ice. Therefore all the Terraces A-F must have resulted from the melting of an earlier ice sheet, the Southern Upland ice sheet being the obvious one.

Terraces G and H are not covered by Roslin Till but, as fig. 4.5 shows, Roslin Till blankets the flanks of T209 (Terrace H) and so post-dates this glacio-fluvial deposit. Also Terraces G and H show up-stream terrace remnants carved from higher Terraces in the way typical for A-F. Therefore G and H are considered with A-F as one set A-H.

Terraces I-K are somewhat different in character, and there are several factors which suggest they have a separate origin. There is a fall of 130 feet between the terminal heights of H and of I (Table 8.1). This is the largest gap between any Terraces; A-H have an average height interval of 60 feet, and I-K have intervals of 50 feet. A second point is the lack of any upstream terrace development of I, J and K much beyond the terminal zone of H; although I-K are individually very large features and each of the two lower Terraces is formed by dissection of the next higher one, the set of three do not make any contact with the other higher Terraces. Third, the Sheriffhall esker, which can hardly have survived a later readvance and so must be a product of decay of the Highland readvance, may be associated with part of Terrace I. A final point is that the Roslin Till has not been found anywhere near these three low Terraces, either on top or below; the sections at Park Burn (fig. 4.11), which underlies T228 (Terrace K), and elsewhere in this vicinity show that the only tills are of the basal, far-travelled variety.

On this evidence, Terraces I, J and K are regarded as having been formed during the retreat of the Highland readvance ice-sheet.

There is no recognisable southern limit to the readvance of the Highland ice into the Esk Basin. The limits of Roslin Till are ill-defined (fig. 4.2), particularly where the till occurs over bedrock or another till. West of the River North Esk, Roslin Till is found at Bush and Milton Bridge. It is also thought to occur just southwest of Glencorse Burn near Glencorse House, and possibly extends to Mauricewood. It is not considered to have extended as far south as Cuiken or to be responsible for the ice-contact slope near this (6; fig. 7.2); this feature is related to the melting of a much thicker and earlier body of ice.

East of the River North Esk, there are few proved occurrences of Roslin Till. Those patches of till that have been found are adjacent to the Esk. The till has not been found east of the River South Esk nor east or north of Dalkeith.

Soil Survey officers have reported that the red soils that are associated with the Roslin Till west of the Esk have a southern limit east of the Esk roughly east-west from Kirkettle to Carrington (pers. comm., 1964). The only additional field evidence by the writer that supports such an extension is in one section at Kirkhill on the South Esk (fig. 4.2). In the sections where basal and intermediate tills occur (till fabrics 67 and 68), there is a capping of stony clay with a stone count similar to that of the Roslin Till, lacking the high proportion of greywacke found in the intermediate till a few feet beneath.

One meltwater channel related to the melting Highland readvance ice-sheet is that at Oatslie (fig. 4.6). This cuts through the Roslin Till and underlying sand (terrace 152) before joining the North Esk. Other smaller channels northeast of Roslin are of similar origin. East of the Esk, the channels derived from the melting back of two ice-sheets in the same direction cannot be convincingly separated. The essentially northeast subglacial drainage from Rosewell to Dalkeith may be a product of the Highland ice rather than of the Southern Upland ice as previously described. The lower eastern terraces of the outwash zone E (T176-178) have not been related to other Terraces, and may be more recent than T169 and 171 adjacent. These hypotheses can only be realistically investigated if an elaborate programme of augering is carried out to confirm the limits of Roslin Till in this district.

On the basis of the available evidence, it is suggested that the last Highland ice advanced into the lower Esk Basin from the northwest, and its limit was approximately southwest-northeast along the line Kirkettle-Rosewell-Eskbank. Further work might enable this limit to be extended.

To condense the argument of the last few pages, it is suggested that, following the original movement of Highland ice west to east, Southern Upland ice dominated in the southern part of the basin, and that ice from the two sources fused together in the northern districts. The thinning of this ice-sheet produced an eventual split near the present watershed area.

Southwards the ice-margin retreated towards the Southern Uplands; northwards it retreated towards the Firth of Forth, this northward retreat being interrupted by a slight readvance up into the basin.

For the Upper Tyne Basin in East Lothian, a similar glacial succession may be postulated, if only because the events in the Esk Basin were on too large a scale for the effects to have been confined to so limited a district. No systematic mapping of landforms was done in the Tyne Basin, but the till fabric evidence is a repetition of that for the Esk Basin. Above the basal and intermediate tills, there are outwash sand deposits similar to those in Midlothian although more limited in extent to a belt between 550 and 750 ft. O.D. This sand was deposited subaerially or in temporary lakes against an ice-mass to the north, which eventually thinned, causing the ice-margin to retreat northwards (Sissons, 1958a). It is suggested that a subsequent readvance or oscillation of Highland ice which brought the ice-margin back over Roslin at 500 ft. O.D. would have also brought it over Keith in East Lothian at the same height, but the nature of the top capping of till at Keith has not been satisfactorily established as readvance moraine.

There is not yet any accurate absolute chronology for the glacial succession suggested in this chapter. No absolute dating has been obtained from within the glacial deposits of the Lothians, and so the succession can only be placed very roughly by relation to dated events of other areas. A recently published date of 28,000 years B.P. from shell-bearing sand beneath a till-sand complex on the Cheshire Plain (Boulton and Worsley, 1965) gives an upper limit to the formation of the last till in the Lothians area, as it is hardly possible to have an ice sheet from the Irish Sea passing over the Cheshire Plain without there being at the same time an ice sheet over central Scotland. This date of about 28,000 years B.P. may be an interstadial period through Northwest Europe generally; of the local deposits, the Roslin Till at least must be more recent than this.

The periglacial features from beneath the Roslin Till have been described by Galloway (1958) as marking an interstadial period but, if this is correct, it has still to be dated with respect to other events.

An extreme lower limit for final ice retreat is 5500 years B.P., the date obtained for post-glacial peat deposits on the 30-foot (sic) beach at Dunbar by H. Godwin and W. W. Newey.

This thesis in glacial geomorphology contains certain conclusions, on till fabric procedures, on landform measurement, and on the glacial succession at large, which are entirely novel. To end the exposition, it may be noted that one important conclusion is by no means novel, as it was first presented by Charlesworth forty years ago. Considering the glacial succession in the Lothians, Charlesworth envisaged an ice-sheet east of the Pentlands that split and withdrew northwards and southwards as two lobes, just as the present writer has suggested. Although opinion differs on the source of the ice-sheet, an essential part of the deglaciation is interpreted in the same way. Over four decades the style of fieldwork has changed and the attention given to small detail has increased. Charlesworth certainly did not fully appreciate the complexity of the story. But then, the complexity is as certainly not fully appreciated today.

APPENDIX A.

SAMPLING ERROR OF STONE COUNTS

In Tables 4.1 and 4.2, 37 sets of stone counts are tabulated. The sample collections vary from 79 to 343. In each case, the sample is divided into 5 groups, expressed as percentages. The sample error for each collection can be calculated by regarding the sample as a series of binomial distributions. The formula for the standard error of the sample is $\sqrt{\frac{p.q}{n}}$, where:

p = percentage of chosen lithological suite
q = remaining lithologies = 100 - p
n = number of stones in the collection.

The true percentage at a given level of probability is then expressible as a range about the sample percentage. At an acceptable level of probablity (taken to be 95%), the true percentage varies by 2 standard errors (actually 1.96) from the sample percentage, and an estimate can be made of the accuracy of the stone count. Two examples with different sized collections make this clear.

Example 1. For Bilston (3); n = 100

Carb. Ls. Standard error = $\sqrt{\frac{30.70}{100}} = 4.58$

Ign. volcs. " " = $\sqrt{\frac{20.80}{100}} = 4.00$

O.R.S. " " = $\sqrt{\frac{3.97}{100}} = 1.98$

Greywacke " " = $\sqrt{\frac{0.100}{100}} = 0.00$

Others " " = $\sqrt{\frac{47.53}{100}} = 4.99$

Therefore the true percentages of lithological suites at the 95% level of probability are:

Carb. Ls. 30% ± 2(4.6) = 39.2% to 20.8%
Ign. volcs. 20% ± 2(4.0) = 28% to 12%
O.R.S. 3% ± 2(2.0) = 7% to 0%
Greywacke 0% ± 2(0.0) = 0%
Others 47% ± 2(5.0) = 57% to 37%

<u>Example 2</u>. For Lead Burn, Howgate (42): n = 300.

The true percentages of lithological suites at the 95% level of probability are:

Carb. Ls. 5% ± 2(1.3) = 7.6% to 2.4%
Ign. volcs. 27% ± 2(2.6) = 32.2% to 21.8%
O.R.S. 2% ± 2(0.8) = 3.6% to 0.4%
Greywacke 53% ± 2(2.9) = 58.8% to 47.2%
Others 13% ± 2(1.9) = 16.8% to 9.2%

Therefore a larger sample produces a correspondingly closer estimate of the true percentages at the chosen level of probability.

The main conclusion on the reliability of the stone counts is that they give a general but very imprecise indication of true percentages. By the nature of the standard error, small percentage occurrences show a smaller range of true percentages than large percentage occurrences (cf. Carb. Ls. and Ign. volcs. in Example 2 above). The occurrence of zero samples in any suite is more significant from a large population than from a small population, although the standard error sampling does not show this. The stone counts therefore only indicate the broad distribution of erratics, and no significance can be paid to specific percentages, except in the case of zero percentage based on n > 300. Figure 4.18 should be considered with this in mind.

APPENDIX B

TILL FABRIC ANALYSIS : BOOKING AND CALCULATION OF CHI-SQUARE TEST OF ORIENTATION

The basis of the computation is derived from Harrison (1957a), a paper to which reference should be made for a fuller description and for the derivation of chi-square for a circular function.

The complete worked example of till fabric 53 (Park Burn, Dalkeith Park) is given below. The steps in the calculation are straightforward. First, replot the 360° distribution of the original till fabric plot as a 180° distribution. The contemplated (average) frequency in each 10° class interval then exceeds the minimum of 5. The observed frequency (column 3 in the worked example) represents the number of points in each 10° sector. Then evaluate two numbers C and S, and find χ^2, where $\chi^2 = C^2 + S^2$. For this example, $\chi^2 = 52.4$, a value well in excess of the value of χ^2 at the 99th percentile for 2 degrees of freedom (9.21; from Lindley and Miller, 1962, Table 5). Therefore there is significant departure from a random orientation, in other words a strong preferred orientation.

The penultimate step is to find the orientation from $\tan 2\theta = \frac{S}{C}$, the sign of the sine and cosine indicating the quadrant in which the angle lies. Finally, add a class interval unit of $2^\circ\,30'$ to θ to find the apparent preferred orientation.

This class interval unit differs from that in Harrison's method, in which 5° is added to θ, 5° being the mid-point of the first class interval. Whereas Harrison plotted orientations to the nearest 1° (see Harrison, 1957b), the present writer has plotted orientations to the nearest 5°, and it has been shown empirically that the addition of half the first class interval in this case introduces a systematic error. Preliminary tests using both field data and also ideal symmetrical distributions around a known orientation, and plotting orientations to the nearest 5°, show that the value of θ is influenced by the grouping arrangement adopted. The values of θ derived from grouping the bearings as $0-9^\circ$, $10-19^\circ$, $20-29^\circ$ ...... and as $1-10^\circ$, $11-20^\circ$, $21-30^\circ$ ...... differ by exactly 5°, the former style of grouping giving the numerically higher result. For example, till fabric 40 under test gives the following results:

	Class intervals	χ^2	θ	$\theta + 5^\circ$
1.	$0-9^\circ$, $10-19^\circ$, ...	120.9	86°	91°
2.	$1-10^\circ$, $11-20^\circ$, ...	122.6	81°	86°
3.	Mean of 1 and 2, being: $5 + \frac{0+10}{2}$, $15 + \frac{10+20}{2}$,	120.6	$83^\circ\ 30'$	$88^\circ\ 30'$

The correct answer for apparent preferred orientation is therefore taken to be the mean of the first and second class interval groupings, being for the $0-9^\circ$, $10-19^\circ$, ... grouping:

$(\theta + 5^\circ) - 2^\circ\ 30'$ or $\underline{\theta + 2^\circ\ 30'}$;

and being for the $1-10^\circ$, $11-20^\circ$ ...... grouping:

$(\theta + 5^\circ) + 2^\circ\ 30'$ or $\underline{\theta + 7^\circ\ 30'}$.

For the present fabric orientation calculations, the class interval grouping $0-9^\circ$, $10-19^\circ$ ...... has been used, with the apparent preferred orientation as $\theta + 2^\circ\ 30'$.

Fabric Booking Sheet

Site Description:

South side Park Burn in
deep river bank cutting.
Orientation of face N 70E true.
Working depth 3¼ – 4 ft. below
top of basal till. (See fig. of section).

Analysis No: 53 (1-50).

Location PARK BURN,
DALKEITH PARK
62 : 332 689

Date: 9-v-64.

No.	Dir.	Dip.	Shape.	Remarks.	No.	Dir.	Dip.	Shape.	Remarks.
1.	240	H			26.	290	W10		
2.	100	W15			27.	140	NW10		
3.	75	E5			28.	300	E5		
4.	145	N5			29.	80	W5		
5.	75	W5			30.	65	E15		
6.	70	W10			31.	40	H		
7.	150	H			32.	270	H		
8.	30	S30			33.	70	W5		
9.	140	SE5			34.	50	E5		
10.	335	S10			35.	310	W5		
11.	45	H			36.	60	W5		
12.	50	E5			37.	280	E5		
13.	270	W15			38.	85	H		
14.	80	E15			39.	50	S10		
15.	175	S10			40.	55	W10		
16.	35	S40			41.	285	W10		
17.	70	N25			42.	50	E10		
18.	55	E5			43.	70	W15		
19.	30	S55			44.	75	W25		
20.	285	N5			45.	55	W20		
21.	290	W5			46.	290	W30		
22.	85	W5			47.	65	H		
23.	30	H			48.	135	NW10		
24.	20	S5			49.	60	E10		
25.	75	N20			50.	25	N35		

oil-shale industry, now defunct in Midlothian, has produced a shale tip at Straiton. Working of limestone, sandstone, ironstone, brick clays and igneous rocks have all assisted in disturbing the natural landscape.

Although somewhat greater in altitude, the Tyne Basin in its upper parts is similar to the Esk Basin in having a gradual fall in height from the south, a similar sharp southern boundary (fig. 2.2A), and a comparable system of glacial deposits (see Chapter IV). It differs in being fronted by the broad till plain of East Lothian, interrupted only by isolated igneous intrusions.

In contrast to both these areas, the plain to the west of the Pentland axis presents no such uniform gradient. The topographical features of parts of this district are essentially those of a drumlin country on a small scale. For example, between Queensferry and Kirkliston, the long, low parallel ridges, dovetailed into one another and separated by slight depressions, are characteristic of an ice-moulded country. True drumlins, rock-cored drumlins and drift-free crags all exist. The most prominent crags are those within the City of Edinburgh or its neighbourhood: Arthur's Seat, the Calton Hill and the Castle Rock; to the west the prominent landmark of Corstorphine Hill, further south the Braid, Blackford and Craiglockhart Hills beneath the steep northern face of the Pentlands. In addition to these crags and hills, there are many long ridges, such as the George Street Ridge in central Edinburgh, which tend to increase the undulating character of the lowland.

Similar in appearance to the igneous crags is Craigmillar Hill in southeast Edinburgh. But this is composed of Old Red Sandstone conglomerate, and the Liberton-Craigmillar Ridge is really to be regarded

T.f.a. number: 53

180° plot
10° intervals

N = 100
Contemplated = 5.6

$$x = \frac{\text{Obs.-Contempl.}}{\text{Contempl.}^{\frac{1}{2}}}$$

$= 0.424$ (Obs.-Cont.)

0-180° intervals	θ	Obs.	Obs.-Cont.	x	Cos 2θ	Sin 2θ	xCos 2θ	xSin 2θ
0-10	0	0	-5.6	-2.37	1.00	0.00	-2.37	-0.00
10-20	10	3	-2.6	-1.10	0.94	0.34	-1.03	-0.37
20-30	20	6	+0.4	+0.17	0.76	0.64	+0.13	+0.11
30-40	30	3	-2.6	-1.10	0.50	0.87	-0.55	-0.96
40-50	40	13	+7.4	+3.14	0.17	0.98	+0.53	+3.08
50-60	50	11	+5.4	+2.29	-0.17	0.98	-0.39	+2.24
60-70	60	17	+11.4	+4.83	-0.50	0.87	-2.42	+4.20
70-80	70	15	+9.4	+3.99	-0.76	0.64	-3.03	+2.55
80-90	80	8	+2.4	+1.02	-0.94	0.34	-0.96	+0.35
90-100	90	5	-0.6	-0.25	-1.00	0.00	+0.25	-0.00
100-110	100	4	-1.6	-0.68	-0.94	-0.34	+0.64	+0.23
110-120	110	1	-4.6	-1.95	-0.76	-0.64	+1.48	+1.25
120-130	120	2	-3.6	-1.53	-0.50	-0.87	+0.76	+1.33
130-140	130	5	-0.6	-0.25	-0.17	-0.98	+0.04	+0.24
140-150	140	3	-2.6	-1.10	0.17	-0.98	-0.19	+1.08
150-160	150	2	-3.6	-1.53	0.50	-0.87	-0.76	+1.33
160-170	160	1	-4.6	-1.95	0.76	-0.64	-1.48	+1.25
170-180	170	1	-4.6	-1.95	0.94	-0.34	-1.83	+0.66

$\Sigma = -11.18$ $\Sigma = +18.57$

$$C = \frac{\Sigma x\text{Cos } 2\theta}{(\Sigma\text{Cos}^2\ 2\theta)^{\frac{1}{2}}} = \frac{-11.18}{2.994} = -3.73$$

$$S = \frac{\Sigma x\text{Sin } 2\theta}{(\Sigma\text{Sin}^2\ 2\theta)^{\frac{1}{2}}} = \frac{+18.57}{2.994} = +6.20$$

$C^2 = 13.91$

$S^2 = 38.44$

$\chi^2 = 52.4$

$$\text{Tan } 2\theta = \frac{S}{C} = -\frac{6.20}{3.73} = -1.662$$

$2\theta = 58°58'$ (2nd quadrant)

$$\theta = \frac{180° - 58°58'}{2} = 60°\ 31'$$

Apparent preferred orientation = $\theta + 2°30'$ = 63°.

APPENDIX C

COMPARISON OF TILL FABRIC STRENGTH OF ORIENTATION

The strengths of fabric orientation are given by the values of chi-square (χ^2) in Tables 6.1 and 6.2. From these tables, certain values are tabulated in 3 groups, representing the basal till (b), the Roslin Till (R or r), and the deposits showing slump movement including the head (s). By calculating the standard error of the difference and applying Student's t Test for each pair of the 3 groups in turn, it can be seen whether the between-group values are significantly greater than the range of values within the groups. In this way can be calculated whether the chi-square values are distinctive for the 3 groups to which they relate.

Example. Comparing the strengths of orientation of the Roslin Till and the slump deposits.

r	s	$r-\bar{r}$	$(r-\bar{r})^2$	$s-\bar{s}$	$(s-\bar{s})^2$	
49.5	70.0	7.9	62.41	-7.6	57.76	
31.0	11.3	-10.6	112.36	-66.3	4395.69	
46.4	120.9	4.8	23.04	43.3	1874.89	
42.8	79.9	1.2	1.44	2.3	5.29	
32.1	87.6	-9.5	90.25	10.0	100.00	
47.8	82.2	6.2	38.44	4.6	21.16	
57.6	91.0	16.0	256.00	13.4	179.56	
42.2		0.6	0.36			
15.1		-26.5	702.25			
51.8		10.2	104.04			
416.3	542.9		1390.59		6634.35	Totals
41.6	77.6		139.06		947.76	Means

$\bar{r} = 41.6$ $\bar{s} = 77.6$

$n_r = 10$ $n_s = 7$

standard deviation $\sigma_r = \sqrt{139.06}$

$\sigma_s = \sqrt{947.76}$

Then, standard error of difference:

$$\text{S.E.}\ (\bar{r} - \bar{s}) = \sqrt{\frac{\sigma_r^2}{n_r} + \frac{\sigma_s^2}{n_s}} = \sqrt{\frac{139.06}{10} + \frac{947.76}{7}}$$

$$= 12.2$$

Students t: $$t = \frac{(\bar{r} - \bar{s})}{\text{S.E. of diff.}} = \frac{36.0}{12.2} = \underline{2.94}$$

Degrees of freedom $= n_r + n_s - 2 = 15.$

From Table 3, Lindley and Miller (1962), the difference of 36 between the two means is about the 1% level of probability, indicating that the difference between the fabric strengths of the Roslin Till and the slump deposits is significant.

APPENDIX D

TERRACES OF RIVER ESK :

NATIONAL GRID REFERENCES OF HEIGHTED POINTS

Terraces are listed in numerical order consecutively from 101 to 251b. In each terrace, the points are given as Eastings and Northings, followed by height in ft. O.D. All National Grid references occur in square N T.

Terraces absent from this list have not been heighted by levelling. These terraces are either inaccessible or the heights have been so far modified by building that the heights would not be representative.

T 101

2250	5994	737.8
2252	5993	738.4
2255	5991	738.6
2258	5989	739.5
2260	5988	739.7
2262	5987	739.7
2256	5980	738.8
2258	5983	740.7
2264	5990	737.2
2265	5986	738.9
2267	5985	738.7
2271	5984	739.5
2274	5983	741.0
2278	5981	741.3
2273	5968	739.3
2276	5972	742.9
2279	5975	742.1
2281	5979	740.0
2283	5980	740.7
2285	5983	738.5
2288	5986	735.2

T 102

2283	5968	735.4
2285	5973	734.4
2287	5969	735.5
2289	5964	735.2
2290	5960	734.9
2280	5963	729.5

T 103

2295	5960	722.5
2296	5963	722.7
2297	5966	722.0
2297	5972	717.7

T 104

2273	5946	730.1
2274	5948	727.2

T 105

2287	5950	690.3
2289	5951	689.7
2291	5952	688.4

T 106

2413	5779	764.7
2417	5775	764.9

T 107

2410	5793	764.7
2413	5794	765.2

T 108

2368	5752	781.6
2365	5755	781.1
2362	5759	779.0
2359	5762	779.6
2357	5765	778.6
2353	5768	778.4
2351	5771	776.7

T 109

2312	5812	777.2
2318	5816	776.5

T 110

2322	5923	720.5
2325	5920	721.8
2330	5918	721.2
2335	5915	720.7
2339	5912	721.0
2342	5910	721.4
2347	5907	719.6
2326	5923	721.3
2330	5922	721.0
2335	5921	720.7
2339	5920	721.6
2342	5919	718.2
2346	5918	717.6
2351	5917	716.5
2355	5916	715.8
2334	5907	719.9
2335	5911	718.3
2336	5915	719.8
2337	5918	721.7
2337	5921	721.0
2338	5924	719.8

T 111

2339	5931	688.5
2343	5930	686.7
2346	5929	686.9
2349	5928	686.1
2352	5927	684.0
2356	5926	683.3
2348	5932	684.5
2352	5931	684.1

T 113

2385	5999	678.7
2387	6004	674.3
2389	6008	672.3
2376	6019	673.5
2383	6021	670.7
2384	6025	669.8
2386	6028	671.6
2388	6031	670.0
2397	6025	672.3
2393	6027	670.1
2389	6028	671.3
2385	6029	670.9
2380	6031	670.6
2378	6031	669.5

T 114

2395	6036	655.3
2396	6040	652.3
2398	6043	649.0
2403	6036	654.0
2399	6038	651.9
2394	6042	651.8
2389	6045	651.3
2385	6048	649.6

T 121

2425	5970	689.7
2428	5973	685.7
2430	5977	681.6
2432	5980	679.8
2435	5983	677.3
2437	5986	675.3
2439	5990	674.5
2441	5993	674.4
2444	5997	673.1
2448	6002	672.9
2450	6006	672.3
2452	6009	672.6
2455	6012	672.7
2457	6015	671.8
2460	6020	669.5
2464	6022	670.6
2462	6024	670.7
2459	6026	670.5
2465	6027	669.8
2467	6031	669.6
2470	6033	666.6

T 122

2458	6035	641.1
2460	6036	642.3
2463	6039	640.3
2465	6040	634.9

T 123

2472	6056	634.1
2474	6059	632.9
2477	6062	630.4
2480	6066	627.3
2483	6069	626.9
2485	6073	625.4
2487	6075	623.5
2485	6051	630.0
2488	6054	630.1
2489	6058	629.9
2491	6060	629.7
2494	6064	628.3

T.123 (cont.)

2496	6068	627.0
2499	6071	625.4
2502	6076	620.8
2491	6062	629.8
2488	6065	627.0
2484	6068	625.4
2479	6071	627.2
2477	6073	625.0

T 123A

2460	6061	571.7
2462	6064	572.2
2464	6066	571.8

T 124

2498	6085	584.4
2501	6089	583.8
2504	6093	581.6
2508	6097	584.8
2511	6101	585.9
2515	6106	587.9
2519	6110	587.3
2522	6114	585.7
2524	6117	581.2

T 124A

2495	6108	560.5
2498	6112	557.3

T 124B

2476	6084	571.0
2479	6088	571.7
2482	6092	570.4
2485	6097	568.0

T 125

2497	6121	548.2
2500	6125	546.8
2502	6128	547.0
2499	6131	547.3
2494	6126	547.2

T 125A

2491	6115	528.9
2492	6118	531.6
2492	6121	530.4

T 126

2484	6138	534.1
2487	6143	533.7
2491	6149	533.3

T 126 (cont.)

2494	6154	533.1
2494	6144	532.2
2487	6145	533.6
2484	6146	534.3

T 127

2489	6161	522.4
2493	6164	523.3
2497	6167	523.8
2500	6170	522.3
2497	6162	523.5
2491	6166	523.3

T 128

2492	6196	550.6
2491	6201	548.8

T 129

2497	6190	530.7
2499	6195	531.1
2500	6198	531.7
2502	6200	530.6
2504	6196	530.9
2507	6194	527.8
2509	6193	524.4
2512	6192	521.3
2515	6190	519.8
2505	6190	524.5
2508	6193	524.6
2510	6198	523.0
2511	6187	521.6
2513	6189	521.5
2515	6193	521.8

T 129A

2526	6193	514.4

T 130

2526	6183	501.1
2528	6185	500.2
2530	6188	501.0
2532	6190	501.9
2534	6192	502.3
2527	6188	502.0
2529	6186	501.9
2532	6184	499.1

T 133

2481	6110	471.1
2480	6112	470.4
2480	6115	469.3

T 133 (cont.)

2480	6118	469.5
2479	6121	468.4
2479	6125	468.6
2478	6128	468.0
2478	6131	464.1
2477	6134	463.9
2477	6137	463.0

T 134

2470	6135	462.5
2473	6144	464.6
2474	6146	462.3
2475	6150	460.5
2477	6154	458.9
2478	6157	457.1
2480	6161	452.6

T 134A

2466	6140	458.8
2466	6149	457.8
2468	6152	456.6
2469	6154	455.4
2472	6158	454.2
2475	6162	453.0

T 135

2509	6164	494.4
2509	6152	490.5
2507	6148	496.1
2510	6144	494.8
2512	6141	494.8
2517	6143	490.4

T 137

2558	6174	550.9
2558	6178	551.5
2559	6183	549.7
2560	6188	548.7
2561	6193	547.5
2562	6197	547.2
2565	6198	546.1
2569	6199	545.3
2573	6200	543.3
2577	6201	544.2
2982	6202	540.2

T 138

2546	6194	502.4
2547	6192	503.9
2548	6189	502.5
2548	6185	502.9

T 138 (Cont.)

2547	6182	507.2
2547	6178	507.4
2546	6175	507.9
2545	6170	504.4
2542	6168	500.0
2540	6167	499.2

T 139

2555	6165	523.4
2559	6166	524.3
2563	6167	524.3
2566	6168	522.8

T 142

2590	6154	513.0
2594	6156	513.1
2598	6158	512.3
2603	6160	511.0
2611	6164	512.4
2614	6166	513.6
2618	6168	513.5
2622	6169	512.1
2626	6171	512.5

T 142A

2604	6164	497.9
2609	6166	500.4
2614	6169	499.7
2620	6171	500.1
2625	6173	498.0
2629	6175	495.8
2634	6177	492.3

T 143

2614	6157	529.0
2618	6158	526.9
2622	6161	525.7
2626	6163	524.6
2631	6166	522.9
2635	6169	520.6
2638	6171	520.2
2642	6173	522.0
2646	6175	519.2
2650	6177	518.7
2649	6181	517.4
2648	6182	518.1
2654	6180	517.2
2657	6182	515.4
2661	6184	513.7
2665	6186	512.7

T 143 (cont.)

2668	6189	511.4
2671	6191	510.8
2675	6193	507.4

T 144

2613	6140	570.4
2617	6142	569.0
2621	6145	566.9
2625	6147	560.3
2628	6149	556.7
2635	6152	555.7
2638	6154	553.0
2645	6158	550.8
2649	6160	548.8
2654	6163	545.9

T 152

2604	6265	557.7
2606	6261	555.3
2607	6256	555.5
2609	6252	555.4
2610	6247	553.4
2612	6243	553.5
2614	6239	551.6
2615	6235	550.7
2617	6231	549.7
2618	6227	549.6
2611	6224	549.4
2615	6226	551.3
2622	6228	546.7
2620	6222	548.4
2621	6218	545.5
2627	6217	542.0
2609	6257	556.9
2619	6264	555.5
2623	6269	554.5
2628	6273	552.4
2631	6277	549.2
2635	6281	547.7
2638	6285	548.3
2647	6281	547.0
2649	6283	544.2
2651	6285	545.1
2653	6287	545.8
2657	6290	545.5
2660	6293	543.8
2664	6297	539.5
2667	6300	537.8

T 152A

2700	6287	443.0
2704	6290	443.4
2708	6292	443.2
2712	6296	441.5
2715	6297	438.9
2719	6298	437.7
2722	6300	437.3
2726	6302	437.3
2702	6286	441.6
2709	6290	444.2

T 152B

2634	6217	506.3
2640	6246	494.2

T 153

2647	6216	463.6
2646	6221	457.9
2646	6225	453.8
2645	6229	453.3
2644	6233	453.6
2643	6237	456.1

T 154

2694	6229	495.9
2690	6231	498.2
2687	6233	496.5
2684	6235	497.4
2682	6234	497.6
2680	6238	496.8
2676	6240	497.0
2673	6226	500.2
2675	6229	499.8
2679	6231	498.2
2685	6236	496.0
2688	6238	495.4
2674	6235	499.3
2675	6236	499.6
2676	6238	495.8
2679	6242	492.3
2682	6246	491.0

T 155

2701	6242	465.6
2698	6248	464.1
2697	6252	463.4
2696	6255	465.1
2696	6243	464.9
2702	6247	465.6
2707	6250	464.1

T 160

2764	6239	534.6
2764	6243	532.9
2765	6246	530.8
2766	6250	531.6
2767	6254	531.5
2768	6258	528.0
2769	6262	527.0

T 160A

2760	6252	507.6
2761	6256	505.9
2764	6263	503.1
2768	6267	501.2

T 161

2790	6272	497.4
2784	6275	497.1
2793	6274	494.8
2791	6277	498.0
2789	6279	497.4
2796	6277	495.2
2792	6282	496.9

T 163

2769	6317	491.0
2768	6322	489.5

T 163A

2784	6323	458.2
2786	6333	455.8

T 164

2769	6404	475.0
2772	6406	474.2
2774	6409	471.4
2778	6412	469.3

T 165

2786	6427	468.7
2789	6431	469.8
2793	6435	469.8
2796	6441	467.8
2800	6446	466.3
2805	6451	466.5
2808	6456	466.4
2811	6461	464.3

T 166

2824	6432	435.8
2825	6437	435.6
2826	6442	435.9
2827	6446	435.2
2828	6450	432.9
2830	6456	432.9

T.167

2818	6353	442.8
2822	6358	441.8
2826	6362	442.6
2831	6365	440.6
2835	6368	441.4
2838	6375	441.6
2841	6380	438.8
2844	6385	437.1

T 167A

2795	6336	427.7
2802	6346	420.8
2805	6350	421.2

T 168

2836	6345	447.4
2842	6348	445.2
2846	6350	444.6
2851	6351	444.0

T 169

2802	6292	495.3
2804	6296	495.8
2807	6300	495.0
2809	6303	493.5
2812	6306	491.8
2814	6309	493.3
2819	6326	492.6
2821	6323	493.2
2826	6315	492.5
2828	6311	492.0
2822	6316	495.1
2825	6319	493.4
2828	6322	492.0
2832	6324	491.9
2834	6326	492.1
2837	6329	490.8
2841	6332	490.6
2845	6334	490.3
2849	6337	490.1
2853	6340	490.8
2856	6341	490.3

T 169 (cont.)

2859	6343	488.6
2862	6346	491.4
2866	6348	491.8
2871	6351	488.6
2875	6354	486.9
2878	6356	486.7
2879	6352	487.7
2880	6349	489.9
2881	6345	485.6
2882	6342	484.3
2883	6339	486.1
2885	6335	488.2
2887	6332	490.0
2888	6329	489.2
2891	6325	489.5

T 170

2798	6262	523.0
2807	6277	514.0

T 179

2893	6376	477.9
2896	6380	475.6
2898	6386	472.3
2899	6391	468.8
2901	6395	466.2
2900	6379	477.2
2895	6379	475.8
2891	6380	474.9
2888	6380	472.2
2884	6381	470.2
2878	6381	469.4
2874	6382	467.4
2868	6379	464.8
2869	6382	465.9
2871	6389	465.0
2872	6392	466.8
2874	6395	464.2
2875	6400	460.9

T 179A

2865	6388	433.9
2865	6393	432.5
2867	6396	431.6
2869	6400	430.6
2873	6404	424.0
2876	6406	419.4

T 180

2870	6415	384.3
2868	6410	384.9
2867	6412	385.4
2865	6414	385.2
2862	6419	382.0
2864	6408	386.2

T 181

2849	6411	288.2
2847	6415	284.7
2843	6418	281.9

T 181A

2845	6405	309.7
2842	6408	310.6
2839	6412	312.1
2837	6416	311.0
2833	6422	311.7
2838	6426	311.4

T 182

2848	6418	282.4
2848	6422	281.2
2847	6426	280.0
2846	6430	279.3
2846	6435	274.5
2846	6440	272.5
2846	6444	274.8
2849	6448	273.8

T 183

2867	6438	311.4
2864	6440	311.0
2863	6443	310.0

T 184

2863	6434	278.0
2865	6435	278.6
2869	6435	276.4
2872	6434	275.1

T 184B

2861	6433	267.9

T 184C

2858	6432	262.2
2859	6430	261.5

as an extension at a lesser height of the Pentland Hills.

Examination of the rivers of the district (fig. 2.1) reveals the uncomplicated nature of the drainage system. None of the rivers attains any considerable size, and many tributaries represented on the map are only tiny burns one or two feet wide. The three distinct drainage systems, the Esk, the Water of Leith, west of the Pentlands, and the Tyne east of the Roman Camp Ridge, all drain to the northeast. An exception is the South Esk which maintains a more northerly course until it unites with the North Esk at Dalkeith.

Most of the present river valleys are post-glacial; the rivers cut into glacial deposits and their direction is controlled by the regional slope of the surface of the drift. This has produced a regular dendritic stream pattern. For example, the left bank tributaries of the upper North Esk all begin on bedrock slopes of the Pentlands, pass over thick drift and then cut into the drift to join the incised North Esk accordantly. Similarly, the right bank tributaries begin as sub-parallel consequents draining the Auchencorth Moss, with their courses becoming progressively more incised as they cross the glacio-fluvial depositional zone south of Penicuik.

For the South Esk, the two left bank tributaries, Fullarton Water and Dalhousie Burn, also join the main stream accordantly after gradually cutting into thick drift.

The main streams are often spectacularly incised into drift or bedrock. In most cases, the present stream either occupies a glacial drainage channel or occupies a valley whose cutting has been assisted by glacial meltwaters. For example, the upper North Esk north of Carlops

T 187

2907	6424	471.9
2911	6421	471.8
2913	6426	471.7
2915	6428	469.1
2917	6427	471.6

T 187A

290	644 (approx.)	382.5

T 188

2888	6447	283.5
2892	6453	284.9

T 189

2930	6455	432.9
2934	6459	434.7
2938	6462	432.0
2942	6466	430.4
2947	6470	430.2
2951	6474	429.6
2955	6476	428.6
2957	6479	426.8
2961	6482	425.0
2965	6485	424.5
2969	6489	423.8
2973	6492	422.9

T 190

2887	6465	283.5
2891	6467	283.7
2894	6470	283.8
2898	6473	284.9

T 192

2903	6505	230.7
2905	6508	228.4
2908	6512	227.7
2911	6515	224.7
2913	6519	223.7
2915	6522	222.4

T 193

2895	6522	283.9
2898	6525	280.6
2903	6529	274.9

T 194

2918	6530	229.1
2922	6533	223.0

T 194A

2914	6535	246.7
2917	6539	238.8
2921	6542	238.0

T 195

2919	6519	223.7
2923	6521	222.6
2926	6523	221.0
2931	6526	219.4
2935	6528	219.1
2939	6531	216.3
2944	6533	215.5
2948	6536	215.5

T 196

2935	6517	267.6
2939	6519	266.1
2943	6521	265.3
2949	6523	264.3
2956	6520	267.3
2954	6526	263.3
2952	6529	261.1
2958	6528	261.2
2963	6530	256.7
2969	6533	253.9

T 196A

2926	6514	246.6

T 197

2936	6546	220.5
2936	6540	220.5
2941	6541	220.4
2947	6542	219.2
2951	6550	218.0
2952	6544	217.6

T 201

2916	6568	370.8
2918	6570	370.0
2921	6572	370.2
2924	6574	368.6
2928	6576	368.4
2932	6579	367.4
2935	6582	365.5
2939	6585	364.3
2906	6565	370.7
2910	6562	371.0
2914	6558	371.3
2918	6561	371.6
2923	6564	369.5

T 201 (cont.)

2928	6565	364.6
2933	6567	362.0
2938	6573	362.2
2941	6579	363.9
2943	6584	362.4
2948	6597	364.5
2952	6605	362.0
2952	6614	364.4

T 201A

2917	6612	430.6
2920	6613	428.8
2923	6614	425.2

T 202

2961	6635	363.8
2965	6636	364.2
2969	6637	364.1
2975	6638	364.1
2981	6640	361.6
2991	6646	355.3
2986	6651	355.8
2983	6655	358.2
2981	6660	358.4
2978	6664	357.5
2976	6667	357.8
2974	6670	357.5
2971	6674	357.6
2966	6682	354.9
2962	6688	355.6
2957	6694	355.5
2965	6679	357.3
2970	6680	357.6
2974	6683	357.9
2979	6684	357.6
2983	6686	355.9
2987	6688	354.8
2992	6690	351.7
2996	6691	351.3
3000	6693	349.1
3004	6695	347.2
2993	6692	350.2
2992	6695	351.0
2992	6698	350.4
2996	6700	351.4
3000	6703	348.4
3004	6706	343.7
3008	6709	341.1
3012	6712	338.7

T 202A

2996	6736	344.2
3000	6740	339.0
3004	6743	333.5

T 203

2975	6622	339.1
2979	6620	335.2
2982	6623	332.6
2986	6626	335.7
2988	6624	334.1

T 205

3009	6625	258.8
3018	6626	251.5
3020	6631	250.0

T 208A

3049	6648	182.7
3051	6645	181.4
3054	6643	181.0
3057	6642	180.2
3059	6641	180.3

T 209

3070	6585	347.3
3073	6586	344.5
3077	6590	341.1
3082	6596	345.6
3090	6603	344.7
3097	6611	344.6
3103	6617	341.1
3110	6624	341.6
3114	6629	340.3
3119	6634	338.4
3124	6639	337.0
3127	6642	330.9
3131	6645	327.1
3133	6649	315.2
3136	6651	303.1
3138	6654	296.0
3141	6656	287.7
3145	6661	274.7
3150	6666	266.9

T 210

3047	6652	186.0
3049	6650	185.4
3053	6649	184.6
3054	6648	183.1

T 211	3061	6651	186.0
	3064	6655	193.8
T 212	3057	6660	193.8
	3061	6670	193.8
	3058	6671	193.0
T 213	3068	6667	177.8
	3072	6667	178.0
	3074	6671	175.4
	3075	6676	173.6
	3075	6681	172.0
	3075	6686	170.1
	3080	6686	168.2
	3084	6690	167.6
T 214	3082	6673	180.8
	3090	6674	179.3
T 215	3086	6668	183.3
T 216	3080	6687	168.2
	3084	6683	172.0
	3089	6681	170.5
	3094	6681	169.8
	3100	6683	168.9
	3108	6684	167.3
T 217	3089	6690	167.0
	3097	6695	170.4
	3095	6687	163.6
	3103	6689	162.6
	3110	6694	160.6
T 217A	3106	6702	167.4
	3111	6698	165.2
	3119	6704	161.1
	3120	6709	164.6
	3127	6710	159.7
	3130	6712	158.8
T 218	3098	6667	237.7
	3108	6674	235.7
	3116	6680	228.2
	3123	6687	226.0
T 219	3087	6658	257.2
	3091	6661	251.8
	3099	6663	253.9
	3103	6665	253.9
T 220	3115	6721	235.2
	3117	6721	235.5
	3123	6726	233.8
	3123	6728	233.2
	3123	6730	233.6
	3128	6722	233.4
	3137	6721	232.7
	3142	6725	229.5
	3142	6729	230.5
	3142	6732	230.7
	3147	6721	229.4
	3158	6719	226.5
T 223	3171	6714	161.9
	3175	6714	161.7
	3180	6714	161.8
	3186	6714	161.3
	3191	6714	164.0
	3191	6710	160.3
	3195	6710	161.7
	3200	6711	159.1
	3205	6711	159.6
T 224	3052	6708	271.2
	3056	6709	271.8
	3061	6710	272.5
	3072	6703	275.3
	3070	6706	275.0
	3068	6708	274.1
	3066	6710	272.4
	3069	6713	272.3
	3072	6715	273.2
	3075	6717	270.9
	3078	6720	269.1
	3081	6721	267.9
	3084	6724	266.2

T 224 (cont.)

3087	6726	265.0
3090	6728	264.4
3093	6731	263.8
3096	6733	263.5
3099	6735	262.8
3103	6738	262.7
3106	6741	261.0
3111	6744	257.5
3119	6750	254.7
3125	6755	251.6
3134	6760	244.6

T 225

3136	6766	241.0
3141	6764	240.2
3145	6761	241.0
3149	6760	239.8
3151	6758	240.5
3155	6756	239.2
3159	6754	240.6
3164	6752	240.0
3168	6750	239.1
3166	6746	239.2
3169	6745	238.7
3173	6743	238.5

T 226

3202	6737	233.8
3206	6735	233.2
3210	6734	232.6
3215	6732	232.2
3218	6730	233.6
3223	6729	235.8
3226	6728	233.8
3232	6729	225.0
3240	6734	217.1

T 226A

3213	6746	224.1
3213	6748	223.9
3213	6750	221.9

T 227

3254	6772	210.2
3258	6771	208.6
3262	6770	207.6
3259	6768	207.4
3264	6773	206.3
3268	6776	206.4
3271	6779	205.1

T 227 (cont.)

3255	6781	206.5
3259	6787	202.9
3263	6788	204.1
3268	6784	203.9
3271	6782	202.5
3273	6779	201.9

T 227A

3250	6723	216.9
3251	6727	215.5
3252	6731	214.8
3253	6736	215.9
3254	6740	215.8
3255	6744	214.8
3261	6745	214.3
3258	6746	212.1
3256	6748	213.5
3253	6748	214.6
3248	6750	215.1
3257	6751	212.6
3258	6754	212.3

T 228

3222	6773	197.6
3226	6776	192.1
3229	6780	188.1
3234	6784	185.1
3236	6786	182.9
3240	6790	181.1
3243	6793	179.1
3247	6797	177.3
3251	6800	176.3
3254	6797	178.2
3257	6798	177.9
3260	6800	177.5
3264	6802	177.2
3268	6803	176.7
3272	6806	175.6
3276	6807	175.9
3279	6809	174.3
3283	6810	174.0
3231	6807	184.4
3232	6809	180.7
3234	6812	178.3
3237	6815	177.0
3240	6818	176.3
3242	6822	174.5
3244	6824	173.6
3246	6827	172.7
3248	6831	172.5

T 228 (cont.)

3251	6834	171.7
3252	6836	171.6
3280	6824	173.8
3284	6824	174.1
3289	6824	173.7
3292	6824	174.2
3296	6825	173.0
3299	6825	172.0
3288	6821	174.6
3291	6830	173.8
3292	6833	173.6
3293	6837	171.9
3293	6840	170.5
3294	6844	170.3
3295	6848	170.7
3297	6852	171.0
3299	6856	169.1
3300	6860	168.1
3300	6865	166.5
3302	6869	165.3
3304	6872	163.0
3306	6875	160.8

T 229

3315	6826	150.9
3314	6832	148.9
3313	6838	147.8
3312	6842	146.4
3311	6847	146.0
3308	6846	149.6
3309	6849	145.3
3311	6852	144.4
3313	6855	143.6
3316	6859	142.7
3318	6864	142.3
3319	6866	141.7
3321	6870	140.4
3323	6874	139.0
3325	6878	138.8
3327	6881	138.5
3328	6883	137.4

T 229A

3328	6819	137.3
3327	6826	134.6
3326	6832	132.6
3326	6838	131.5

T 230

3294	6906	173.6
3298	6911	172.6
3303	6916	169.3
3308	6913	172.2
3310	6915	169.7
3312	6918	167.6
3314	6921	165.8
3316	6924	165.4
3318	6926	163.8
3320	6929	162.7
3318	6931	161.9
3316	6932	160.1
3313	6934	159.0
3315	6936	159.6
3317	6939	157.5
3318	6941	155.6

T 231

3342	6894	136.9
3346	6899	136.1
3349	6902	136.7
3352	6905	135.3
3354	6908	134.0
3357	6911	133.0
3360	6913	132.2
3362	6915	130.5
3366	6918	128.5
3369	6920	128.2
3373	6922	128.2
3377	6926	129.6
3380	6928	128.5
3384	6932	127.0
3388	6936	126.2
3392	6940	125.6
3375	6929	129.4
3373	6931	128.7
3372	6933	129.6
3370	6936	128.9
3368	6939	129.4
3365	6942	130.2
3364	6945	130.2
3361	6948	129.8
3359	6951	129.3
3393	6947	122.6
3391	6950	125.7
3388	6955	125.0
3386	6960	125.0

T 231 (cont.)

3382	6964	123.9
3379	6970	122.3
3376	6972	119.6
3373	6975	116.0
3369	6979	113.9
3366	6982	114.9
3364	6983	112.9
3361	6986	113.9
3334	6962	129.2
3337	6965	125.2
3341	6968	122.4
3343	6970	121.7
3346	6972	120.8
3349	6975	119.2
3352	6976	117.1
3355	6979	115.1
3358	6981	113.6
3361	6984	112.7

T 237

3354	6800	164.8
3355	6806	163.5
3355	6811	162.7
3355	6815	161.2
3356	6819	160.8
3356	6824	160.7
3356	6827	161.8
3357	6831	161.4
3357	6835	161.4
3357	6840	160.1
3358	6845	158.7
3358	6849	158.9
3358	6853	158.4
3358	6858	157.6
3359	6863	157.8
3359	6867	157.1
3359	6871	154.9

T 237A

336	3842	131.4
3339	6845	129.0
3342	6850	125.7
3344	6852	123.9
3345	6855	123.0

T 237B

3331	6845	106.0
3333	6848	105.1
3336	6850	103.8

T 237B (cont.)

3338	6852	101.3
3340	6855	100.2

T 237C

3328	6841	89.7
3330	6843	87.8
3334	6846	85.2
3337	6847	82.0

T 237D

3330	6855	83.5
3331	6856	82.2
3333	6858	81.6

T 238

3381	6868	131.0
3378	6872	130.3
3375	6874	128.0
3372	6876	127.4
3383	6873	129.6
3384	6878	128.4
3386	6884	127.4
3389	6891	121.8
3390	6896	120.5
3392	6900	118.5

T 238A

3353	6873	123.5
3360	6877	122.7
3364	6878	121.3

T 239

3377	6890	111.6
3380	6893	110.6
3382	6897	108.7
3385	6900	107.5
3387	6902	105.4
3389	6905	103.3
3390	6908	101.0

T 239A

3350	6876	111.1
3354	6880	111.4
3358	6884	110.3
3363	6886	111.0
3367	6889	109.8
3372	6890	108.6

T 239B

3344	6885	93.7
3348	6888	91.5
3352	6890	90.7
3357	6892	90.8
3361	6894	88.9
3366	6896	87.9

T 239C

3344	6889	81.2
3347	6891	78.5
3351	6893	74.6
3356	6895	73.6

T 240

3383	6923	109.0
3386	6924	108.5
3391	6924	107.5
3394	6925	107.2
3405	6932	102.8
3408	6934	101.8
3411	6936	99.4
3413	6939	98.3
3415	6942	97.4

T 241

3388	6926	113.4
3391	6929	112.8
3395	6932	112.2
3398	6935	111.3
3401	6940	110.5
3404	6943	109.4
3406	6947	108.2
3403	6952	109.4
3408	6950	108.2
3412	6947	108.3
3411	6955	106.2
3413	6959	103.3

T.242

3418	6805	138.6
3419	6807	137.6
3420	6810	136.8
3420	6812	136.1
3421	6817	134.6
3423	6821	133.7
3425	6826	132.5
3441	6828	131.7
3437	6829	132.5
3433	6830	131.6
3427	6832	131.6
3423	6833	131.6

T 242 (cont.)

3419	6834	130.9
3428	6837	130.7
3430	6842	130.3
3431	6847	129.1
3432	6851	128.4
3433	6855	128.9
3425	6860	128.2
3425	6863	127.2
3424	6868	126.4
3424	6872	125.8
3423	6876	124.8
3422	6881	122.6
3422	6886	122.2
3421	6891	121.5
3421	6896	120.7
3421	6900	118.8
3421	6904	118.2
3420	6906	117.7
3420	6910	116.1
3426	6914	115.0
3430	6917	114.7
3435	6920	114.6
3438	6923	114.1
3442	6926	114.2
3446	6929	113.4
3449	6932	113.1
3453	6934	112.3
3456	6936	110.6
3460	6939	109.0
3463	6942	108.3
3467	6944	109.2
3469	6947	108.8
3472	6949	108.0
3475	6952	105.6
3478	6954	103.8
3482	6956	101.9
3484	6957	101.8
3486	6959	100.8
3480	6934	113.4
3477	6939	112.1
3475	6942	110.8
3472	6946	108.5
3469	6951	108.8
3466	6955	107.7
3463	6960	106.9

T 243

3381	6903	83.9
3384	6907	83.0
3388	6910	82.1

T 243A

3397	6910	81.9
3399	6912	80.3
3403	6916	77.9
3407	6917	77.7
3411	6919	77.0

T 244

3428	6933	97.2
3432	6938	97.7
3435	6944	95.6
3428	6947	94.1
3439	6939	93.8
3438	6948	92.8
3441	6952	86.9
3444	6957	85.5
3447	6960	83.5

T 246

3394	6858	93.6
3395	6862	91.3
3397	6866	92.8
3397	6871	92.4
3397	6875	90.9
3399	6879	95.3
3400	6881	92.9

T 246A

3389	6856	112.1

T 246B

3395	6882	114.7
3395	6884	114.4
3395	6887	111.5
3395	6893	110.2
3394	6896	106.7

T 247

3393	6905	84.5
3392	6908	82.2
3392	6912	84.8

T 248

3388	6890	132.8
3391	6895	130.5
3394	6900	128.8
3396	6906	126.7
3398	6910	125.6
3402	6916	123.9
3404	6922	121.9
3405	6926	118.6

T 248 (cont.)

3406	6930	116.5
3407	6934	115.9
3409	6937	114.6
3410	6941	112.6
3411	6946	111.6
3413	6950	110.5
3414	6954	110.0
3415	6957	108.3

T 249

3388	6780	110.1
3387	6782	105.5
3385	6786	106.5
3383	6790	107.7
3382	6795	109.0
3381	6798	107.7

T 249A

3391	6822	102.8
3393	6825	101.9
3396	6830	100.1

T 249B

3408	6853	93.2
3412	6860	90.2
3415	6865	87.9

T 249C

3377	6846	85.7
3380	6850	84.6
3382	6852	83.0

T 250

3416	6767	168.7
3416	6771	167.8
3421	6775	166.7
3417	6775	166.0
3413	6776	166.2
3409	6776	167.1
3406	6776	166.0
3418	6779	166.6
3418	6784	167.8
3421	6788	166.9
3423	6792	165.8
3425	6796	165.5
3427	6800	163.6
3426	6767	168.3
3428	6770	168.7
3429	6773	167.4
3431	6777	165.8

T 250 (cont.)

3432	6780	166.5
3434	6784	164.7
3436	6787	163.6
3437	6790	165.9
3438	6794	166.8
3441	6799	166.5
3444	6803	165.7
3446	6807	165.6
3449	6810	164.6
3453	6814	164.3
3456	6818	163.7
3450	6822	164.9
3451	6826	163.0
3452	6830	161.6
3453	6835	162.1
3455	6839	160.7
3456	6843	160.0
3458	6848	159.6
3460	6853	159.0
3461	6858	159.5
3463	6863	157.5
3466	6867	157.1
3468	6872	155.0
3470	6877	151.0
3471	6883	150.3
3471	6890	150.7
3470	6895	147.4

T 251A

3451	6968	58.2
3455	6971	57.1

T 251B

3449	6971	63.8
3452	6974	61.3
3453	6978	58.3
3454	6981	56.8
3454	6984	54.8

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cuts a substantial gorge, the result of meltwaters from the southwest (Sissons, 1963a). Further down-stream, the Glencorse Burn tributary drains the large glacial drainage channels of the north Pentlands, and occupies a substantial valley cut into drift and bedrock throughout its length. On the South Esk, there occurs a major example of glacial diversion: the main right bank tributary, the Gore Water, has captured the waters of Middleton North Burn and Middleton South Burn from the River Tyne. A simple physical description of this area is given by Peach et al (1910) and an explanation of the capture by Cossar (1911-12).

Both the North and South Esk have considerable lengths of meanders incised in their deep gorges. During and after the late-glacial period of oscillation of land and sea level, the rivers in readjusting themselves to present sea level, locally excavated these deep gorges in glacio-fluvial deposits, till, and bedrock, and in so doing formed alluvial terraces at successively lower levels. The terraces of the Esk are closely related to changes in sea level, a topic which will be developed in Chapter VIII.

Along the coasts, the oscillations of sea level have produced two main spreads of raised beach deposits, each tilted but being at their highest about 90 ft. and 30 ft. O.D. respectively. Each old beach often ends inland against an old coastal cliff or line of bluffs. At the mouth of the River Esk, the raised beach deposits extend inland for two miles, grading into glacio-fluvial and alluvial deposits.

The pre-glacial river courses have not been fully located, although a great deal of evidence exists relating to sections of buried channels, for example, in the upper estuary of the River Forth (Cadell, 1881) the River Almond (Cadell, 1903), and the Water of Leith (Tait, 1930). It is

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noticeable how the present stream courses of the Almond and Water of Leith approximate to the former courses, often re-excavating buried valleys. In the Esk Basin, borings for mineral exploitation have revealed nine buried channels, which have been described by Tulloch and Walton (1958). Their locations are shown approximately on fig. 2.1. Deep rock-cut gorges, filled with till which is being re-excavated by the present streams, occur in the Esk Basin; these gorges are also taken to be elements of the pre-glacial drainage pattern. There is not yet sufficient information to put the sections together as an integrated pre-glacial drainage system as the sections are scattered and can be related to the present drainage system only in the most approximate sense. Recent bores near the mouth of the River Esk at Musselburgh have proved about a hundred feet of surface deposits, indicating that the floor of the buried river channel is here at least this depth below sea level. Fuller discussion of the pre-glacial Esk drainage pattern is included in a later chapter.

CHAPTER III

THE GROWTH OF KNOWLEDGE OF LOCAL GLACIAL HISTORY

> "To explain these (superficial soft) beds
> has been the anxious effort of several
> generations of geologists, and the
> difficulty of the task may be measured
> by the divergent theories which have been
> forthcoming about them, and by the
> further fact that they still remain in
> many respects the despair of geology."
> Sir Henry H. Howorth, on the
> Glacial Nightmare and the Flood, 1893.

First phase, to 1863: acknowledgement of glaciation. The Edinburgh district has been the scene of investigation into glacial geomorphology for one hundred and fifty years, a much longer period of investigation than in almost all other formerly glaciated parts of the world. A number of famous geologists made their more notable observations in the area and, although scientific work has not proceeded continually from the earliest period, much has been written on the local effects of glaciation. Some of the earliest descriptions still prove to be accurate and useful sources of information.

This early growth of geological investigation was due to plentiful local enthusiasm directed to the investigation of particularly clear field evidence. From an early date, the city of Edinburgh had a tradition of intellectual curiosity and scientific achievement, fostered by several local societies, especially the Royal Society of Edinburgh (from 1783) and the Geological Societies of Edinburgh (from 1834) and of Glasgow (from 1850; officially constituted from 1858).

The simple fact that the landscape in the Edinburgh neighbourhood had been subjected to some flow-movement west to east was first described by Sir James Hall, after he had examined, labelled and then associated "dressed rock", "craig and tail", ground mouldings, and stoss and lee effects of striae and drift distributions (Hall, 1812). As examples of crag and tail, Hall quoted Corstorphine Hill, Castle Rock, Ravelstone, Craigleith, and Calton Hill, all notable eminences within the city. These hills are now commonly quoted as the type-examples of crag and tail ice-moulding (for example, Charlesworth, 1957, Vol. 1, p.254), as the volcanic necks and sedimentary flanks have been particularly susceptible to ice sculpturing into streamlined forms.

Although Hall's observations were acute for their time, the evidence for a movement west to east in the neighbourhood of Edinburgh would now be considered obvious. In the words of A. Geikie: "No one can have passed through this district from south to north without observing that the region is deeply furrowed in an east-west direction. Long smooth-backed ridges follow each other in endless succession and on these we can trace every gradation of eminence, until we reach the true typical form of crag-and-tail" (Geikie, 1863).

Following Hall after a considerable interval, records began of other features related to the streamlined forms: striations were noted by many observers, including Buckland (1840), Milne (1840), Maclaren (1849), and Chambers (1852 and 1857); and further examples of ice-moulding of the landscape were mentioned by Chambers (1852). Supplementary evidence came from new methods of investigation: for example, the pattern of striations on boulders, and the direction (Miller, 1850) and dip (Fleming, 1859) of the long axes of the boulders themselves. This work showed very keen observation, and was not improved upon anywhere until the 1930's. To take other examples, Fleming described how the decomposed ends of exposed, upturned, Carboniferous bedrock are bent or squeezed in an easterly direction (Fleming, 1859; fig. 31). Also, Chambers noted that much rock debris was littered to the east of its bedrock outcrop, for example, greenstone from Arthur's Seat has been carried eastwards along the slope of the hill, to the extremity of the Queen's Park (Chambers, 1857). More startling manifestations of this west to east movement were the many far-travelled erratics eventually found throughout the area. The first erratic to be described was accorded a paper to itself (Forbes, 1829). Another well-known early example was the 8-10 ton Highland boulder of mica-slate discovered in the Pentlands at 1000 ft. and described in 1839 by Maclaren (see Maclaren, 1866). When the provenance of erratics could be decided, it always proved to be from the west.

Taking the evidence together, the striations, the mouldings and the indicator stones are consistent in a direction east-northeast and "such being the general direction of the Forth Valley itself" (Chambers, 1850), it was obvious to assume that a single ice-movement along the valley was responsible for all the effects. To quote A. Geikie again: "When it is recollected how exactly these ridges coincide with the general moulding and striation, it seems reasonable to ascribe the whole to the operation of the same great force acting steadily for a vast period of time in an east and west direction" (Geikie, 1863).

It was not immediately agreed that glacial ice was in fact the agency responsible for the features noted. The academic controversy between the 'diluvialists', seeking an explanation in terms of phenomena then known to them, and the 'glacialists', guided by Agassiz into comparing local signs with glacial markings in the Alps, lasted until the death of some of the older protagonists. And in the history of glacial geomorphology, this controversy is associated with Scotland, as the arguments revolved around the local Edinburgh evidence.

Maclaren (1849), Chambers (1852), Jamieson (1862), and A. Geikie (1863) in turn drew together the threads of evidence in a reasonable and common-sense way, so that the argument for glaciation was effectively proven by about 1863. Fleming's monograph in 1859, stating (p.26) that water moved "over the surface in an easterly direction with great impetuosity", was the last work upholding the diluvial doctrine. The case for the action of ice-bergs rather than of land-ice continued to be argued however, particularly by Milne-Home (1877; and earlier papers).

Whatever the argument on the agency responsible for the movements, the field evidence for a powerful scouring in a direction roughly along the main axis of the Firth of Forth was noted at an early date. The reliable field observations up until 1863 are shown on fig. 3.2. In the light of later information, the most interesting facts shown by this map are the strong evidence for glacial movement in one direction, and the lack (apart from some striations) of any conflicting evidence. Glacial movement in other directions, now known to have occurred, was not suspected at this time.

As fig. 3.2 shows, the accumulated evidence was almost entirely for the coastal area of the Firth of Forth through Edinburgh, and for the Pentland Hills. There was little information relating to the interior of the Midlothian Basin.

Second phase, 1863 to c. 1939: appreciation of main indications of glaciation and deglaciation. The early descriptive writings on Scottish glaciation were often of excellent quality. A. Geikie's extended essay (1863) on the form and location of Scottish Pleistocene deposits gave the complete sequence of the superficial deposits as well as a partial interpretation of their origin. But his interpretation of the glacio-fluvial deposits as of marine origin spotlights the difficulties of proceeding beyond simple description: what would now be regarded as a reasonable interpretation had to await a much clearer overall appreciation of the characteristics of glaciation and deglaciation. Through ignorance of contemporary glacial conditions, Scotland lost its very early lead in knowledge of glaciation.

The second historical phase saw the necessary widening in appreciation of Pleistocene conditions, based on the evidence recorded from the local area, from adjacent parts of Scotland, and also from other parts of Britain. The third edition of J. Geikie's The Great Ice Age (1894) gives a balanced summary of the effects of glaciation as indicated by the most obvious lines of evidence.

More facts were being brought to light. The second half of the nineteenth century saw the introduction of railways into the Edinburgh district. As a result of this and the continuing building within the city, there exist descriptions of very many temporary sections. Many of the papers of this period are little more than descriptive notes on these sections, but the number of references to them in later chapters indicates that they are still useful sources of factual information.

Although by 1863 the west to east ice-movement had been accepted beyond serious argument, the magnitude of the ice body involved was admitted only after some initial incredulity. Croll describes striations from one of the northern summits of the Pentland Hills "all in a uniform direction, nearly east and west", as well as small particles of till, and concluded that the ice flowing eastwards had been at least 1900 ft. thick and 60 miles broad (Croll, 1870).

Evidence from the position of erratics suggesting two directions of ice movement in the Pentland Hills is recorded by Somervail (1879). If correct, these two directions, from the southwest and from the northwest may represent mere variations in the direction of movement within a single ice-sheet, and not the characteristic directions of movement of two distinct ice-sheets. But the important fact that more than one glacial episode had occurred during the Pleistocene, with its implications of climatic change and fluctuations in sea level, was suggested by several other lines of evidence. Young's discovery of late terminal moraines in the central Southern Uplands proved at least one ice readvance (Young, 1864).

From comparison with the terminal moraines in the SouthernUplands, local valley glaciation in the Pentland Hills was proposed by Brown (1872 and 1874b) and by Henderson (1874a), although only scanty evidence was presented at this time, and has not been substantiated since.

On lower ground, superposed tills were early taken as an indication of multiglaciation. Croll and J. Geikie have been credited with postulating glacial stages on the basis of interstratification of till and glacio-fluvial deposits, and other workers associated themselves with this idea from local evidence (for example, Bennie, 1868; Brown, 1874; A. Geikie, 1901; Tait, 1916). The logic of necessarily recognising in every bed of till a separate glaciation was challenged at an early date by Somervail (1877), and some aspects of this problem are still under discussion. For example, the implication of interstratifications of till and sands in Midlothian and East Lothian are discussed in the context of observations by the writer, in Chapters IV and VI.

The presence of old preglacial river courses filled with glacial drift and sometimes re-excavated was first noted in the Central Valley of Scotland by Bennie (1868) and Cadell (1881) and for two rivers in Midlothian by Cadell (1903) and Tait (1930). An early paper by Henderson (1873) suggesting an old river course at the Water of Leith deeper than the existing course is not now conclusive, and should be discounted (Mitchell and Mykura, 1962, p.108); the argument depends on till overlying river gravel, and it is possible that the till had slumped.

Although depositional evidence of deglaciation, in the form of glacio-fluvial deposits, was identified at an early date, the corresponding erosional forms, glacial drainage channels, were not identified until the work of Kendall and Bailey in East Lothian (1908); work extending to this area the principle developed some years before in the Cleveland Hills (Kendall, 1902) and in the Cheviot Hills (Kendall and Muff, 1902). Two minor papers by Anderson (1923a, 1923b) applied the ideas of Kendall and

Bailey to channels in the vicinity of Edinburgh for the first time. But here again, correct interpretation has lagged on description, and the origins of many glacial drainage channels in southeast Scotland have been re-interpreted, notably in a recent series of papers by J. B. Sissons.

Also symptomatic of the lag of interpretation upon description is the early paper by Charlesworth (1926) on a 'kame-moraine' along the northern edge of the Southern Uplands, an interpretation since refuted by several workers in the present phase of the development of our knowledge.

Third phase, 1939 to present: attempts at summarising glacial history in the Edinburgh area. When a full description and an approximate interpretation of the glacial features had been made, the general pattern of glaciation and deglaciation became clear. The most recent phase in the growth of knowledge has been a re-examination in detail of the field evidence, linked with the application of new theories, particularly Scandinavian and North American theories, in attempts at restating the sequence of glacial events more exactly. Some features still excite controversy, for instance, the position of many glacial drainage channels with respect to the melting ice-edge, and the exact significance of particular types of glacial drift; but the limits of disagreement are being reduced by the current research methods. By these, the field evidence is examined more closely, and attempts are made to form the glacial features into compatible groups, for example, to associate subglacial erosional and depositional meltwater forms.

The Geological Survey of Scotland has remapped all the area of Sheet 32, the Edinburgh area, between 1937 and 1956, and mostly since 1947. The published six-inch sheets provide a very adequate source of

TABLE OF CONTENTS

VOLUME ONE - TEXT

data on the topmost drift deposits, as well as a summary of a few of the vast numbers of boreholes on the site of the Midlothian Coalfield and the City of Edinburgh.

The accompanying memoir "The Geology of the Neighbourhood of Edinburgh" was published in 1962 (third edition; Mitchell and Mykura, 1962). The first edition (Howell and Geikie, 1861) was written before the role of land ice was realised, and the second edition (Peach et al, 1910) contains no systematic re-examination of the glacial deposits. In the completely rewritten third edition, two chapters by W. Mykura, the first on the Tertiary landscape and pre-glacial topography, the second on glacial and recent deposits, are the most important work of reference to the present research, complementing and sometimes anticipating much of the work contained in this present study. These chapters are much more than standard compilations of field observations; the latter chapter includes a comprehensive account of the glacial history based on examination of all types of local evidence.

Most of the recent papers (to 1960) on the local glacial phenomena are listed in the above memoir. The contents of these papers frequently have as a theme the relationship between Highland and Southern Upland ice along the southern edge of the Central Valley and this is a principal point of interest in the present study also.

Viewed in the context of all Scotland, the Esk Basin is a small piece of low ground in the east-centre. It is seventy miles southeast of the main Highland glacial source, the southwest Grampian Mountains, and about thirty miles north-northeast of Broad Law at the core of the high ground in the Southern Uplands. Each of these areas has contributed to the glaciation of east-central Scotland, but in spite of much research by a variety of methods, the relative impact of the two sources and the chronology of invasions is not fully known.

Highland ice passed through the central valley of Scotland in an easterly direction. The Pentland Hills lie obliquely across this easterly movement and if the Highland ice were thin, might be expected to have deflected it northeast into the Firth of Forth axis. But the ice was sufficiently thick to overtop the Pentlands without being deflected (see fig. 3.2). The southern flank of ice as thick as this must have at least abutted against the Southern Upland edge, and could have been sufficiently far to the south to have passed up the Clyde valley and eastwards around the southern end of the Pentlands through the Biggar-Dunsyre gap. This then was in fact proposed in various papers by Kendall and Bailey (1908), Charlesworth (1926), and Linton (1933).

Charlesworth argued (1926) that Highland ice had invaded the Southern Upland hills to a height of over 1000 feet in places. The limit of movement was marked by "kame-moraines", extending discontinuously along the Southern Upland edge from coast to coast of Scotland. Furthermore, as Highland erratics were found beyond the limit of this kame-moraine belt, the erratics must denote an earlier glaciation from the Highlands, and the kame-moraines a readvance from the same quarter.

Even if the identification of the kame-moraine forms had been correct, this theory discounts the possible effect of ice from the Southern Uplands itself. The Southern Uplands source area is much smaller than the Highland source, but the ice divide is nearer. That the Southern Uplands had been a primary source of glacier ice was recognised from the beginning by A. Geikie (1863 and 1887). In the third edition of "The Great Ice Age" (1894), J. Geikie, writing of the deflection of ice-currents in the Central Valley of Scotland, came immediately to the present problem:

> "There was a 'debatable ground' between the northern and southern currents, over which sometimes the one (Highland ice) and sometimes the other (Southern Upland ice) prevailed" (J. Geikie, 1894, p.77).

Southern Upland ice moving north into the Central Valley would have been able to restrict Highland ice to low ground, even though it was deflected eastwards by the more massive Highland outflow when both were at their maximum.

Charlesworth's interpretation is discounted by more recent work suggesting that much of the kame-moraine belt is related to Southern Upland ice and does not mark the limit of a Highland readvance. The belt is of glacio-fluvium formed in association with dead ice. Furthermore, the east and central parts are even of different ages. In Midlothian, remapping by the Geological Survey has also not confirmed the distribution of Charlesworth's morainic belt (Mykura, in Mitchell and Mykura, 1962). The arguments are clearly stated by Sissons (1961a), and depend on several individual studies, most of them also by Sissons. In the middle Clyde area, the Thankerton esker system is derived from glacial meltwaters of ice that had been moving northeastwards, that is, from the Southern Uplands (Sissons, 1961b), and the Carstairs ridges are re-interpreted in the same way as a complex esker system derived from Southern Upland ice (Sissons 1961a). Investigation by Goodlet of the most recent excavations in the Carstairs ridges leads him to suggest the forms are a combination of terminal moraine and kames, rather than esker, but still derived from Southern Upland ice (Goodlet, 1964). It is suggested from the proportions of erratics that Southern Upland ice had advanced over ground earlier occupied by Highland ice.

In the Eddleston-Dolphinton area, south of the Esk Basin, the last ice-movement is thought to have been from the Southern Uplands. This is proposed by McCall and Goodlet (1952) and by Eckford (1952) on the basis of indicator erratics; by Bailey and Eckford (1956) from drift lithologies; and by Sissons (1958b) from the regional slope of glacial meltwater channels and the bedding of glacio-fluvium.

In the upper Tweed valley just to the west of Broad Law, the movement is still found to be from the south, on the evidence of the slope of glacial meltwater channels (Price, 1960).

From the conclusions given above, the kame-moraine of Charlesworth (1926) in the Eddleston-Dolphinton area can more reasonably be interpreted as due to wastage of the last ice to invade the area from the Southern Uplands. But Highland ice is not precluded entirely. According to the erratic indicator evidence of McCall and Goodlet (1952), the Southern Upland ice was preceded by Highland ice advancing eastwards through the Dunsyre-Biggar gap and then retreating. In East Lothian, the kame-moraine has been interpreted again as glacio-fluvium, but associated in this case directly with wasting Highland ice (Sissons, 1958a).

In all the recent work summarised above, the relative influence of Highland and Southern Uplands ice has been of prime concern. Attempts at summarising the glacial history in the Edinburgh area revolve around this relationship. The simplified interim summary of events is that Highland ice advanced, retreated and was succeeded by Southern Upland ice extending into the southern part of the area. Finally, small valley glaciers in the central Southern Uplands extended down to about 1000 ft. elevation. There is as yet no direct correlation with the glacial sequences described from the north and west of Scotland. And the various glacial and interglacial stages that have been recognised in England and in continental Europe cannot as yet be distinguished.

CHAPTER IV

THE DRIFT COVER

> "It differs entirely from any other thing on the earth's surface." Mr. Robert Dick of Thurso, on Till. (No date).

Introduction. Mention has been made in the previous chapter of early writings on superposed tills and interstratifications of till and glacio-fluvium. Accurate descriptions of drift stratigraphy date from the mid-nineteenth century and often stress this variety of drift types.

The range of local drift types was first recognised and put into order by A. Geikie (1863), as has been related. A simple summary of the sequence of events accounting for the deposits is given by MacGregor (1945), and need not be repeated here. Till, the direct product of glacial movement, is usually present in any inland drift section extending down as far as bedrock. Washed till, which is a naturally-occurring stage in a continuous series from non-size-sorted to well-size-sorted, is uncommon.

Glacio-fluvial deposits (glacio-fluvium), representing the retreat stage of glaciation or a period with available meltwaters, are present in large quantity, mainly in fairly definite belts. Some of these belts trend along the major river valleys, while others bear no relation to the present drainage system, and may be situated at any altitude above sea level.

Associated with Pleistocene fluctuations in sea level, beds of gravel, sand, and laminated silt and clay were deposited in the Firth of Forth. During and after the period of oscillation of land and sea level the rivers, in readjusting themselves, cut down through the glacio-fluvium, locally excavated deep gorges in till or bedrock, and in the major valleys formed terraces of alluvium at successively lower levels.

Most recently, some raised beach deposits have become covered by wind-blown sands. Inland, there are small isolated pockets of loess. Many of the numerous lakes left in kettles or drift-blocked hollows have been filled in by accumulation of clay, marl, or peat, or have been artificially drained.

All drift materials have been influenced by periglaciation in interglacial, interstadial and immediate postglacial times, and by normal weathering, soil formation, and human interference since this time.

Just as glacial drift is classified both in terms of its composition and structure as a sediment, and in terms of its morphological form, so likewise any description of glacial drift relies both on structural and morphological evidence. This is particularly so of glacio-fluvial deposits. This chapter investigates drift deposits with the aim of deciding on their origin, taking into account the evidence of internal composition and structures. The morphology and fuller interrelationships of the drift types are treated separately in Chapter VII.

Basal till. Of the several identifiable tills in the Esk Basin, the basal till is most easily recognised and described. Basal till is the term used to identify the till immediately overlying bedrock. This is not necessarily all one stratigraphic unit, but it is a lithological horizon.

From geological drift maps, borehole evidence, and field observations, the basal till is seen to cover almost all the low ground but little of the upstanding hills. The altitudinal limit of the basal till is a function of steepness rather than of absolute height. Till is preserved on the highest flat parts of the Pentlands above 1500 ft., but on the sides may be represented only by smears of exigenous drift or by erratic stones. Nothing more than a skeletal till is present on the Roman Camp Ridge within about 200 feet of the top, or on the northern part of Gilmerton Ridge. In certain other areas the till appears to have been eroded away, as, for example, on the west side of the River North Esk in Dalkeith Park where later glacio-fluvium overlies bedrock.

The basal till in thick, unweathered sections is a tough, dark deposit. In the Esk Basin the matrix is usually dark bluish grey, the colour Pettijohn (1957) regards as normal for unoxidized till.

Maclaren describes this till exposed in section during the construction of the railway from Edinburgh to Dalkeith:

> "The lowest bed, which reposes on the rock, was an extremely stiff black or bluish clay, in which were thickly interspersed rolled stones of all sizes up to four or five feet in diameter; but those exceeding eighteen inches were not abundant. The lower bed at Whitehall Mains was about 24 feet thick, and the stones were pretty equally disseminated through it, both as to size and number, from top to bottom." (Maclaren, 1866, p.288).

The basal till is nowadays seldom as finely exposed as this. An exceptional present-day exposure is the three hundred yard cut at Kirkhill providing a diversion for the River South Esk. In this exposure the basal till is seen immediately overlying Carboniferous bedrock. The till in this position is not the usual grey mature deposit with a uniform matrix and considerable lithological variety. Instead it is extremely immature in appearance: the large particles are more angular, while the matrix is sandy and clayey in patches. It is several feet up into the till before the matrix becomes uniform in colour and texture.

At most sites, the quantity of large stones in till is not so great that they are jostling together. In the Esk Basin all analysed samples of the basal till contained at least 47.5 per cent of silt and clay combined, a proportion sufficient to produce a massive, compact formation (Flint, 1957, p.112). The unweathered till is in fact often so tough that spade or pick will only remove small chips at a time. Till with exceptionally high stone content forms the strongly drumlimized area west of Edinburgh: rounded boulders were calculated to occupy as much as a sixth of the total volume and, with a high proportion of sand, the till here is very loose and workable.

About a half of the basal tills examined in section showed a fissile structure, or irregular plates of till, roughly horizontal, 2-8 cm. thick, and of no definite area. The plates are veneered with a black film resembling coal dust. Such fissile structures have been mentioned repeatedly in the literature. Miller (1884) describes them as "an incipient sort of cleavage, a rude stratification"; and J. Geikie (1894) as pressure-planes. They are thought by Virkkala (1952) to be an original feature of till placement, the thin irregular plates being successively plastered down in the process of deposition. Coal dust is always separated out by free water in sedimentary deposits and, in this instance, may indicate that moisture has been pressed out of the plates during the process of accretion. In a photograph shown by Virkkala, the coal dust is replaced by minute amounts of sorted fine sand. As a more local example, Tait describes such foliation in till exposed during building in George Square, central Edinburgh:

> "There can be seen a faint horizontal cleavage or foliation... the (boulder) clay came away in rough slabs, one or two inches thick, with undulating nearly parallel surfaces. ... This seems a structural character given to the boulder clay by the movement of the ice over it". (Tait, 1939, p.458).

There is a coarser form of fissile structure, called by Virkkala (1952) the bed limit, which Virkkala describes as the first stage in an interruption of the till sedimentation. Such a form is mentioned later in connection with till and glacio-fluvial interstratifications.

Apart from the sub-horizontal fissile structure, a few sections of till show faint vertical cracking. This is thought to be due to desiccation, as the cracks are more evident on old sections exposed for a long time to the air.

Where the local bedrock is of a friable red sandstone, as in parts of the Pentland Hills and in East Lothian between Soutra and Humbie, the till becomes more reddish in colour. This colour characteristic may on occasion be used to distinguish tills, but there is a certain danger in this. The typical leaden colour of the basal till in the Esk Basin and dark chocolate brown of East Lothian is true only of the unweathered material. The top 3-5 feet below an exposed surface shows varying amounts of leaching. In 12 feet of basal till at Jerusalem in East Lothian, gley markings and vertical cracks exist to a depth of 5 feet. The colour gradually changes below the soil layer from red-brown through

Chapter IV (Cont.)

Page

a grey and red leached zone to finally become the original dark brown colour at 6½ feet (fig. 4.1).

A horizontal fissile structure exists in this till at Jerusalem below about 4 feet depth; the plates and all large stones have a fine black veneer. The fabric of the till (see Chapter V) is preserved up to within 1-2 feet of the surface at such sites, pointing to limited penetration by large roots.

Roslin Till. A thin weathered till occurs as the uppermost drift deposit over several miles of Midlothian. Although this is a distinctive local deposit, it has not previously been given a specific label; the local Geological Survey Memoir (Mitchell & Mykura, 1962) refers to it as the Upper Boulder Clay, a term that invites confusion with the drift succession in other districts. Accordingly, in this text, it is named after the locality of Roslin where it is well exposed in several sand pits.

The Roslin Till was first described by Anderson (1940), although an earlier reference by Peach et al (1910) to an "overlying reddish brown boulder clay" in the vicinity of Eskbank and Newtongrange may be to this deposit. Its recognition in the Roslin district depends on the fact that it everywhere overlies thick glacio-fluvium, from which it is immediately distinguishable. The exposures of the Roslin Till as located by Anderson and later Geological Survey mapping are given by Mitchell and Mykura (1962, Plate IV) and repeated with additions by the writer on fig. 4.2.

The Roslin Till varies in thickness from one foot up to about eight feet. In a large exposure at Burghlee, the thickness was only 14 inches, but increased to 3 feet in another part of the same face. At Clippens and New Pentland, the thickness was more consistent at about 4 feet, and at Oatslie usually 5-6 feet. It seems likely that on occasions the deposit of Roslin Till is too thin for the till to be confirmed to exist at all.

As it overlies permeable sands and gravels, the Roslin Till has been oxidized throughout its thickness to an ochrous red-brown colour. Grey clay-lined vertical cracks often extend 4-5 feet down into the till, producing a secondary columnar structure. Worm casts and root remains penetrate to 3 feet, and hair-roots to 4½ feet. No fissile structure like that common in basal till has ever been noticed. The oxidization has affected the stones as well as the matrix of the till. All the particles have a rust-brown veneer and only the fine-grained igneous lithologies are not to some extent decomposed. The softer lithologies have a decomposed outer shell while some grits and mudstones have disintegrated completely. It is estimated that of the stone content in the Roslin Till at Bilston sand pit, 35 per cent disintegrated when dug out. Identification of the particles proved to be much more difficult than with unweathered till.

A number of fabric analyses were carried out in the Roslin Till; all gave consistent and unexceptional results, indicating that the leaching and other disturbance of the till was not accompanied by any significant physical movement.

A thin till forming the uppermost layer of drift and separated from any basal till by thick glacio-fluvium has been found at a number of places outside the area of known Roslin Till. Because of stratigraphic position and similarity in appearance to the Roslin Till, these tills were all originally taken to be the same deposit, and the occurrence of Roslin Till correspondingly extended (fig. 4.2). Sites will be described at Haveral Wood, South Melville and Easter Bush.

The exposure at Haveral Wood is illustrated in fig. 4.3. The glacio-fluvial ridge of sand between Loanhead Farm and Wading Burn is capped by a few feet thickness of till. A sand pit at the Wading Burn end of the ridge (opened in November 1961) exposes the drift across the width of the ridge. In the section illustrated, the till averages 2 feet but thickens to 4 feet on a slight shoulder in the underlying sand. On the south side the till has slumped into a glacial meltwater channel which cuts through both the till and sand. The till is visually identical to that atRoslin, being very leached with vertical grey cracks. There are numerous small sandy pockets. The junction between till and underlying sand is clear-cut, the till peeling up off the sand quite cleanly. Apart from some small silty layers in the top few feet, and some coal dust, the sand is very uniform. The current-bedding in the sand is parallel to the surface where seen. Stone counts, mechanical analysis and till fabric analysis at this site will be described later.

At South Melville, on the east side of the North Esk gorge, a temporary 6--foot section (open January - May, 1964, revealed a complicated arrangement of beds, including till overlying thick sands (fig. 4.4). The drift deposits were examined by the writer and several colleagues, and the beds heighted by levelling. The higher ground on the southeast of the section is the edge of the high flat area occupied by Lasswade golf-course, and known on other evidence to be composed of thick glacio-fluvial sand. This sand is exposed at the top of the section and reappears again lower down. Till occupies a position plastered onto the 10° slope of the gorge-side, on top of the sand. The till is dark brown and less leached than the Roslin type. The lower part of the till appears to have slumped, probably as the result of under-cutting when the adjacent glacio-fluvial river terrace was being formed. The lower exposure of the Lasswade sand grades laterally into alluvium underlying this terrace. In the more recent valley of the present River North Esk, basal till is exposed as a bluish grey clay. The drift sequence at the top of this section (fig. 4.4) is repeated on the southeastern flank of the Lasswade sand feature (fig. 4.5 and photo. 1).

Where the Roslin Till was suspected to occur, but no section existed, it was sometimes possible to prove its presence by augering. A heavy-model screw-auger was used, with extension pieces after the fashion of gas-piping. This will penetrate sand, stoneless clay and leached till, as long as it avoids large stones. By augering, the Roslin Till was proved at Easter Bush, where 4½ feet of till overlies 7+feet of sand; and also north of Pentland Mains Farm where 4 feet of till overlies 6+ feet of sand. At several other sites where Roslin Till was suspected to occur, the auger was held up by stones, or continued in till to a depth greater than Roslin Till usually exists, suggesting the auger had passed into a lower till. In either case, Roslin Till could not be proved to exist at the surface.

A further result of augering into the Roslin Till may be mentioned at this point. The flat surface (terrace 152: Chapter VIII) at Oatslie, composed of thick glacio-fluvial sand overlain by Roslin Till, is interrupted to the southwest by a small subglacial drainage channel falling towards the present river North Esk. Augering proved the following drift at the sites indicated on fig. 4.6:

Site 1	Site 2	Site 3
1 ft. soil	2 ft. soil, becoming sandier at base with stones	2 ft. soil
2½ ft. till		1½ ft. till
2+ ft. sand		3+ ft. sand

At Oatslie the Roslin Till is usually 5-6 feet thick; it also tends to fill in original depressions in the underlying surface. The very thin till in the base of the channel at Site 3 (fig. 4.6) appears to be the result of solifluction or slumping down the steep eastern slope of the channel. The channel is interpreted as being cut through both till and glacio-fluvium by meltwaters from the ice depositing the Roslin Till. Other channels in the area are similarly interpreted as post-dating the Roslin Till.

The limited area of Midlothian where Roslin Till can be shown to exist could not represent the full extent of this deposit unless its source were immediately adjacent in the Pentland Hills. There is no morphological evidence to suggest this is the source; much more likely is a more distant southerly source or even a northwesterly source (see Chapter IX). Roslin Till has not been recognised outside its type-area, partly because it is overlain by its own meltwater products and partly because it often directly overlies another till, and the division between the two tills is not found. For example, at New Pentland, in a continuous 6-foot temporary trench over 400 yards long (open May 1963), the Roslin Till was found overlying a variety of other drift types (see figs. 4.7A, 4.7B; photo. 2). In the middle of the section, the Roslin Till is 3½ feet thick and overlies 2 feet of bedded sands and silts in turn resting on dark grey till. The Roslin Till is visually similar to that elsewhere, being red-brown and gleyed throughout with some particle decomposition. At each end of the trench, the Roslin Till was seen to be underlain directly by clay and till; at these points it is much less leached, as water is less able to drain freely right through it. The junction between Roslin Till and underlying clay and till was clear near the central sand lens, because the sand thins away laterally into a darker line of silt. But where this ceases, there was no break visible between the Roslin Till and the underlying basal till. Where the trench was 13 feet deep at its northern end, the two tills are not separately distinguishable, but darken downwards as one unit as weathering becomes less.

Superposed tills in Esk Basin. In the section described above at New Pentland, the Roslin Till and underlying basal till could not be separated by their field appearance when in direct contact. However, they were later differentiated by the aid of fabric analyses and stone counts. Other cases of superposed tills were recognised directly in the field, because of different appearance or slight textural variations in the beds. In the examples of superposed tills described below, neither of the tills can be directly correlated on stratigraphic evidence with the Roslin Till, but one or other may subsequently be equated with it from other evidence.

Fresh sections were made available on both the northwest and the southeast flanks of Gilmerton Ridge during the period of field study. On the northwest flank a temporary 6-foot trench section (open January - March 1964) extended N80°W obliquely down the slope. The ground surface slopes at 5° to $N60^{\circ}W$. The section showed at the surface 3 feet of till overlying 3+ feet of darker till. Separating the tills is a layer of sand 6-12 inches thick (see fig. 4.8; photo. 3). This sand thins upslope to a series of sand lenses at the same depth, and is absent at the higher end of the section, which was below the road along the ridge-crest. The upper till is gleyed and shows vertical cracks and worm holes throughout; many particles are decomposed. The lower till is distinguishable from the upper till even when the sand layer is absent by its darker colour and greater compaction. The sand layer, which contains fine bands of coal dust, is sloping at 6° where measured, suggesting it accumulated in sequence with the two tills beneath ice.

At a similar distance along the Gilmerton Ridge on the southeast flank, an opencast shale working provides a long drift section. The section was fresh when examined in July 1961 but is now (1965) deteriorating. The succession (fig. 4.9) is similar to that described above for the other flank of the ridge, with the addition of 4 inches of black earthy material occurring beneath the sand. Although it is tempting to consider this as a soil layer (see section on Vegetation Remains, below), no distinctive vegetable matter could be isolated; the layer is most probably fragmented bedrock washed down the slope. The lower till is 5½ feet thick, resting on black Carboniferous oil-shale.

At a second site in the shale working, 140 yards further northeast, no sand or black earthy layer was seen.

The western edge of Penicuik townsite extends up onto the edge of a broad bench or terrace composed of till and roughly paralleling the Pentland Hills. The Cuiken Burn descends to Penicuik across this terrace.

In its centre part where it turns along the length of the terrace, the burn cuts down through till to a depth of 18 feet. A borehole datum showing 20 feet of drift and the exposures nearby at Cronbank estate during house building (July-September 1964) indicate that in this centre part of the terrace the 18 feet of till is about the total thickness and further stream incision is limited by bedrock. The transverse profile of the burn suggests movement laterally southeastwards of the stream bed.

The 18 feet of till forming the Cuiken terrace consists of two separate deposits, a lower till 12 feet thick being separated by a 2-inch sand layer from an upper till 6 feet thick (fig. 4.10). The lower till is grey-black, unweathered, tough, and shows good fissile structure. Particles in the till seem to be aligned very markedly in a common direction. The upper till is red-brown and gleyed in light grey and ochre. Vegetation roots extend down to 3 feet depth, and worm holes to 5 feet. This till has no fissile structure but does have vertical fissures, probably secondary. The texture appears sandier than that of the lower till, and small lenses and narrow layers of sand occur down to its base.

A striking case of superposed tills is intermittently exposed at stream level along Keith Water (NT 44 63). Two tills of completely different colour are in direct contact, the lower being grey-black basal till and the upper a clayey brick-red till. Four feet of the red till is preserved under river alluvium.

A similar succession of two tills in direct contact may be seen at Pogbie in the same district (NT 46 61). A section in a deep drainage ditch at the edge of a field shows 3 feet of reddish till overlying 4+ feet of dark till. The contact between the tills is undulating but distinct, and marked for a short distance by a lens of sand. The red till in each of the above East Lothian sections is known as Humbie-type till by the Soil Survey of Scotland.

Superposed tills occur much more widely than the limited number of examples above would suggest. There are other cases where, although visual inspection may show only one unit, further tests indicate significant divisions.

When there is a separating layer of washed deposit between two thicknesses of till an immediate division is possible, but the further problem then arises in deciding whether the washed deposit represents a major change in conditions of deposition or is an isolated insignificant variation. Every gradation is found in the Esk and Tyne basins from thin wisps of sand caught up in till, as has been described from some sections above, to beds of sand and gravel 50 feet thick. Apart from looking for variation between the layers of till directly, a partial decision on the meaning of the oscillations in the type of deposit can be made from the thickness and continuity of the beds and the degree of vertical gradation between them. These factors are considered together in a later section. An interstratified deposit is taken to be one containing more than one of each of alternating layers of till and glaciofluvium; some of the best examples are now described.

In Dalkeith Park, an excellent exposure in drift occurs as the right bank of Park Burn, three hundred yards before it enters the River North Esk. The section shows an alternating sequence of till and sands, the individual beds generally thinning upwards except for the topmost bed, which is of sand and quite thick. Five layers of till are exposed (fig. 4.11), the top one at the base of a wooded slope being weathered and not well revealed. At the base of the succession is exposed 5½ feet of basal till. Slumpage conceals the 4 feet below this down to stream level, but it is almost certainly the same basal till, the total of 9½ feet representing the total thickness of basal till: from local evidence in the gorge of the North Esk nearby, Park Burn must be near or on the bedrock, being a tough, unweathered, dark grey deposit with fissile structure. Boulders occur up to three feet in length.

The basal till grades upwards into 8 feet of various water-sorted deposits. The gradation takes place over a distance of a foot, the material in this distance being grey silt, sand, and a 3-inch till layer. In other words, there is a transitional state as regards colour, grain-size, and the degree of water-washing. The 8 feet of glacio-fluvium consists, from the base, of 3 feet of yellow-grey sand containing coal fragments, 3 feet of gravels and sandy gravels, also containing coal fragments, and 2 feet of fine sand, yellow-brown and cleaner than the beds beneath.

Following this glacio-fluvium, the section shows three further layers of till varying from 3 to 15 inches in thickness, and a final layer of till 1+ feet thick. The tills have the same appearance as the basal till. Separating the layers are thin bands of clayey sand, sand, and gravel (fig. 4.11). The remaining 24 feet of the river bank is sloping and tree-covered. Sand is exposed at the top surface, which is an outwash terrace (terrace 229), and in a rabbit-hole at 12 feet below the surface.

Glacio-fluvium denotes temperatures high enough for running water.

VOLUME TWO - ILLUSTRATIONS

The alternations of glacier-deposited till and water-deposited bedded sands represent fluctuations in the temperature conditions at the time of deposition. These fluctuations can be local, and related for example to release of pressure or movement of ground heat beneath a small part of an ice-sheet; or they can be regional, representing a considerable change in climatic or water-table conditions. In the latter case, the associated deposit is more likely to be thick and occur widely. In the Park Burn section, none of the water-lain deposits is very thick or coarse-grained, and so only small, short-continued rises in temperature need to be invoked.

Immediately above the basal till the grey silt represents the transitional period with an increasing amount of available water. The coarsest bed is the 3-feet gravel bed representing the condition of maximum available water. Decrease in temperature brings a decrease in available water, shown by a 2-foot deposit of finer material. Finally there is a junction zone sand-to-till of 1-2 inches. Thereafter glacial deposition is re-established.

This alternating cycle is repeated twice more. The presence of gravel rather than silt in the thinner water-lain deposits of the later cycles suggests briefer episodes of the same intensity rather than periods as long but with less temperature variation.

A small piece of field evidence provides further information on the deposition. The till layer 15 inches thick is cut almost in two by a gully trending N10°E almost at right angles to the exposed face (see fig. 4.11 - inset). The gully extends from the top surface of the till almost to its base. It is of square cross-section with vertical walls. There is an abrupt junction between the surrounding till and the filling of the gully, which is fine washed gravel and sand. The gully extends 3½+ feet into the face, narrowing slightly to the rear. At the top of the gully, the gravel filling extends laterally as a ½-inch layer to separate the host till from a very narrow band-till, only 3 inches thick, on top. The ½-inch layer of sand and gravel would not have been noticed, were it not for the gully associated with it.

This gully is interpreted as a wash-out, formed by meltwater running over a surface of freshly deposited till. The shape makes it unlikely to be a desiccation crack; nor is it a frost-wedge as again the shape is wrong, and the sand bed beneath is undisturbed. Differential compaction explains the slight bulges of the floor, roof and left hand side of the gully. The gully was formed after the deposition of the host-till and before the thin overlying till. Therefore the deposition of till was discontinuous, and the section as a whole illustrates a microcosm of glacial deposition in phases, with sub-glacial fluctuations in temperature.

Stone counts from the two lowest tills give very similar results, suggesting that the 8-foot glacio-fluvial deposit is not separating two different tills. As the other interstratified bedded deposits are much thinner, and there is no vegetation or weathering evidence in the section to suggest major climatic breaks or subaerial exposure between the tills, it might be concluded that the higher tills are also of the same origin as the basal till. In any event, the evidence is sufficient to indicate that the comment that "the basal boulder clay shows no evidence of separate phases of ice-movement" (Mitchell and Mykura, 1962, p.111), should be modified.

The highly relevant till fabric analyses carried out in each of the till layers in the Park Burn section are described in Chapter VI.

A section showing interstratification of till and washed deposits, and one that provides interesting analogies with the Park Burn section, occurs as a river bank cutting of the Black Burn, on Auchencorth Moss. This is a right bank section facing north, about a half mile upstream of Halls Bridge and the junction with Lead Burn.

The base of the section (fig. 4.12) shows 12½ feet of dark red-brown till. A further 9 feet of slumpage almost certainly conceals the same till, as seen in other nearby sections at stream level. The stream is now cutting into the surface of the Millstone Grit bedrock. The basal till is a tough, homogeneous, unweathered deposit containing large boulders. At the top of the basal till, there is a gradation in texture over about a foot; the till becomes more silty and loses its large particles. The silty layer is followed by 1 foot of bedded sands containing coal particles. There is no change in colour from the basal till up to this sand layer.

The top of the red-brown sand is marked by an abrupt break, followed by 3¾ feet of grey till. The grey colour is retained as this till in turn grades upwards to 9 inches of bedded sands. The texture is then retained but the colour changes: the grey sand is succeeded by 6¾ feet of brown washed deposits, a suite of very variable sediments comprising six distinct beds. The succession is completed by 1½ feet of a uniformly fine, light brown silt resembling loess, and a soil layer.

The abrupt change in texture and colour midway up this section suggests two separate tills rather than a pause during the deposition of one glacier load. The basal till and grey till each grade upward into meltwater deposits of the same respective colour, but there are no beds linking the two colour units. To this obvious difference in appearance will be added in a later section the results of stone counts and fabric analyses from the two till layers.

At this section on Black Burn, the 6¾ feet of brown washed deposit is of local occurrence. There are small spreads of sand and gravel along the burn, remnants of the deglacial phase when the stream was initiated. These are shown on the appropriate six-inch geological map. The topmost deposit, of silt and fine sand, is also of local occurrence.

An interstratified deposit of quite a different type has been visible for a number of years below Kirkhill cemetery within Penicuik townsite. It occurs on the southwest flank of a large area of outwash sands, subsequently dissected by the River North Esk and Loan Burn. Most of this dissected surface is now built up. The deposit was formerly worked for sand, but digging reveals that as well as sand, the 40-foot section includes a 3-foot band of till, rather less than half way up (fig. 4.13). The till is an unweathered compact deposit, rather sandy in texture and with some sand lens inclusions. Boulders up to 1½ feet long were noted. There is a clear-cut junction with bedded sand both at the top and bottom of the till layer. The sand above and below the till is uniformly medium in grain size and contains coal fragments. The only variation is a 2-foot band of laminated silt and clay in the upper part, dipping north.

The type of bedded deposit suggests relatively long-continued deposition by meltwater under quiescent conditions. This was interrupted by a period of glacial deposition and must all have been preceded by a glacial episode, although the basal till is not revealed. In particular, the thickness of the lower bed of sand seems more likely to be separating two distinct glacial phases than marking a temporary sub-glacial cessation in till emplacement.

Superposed tills in Tyne Basin. In East Lothian, a number of sections along the tributaries of the River Tyne show successions of drift including more than one till. The best-known section is Red Scar, an abandoned river cutting at Costerton. This section was first described by Kendall and Bailey (1908) and remains as clear today as when they examined it (photos. 4 and 5). Four main deposits occur above river-bank level (fig. 4.14). Thirty-two feet of dark till at the base is succeeded by about 15 feet of bedded sands, the two deposits merging and being interbedded over about three feet. The sand is medium grained except for a 1-foot thickness of laminated clays and silts near the top (fig. 4.14, layer a); there are about 30 thin laminations, including both red and chocolate-coloured layers. Pollen analysis from the laminated layers, carried out by W. W. Newey, showed them to be lacking in organic material. No pollen grains were observed; the only identifiable remains were derived spores of Carboniferous type.

The top of the sand is marked by a sharp break, and then follows 13 feet of dark till grading upward into the top formation which is 54 feet of bedded sands with some gravel bands. There is a transition over 1½ feet between the upper till and the topmost sand: the till changes colour upward from dark brown to light brown, and then loses its texture, becoming clean silt and finally sand. There is no distinct line marking an interruption in the sedimentation process. Within the upper till there is a distinctive 1-foot band of black shale and black and ochre clay (fig. 4.14, layer b). This was shown not to be a soil layer by pollen analysis which again produced no identifiable remains of post-Carboniferous type and no recognisable macro-fragments.

The Red Scar sequence of deposits can be traced along the course of Keith Water for a half mile downstream and at least one mile upstream of this site through occasional smaller sections and by examing the vegetation of the valley sides. The upper till is marked very clearly by a wet zone and by reeds forming a discontinuous belt along the slopes. In the Routing Burn tributary of the Keith Water just north of Fala both tills are exposed in a clean section; elsewhere either one or other till is exposed.

One of the downstream sections along the Keith Water, previously described by Kendall and Bailey (1908) is not now as clear overall as formerly (photo. 6). An estimated 17 feet of dark basal till grades upward into silty till and then into bedded sand (fig. 4.15). Near the base of the sand are inclusions of red till and higher up a 3-foot bed of red till. The sands are fine- and medium-grained and thin-bedded. The 15°-20° dip of some of the bedding indicates post-depositional movement, by slumping against melting ice. The included pieces of red till appear to have been washed rather than dropped into the sands, as shown by the bedding around them. The presence of pieces of till at a lower horizon than the till from which they are apparently derived may be explained in two ways. In the first place, they are not necessarily derived directly from the till above, but can have been washed and slumped into their present position during the sub-glacial dissection which accompanied deglaciation in this area. Alternatively the pieces of till may have been washed into the sand in front of a re-advancing glacier which subsequently covered the sand and deposited the bed of till. This pro-glacial explanation is less satisfactory in this location as it requires the sand to be the product of the re-advance glacier. The fact the sand grades up from the basal till, and so is associated with the melt phase of the first glaciation rather than with the approach of the second.

The extreme top of this section shows 7 feet of a further bed of till. From field examination this till appears to be a water-modified equivalent of the red Humbie-type till, although the colour is less distinctive. There is a sharp junction between this till and the underlying sand, but the sand does have 1½ feet of silty layers near the top.

Two further sections from the same area add to the information from Red Scar and Keith Water above. These are exposed in old sand pits adjacent to the B6371 road, one each side of Keith Bridge (figs. 4.16 and 4.17). As these sections are only a quarter mile apart and their top surfaces are at 506 and 508 ft. O.D. respectively, as measured by aneroid, they can be directly linked. Also they probably show beds equivalent to those in the Keith Water section (fig. 4.15) further upstream, the top of which is at 527 ft. O.D. Each section shows only the upper part of the complete succession; in each case, at least the basal till is not exposed, but may reasonably be inferred. Thick horizontally-bedded sand is overlain by beds of till of varying thickness, interstratified with sand and stoneless clays. This thin-bedded sequence is not consistent from section to section; in particular the two exposures in the Keith

Marischal sand pit do not fit together, at one point the bedded sand being truncated against red till as the result of ice-contact deposition. In general the sections show 2½ feet of till grading into sand at its top and base. Above this occurs a further bed of till, distinctively red where it is preserved unweathered.

These sections in East Lothian showing multiple tills can be supported by many more showing just one or two formations, and from these the glacial stratigraphy can be established. This is attempted after the till fabric analyses and stone counts from some of the sections have been considered.

<u>Stone counts from till</u>. As an independent method of investigation of the till layers in the Esk and Tyne Basins, stone counts were made at 39 sites. Tables 4.1 and 4.2 summarise the details of the stone counts, and fig. 4.18 shows the location of the sites and the proportion of rock types at each.

Suitably-sized particles for hand examination were collected. In the collections totalling exactly one hundred the particles were those used in the till fabric analyses at these respective sites, to be described in Chapter VI. There is a slight possibility with these that the proportion of different lithologies is not truly representative of the total particle population because, as only elongate particles were used, a rock type characteristically producing rounded pebbles for example, would have been passed by. However, it is thought that the collections are at least broadly indicative of the proportions of the lithologies in the till (Appendix A). The particles extracted were usually only a few centimetres long; these are better indicators of long-distance movement than large boulders, locally derived.

Because there are so many different bedrock lithologies in the Edinburgh area, particularly to the southwest, it would have been

TABLE 4.1

STONE COUNTS FROM TILL - ESK BASIN

		Lithological suites (%) and sources				
Location and t.f. site number	Total collection	Carb.ls., ss., blaes. Esk Basin and West	Ign. Volcs. Pentlands	O.R.S. Pentlands	Greywackes S. Uplands	Others Widespread
Bilston (3)	100	30	20	3	0	47
Oatslie (4)	100	34	22	7	3	34
Boghall Burn (6)	120	25	33	12	4	26
Boghall Burn (22)	79	10	34	7	1	48
New Pentland (29)	122	10	18	5	0	67
Glencorse House (32)	100	23	41	9	11	16
Milton Bank (33)	100	21	21	12	23	23
Haveral Wood (34)	100	8	15	5	2	70
Black Burn (35)	100	25	34	1	12	28
Black Burn (39)	214	18	17	8	40	17
Esperston (40)	94	61	0	1	24	14
Clippens, New Pentland (19/41)	331	40	18	4	2	36
Lead Burn, Howgate (42)	300	5	27	2	53	13
Flotterstone (43)	219	13	48	7	7	25
Braidwood Burn (44)	202	0	45	5	28	22
N. Esk, Auchendinny (45)	148	36	36	3	1	24
Dalmore Mill, Auch. (46)	261	19	24	10	27	20
Shiel Burn, Rosedale (47)	236	22	14	1	48	15

TABLE 4.1 (Cont.)

Dalhousie Burn (48)	140	11	13	3	48	25
Park Burn, Dalkeith Park (53)	100	7	15	0	3	75
Park Burn, Dalkeith Park (54)	100	7	9	4	2	78
Cuiken Burn (60)	185	16	35	1	0	48
Cuiken Burn (63)	122	16	33	5	6	40
Black Burn (65)	343	8	62	3	10	17
Fullarton Water (66)	204	26	25	3	16	30
Kirkhill Bank (67)	170	10	2	5	74	9
Kirkhill Cut (68)	166	39	19	7	8	27
Silverknowe (S)	322	22	0	0	0	78
Prestonfield (P)	318	44	9	11	2	33
Roslin (R)	322	30	18	3	38	11
Newbigging Quarry (Q)	192	17	15	2	50	16

LIST OF TABLES

TABLE 4.2

STONE COUNTS FROM TILL - TYNE BASIN

		Lithological suites (%) and sources				
Location t.f. site number	Total collection	Carb.ls. ss., blaes. Tyne Basin and West	Ing. Volcs. Pentlands	O.R.S. Pentlands & E. Lothian	Greywackes S. Uplands	Others Widespread
Keith Water (9)	173	39	8	2	21	30
Red Scar Costerton (10)	286	50	0	1	43	6
Milton Bridge (51)	223	30	16	3	1	50
Birns Water (52)*	373	33	16	6	21	24
Keith Water (69)	232	16	1	13	64	6
Keith Marischal (70)	220	46	7	3	14	30
Partridge Burn (71)	309	48	4	5	26	17
Cotty Burn (72)	151	44	12	9	11	24
* Comprising						
Birns Water (52A)	223	32	17	5	25	21
(52B)	150	33	16	8	15	28

impossible in this essentially subsidiary line of investigation to identify every particle, short of thin-sectioning it. What is possible is either to plot the location and frequency of occurrence of a particular indicator erratic or, considering the total particle sample-population, to divide it into suites of rocks according to local stratigraphical provinces.

In this work, on the advice of E. K. Walton (pers. comm., 1963), the second course was followed and no particular indicator erratic was selected. The population was divided into suites, comprising : greywackes, monotonously characteristic of the Southern Uplands; the Devonian extrusive igneous rocks of the Pentland Hills; the Old Red Sandstone outcropping at the northern tip and over much of the southern part of the Pentlands; and the considerable variety of Carboniferous grits, limestone, sandstone, coal and blaes forming both the Midlothian Basin and the low ground west of the Pentlands.

All lithologies not identifiable as one of these four categories were grouped together in an "others" category, which therefore contains scores of individual rock-types, particularly fine-grained igneous rocks that can be identified only by thin-sectioning, but also occasionally pieces of Highland granite and schist.

No thin-sections were made: the specimens were compared by eye against a collection of about 80 rock samples taken by the writer from identified bedrock exposures. As the reference collection was by no means complete, particularly for volcanic rocks, the "others" category also includes all specimens that could not be recognised at all, but were not from the four described suites. Many of the erratics in the basal till are known to have originated in the west of Scotland (for example, Peach, 1909); as the division stands, paucity of the four local suites of rocks indicates a distant source by default.

Tables 4.1 and 4.2 show that the proportions of all the rock suites fluctuate considerably according to site. The most consistent suite is the Pentland igneous volcanics which occur at all sites except Silverknowe northwest of the Pentlands, and Esperston under the Moorfoot Hills in the southeast. Old Red Sandstone is also consistently present but in smaller proportions.

As most of the sites are located on Carboniferous rocks, the proportion of these lithologies is lower than might be expected. Carboniferous rocks from the Esk Basin were not found at Braidwood Burn (44), five hundred yards east of the Pentland Fault, but do occur in small proportion at Flotterstone (43) a rather greater distance on the other side of the fault-line, and so must have been carried into the Pentlands from the south or east.

The proportion of Southern Upland greywacke varies a great deal. Greywacke becomes less common northwards away from its source area, but the quantity by no means diminishes at a regular rate. In the southern part of the Esk Basin the distribution of greywacke shows several anomalies. At sites 33, 40, 42, 44, 46, 47, 48, Q and R, all in basal till, greywacke forms a considerable proportion of the total stone count, rising to over a half of the total at Lead Burn, Howgate (42) which is within a mile of greywacke outcrop. But there are several other sites also in basal till and as close to the Southern Uplands with a much lower proportion of greywacke. At sites 32, 35, 43, 45, 60, 65 and 68 greywacke does not contribute much more than a tenth of the total stone count. At Glencorse House (32) and Flotterstone (43), this may be the result of local over-representation by the Pentland volcanic rocks; at least greywacke is present as 11 and 7 per cent respectively. At North Esk, Auchendinny (45) and Cuiken Burn (60), sites a mile closer to the Southern Uplands and further removed from the Pentland lithologies, only one particle of greywacke was found in a combined stone count of 333 particles. No explanation of over-representation appears valid and, in any case, site 45 is adjacent to site 46 where greywacke is abundant.

The five stone counts west and east of Howgate provide further information. Of these, numbers 35 and 65 are from the basal till and 39 from a thin higher till, all exposed at Black Burn. The basal tills each have a low proportion of greywacke in spite of their short distance from the greywacke outcrop, suggesting that the depositing ice moved from the southwest rather than from the south. The reverse appears true form the greater proportion of greywacke in the higher till at Black Burn (39) and from site 42 on Lead Burn. The fifth site at Fullarton Water (66) revealed only 16 per cent greywacke, although half-ringed by this bedrock to the south. The mixed lithologies suggest an ice movement from the southwest, avoiding a long carry over greywacke exposures.

If any conclusion is to be drawn from this limited evidence on the stone counts of the basal till, it is that the basal till is not a homogeneous deposit but is derived from different sources, travelling by different routes. It is not clear whether the variations in the stone content occur laterally in one horizon, or indicate separate beds, each bed having its own characteristic suite.

The contrast in stone counts between different tills at the same site is strongest at Kirkhill by the River South Esk. The raw bluish-grey blocky basal till exposed in the river-diversion cutting contains a mixed lithology, with local material dominating and only 7 per cent greywacke. The sections at the very top of the South Esk gorge show a red-brown till with a quite different stone count. Greywacke now comprises three-quarters of the total number of stones counted. Local bedrock is represented by only a tenth of the total and the proportion of Pentland volcanics is also much reduced. The proportion of local bedrock may not be a good indicator, because of local over-representation, but from the contast between Pentland and Southern Upland proportions, the two tills appear to result from two different directions of ice movement, an earlier movement with a dominantly westerly component, a later one with a southerly component.

Stone counts from the Roslin Till were taken at sites 3, 4, 6, 34 and 19/41. These have in common a moderate proportion of igneous volcanic rocks and small quantities of Old Red Sandstone and greywacke. The four sites nearest to Roslin also give between 25 and 40 per cent of Carboniferous lithologies. The proportion of rock suites does not suggest any particular origin. In marked contrast, site 34 at Haveral Wood has only 8 per cent of Carboniferous lithologies, and the collection does not break down into the normal suites. The great variety of material, which includes only 2 small particles uncertainly attributed to the Southern Uplands, suggests an origin for this till which is neither local nor from the south.

The remaining sites in the northern part of the area, at Boghall Burn

(22), New Pentland (29), Park Burn (53 and 54), Silverknowe (S) and Prestonfield (P) all have a high proportion of rocks outside the four named suites. Greywackes are very uncommon. Both of the lithologies were recognised as of western origin; for example, quart-dolerite of Dalmahoy type was picked out. The large amount of Carboniferous types at Prestonfield (P) are of the type produced from the Calciferous Sandstone Series, widely exposed west of the Pentlands. Apart from some Calciferous Sandstone Series, the site at Silverknowe (S) yielded only the "other" category of material, largely mafic igneous material. No schistose Highland rocks were noticed.

A western source for many erratics in this northern area is of course certain, as seen in many previous records (for example Peach et al, 1910). Not only the basal till (sites 53, S, and P) shows this western influence. It is seen also in the band till at Park Burn (54), the skeletal basal till at New Pentland (29) and, as has been stated, in the Roslin Till at Haveral Wood (34). The origin of the till at Haveral Wood as Roslin Till seems doubtful.

The method of stone counts has previously been applied to Southern Midlothian by several other workers. The results as so far described in this text to some extent only reinforce earlier conclusions. Anderson (1940) gives the results of a stone count from the "overlying boulder clay" near Roslin (the Roslin Till), this being the same exposure as Oatslie, site 4 in Table 4.1. His conclusion is that the vast majority of rocks are either igneous, many being local from the Pentlands, or Devonian and Carboniferous sedimentaries. Greywackes were found to be rare (1 per cent). This agrees tolerably with the Oatslie stone count (4).

Anderson considered that the few greywackes present may have been derived from the Pentlands rather than from the Southern Uplands, an origin for greywackes which would explain the presence of the few in the northern sites in this study.

Anderson does not draw any conclusion as to the origin of the Roslin Till. Mykura wrongly attributes him as concluding (in Mitchell and Mykura, 1962, p.114) that the till bears evidence of a readvance of Highland ice.

More detailed evidence on the lithologies represented in the local tills has been presented by McCall and Goodlet (1952). This paper decides on directions of ice movement from a study of selected indicator erratics rather than by dividing the whole sample-population into suites. In the Roslin Till (referred to as the Midlothian Upper Boulder Clay), the presence of felsite from Tinto Hill to the southwest, and the absence of Highland rocks (contrary to Anderson, 1940) is taken to indicate a carry from the south. The status of Southern Upland greywacke is not considered. But the principal formations below the Roslin Till, the basal till and the "Middle Sands and Gravels", are found by McCall and Goodlet to contain Highland rocks fairly frequently and common occurrences of felsites (referable) to North Black Hill, at the north end of the Pentlands. This is taken to mean that the two deposits are directly related. The original ice movement was postulated as from the Highlands around the north and south ends, and subsequently over the top of the Pentland Hills. During retreat of this Highland ice the Middle Sands and Gravels were deposited and following this the Roslin Till was deposited from the south.

The results of McCall and Goodlet are a valuable contribution to the background of the present study and not only because their paper is one of the few directly concerned with Midlothian. Indicator erratics studied in large numbers offer a much more precise method of determining direction of ice movement than does the simple division into suites performed by Anderson and the present writer. Nevertheless, as Mykura points out (Mitchell and Mykura, 1962, p.112), a really detailed study of the boulder content of these drifts has yet to be carried out. McCall and Goodlet's paper is merely introductory, and limiting in the respect that the divisions and regional variations within the Roslin Till and the basal till are not recognised. It is obviously rash to associate material from different horizons of the basal till and from different localities without extreme caution. Examining the content of the basal till at Black Burn, an area where sections show two tills (see fig. 4.11), McCall and Goodlet remark that "greywackes are common but seem to come mainly from the upper part of the section" (1952, p.406). Also, that "felsites were not found", at Black Burn, "but were collected from the boulder clay in the North Esk at Roslin, and proved all to be referable to the North Black Hill of the Pentlands". Roslin is five miles north of Black Burn, and the same basal till cannot be assumed to occur at each. The absence of the North Black Hill felsite and the presence of greywacke at Black Burn suggests that in the upper part of that section, the source is much more likely to be southerly or southwesterly than westerly, contrary to their general conclusion. The stone count sites 35, 39 and 65 at Black Burn do support McCall and Goodlet's comment on the greywacke distribution; greywacke is much more common on the higher site 39 than in either of the sites in the thick basal till. Examination of the stone counts adds considerable weight to the visual impression, already described, that there are two distinct tills present. This point of detail and other previous remarks on the anomalous proportions of rock suites at some sites will be referred to again following the till fabric analysis results in Chapter VI.

The main points of interest relating to the sites in the Upper Tyne Basin (fig. 4.18; Table 4.2) is their nearness to the Southern Uplands edge, and to a local outcrop of Old Red Sandstone. Ice movements from the southerly quadrant would be expected to produce till with a high content of greywacke and red sandstone. Only one of the five stone counts, from the red till at Keith Water (69) previously described shows this. On the other hand, most of the other stone counts in the Upper Tyne Basin include about 20 per cent greywacke. Two stone counts from adjacent sites that show a contrast are numbers 51 and 52 along Birns Water; the figures from Table 4.2 suggest there are two tills present here.

The stone counts in themselves are not conclusive on any major points. They generally confirm earlier conclusions on directions of ice movement, although indicating that the ideas were rather simplified. But it will be seen that the stone counts considerably enhance the fabric analysis results, and themselves then take on more significance. The two will be shown to be meaningfully related in almost all cases.

Mechanical analysis. The division of tills into their particle size components is a standard method for differentiating and correlating them. As there were known to be different tills present in the Esk Basin, it was considered that particle size might be a useful parameter in identifying them. Twenty-seven samples were analysed mechanically. These comprised twenty samples of till and seven of various other deposits. The till samples included basal till, an intermediate-depth till, and the Roslin Till.

All samples were subjected to the same fine-grain sorting procedure to separate the sand, silt and clay fractions; and the sand fraction was further broken down by sieving in five of the till samples. After each field sample had been thoroughly air dried, the larger aggregates were broken down by crushing the sample gently with a rubber sheathed pestle. Gravel and all larger particles (particles over 2 mm.) were abstracted by dry sieving through a B.S. number 8 sieve. The sample was then coned and quartered.

For fine-grain analysis, it was found empirically that a test-sample of about 50 grams of till and 30-40 grams of other deposits was most suitable. The method used is the hydrometer method as described in D.S.I.R. (1952) pp.39-49 and 60-62. The test sample was dispersed for 25 minutes using 150 ml. of 2% solution of sodium hexametaphosphate (Calgon). To this was added a further 200 ml. of water to prevent splashing from the dispersing cup. The dispersed sample was then transferred to a litre cylinder, topped up and shaken for 1 minute. Hydrometer readings were taken after 30 secs., 45 secs., 1 min. and with increasing intervals to 24 hours. The calculated percentages finer by weight were plotted in the usual way on semi-logarithmic paper and from the plotter curves the total percentages of sand (0.06 to 2.0 mm.), silt (0.002 to 0.06 mm.) and clay (less than 0.002 mm.) were tabulated (Table 4.3) and transferred to a triangular diagram (fig. 4.19A). Duplicate analyses were run on two of the till samples and two of the various other deposits. The good agreement between the duplicate runs indicates that a single analysis was adequate.

LIST OF MAPS AND DIAGRAMS

Figure

TABLE 4.3

MECHANICAL ANALYSIS OF TILL AND OTHER DEPOSITS

Sample	Location	Material	Percentage by weight		
			Sand	Silt	Clay
1	Bilston	Roslin Till	43.7	32.3	24.0
19	New Pentland	" "	49.0	29.5	21.5
20	New Pentland	" "	47.0	31.5	21.5
21	Burghlee	" "	52.5	28.9	18.6
24	Oatslie	" "	44.7	37.0	18.3
32	Glencorse House	Intermediate Till	48.5	26.0	25.5
34	Haveral Wood	Upper Till	46.4	29.1	24.5
35	Black Burn	Intermediate till	46.3	27.0	26.7
36	Liberton Hospital	Upper Till	50.0	28.7	21.3
37	Blackford Hill	Basal till	45.8	30.5	23.7
43	Glencorse Burn	Intermediate till	53.0	25.0	22.0
44	Braidwood Burn	" "	51.8	22.6	25.6
45	River N. Esk, Auchendinny	Basal till	43.0	33.6	23.4
46	Dalmore Mill, Auchendinny	Intermediate till	46.9	26.8	26.3
47	Shiel Burn, Rosedale	" "	47.3	28.5	24.2[1]
48	Dalhousie Burn	Basal till	39.0	32.0	29.0[1]
49	Gilmerton Ridge	Upper till	38.2	31.9	29.9
50	Gilmerton Ridge	Basal till	40.3	32.6	27.1
60	Cuiken Burn	" "	50.0	26.5	23.5
63	Cuiken Burn	Intermediate till	50.7	27.0	22.3

TABLE 4.3 (cont.)

101	Straiton	Kettle filling	30.3	54.2	15.5[1,2]
102	Straiton Moss	" "	19.4	49.8	30.8[1,3]
103	Park Burn	Glacio-lacustrine deposit	8.1	49.4	42.5[3]
104	Easter Burn	Kettle filling	46.0	31.8	22.2[3]
105	Middleton	Colluvium	34.8	46.0	19.2[2]
106	Shiel Burn, Rosedale	"	20.1	51.0	28.9[2]
107	Goodie Water, Lake of Menteith	Estuarine Carse deposit	1.0	47.5	51.5[3]

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1. Percentages are average of duplicate runs.

2. Complete sample contains small number of pebbles up to 4 cm. long.

3. Complete sample contains no particles larger than 2 mm.

In addition to the above procedures, five of the till samples were subjected to a coarse-grain analysis by dry-sieving through a short set of sieves, B.S. numbers 8, 30, 72 and 240. Test samples of about 100 gr. were used, each fraction trapped being pestled and sieved repeatedly until it was thought all concretions had been broken down. Duplicate analyses were run on two of the test samples and showed moderate but not good agreement.

Comparison of the fine-grain and coarse-grain analysis shows that the latter must contain a considerable systematic error. The coarse-grain analysis gave much too low values for the residual proportion of silt and clay. It is concluded that with dry sieving, clay and silt aggregates remained on the 240 sieve as concretions and attached to coarser particles. The results of the coarse-grain analysis were accordingly rejected.

The results of the fine-grain analysis are shown on fig. 4.19A; an enlargement of the centre part of this diagram containing the till percentages is shown as fig. 4.19B. In several investigations by other workers, mechanical analysis has had varying success in showing significant differences in the composition of tills. A distinct difference in grain size was found between the Cary and Valders till of northeastern Wisconsin (Murray, 1953) and between the upper and lower tills along the north shore of Lake Erie in southern Ontario (Dreimanis and Reavely, 1953). On the other hand, Jarnefors (1952) describes two tills from Northern Sweden, well distinct in structure, colour, stone content and size of their large boulders, yet showing by mechanical analysis to be almost identical in grain size. In another example, from central Minnesota, a total of thirty-two analyses of three tills indicated that the tills are texturally similar; it was found impossible to separate them by the mechanical analysis (Schneider, 1961).

From fig. 4.19B it can be seen that the different tills from the Esk Basin have very similar textures. For all the types of till, there are no significant differences in the proportion of sand, but the Roslin Till and related types of till have a slightly greater proportion of silt than the intermediate-depth till. The basal till is represented by only 5 samples, too few for firm conclusions. A further conclusion is that, unlike the tills described by Schneider (1961) there is no textural difference between two tills in stratigraphic contact: for example, the two tills previously described on Gilmerton Ridge (samples 49 and 50) have matching particle size analyses. Similarly the distinctly different superposed tills at Cuiken Burn (samples 60 and 63) have almost identical composition.

The lack of any distinguishing criterion from the mechanical analysis greater than slight differences in silt content is disappointing, particularly as the fines analysed represent the far-travelled component of the ground moraine, with part probably from the Highlands or Southern Uplands. Mechanical analysis of the cobbles, pebbles and gravel fraction might produce significant contrasts; but this coarser material may be presumed to be of more local origin and, considering the variety of bedrock types, any differences could be attributable to more local factors. Other standard laboratory methods, such as determination of pH and carbonate content, would also be expected to reflect local bedrock factors.

Several samples of drift other than till were subjected to fine-grain mechanical analysis. These analyses provide a comparison with the till analyses (fig. 4.19A) and have also helped in their own identification. Six of the samples are silts (as defined on the basis of most systems of nomenclature of sand, silt and clay mixtures), containing 45-55 per cent of silt. Samples 105 and 106 are defined as colluvium, probably aeolian deposits. Two more samples, 101 and 102, although deposited in kettle-holes probably also have an aeolian origin. Samples 103 and 107 are a clayey silt and a silty clay respectively, the latter being estuarine carse material from the upper Forth Basin west of Stirling. This is outside the area of study, but the sample analysis is included for comparison. The final sample, number 104, has percentages of sand, silt and clay typical of till, but the deposit from which the sample was taken contains nothing coarser than sand; it occurs as the infilling of another small kettle surrounded by till and glacio-fluvium.

Washed tills. Part of the till near the surface over the coastal plain of East Lothian and the lower Esk valley has a distinctive washed appearance. This is not confined to till of a particular horizon or texture, but appears to be a modification of all the tills in certain localities. The water-washed appearance was first pointed out to the writer by members of the Soil Survey of Scotland, who are more specifically concerned to locate and explain it as a distinctive soil-forming unit. Washed tills have only recently been recognised, and their origin cannot yet be explained.

The typical basal till of the coastal plain is a tough, dark brown deposit, as already described from Jerusalem (fig. 4.1). The surface layers of this till are lighter in colour due to weathering but remain clayey. Elsewhere the till is more water-modified and the surface layers are more sandy. The difference between the normal (clayey) and the water-modified (sandy) tills is appreciable, and immediately noticeable in the hand. Both can show gleying near the surface and decomposition of larger particles. But the clayey or sandy texture is independent of this. Usually sections show either one or other type of till, but the water-modified layer is thought from limited evidence to occur above normal till. The ground surface where the two types of till occur is usually featureless and so does not help to distinguish them. In East Lothian, later tills are also recognised in the normal and water-modified varieties.

Whether the modification is a glacial or post-glacial effect is not known. Washed till can be either an original deposit under conditions where a moderate amount of water is present, as in an ablation till, or a secondary formation where the fine content has been altered (Flint, 1957; Kirby, 1961b). In the Lothians, the washed till is mainly located on low ground, (J. M. Ragg, pers. comm., 1961), suggesting it is the result of water-logging. However, it covers only a part of the low ground, and has also been found on slopes and hill-tops, suggesting a subglacial depositional environment.

The washed till is sufficiently distinctive to receive its own appellation from the Soil Survey of Scotland. For example, the basal till near Tranent is identified either as Winton-type till, the unmodified variety, or Macmerry-type till, the water-washed type. These give rise to distinctive soils, the Winton and Macmerry Series respectively. Further examples are provided in the local Soil Survey Memoir (in preparation, 1965).

Within the Esk Basin, the most notable example of washed till occurs on the southern outskirts of Dalkeith at Hardengreen. The eastern flank of the high glacio-fluvial spread occupied by Lasswade golf-course (fig.4.5) is covered below about 200 ft. by 6+ feet of a sandy till in which most particles are decomposed. This was seen in temporary trenches between the railway lines in the fields southwest of Hardengreen Farm, and continues down to the upper edge of the River South Esk gorge. It is plausible that here too the washed rotten till indicates water-logging conditions, and so points to the former presence of a body of standing water. No independent evidence in support of this, for example, morphological shoreline evidence, has been found.

Junction between beds of till and glacio-fluvium. In some cases the junction or contact zone between the individual bedded and unbedded deposits is quite precise and definite; in other cases, there is a gradation between the deposits extending over several feet. This fact will already be clear from descriptions of sections, but the topic is considered sufficiently important to warrant some separate comments. It has received little attention in the modern published literature on glacial deposits.

In terms of general glacial regimen, a single ice-sheet glaciation should be indicated by till, as the product of active ice-movement, covered by glacio-fluvium, representing relatively high temperatures and the ablation of the ice-sheet. The pair of deposits represent a unit for the single glaciation. A tripartite depositional unit including at the base glacio-fluvium as proglacial outwash is possible in some cases; but for ice-sheet conditions, the two-member unit is more usual. In the unit of two deposits, the till is everywhere beneath the glacio-fluvium although not necessarily with the same horizontal extent. The running water at the deglaciation stage is controlled extra-glacially by the topography, and sub-glacially by the relief, by structures in the ice, and in certain cases by the subglacial hydrostatic pressure (for example, Gjessing, 1960). If sedimentation of till and glacio-fluvium is continuous, as for example, in a natural depression beneath the ice-sheet, then a very slight temperature rise will produce at first only slight ablation, and till still being deposited from the ice will be progressively washed. The washing and water-sorting will increase with the amount of free water, and a graded succession results, with the higher beds increasingly water-sorted. This hypothesis is equally possible with either the lodgment theory of deposition, which is the long-established majority opinion, or the englacial theory, which suggests that till is developed by the slow melting out of the debris-charged basal zones of glacier ice, an alternative theory of which Carey and Admad (1961) are the most recent proponents.

The reverse argument, that the absence of gradation implies two deposits not ultimately derived from the same glacier-ice, does not hold, as sedimentation may not have been continuous, or the finer glacio-fluvium may have been re-sorted later by greater volume of water. The lack of the upper member of the pair at one site is also not significant in a regional setting.

Further glaciations should ideally produce further units of glacial deposition, each composed of a till overlain by glacio-fluvium. There is much more likelihood of an abrupt break between the units, that is, at the base of a till, than between the members composing the units as, during interglacials, interstadials and oscillations of an ice-front, the pattern of sedimentation will be broken.

The passage upward from glacio-fluvium to a higher till may be marked by some exogenous sign indicating a major break in climatic conditions, perhaps periglacial phenomena, soil formation and vegetation remains in the case of an interglacial or interstadial break. Where such signs are absent, the reverse argument again does not hold, although only a minor break, less than an interstadial, can be assumed. Where the units are thin, it is safer to regard even a minor break as unproven, and consider the beds as indicating slight oscillations in subglacial temperatures during deposition of the load.

A clear description of the gradation upwards between the till and glacio-fluvium members within a single depositional unit, as seen during excavations in central Edinburgh, is given at an early date in Fleming's Lithology of Edinburgh:

> "Towards the top of the bed the (boulder-) clay becomes of a lighter colour, the proportion of sand increases, and distinct traces of horizontal stratifications are readily discernible. ... this transition from stiff clay with innumerable boulders, and of an unstratified appearance, into sandy clay, with small stones or rather gravel, and this again into fine stratified sand, may frequently be observed." (Fleming, 1859, p.58).

At contemporary sections, the details at the junctions between member beds and between depositional units were particularly noted. The section previously described from Black Burn (fig. 4.12) shows two depositional units, internally graded, with a precise ungraded contact between them, which suggests an interstadial break. The section at Red Scar, Costerton, (fig. 4.14) similarly shows two units internally graded with a sharp break between them. At Keith Water, the main section (fig. 4.15) shows one depositional unit internally graded and the lower member of a second unit. The 3-foot bed of red till and the inclusions lie within the lower full unit.

Between thin band tills, the style of junction is thought to be a critical factor in deciding on their origin. At Park Burn (fig. 4.11), the basal till grades into the overlying glacio-fluvium. This fines upward, ending with 1-2 inches of silt which in turn merges into the next till. Even the thinnest beds above this show a slight gradation, proving there is not even a minor break in deposition. ?

The thin bands of till in the East Lothian sand pits at Keith Bridge and Keith Marischal show both sharp and graded junctions with adjacent beds. The lowest beds in each case are graded, suggesting the till is ablation material deposited on the subglacial glacio-fluvium. The half-dozen very thin layers of till that succeed this, each separated by sand or stoneless clay, are not individually graded, but the group taken together represents transitional conditions of deposition. At the top in two sections is further red till at least 3½ feet thick. This succeeds after a clear-cut junction which indicates at least a minor break in deposition. If a greater thickness of the topmost red till could be established, this till could be taken as the lower member of another depositional unit.

In the Esk Basin, the base of the Roslin Till is frequently exposed in contact with glacio-fluvium of a lower depositional unit. The glacio-fluvium is in some areas as much as 50 feet thick, suggesting a time-interval of at least interstadial proportions between the Roslin Till and the next lower till. The nature of the junction is very well exposed; it is usually so precise that a knife-blade can be inserted between the

MAPS AND DIAGRAMS (cont.)

Figure

two beds. This is the case at Haveral Wood (fig. 4.3) and at Bilston. In contrast to the glacio-fluvium at Park Burn, for example, the glacio-fluvium below the Roslin Till shows no increase in fines content as the base of the till is approached. There is no silt layer of a few inches thickness to provide a merger in grain-size between the two. The break in sedimentation suggests that the Roslin Till and the sand beneath are not from one depositional unit.

At Burghlee, although the Roslin Till and underlying sand are precisely separated, there are small lenses of till within the topmost few inches of sand (photo. 7). The lenses are distinct units with sharp boundaries, as though they are inclusions rather than natural concentrations within the sand. It is partly the occurrence of these sand lenses that resulted in the correspondence between Anderson (1941; 1942) and Carruthers (1941; 1942) concerning the origin of the sand and overlying Roslin Till. Anderson drew attention to the till deposit (Anderson, 1940), and subsequently both persons inspected the deposits and interpreted them differently. Carruthers argued that there were lenses of till within the sand, which is what the present writer noticed at Burghlee; Anderson described sandy layers within the till. Sandy lenses do exist in the Roslin Till, which is expectable for a ground moraine partly derived from sand by movement over it; but the till lenses in the sand which occur near the junction are explained by a slight disturbance and reworking of the top inches of sand by the readvancing glacier. The minor inclusions are not equivalent to a grading of the deposits, which would suggest a continuous sand-to-till deposition. Carruthers' opinion of one set of subglacial melt deposits, as set out in his paper on northern glacial drifts, (Carruthers, 1939) is not supported on this evidence.

Mykura describes minor overfolds with thrusts in the top of the sand at Burghlee sand pit, suggesting overriding ice from the south (Mitchell and Mykura, 1962). A similar phenomena was seen in a temporary trench section (open February, 1964) at Straiton. A large boulder had become slightly embedded in the sand and acted as a roche moutonnée (fig. 4.20). Just adjacent to the boulder is a lens of unbedded sand 4 feet long and 1 foot deep. This contains wisps of the overlying Roslin Till, and represents a zone of disturbance behind the boulder resulting from the ice re-advance. Direction of movement could not be judged with any accuracy. Along the remainder of the open trench, there was a sharp break between sand and till with no disturbance.

Glacio-fluvial and glacio-lacustrine deposits. In contrast to the almost complete coverage of till in the Esk and Tyne Basins, glacio-fluvial and glacio-lacustrine deposits cover only about a third of the low ground. The glacio-fluvial deposits are commonly 20-40 feet thick and composed mostly of bedded sands rather than of gravels or of silts and clays. They occur in many different associations, from massive single units with a variety of internal structures and composition to thin layers alternating in a series with till, as already described. The glacio-lacustrine deposits overlap with them in facies and are composed of finer materials.

A clear map showing the distribution of glacial sand and gravel and of lake deposits (sic) is included in Mitchell and Mykura (1962; Plate IV). In the Esk Basin, glacio fluvium occurs as an almost continuous belt from Carlops down the course of the River North Esk to merge with raised beach deposits at Whitecraig; it also continues in a broad belt eastwards from

Penicuik through Carrington and Temple to Borthwick in association with glacial drainage channels on the southern slopes of the Midlothian Basin. A further belt extends close to the Pentlands from Penicuik northeastwards to Liberton. In East Lothian the main belts are along the northern slopes of the Lammermuir Hills and down the Tyne and its tributaries. Glaciofluvium is notably absent from the River South Esk and from the western slopes of Roman Camp Ridge.

The main points of interest in the glacio-fluvium as indicative of the regional deglacial history are its present regional setting and the specific forms represented. Studies of the internal structures and composition of the deposits are only relevant in this context where they help towards identification of the forms. Current classifications of stratified drift (for example, Flint, 1957, Ch.8) incorporate both genetic and morphological yardsticks, and there is such a variety of composition and form that working classifications must continue to be of this style. Hence some investigation of structures and composition is inevitable.

This investigation of stratified drift is a degree less critical than the study of till. Whereas till occurs only as a featureless ground moraine and the studies described in this chapter and Chapter VI are concerned to distinguish possible variation within the ground moraine, the corresponding examination of stratified drift is to produce a genetic label for each form. A comparative study of the stratified deposits remains to be carried out. The specific forms of stratified drift are described in a regional setting in Chapter VII. The present section is confined to comments on internal features in so far as these help to identify the forms more precisely.

Although the glacio-fluvial deposits in the Esk Basin have a variety of forms, the good sections are confined to sand pits, and do not occur in river-banks. Almost all of the sand pits are cut into flattish-topped spreads of sand (Haldane, 1948); the similarity of form is reflected in certain common characteristics of internal structures and composition.

The size range of washed materials is dominated by the sand grade. Although every size from clay to cobbles occurs in bedded form, there is a preponderance of sand. Sand pits are by their very nature not representative of all the bedded deposits, but their location and spread indicates how great is the proportion of sand overall. The bedded deposits may be best seen at Clippens sand pit, currently the deepest pit, and at Melville Mains sand pit, currently the most extensive. At both of these, there is little other than sand present.

The succession of drift at Clippens sand pit is shown in fig. 4.21A. The form of the ground is controlled by the thick bedded deposit; the 4-7 foot cover of Roslin Till has no effect. The bedded material is 35-50 feet thick, mostly thick-bedded sands. Although details vary in different parts of the pit, the southwestern end is representative: the visible succession is 10 feet of sand, 3 feet of silt, 12 feet of sand and finally 12 feet of thin-bedded gravel and sand. It was possible to examine the complete succession down to bedrock for a short period in April 1962 when part of the floor of the pit subsided into an old mine working. The subsidence hole revealed several feet of bedded grey silt below the thick sand (fig. 4.21B; photo 8). The silt grades up into the sand and is not a separate formation. The bottom bed is a skeletal basal till, less than a foot thick and sharply marked off from the grey silt. The till is dark grey but more sandy than is usual with basal tills; the bottom few inches are washed.

The 3½ feet of grey silt consists of two sets (fig. 4.21B; X and Y) identical in lithology, colour, and thickness, as indicated. The upper set is without inclusions, but set Y contains pebbles scattered throughout in considerable numbers and in positions with respect to the bedding suggesting they have been dropped from above. The pebbles are well-rounded and occasionally striated. A collection was made from set Y and from the skeletal basal till. From small samples, the pebbles are seen to be from the same population, with a low proportion of local bedrock (see Table 4.1; New Pentland (29)).

The style of bedding at Clippens becomes coarser upwards from silt to sand and gravel, the coarser-grained beds being generally the more massive. The top of the bedded deposit is truncated by the present ground surface. Bedding is not regularly developed (figs. 4.21C and 4.21D). There is much cross-bedding; fine, current-bedded sand may be abruptly terminated by a thick gravel bed which in turn may speedily merge into sand and silt laminations, all in a way suggesting shallow-water deposition with a braided current system. However, ripple marks, which are generally considered to be formed in water only a few inches deep (Allen, 1963) are not commonly found at Clippens. The bedding is mostly at a very shallow angle. Examples can be found of beds dipping in all directions, but from measurements on two of the more continuous silt horizons, it is judged that the preponderance of dips are to N30°E at a low angle.

The two general characteristics illustrated from Clippens sand pit, that sand is the dominant grain-size and that the beds in thick vertical section coarsen upwards, are true also for the Melville Mains sand pit. In this case the top of the succession is complete and not truncated by later meltwaters or covered by any readvance till. The base of the succession is not exposed, although there is known to be an impermeable layer above bedrock holding up vadose water. There is a continuous section of 1500 feet aligned N70°E and at the western end a further 400 feet at right angles to this (photos. 9 and 10). The average exposed height of the deposit is 40 feet at the western end and 25 feet at the eastern end.

Although there is tremendous variety in the grain size and structure at Melville Mains, sand is the normal constituent, with thin-bedded sand dominating. Thick-bedded sand occurs near the base of the face in the central section (photo. 11); gravel occurs in pockets throughout and also as a thin capping overall (photos. 9 and 11). At the western end, the bedding shows broad shallow festoon cross-bedding (Pettijohn, 1957, p.170), as seen in transverse-section (western face) and as seen in side-section (northern face). As the sand thins eastwards on the long northern face, the confused cross-bedding develops into a number of continuous sand beds dipping consistently northeast at angles of up to 20° (photo. 12). The gravel capping 1-3 feet thick is bedded parallel to the surface and so truncates the bedding in the sand beneath.

There are a number of other sand pit exposures in the Esk Basin of similar appearance to the upper part of Clippens sand pit, being predominantly of sand, showing mild near-horizontal cross-bedding, occasionally with ripple marks. The sand is generally devoid of striking internal structural features, and at no sections other than the two already described is it possible to say that the deposits become coarser upwards. In a number of cases, as at Haveral Wood and Oatslie, the existing surface truncates the bedding in a way that proves the feature has been dissected.

Bedding structure in sedimentary deposits is clearly related to the velocity of the water currents involved. The presence of delicate laminations, for example, points to quiet-water conditions such as could exist in extensive or deep glacier-dammed lakes, while weak cross-bedding is indicative of fluvial deposition under mildly turbulent conditions. Also, the amount of cross-bedding is determined by the regularity and persistence of the current in one direction. Cases with much cross-bedding suggest braided outwash, with the bed load at the limit of the carrying capacity of the stream for the grain size present.

Both glacio-lacustrine and outwash deposits are characterised by cross-bedding and inclined bedding, although the stratification of deposits in marginal lakes may be more irregular due to the proximity of an unstable ice-margin (Okko, 1955). Ideally, glacio-lacustrine deposits also become coarser upwards, and show a deltaic arrangement of bedding.

In Midlothian, the main stratified drift both of the Penicuik-Liberton belt and along the River North Esk, was deposited under conditions of moderate current velocity, either subaerially or in shallow water. In sections along the Esk, the mild cross-bedding suggests braided stream patterns and a valley-train form of outwash. At some of the sites away from the river, the increasing coarseness of sediment towards the top, characteristic of marginal lakes, suggests deposition in shallow water. There is less physical restriction at these sites than along the Esk

Valley, so a more spatulate form of outwash or lake deposit is possible.

The material at Melville Mains is that of a glacio-fluvial outwash delta, strictly, a glacio-lacustrine deposit. The main mass of thin-bedded sand represents the foreset beds with large-scale cross-bedding, and the coarser top layer of gravel represents the topset beds. Features with sections very similar to that at Melville Mains are illustrated by Flint (1957, p.143) and Okko (1962, p.72). The ground surface at Melville Mains slopes to the northeast at the rate of 1 in 105. This surface slope is rather higher than average for outwash deltas in the Esk system (see Chapter VIII). It may be compared with 1 in about 180 (5½ m./km.) for the slope of a larger glacial outwash plain measured by Sissons (1963b), and with very much gentler slopes of tilted raised beach shorelines.

The rhythmic grey silt at the base of the stratified drift at Clippens is only exceptionally exposed. This deposit is considered glacio-lacustrine, with deeper water than in other cases, the pebbles in the lower silt being ice-rafted. As the lake filled, the sediment becomes more typical of the coarser glacio-fluvial deltaic sediments.

Rhythmites occur also within the gorge at the River North Esk at New Saughton Hall. As fig. 4.22 illustrates, there are eighteen couplets in a height of 15 feet. The set occurs above an estimated 20 feet of basal till, the junction being concealed. The top of the succession is interrupted by river alluvium forming a river terrace (terrace 193) on the side of the gorge. The rhythmites are very coarse and variable in character by normal standards. Each couplet consists of a unit of silt or fine sand coloured grey, and a unit of fine or medium sand coloured rusty brown.

There is no regularity in the thickness of the couplets. The bottom couplet exposed is several feet thick, while those in the middle of the succession are commonly 9-12 inches thick (photo. 13). The couplets XI to XIV (photo. 14) are all thin and exhibit considerable involutions, often the sand layer being extremely contorted between layers of silt that have been just buckled gently. The topmost couplets are also thin and poorly preserved.

This set of rhythmites is thought to have been produced in the normal way as the product of glacial meltwaters entering a pro-glacial lake. There is no direct evidence that the eighteen units represent annual layers, although this verdict would be acceptable. The involutions in the upper couplets indicate either differential compaction of the sediments; or frozen ground conditions, possibly the freezing of a shallow lake through its base with hydrostatic differences in the different-sized sediments.

At other sections of stratified drift in the Esk and Tyne Basins, the structure and composition of the bedded sands indicate fluvial deposition with moderately turbulent conditions but whether this deposition is subaerial or in shallow-water is not clear from internal evidence alone. Subglacial, ice-contact stratified drift may be distinguished from outwash by its greater heterogeneity as well as its deformed bedding. The only example showing marked ice-contact deformation is at the southeastern end of Burghlee sand pit where the twenty feet exposed sand, normally horizontally bedded, is replaced by slumped sand and gravel bands in thin-bedded alternation. Ice-contact deformation of the bedding has to be distinguished in this district of Scotland from recent disturbance due to mining subsidence. At the Haveral Wood sand pit, settlements of over two feet along a zone through the pit has produced numerous small faults and slumps in the sand.

Considering all the stratified drift in the Esk Basin, there is no obvious variation in grain size between different districts or along the distinct glacio-fluvial belts. On the contrary, most locations exhibit a range of grain size. Thus it is not possible to infer directly that one set of meltwaters deposited the sediment of an entire system, the sediment becoming finer away from the source. In the vicinity of Melville Mains sand pit however, there is a local variation, the material becoming finer to the northeast. The Wadingburn sand pit immediately to the west contains more gravel and cobbles than sand, and is clearly part of the same glacio-fluvial deposit, with meltwater from the west or southwest. This gradation in grain size does not continue over a wide area: the Haveral Wood sand pit 500 yards further southwest again beyond the gravel and cobbles consists entirely of sand. Any horizontal grain-size gradation of stratified drift appears to occur in local spreads rather than over a district.

In terms of the significant dips within the stratified drift, there is more of a common design. In spite of the large range of dip direction in the cross-bedding, the larger beds dip to the north, as for example as seen at Kirkhill (fig. 4.13). On aggregate, there is a regionally consistent pattern of north-dipping beds, indicating the glacial meltwater flowed from the south.

Stone counts were made from glacio-fluvial deposits at three sites, at Melville Mains and Clippens sand pits and in the esker of Cameron Wood at Old Pentland. The sites are indicated in fig. 4.18 and the results in