TRANSACTIONS.

I.—The Glaciation of East Lothian South of the Garleton Hills.* By Professor P. F. Kendall and Mr E. B. Bailey, B.A., of H.M. Geological Survey. *Communicated by* Dr JOHN HORNE, F.R.S. (With Four Plates, Map, and Seven Text Figures.)

(Read May 20, 1907. MS. received August 23, 1907. Issued separately January 10, 1908.)

The glaciation of East Lothian has already been dealt with separately by Professor JOHN YOUNG, who, when attached to the Geological Survey, treated this subject in the memoir of the district published in 1866. His account of the phenomena, striæ; boulder clay, dry valleys, etc., is concise and clear, but he does not enter deeply into a discussion of causes. A guarded reference to submersion to account for the presence of an erratic boulder of carboniferous sandstone at a height of 1500 feet above sea-level shows in fact that he had not arrived at a full conception of the possibilities involved in glaciation by land ice. He was, however, quite definite in ascribing many important erosion effects in the district to the work of an "ice-stream." In this as in most other points he had been forstalled by Sir ARCHIBALD GEIKIE,† who had already described the immediately adjoining area to the south.

Since Dr YOUNG's time no one has made a special study of the district. In common with the rest of Scotland, our knowledge has of course advanced with increased experience won in more extended fields. The writings especially of Sir ARCHIBALD and Professor JAMES GEIKIE have fully shown the connection of the local phenomena of the county with the wider problems involved in the glaciation of the country considered as a whole. With regard to the results produced by the flow of land ice across the district we find but little that is new to add.

It is different, however, in respect to the phenomena of the retreat of the ice sheet. These have never been referred to in other than indefinite terms so far as this particular region is concerned. The special feature of our communication is therefore the treatment of this part of the subject.‡ As the historical development of research in this direction has, however, been recently discussed in some detail,§ we have not thought it necessary to re-state it here.

We must further express our indebtedness to various members of the Geological

* Published, so far as Mr BAILEY's observations are concerned, by permission of the Director of H.M. Geological Survey.

† *Geology of East Berwickshire*, 1863.

‡ J. GEIKIE has already given illustrations of the main phenomena which accompany the retreat of an ice-sheet from a hilly country. *Great Ice Age*, 1894, ch. xiv.

§ P. F. KENDALL, *A.G.J.S.*, 1902, p. 471, "A System of Glacier Lakes in the Cleveland Hills."

TRANS. ROY. SOC. EDIN., VOL. XLVI. PART I. (NO. 1).

Survey staff who have mapped or revised the drift of this area. Foremost among these is Dr PEACH, whose earliest experience of survey work was gained in East Lothian under Dr YOUNG. He probably was the first to realise that the Lammermuirs had been completely overwhelmed by land ice, and as he worked for several years, at a later date, in the area lying south of the watershed, he was able to establish the point beyond any doubt. His experience in this and other matters has always been at our disposal. The same may be said of Messrs CLOUGH, HINXMAN, MUFF, and CRAMPTON, who have been engaged in the revision of the area for the Geological Survey, and in close connection with whom one of ourselves has been acting. We would further observe that Mr BARROW has simultaneously been employed in investigating the allied problems of the Garleton Hills, which are situated in East Lothian, but which constitute a naturally

FIG. 1.

self-contained area. His description will appear in the new edition of the East Lothian memoir. Our best thanks are also due to Mr LUNN of the Geological Survey, whose excellent photographs supply the illustrations chosen for this paper. And lastly we would like to record our belief that had it not been for the kindly interest and support continually given to our work by Dr HORNE, it is doubtful whether the paper would ever have been written at all.

THE MAXIMUM GLACIATION OF EAST LoTHIAN.

The glacial history of East Lothian is one of considerable complication. Our evidence clearly points to a period of maximum glaciation when the hills were completely overridden by a foreign ice sheet; then came a time when the latter began to fail in strength and was unable, even with bulging upper surface, to force a passage for itself, but had rather to accept the high plateau region as an independent centre of

dispersion. Later still the great ice sheet became further enfeebled and shrank away back from the hills, merely leaving small local glaciers to linger on for a while in the deeper recesses of the upland valleys.

No doubt similar complications attended the growth of the great ice sheet, so that one naturally feels some uncertainty in deciding the proper place in the glacial history of the county of any particular event whose record has been preserved. Nevertheless, the tale of the maximum stage of glaciation is not hard to decipher in its broad outlines, and the approximate direction followed by the bottom currents of the great ice sheet will be found indicated on the accompanying sketch map. We would, however, recommend the reader to consult Sir ARCHIBALD GEIKIE's* glaci- ation map of Scotland,

FIG. 2.

1. Coal-bearing divisions.	7. Old Red conglomerates.
2. Lower limestone group.	8. Old Red andesites, rhyolites, etc.
3. Calciferous sandstone series.	9. Old Red granites, felsites, etc.
4. Carboniferous volcanic rocks.	10. Silurian and ordovician.
5. Carboniferous dolerites.	11. Transported masses of limestone in
neighbourhood of Kidlaw and Fala.
6. Old Red Sandstones.	

since to understand the progress of events in East Lothian he must have a grasp of the main features of the glaciation of the whole central valley. Thus in the west the main ice cap of the Southern Uplands proved sufficiently powerful to ward off invasion from the Highlands, and the two great ice-streams meeting at the base of the southern hills in the plain of Ayrshire turned north-east and south-west to escape either way along the central valley. But the Lammermuirs are low, and are bordered to the east by the plain of the floor of the North Sea, so that before reaching them the Highland stream was able to push its southern companion back upon itself and to creep up obliquely on

* *Scenery of Scotland*, 1901, pl. iv.

to the Silurian Uplands. Once upon the top of the watershed the current turned for a while into a direction markedly south of east; and the same deflection is noticed where the congestion in the basin of the North Sea began to make itself felt upon the great ice stream issuing from the Firth of Forth; for the latter had to pass out in both directions, and thus the current crossing the eastern Lammermuirs bent round into approximate parallelism with the coast towards St Abb's Head. The record of the march of the ice sheet is chiefly preserved in the boulder clay, which it deposited as it went. Our own observations in this connection relate for the most part to the northern front of the Lammermuir Hills and to the district intervening between them and the Firth of Forth. They have enabled us in the first place to confirm Prof. GEIKIE's * record of Highland erratics, since the latter occur throughout the whole area and may be recognised in good numbers even as far to the south-west as Tynehead. Boulders of carboniferous rocks have been carried in company with those from the Highlands far out on the Silurian Uplands, and, according to Dr PEACH, over the other side into the Merse of Berwickshire; while to the north, along the Old Red and Calciferous Sandstone tracts lying at the foot of the hills, the whole country is swathed in boulder clay abounding with limestone, coal, and andesite fragments, all indicating a carry from the west in a direction oblique to the course of the Lammermuirs. East of the outcrop of the Garleton volcanic zone the same tale is told by the appearance of trachytes and basalts among the boulders of the drift; for instance, fragments of the former have been found in boulder clay as far to the south-west as White Castle, where the road leads across the hills from Garvald. Only two more instances need be cited, and these are of special importance, as they serve to indicate in an unusually emphatic manner the direction of the ice flow for the districts which they represent. At Port Seton and along the coast to the east certain conspicuous boulders of conglomerate occur which resemble the Craigmillar conglomerates of the Edinburgh district, and Mr CLOUGH has met with a train of similar erratics along the coast for a mile east of Dunbar. This would indicate an average direction of transport of E. 5° N. across the intervening district. The second example illustrates the deflection of the course of the ice sheet when once it had crossed the watershed. Dr PEACH has traced the carry of the granite boulder derived from the Priestlaw mass, and found that they indicate an ice flow in a south-easterly direction towards Longformacus.

The evidence just considered may usefully be supplemented by reference to the erosion effects produced by the great ice sheet. Striæ have been but poorly preserved, and all records come from the low-lying districts.† They may be tabulated as follows, from west to east:—

Kippie Law (half a mile N. of Traprain Law), E.

Traprain Law (steep south-western face), E. 10° S.

* *Great Ice Age*, 1894, p. 195.

† Striæ in the Garleton Hill area are abundantly preserved, and are well known. Their direction is entirely in accord with that indicated in the sketch map.

Dunbar, E. 5° S. (Mr MUFF).

Catcraig Quarry (two miles E. of Dunbar), E. 15° S. (Professor YOUNG).

Shore close to Catcraig, E. and E. 10° N. (Mr CLOUGH).

A striated pavement, Thorntonloch (5 miles S.E. of Dunbar), E. 10° S. (Professor YOUNG).

St Abb's Head, E., 25° S. (Professor YOUNG).

Professor YOUNG* further noticed that the minor inequalities of the low ground have a tendency to run in lines almost parallel with one another, a fact which is well illustrated in a shaded copy of an Ordnance one-inch map (Sheet 33). He attributed this to the result of direct sub-glacial erosion, and noticed that if a line be taken joining Lothian Edge to Tynemouth (see general map), it separates the lowlands into two districts. West of the line the grooving runs E.N.E. or E. by N., but on its seaward side the features "become much more easterly and even a few degrees south of east." This type of ice modelling is not so widely developed in East Lothian as in many parts of Scotland,† but it is well shown in the district south and east of Haddington.

The direction of ice flow indicated by the modelling agrees approximately with that of the few striæ observed, and thus the erosion effects as a whole, where recognisable, serve as a useful check upon the evidence afforded by the deposits. They clearly demonstrate that in the low-lying parts of the county the ice sheet followed roughly the trend of the central valley, until, debouching upon the North Sea plain, it was forced to take a somewhat southerly course, skirting the termination of the Southern Uplands.

The district lying south and east of Haddington affords a good illustration of the special characteristics of an ice-dressed surface upon a large scale. The topography induced is essentially that of a drumlin country. Long low mounds or ridges run parallel with one another, merely separated by shallow broad-bottomed grooves or valleys. If any particular ridge be followed it will presently be observed to sink slowly and gradually until the grooves on either side meet about its termination; others have, however, by this time arisen situated en échelon to their failing companion, and so the group persists though its individual members prove inconstant. The distinction between these mounds and true drumlins depends upon the fact that they have been fashioned in solid rock and are merely coated over with boulder clay, very thin along the crests of the ridges, instead of being entirely formed of the latter. Wherever an isolated resistant mass occurs, this type of sculpture naturally becomes accentuated, and Traprain Law furnishes a familiar example of "crag and tail." By taking note of such where they occur, it becomes evident that the whole grooving must be referred to an ice sheet moving towards the E.N.E. In following this course the current flowed from the area occupied by sedimentary rocks south of Haddington over the igneous rocks occurring south of Traprain Law. The phenomena marking this passage from the soft rocks to

* *The Geology of East Lothian*, 1866, pp. 63, 64.

† Cf. Sir A. GEIKIE, *Geology of East Berwickshire*, 1863, p. 52, and J. GOODCHILD, *Glacialists' Magazine*, vol. iv. pt. 1, 1896, p. 1.

the hard are very beautiful. The grooves persist in their original direction, but gradually rise to surmount the obstruction, and upon the other side sink as gradually to their former level. A small patch of alluvium near Morham Church serves to mark the original presence of a shallow tarn excavated along one of these grooves just east of where the change of slope commences.

Certain of the grooves south of Haddington have been employed as temporary watercourses at a later period, but the work of the streams which thus made use of them was chiefly the deposition of alluvium upon the broad bottoms of the hollows.

Elsewhere the sculpturing is not so well developed as in the district just described, but round the termination of the hills it serves to indicate the deflection of the ice current which has already been referred to.

Let us now return from the consideration of the direct effects of sub-glacial erosion to the correlative phenomenon of deposition. The district furnishes three very fine examples of large transported masses of limestone. The most conspicuous is that of Kidlaw, a mass one-third of a mile long and a quarter broad and well exposed in extensive disused quarries. The view that this great mass might really be a boulder was first suggested some years ago in conversation by Mr HOWELL, and the evidence for this interpretation is threefold.

1. The few exposures in the immediate neighbourhood and general considerations as to the geological structure of the district, point to the conclusion that the limestone is resting on sediments of Upper Old Red or early Calciferous Sandstone age, with associated igneous rocks. The limestone, moreover, has been recognised by Dr CRAMPTON as belonging to the middle and not the bottom of the Lower Limestone group of the Scotch Carboniferous sequence. Under these circumstances one has to account for the apparent absence of a great thickness of strata, all included in a conformable sequence and well developed in the near neighbourhood.

2. The whole mass is in a completely shattered state. Mr HOWELL* in his original description attributed this feature to the proximity of the Lammermuirs fault. But the longest axis of the "outlier" is directed away from the fault, and it would be very difficult, therefore, to maintain this interpretation; moreover, since Mr HOWELL mapped the ground, a large basalt quarry has been opened in the immediate vicinity and equally close to the fault. The basalt sill is there entirely unshattered, though the period of its intrusion certainly greatly antedated the faulting.

3. There is a great abundance of limestone blocks, both large and small, in the boulder clay of the adjoining areas, whether it rests upon Silurian, Old Red, or Carboniferous strata.

The second example is recorded by Dr CRAMPTON at Marl Law quarry, a mile N.W. of Fala. It consists of a contorted mass of limestone and marl, lying not very far from the natural outcrop of the group. It may perhaps not be without significance that the Kidlaw and Marl Law masses lie along the same line of glacial transport.

* *Geology of East Lothian*, 1866, p. 55.

The third example occurs at Woodcotte Park, a mile to the east of Fala. The limestone forms two little knolls known as the Little Hill and Meikle Hill respectively. Here, as at Kidlaw, the field evidence strongly suggests that the limestone is resting on the Upper Old Red Sandstone, only in this case upon the south side of the Lammermuir fault. The exposure was known some sixty years ago to CHARLES MACLAREN* and DAVID MILNE HUME,† who regarded it as belonging to a natural outcrop. MACLAREN remarks, however, that he saw none in place. The evidence for believing that these knolls consist of transported limestone is therefore identical with that put forward in respect to the Kidlaw example, and the probability of the interpretation is heightened in that it is not invoked merely to explain a single occurrence. It is noteworthy that Mr HOWELL in his mapping long ago did not treat these smaller masses as being in place, although one of them was formerly quarried and burnt for lime.

The carboniferous limestone seems in certain other places to figure more largely in the drift than might at first be expected; this suggests that in pre-glacial times the more important beds of limestone may have given rise to conspicuous little escarpments with long, exposed dip slopes, and that these furnished an abundant supply of blocks during their degradation by the ice sheet, while at the same time they may have afforded favourable opportunity for the transport of big masses.

THE RETREAT OF THE ICE SHEET.

We have now examined some of the results of the action of the ice sheet during its maximum development, but perhaps even more interesting still are the circumstances of its retreat. When gradually it was forced to give place to other agents of erosion, it yet was able for a while to impose special conditions upon their operation. Thus step by step the enveloping ice shrank back to leave the Lammermuirs standing like a stone in the midst of melting snows; and stage by stage the memorials of this retreat were furnished by the obstructed drainage of the hill country, joined by the waters issuing from the glacier itself: There are whole suites of channels to bear witness to the former presence of swollen torrents, linking together the long chains of lakes, which then rested in temporary support between the steep ice margin and the slopes of the hill country to the south; and there are also the deposits which accumulated in these lakes and at many an intervening point where the connecting streams had not as yet cut gorges for themselves.

One can even recognise by a careful investigation of the evidence that there were times when the ice sheet renewed its vigour. One can trace its oscillatory re-advances: here it spreads its boulder clay over the floor of a lake where previously sand and silt

* *Sketch of the Geology of Fife and the Lothians*, 1839, p. 74.

† *Coalfields of the Lothians*, 1839, p. 103.

had been collecting, and these re-advancing across the path of a glacial stream it drives the occupant back again into some deserted channel further up the side of the hills.

A point of special interest is the fact that all these effects are restricted below a more or less clearly defined upper limit (see fig. 1). Marginal streams and temporary lakes have scarcely left a trace of their former presence in the higher portions of the hills. Yet it can be demonstrated that this does not mark the upper limit reached by an invading ice sheet, but rather the level at which the retreating ice parted company with its lineal descendants, the little glaciers of its high-level valleys.

Moreover, the district has furnished fresh evidence regarding the relations which locally prevailed between land, ice, and water, when the ice sheet had already withdrawn into the low ground; and, probably what will attract more general interest, it has supplied a number of very beautiful instances of a special type of stream capture, which has greatly influenced the plan of the glacial drainage system. Without entering into detail at present, it is sufficient to say in this connection that there are many cases where a tributary stream has thrown out a cone or delta into a deserted glacial drainage channel and has thus succeeded in establishing a watershed within the latter.*

In order to illustrate the various aspects of the subject alluded to above, we will arrange the evidence under the following heads:—

- I. Phenomena illustrating the general conditions which attended the retreat of the great ice sheet.
- II. Phenomena illustrating the oscillatory nature of the retreat.
- III. The upper limit of these marginal phenomena set by the confluence of the local glaciers with the great ice sheet.
- IV. The influence of corroms † and bridge-deltas in modifying the glacial drainage system.
- V. Evidence regarding the level of the sea at the time of the retreat of the ice sheet.

I. ILLUSTRATIONS OF THE PHENOMENA ATTENDING THE RETREAT OF THE GREAT ICE SHEET.

East Lothian illustrates extremely well two distinct though cognate aspects of the phenomena which attended the retreat of the great ice sheet. One notices everywhere records of the operation of water under special conditions of restraint; in one place the manifestation may take the form of some monumental piece of erosion, in another of deposit, but everywhere the phenomena point to the action of water, and of water impounded in front of the retreating ice sheet. One of the consequences of this

* Dr CRAMPTON independently arrived at precisely this interpretation in accounting for the partial reversal of the drainage in the Borthwick dry valley, to which further reference will be made in the sequel.

† Corrom (cothrom) is a Gaelic word used in place names in the Ardgour district of Argyllshire, to denote a delta-watershed. Its literal meaning is a "balance," and it is intended to illustrate that a stream issuing upon such a cone has the chance of flowing either the one way or the other.

condition of affairs that has continued to this day is the anomalous drainage system possessed by East Lothian and the adjoining coastal district of Berwickshire, the existence of which has long been recognised. In fact, no better introduction to our whole subject can be desired than the descriptions given, now more than forty years ago, by Sir ARCHIBALD GEIKIE* and Professor J. YOUNG.† Besides giving a general account of the anomalous drainage system, both these authors have singled out for special notice examples which seem abnormal even in the strange company of their fellows, and which, as we shall attempt to show later, owe their special peculiarities to the processes of corrom formation. Sir Archibald's account deals with the Berwickshire area, and runs as follows:—

“Besides the ravines . . . which are plainly the work of rivulets, there are certain other narrow glens, defiles, or channels (for they vary not a little in size) in which there are either no streams, or runnels so tiny and local that they cannot be imagined capable by their own unassisted operations of hollowing out such marked excavations as those in which they now flow. On the south side of St Helen's Church, for example, there is a deep winding ravine, quite dry, running along the side of the declivity which here descends gently to the edge of the sea cliff. It is open at both its eastern and western extremity, thus running across the neck of a promontory. With the present configuration of the land no stream could ever have flowed along this ravine. Other, but less marked, examples may be seen along the sea front eastwards towards St Abb's Head. Along with these features ought probably to be classed those valleys which go right across the watershed in different parts of this district. Reference has already been made to the valley traversed by the North British Railway‡ as affording a good illustration.” He then proceeds to give a description of the remarkable course followed by Edmonds Dean Burn, which enters the railway pass “within a few yards of the flat watershed,” the latter being one of the corroms to which special attention will be directed later; and he concludes his account with the suggestion that some of the peculiarities of this drainage system may be due to the modifying influence of direct glacial erosion.

Professor YOUNG, however, in his description of the East Lothian examples, carefully refrains from any expression of opinion as to the mode of origin of the valleys. Having described the glacial grooving, he proceeds:—“In connection with these glacial hollows fall to be considered certain valleys near the base of the hills, which seem to belong to a system different from that of the present day. The flat green valley§ between Deuchrie Dod and Rammer Woods is bounded by steep declivities, covered with low brushwood.” After describing this abandoned waterway, the finest in the district, he passes on to the Presmennan Loch channel, a little to the north, and then draws special attention to the peculiarities of the Thurston and Aikengall drainage systems, peculiarities which we now regard as a sequel to corrom formation. Returning

* *The Geology of East Berwickshire*, 1863, pp. 51, 52.

† *The Geology of East Lothian*, 1866, pp. 63, 64.

‡ Between Cockburnspath and Grant's House stations, east of Dunbar.

§ Pl. I. fig. 1.

to the general aspects of the case, he continues: "In all these cases the course of the dry valleys is the same, north-eastwards, and is, therefore, at right angles to the present stream courses. It is difficult to explain their formation by means of the small brooks which flow in their neighbourhood, and their form is not that which would result from glacial erosion. There are many such valleys, some of which are mentioned in the Berwickshire memoir; the same explanation does not, however, remove the difficulties in each case; their solution must, therefore, wait the results of more extended inquiry."

When we add that many of the most typical examples are excavated entirely in drift deposits, it becomes evident that the anomalies referred to cannot be regarded as vestigial inheritances from a pre-glacial drainage system, nor can they be accounted for as the consequence of a selective erosion acting along lines of geological weakness. From what has already been stated the reader will have gathered that we intend to apply the same explanation here as was developed by one of us* in order to account for similar peculiarities in the Cleveland district of Yorkshire.

Sir ARCHIBALD GEIKIE'S remark with reference to the channel on the south side of St Helen's Church might be repeated a score of times. "With the present configuration of the land no stream could ever have flowed along this ravine." In the particular case he cites, it might perhaps be suggested that the valley has been cut back to by recent marine erosion, but such an explanation carries no weight in view of the numerous inland examples. The inadequacy of "the present configuration of the land" is nowhere better illustrated than in certain cases where stream gorges have been cut into the uniform slope of a hill side, following instead of crossing the contour lines. The Pressmennan Loch channel furnishes an imposing example. During the initiation of this gorge it is necessary to suppose that the ice front itself supplied the northern containing wall of the stream, until the latter had sunk its channel into the solid rock.

Almost equally impressive is the entrance to the Chesters Quarry ravine, a mile north of Garvald. It seems at first sight indeed to have been fashioned in sheer contravention to the ordinary laws of Nature, for it originates on an open plane, and straightway leads across the imposing spur of Whitelaw Hill. But once in imagination replace the ice sheet to the north and the difficulty vanishes. A lake forms behind the rocky ridge, and its escaping waters are forced to take the route which at the present time seems so unnatural.

These are merely examples chosen well-nigh at random from a host. The Chesters Quarry defile may also be noticed here as a representative "dry valley"; for not only was it cut entirely by glacially diverted waters, but being so cut it has in later times failed to retain any stream of its own. Naturally, however, a great number of glacial drainage channels are still employed as watercourses; there is in such cases a very marked tendency leading to the formation of corroms and the consequent establishment of short cuts, so that the inadequacy of "the present configuration of the land"

* P. F. KENDALL, "Glacier-lakes in the Cleveland Hills," *Q.J.G.S.*, 1902.

to account for the origin of the anomalous drainage system becomes all the more obvious in that the latter is so conspicuously unstable.

We shall now pass on to the discussion of the modifications other than corrom formation which may be attributed to the streams which at present occupy glacial drainage channels; and as a preliminary step we may allude to a peculiarity of the original glacial channels which has proved itself of great importance in this connection. They have as a rule been cut to a very gentle gradient, and an example occurs, between Kidlaw and Gifford, which one might more fitly describe as the dry valley of a sinuous canal rather than that of a stream. The feature no doubt must be accounted for by the fact that at certain intervals these channels were called upon to conduct away large masses of water which were able to maintain a current even after they had degraded their beds to the local base level. Already several of these valleys have been dammed to form reservoirs or ornamental lakes, and the number is always on the increase; a low dam serves to impound a considerable body of water owing to the extremely gradual fall in the valley bottom; and in fact at Pressmennan* it has been found necessary to place a dam at the head as well as at the foot of the lake. Small natural tarns and marshes are also frequent along the course of the streamless valleys impounded behind screes or deltaic cones.

The glacial drainage channels still occupied by streams can, as a rule, be readily recognised even upon the map, since they form an integral part of the anomalous drainage system of the county. The gorge in which Spott Burn lies, and which proved so terrible an obstacle to the Scots in their attack upon Cromwell, furnishes an excellent illustration within easy walking distance of Dunbar. The burn itself is of very considerable volume, and as it winds along the broad bottom of the valley it may be seen in many places cutting into the steep bluffs on either side. Here at first sight one might reasonably expect to find evidence of well-marked deepening of the channel since glacial times. But the actual phenomena of the case emphatically negative this suggestion, while they enable us to recognise the modification for which the present stream has been responsible. A little to the west of Spott the valley, as we follow it up-stream, bifurcates,† or rather it is joined from the south by another valley of identical type. The remarkable feature is that the direct continuation westwards of the Spott valley is entirely streamless,‡ for the whole volume of water is supplied by the valley entering from the south. Examination of the dry valley proves that it owes its streamless condition entirely to natural causes, and it may confidently be regarded as an overflow channel which has been deserted ever since the final retreat of the ice front from this neighbourhood. It therefore furnishes a datum from which to reckon the greatest possible vertical erosion accomplished by the Spott Burn in post-glacial times. The dry valley enters flush with the bottom of the stream-containing valley, or at most

* The same is being performed for Lammer Loch now that the latter is being extended to form a reservoir.

† Pl. II, fig. 1.

‡ Pl. I, fig. 2.

the difference between the two does not amount to more than four feet, showing clearly that the post-glacial vertical erosion has, in this case, been quite trivial. Standing below the junction of the two confluent valleys we obtain a good view up both, and are able to appreciate at once their similarities and their contrasts. They are both gorges bounded by steep walls; but while the deserted channel has lost some of its original abruptness of outline, owing to the collection of rain wash, it evidently retains a feature which in the case of its neighbour has been more or less completely obscured by the action of the stream. For at every convexity in the course of the dry valley the outer wall is more steeply cut than the inner, showing that the valley was excavated by a stream accurately proportioned to the channel it was cutting for itself,* and of quite a different order of magnitude to the Spott Burn.

The rôle played by the Spott Burn during post-glacial times may now be readily appreciated. Since ever its volume has become so greatly reduced it has wound in small meanders along the valley bottom, cutting now into the one side, now into the other. In this manner it continually supplies itself with as much material as it can transport, and thus as the meanders work gradually down stream, the valley is widened but nowhere materially deepened.

Two or three equally striking examples occur in the neighbourhood of Garvald, but it is important now to point out that some of the East Lothian streams left in occupancy of glacial drainage channels *have* proved themselves capable of accomplishing a notable amount of vertical erosion, and to recognise that in such cases the resultant changes can readily be distinguished. The Braidwood Burn,† a little south of Innerwick, is an excellent case in point. It is a powerful stream, and has cut for itself a pronounced gorge, but the result is far more accurately described as a dissection of the floor of the old valley, rather than a deepening of the same. For the work of the recent stream, with its greatly diminished volume, has been to cut a gorge that winds to and fro along the old bottom, the latter being in large measure still preserved intact.

It is worth while before leaving the subject of these channels to take note of the enormous volume of water which they must at times have been called upon to conduct away. They served to carry off the drainage, not only of the Lammermuirs, but also of the Moorfoots, and in fact of the whole of the Mid Lothian basin, except in so far as leakage was permitted here and there through the fissured margin of the ice sheet. During the earlier stages of retreat this western drainage sometimes found a short cut across the watershed by the pass between the Moorfoots and Lammermuirs, which has been taken advantage of in our own days for the railway leading south to Galashiels. But the summit level here is 884 feet, so that for a long period this short cut was not available, and the Mid Lothian drainage had perforce to pass right across East Lothian and part of Berwickshire to reach the sea. Several routes were successively employed

* This is a general feature of dry valleys. See *Glacier Lakes in the Cleveland Hills*, p. 483. The type example for East Lothian is furnished by the Danskin Loch channel, two miles east of Gifford.

† Pl. II. fig. 2.

by the waters passing from the one natural drainage area to the other, and one of them is of such importance as to deserve special notice. It is the Borthwick dry valley, connecting the course of the Gore and Tyne waters, and crossed by the railway just south of Tynehead station. The changes which have led to its abandonment will be dealt with in a later section, so that we shall only notice here the advantages which it owed long ago to its particular situation. The Mid Lothian and East Lothian basins are separated by a line of undulating hills, constituting the Roman camp ridge which extends northwards approximately at right angles to the general trend of the margin of the retreating ice sheet. The col at the southern extremity of the ridge is not well marked, but once the Borthwick channel had been established at this ill-defined pass and had been excavated to its present depth, the ice sheet had to retreat fully $2\frac{3}{4}$ miles further to the north before disclosing any opening of lower altitude across the ridge. The Borthwick channel was therefore employed for a protracted period during the retreat, and at one time must have served to drain an important lake occupying a portion of the Mid Lothian basin.

We may now pass on for a while to consider briefly the deposits which were produced by the agency of the same constrained waters as cut out the drainage channels just described.

Great masses of sand and gravel encompass the Lammermuir Hills round about, and have long been familiar to Scots geologists. Like other accumulations of their kind, they appeared to the earlier workers as the memorials of great submergences. Professor YOUNG,* however, in his record of the distribution of the deposits, refrains from offering any suggestion as to their mode of origin; and later, Professor GEIKIE,† in several brief references, rightly regards them as of fluvio-glacial origin.

The glacial age of the gravels is beyond question. They overlie and here and there intercalate with the boulder clay. They everywhere contain erratic pebbles, most conspicuous among which are fragments of coal assorted into special layers in accordance with their low specific gravity, and finally their distribution makes it necessary to believe that they formed in proximity to the retreating front of the ice sheet.

Various factors have been concerned in their production, and we may mention the following main sources from which they have derived their material.

1. The hill country, owing to the melting of its local glaciers, the re-opening of its normal lines of drainage, and the rapid waste of the boulder clay covering its steeper slopes, supplied a very large proportion of the whole. Along the northern front of the hills the contrast between the composition of the gravels and that of the boulder clay is rendered very marked by this circumstance. The boulder clay resulted, as we have seen, during a passage of the ice sheet from west to east, often from low ground to high, while the gravels of this series travelled in large measure from south to north, and always from high ground to low. Thus while the boulder clay, carried on to the Silurian Uplands, is charged with the débris of the rocks of the central valley, the

* *Geology of East Lothian*, 1866, p. 63.

† *Great Ice Age*, 1894, p. 211.

gravels, on the other hand, which extend on to the latter from the hills, are everywhere characterised by pebbles of Silurian *grauwacke*.*

2. The excavation of the glacial drainage channels is responsible for another great part of the material, especially, perhaps, that which litters the coastal plain.

3. The ice sheet itself also no doubt directly supplied some proportion of the deposit.

As to the conditions regulating the accumulation of these sands and gravels, it seems certain that for the most part they formed either as the deposits of temporary ice-dammed lakes or as gravel spreads extending between the ice and the hills and reaching, along the coastal region, far out over the shelving bottom of the sea.

It is difficult now to distinguish between these somewhat differently accumulated deposits, and, in fact, one can only speak with confidence in special cases. It has been found impossible to draw a line separating the gravel spread of the coastal plain into two portions, according as it formed above or below the ancient high-water mark, or in the inland sections to differentiate the material which accumulated in the temporary lakes of the period.

Not only were the original boundaries in the majority of such cases very blurred and ill-defined in their nature, but also the deposits have since frequently taken on outlines corresponding to a mature stage in erosion. We may illustrate this fact by an example from the neighbourhood of Upper Keith,[†] north-west of Fala. Several interesting sections occur here, which render this the type area for the study of the deposits, but their full description will be delayed till the section dealing with the oscillatory nature of the retreat of the ice sheet. For the present it suffices that the sections show a great mass of evenly bedded sands, with here and there a layer of gravel or another of laminated clay or warp. The whole appears as the deposit laid down in the tranquil waters of a great lake, but now so deeply eroded that it has taken on the moundy form which one naturally associates with a sand district. Here and there, indeed, flat stretches do exist which at first sight might be taken to mark an old level of the lake waters; but, as will appear later, these merely indicate the outcrop of a more resistant bed of boulder clay which lies intercalated in the sands, and have therefore an entirely different significance.

With this example in view it would be rash indeed to regard any of the "kame" outlines, which are locally developed, as due to the preservation of original forms of deposit. In fact, the most conspicuous example of kamiform ridges of gravel in this district are afforded near Woodhall, south of Spott, where a section shows that the even and almost horizontal bedding of the deposit bears no relation whatever to the external form of the mounds, but is sharply truncated by the steep hill face. The interpretation is obvious in this particular instance,[‡] for the ridges are part of a gravel-spread which formed between the hills and the ice sheet at a time when the glacial waters were being

* Numerous exposures in the neighbourhood of Upper Keith, for instance, illustrate this point.

† Pl. IV. figs. 1 and 2.

‡ We do not suggest for an instant that true kames of deposit do not exist in other districts.

supplied with such a superabundance of material from west and south that even they were unable to cope with it. Later, when this supply had become in part exhausted, and the passes to the east had at the same time been deepened, the gravel-spread was attacked and kamiform ridges produced. In fact, the latter are here nothing more than the remnants left between successive glacial drainage channels. The disposition of the channels in this case is such as to indicate that they were formed when a re-advance of the ice sheet had carried it forward again over the gravels; but there are equally numerous cases where a wide stretch of sand and gravel has been dissected by glacial drainage channels, for which such an interpretation is quite unnecessary. In imagination place an ice sheet abutting against the front of any hilly tract of country, and suppose that it remain stationary for a long time in the same position. The governing principle operative throughout will be the tendency of the obstructed drainage to furnish itself with a suitably graded channel leading to the nearest available outlet. Hollows and gentle slopes will be loaded with sands and gravels, while ridges, which rise above the general level, will be breached by cross-cut channels: but, supposing the process perfectly continuous, reach after reach, where at first sediments had accumulated, would attain, as it were, its saturation point and, refusing further deposit, would henceforth enter upon a career of erosion.

Under more natural circumstances further complications would be certain to arise: thus we have already hinted several times at the oscillations which marked the withdrawal of the ice sheet from the Lammermuirs; it is possible, however, in a first broad view, to neglect the results attributable to these oscillations, since they affect matters of detail and not of general principle. But even then the account we have sketched above is inadequate, since the opportunities for the destruction of sand and gravel deposits formed in front of a stationary ice sheet are evidently far less numerous than if the ice sheet were slowly and continuously retreating; thus many a time a once continuous terrace must have become reduced to a mere collection of isolated remnants.

We are now in a position to read the evidence afforded by the East Lothian sands and gravels. A remarkable feature in their distribution is that they are for the most part concentrated into two definite and quite distinct areas in which, as we shall endeavour to show, they have accumulated under somewhat different conditions. The first of these areas is a well-marked belt or zone of maximum accumulation extending from Tynehead in the west right round the hills to Oldhamstocks in the east, while the second includes what may be termed the coastal spread.

Examination shows that the first of these two zones or belts is roughly contained within limits set by the 700- and 500-foot contour lines respectively; further, a study of the mode of occurrence of these deposits in the field shows that many of the gaps which break the continuity of the belt are certainly the result of erosion. In fact, it seems tolerably clear that at one time a sand and gravel terrace, similar to that described by Prof. GEIKIE* for the Strathavon Hills, near Glasgow, reached round about the

* *Loc. cit.*, p. 175, pl. iii.

northern and eastern flanks of the Lammermuirs, passing by Tynehead in the west and Oldhamstocks in the east. Between these two villages the continuity of the terrace was broken by two important spurs, namely, Deuchrie Dod and Cocklaw Hill. Behind each of these at one time or another important lakes were doubtless imprisoned, and it seems probable, from the nature of the deposits in the Upper Keith district, that Deuchrie Dod served temporarily as the eastern limit of a narrow marginal lake fully fourteen miles in length. But the history of this terrace was long and varied; we shall presently have to deal with evidences to show that the ice in front of which it formed was frequently oscillating to and fro. In fact, it marks much the most important halt, if such a name may be applied to a limited though restless wandering to and fro, which occurred during the retreat of the ice sheet from East Lothian. Thus it came about that the marginal drainage system of this zone reached a mature development along the lines indicated above. At first almost the whole extent of the marginal area was loaded with sediment, though, of course, the supply varied greatly in amount and from place to place; erosion occurred only across the two spurs already mentioned until the general lowering of the base level caused the emergence of minor ridges and the other consequences which we have indicated above. But before the ice sheet had finally retired, the terrace so formed had been dissected from end to end by marginal streams and the work of its demolition had already far advanced.

Above and below the limits of this great terrace we may recognise others, but never on the same grand scale. A well-marked higher terrace may be referred to leading eastwards from White Castle towards Deuchrie Dod. Its level is approximately 800 feet above the sea.

We shall now consider the other great zone of deposit, that of the coastal spread. At Oldhamstocks it comes into contact with the great Lammermuir terrace, but it is obvious in the field that the deposits of this locality have an extremely complex history, and that those occurring at high levels were formed at a time when the ice sheet must have blocked all direct egress to the sea. The whole coastal spread is, in fact, built up on this plan, and it owes its continuity to the juxtaposition and overlap of deposits formed successively and not contemporaneously. It cannot therefore be regarded as an entity, even in the same extended sense in which that term might be used to describe the complex Lammermuir terrace. It is merely the gravel spread which formed where the mouths of the glacial drainage channels debouched upon the coastal plain, and as these came into being in succession from south-east to north-west, following the retreat of the ice sheet, it is obvious that the coastal gravels near Oldhamstocks, for instance, were formed at a considerably earlier date than those about the mouth of the Tyne.

II. PHENOMENA ILLUSTRATING THE OSCILLATORY NATURE OF THE RETREAT.

We have already referred to the great accumulations of fine sands, silts, and gravels which occur in the Upper Keith neighbourhood. They have all the appearance of having been laid down in a great lake, and it seems necessary to suppose that during the time of their formation the ice sheet of the lowlands lay in close proximity to the north and thus served to dam back the waters in which they accumulated. A closer inspection of the many good sections* occurring in this district confirms this interpretation, since such an examination affords independent and clear evidence of the continued proximity of the ice sheet during the formation of the sands.

Two of the sections, both of them occurring along the course of the Keith water, are specially clear; the first of them constitutes the Red Scar,[†] a little north of Costerton cottage, and the second[‡] lies just to the west of the road from Upper Keith to Ormiston. Their details are as follow :

	Feet.		Feet.
4. Sand	53	Not exposed in this section.	
3. Boulder clay . .	13	Boulder clay (top not seen) .	6
2. Sand	15	Sand	65
1. Boulder clay (base not seen)	37	Boulder clay (base not seen)	33

Even in the Red Scar the section is incomplete, and the upper sands must be fully 150 feet in thickness. The thin gravel beds sparingly interbedded with the sands carry a conspicuous proportion of grauwacke pebbles derived from the Silurian Hills two miles to the south, but the larger blocks of the intercalated boulder clay consist of sandstone, etc., so that it seems necessary to suppose that the latter was deposited by the lowland ice sheet. In fact, we take its presence to indicate that this glacier was not melting away as an inert mass of ice, but that it 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 had previously been collecting. The intercalated boulder clay can be traced with almost complete certainty for a distance of a mile in a direction parallel with the ice margin, and a quarter of a mile at right angles to the same, without any indication of coming to an original limit, so that the oscillation recorded here seems to have been of considerable magnitude. The positions of the best sections in this interesting district are indicated by asterisks placed on the general map.

Many other exposures occur along the Lammermuirs which tell the same tale as those of Upper Keith, but not in so impressive a manner; we need therefore only allude here to the readily accessible exposures in the railway cutting south of Tynehead

* The interstratification of sands and boulder clays here was first noticed by Mr ANDERSON.

† Pl. IV. fig. 2.

‡ Pl. IV. fig. 1.

station, before passing on to indicate other lines of evidence which point equally clearly to the oscillations in which the great ice sheet effected its retreat.

In the first place, still dealing, as at Upper Keith, with the deposits of the great Lammermuir terrace, we may draw attention to the highly significant erosion forms which they locally present. As already noticed at Woodhall, south of Spott, the terrace has been so completely dissected by a series of glacially directed stream courses that its sands and gravels have now assumed a kamiform aspect, and it is obvious in the field that the ice sheet which directed this erosion must have re-advanced after a retreat, until it actually came to stand upon the top of the spread of deposits which previously had accumulated before it.

But this is not the only way, or indeed the most important way, in which oscillations of a retreating ice sheet may be recorded in the erosion effects which it determines, and to make our line of argument more readily appreciated, we have inserted the following explanatory diagram.

FIG. 3.

The contour map and section in fig. 3 show an ideal case of a spur reaching out from a line of hilly country at right angles to the general trend of an ice margin retreating towards the north. The ridge has been breached by two overflow channels,

the one at A, the other at B. It will also be observed that the top of the A channel lies at a higher level than the bottom of the B channel, so that the latter cannot have been excavated to its present depth when the former began to be cut. This indicates that the two were not employed merely during a continuous retreat of the ice front, for under such circumstances no channel could have begun to cut north of B until the ice sheet had withdrawn beyond the 525-foot contour. It is evident, then, that these two were cut, in part at least, during an advance of the ice sheet, so that if there is reason to believe, from the state of their preservation, that they belong to the period of retreat of the ice sheet at all, and not to the period of its growth, we are forced to conclude that the advance which they indicate must have been of the nature of an oscillation affecting the general retreat.

In applying this line of argument it is necessary, in the first place, to compare only valleys that are dry, so as to eliminate uncertainties due to post-glacial erosion. It will be noticed that we here compare the top of A and the bottom of B. Post-glacial change can only be supposed to act so as to lower the former, and, in the case of a dry valley, to raise the latter so that if the top of A be still higher than the bottom of B we may confidently believe that the difference was no less marked in glacial times.

The oscillations of the East Lothian ice sheet have left several memorials of the type described above. Black Law, a little to the west of the kamiform gravels of Woodhall, furnishes an excellent example, for instance; so also does the great Rammer Cleugh channel behind Deuchrie Dod,* described by Professor YOUNG, but in the last-named case there is additional evidence showing that oscillations at this stage were repeated more than once. In the first place, a high-level channel, as shown on the general map, obviously furnished the original eastern continuation of this overflow channel, and must have been blocked by a re-advance of the ice before the eastern portion of the present course came to be employed. Then began the excavation of the magnificent gorge which is known as Rammer Cleugh. It is two hundred feet deep and cut through solid rock, the finest example of a dry valley in the county. It is hardly conceivable that the great ice sheet retreated regularly and slowly during the cutting of this deep channel, since under such circumstances it only had a mile in all to travel before presenting the marginal drainage with a fresh path, for escape, lying to the north of the Dod. We cannot, however, point to any direct evidence indicating oscillations at this stage; but later, when the cleugh had been excavated to its present depth, a re-advance is clearly indicated by a group of morainic mounds charged with great blocks of red sandstone carried from the lowlands, which rest actually on the bottom of the valley near its western extremity. It is interesting to note that while this line of moraines was breached by a continuance of the drainage in an easterly direction, the small stream which now occupies the gap flows in the reverse direction as a result of subsequent corrom formation.

The same kind of evidence is rendered available owing to records of underground

* Pl. I. fig. 1.

operations in the neighbourhood of Ormiston, of which Dr CRAMPTON has kindly given us the following interesting account. "To the west of Ormiston, the light railway follows what has at one time been an important line of drainage. It is shown by bores to be in large measure choked by alternating deposits of sands and gravels, and it is occasionally so completely filled up that its edges no longer make a feature at the surface. Another channel lying to the south and east of Ormiston, and passing close by Pencaitland, has also been proved to contain a considerable depth of clay and sand, and from some of the bore records it can be definitely recognised that boulder clay here occurs superimposed upon sand and mud. The journal of one of these reads as follows :—

Surface, 1 foot.

Clay and stones, 17 feet.

Sand and gravel, 13 feet 10 inches.

The hollow, despite its partial infilling, is still strongly marked and appears to have been reopened to some extent by the flow of water at the time of the retreat of the ice sheet which had deposited the boulder clay mentioned above. The explanation which seems most applicable to these two channels is that they were marginal stream courses formed in front of the ice sheet during its oscillatory retreat, and therefore liable at times to be overwhelmed by a temporary re-advance of the glacier and in this manner choked with boulder clay."

III. THE UPPER LIMIT OF MARGINAL PHENOMENA SET BY LOCAL GLACIATION.

We have, up to the present, been dealing with the phenomena which marked the retreat of the great ice sheet from about the 1000-foot level downwards. Above this the processes at work were evidently somewhat different, for they have left a record of their operations which, though meagre, is still eloquent of the special conditions prevailing during the earlier phases of the retreat. As soon as the Lowland ice had no longer power to surmount the Lammermuirs, the dissected plateau in which this range culminates became for the time being an independent area of dispersal, though still retained within the confines of the great ice sheet. Even when the latter had shrunk back for some little distance from the summits of the hills, every hollow and valley was choked with névé, and many a one nourished its own little glacier, so that every here and there a tongue of ice still reached down the gentler slopes to join its great companion in the lower ground.* So long as this last condition held, it is obvious that marginal drainage on a large scale must have been impossible, and we have at once the explanation of the upper limit referred to above. Later, however, a stage arrived when the Lowland ice parted company with the local glaciers, for while the former continued

* It must not be overlooked that the evidence adduced in this and the preceding section has a most important and direct bearing upon the climatic conditions of the period.

its retreat from the hill country, the latter shrank back into further recesses of the high-level valleys and finally dwindled away to nothing.

Very simple and straightforward evidence of local glaciation is afforded in the neighbourhood of both Lammer Law and Soutra Hill. The former case is illustrated in fig. 4. The Sting Bank Burn follows a deeply trenched valley running eastwards from Lammer Law. A neatly cut high-level channel leads right across the ridge bounding the valley on its northern side. It shows all the characteristics of a winding stream course, with steep banks facing every curve. Its elevation above the Sting Bank Burn is about 200 feet; it is now quite dry, and as it cuts right through the ridge it has no catchment area at its head whatever. It follows the bottom of a faintly marked transverse col, which is lower than any other point for some distance along the ridge to the east. To explain this high-level channel we must admit that the course of the Sting Bank Burn was choked with ice streaming in from the tributaries to the south, but that a small lake was permitted to form in the north-eastern angle of the valley which drained across the col at its lowest point, and thus led to the cutting of a stream course in what one would now style an impossible position. As the water which cut this channel drained outwards from the hill country we have clear indication that local glaciers remained in the high valleys after the great ice sheet had shrunk to a lower level. We need only notice that the configuration of the land emphatically negatives any suspicion that the great ice sheet could block the mouth of the Sting Bank Burn or the Hopes Water into which the latter flows, so as to form a lake whose outflow might have caused this channel, for under such circumstances there could have been no possible escape for a stream across the col, which would itself have been submerged.

An exactly similar deserted high-level channel leading outwards from the hill country is shown on the general map just west of Soutra Hill (see general map); and while it confirms the deductions we have already drawn, it also enables us to appreciate an interesting case of stream diversion which has occurred upon the other side of the same hill. Originally, or rather in pre-glacial times, the Armet Water had its source at Nine Cairn Edge, for the valley still continues naturally in that direction, but the upper portion of the stream has now been diverted to the north and has given rise to the Linn Dean Water. It seems clear on the ground that the local glacier, which occupied the whole of the Armet valley, protruded a tongue northwards to the east of Soutra Hill. The high-level gravels on either side of the Linn Dean Water represent in a sense the morainic deposits of this tongue of ice, while the gorge of the stream was cut by the waters issuing from the same. Certain minor diversions of the stream, moreover, suggest that the glacier sometimes extended forward even into the water-worn channel of the burn and forced it to cut a new course for itself a little to the one side or the other.

It is not impossible that the diversion of the Blinkbonny Burn (north of Sting Bank Burn) should also be ascribed to a precisely similar interference on the part of a local glacier. Originally this stream joined the Harelaw Burn to the east. Such examples

illustrate the final stages which may be reached in a development originating in so small a thing as the high-level channel leading across the col out of the Sting Bank valley.

In the cases so far considered there is no direct evidence* that the local glaciers of the higher valleys came into being during the retreat of the main ice sheet. The excellent preservation of the stream channels described proves indeed that they were produced at a later date than the final overwhelming of the hills by foreign ice, while the oscillatory nature of the withdrawal of the latter itself suggests that climatic conditions were favourable, at the time of the retreat, for a temporary retention of small glaciers in the valleys of the hill country. Fortunately, however, this important point

FIG. 4.

can be settled definitely by a consideration of the complicated series of events recorded in connection with the local glacier of the Cowie Burn valley (figs. 4 and 4A).

The critical sections occur along the ridge which runs northwards from Nine Cairn Edge and forms the western boundary of the Cowie Burn valley. Attention will be restricted to the system of channels lettered in the text map. Of these only the example marked A B C is significant in regard to the question of local glaciation, but it would be unsatisfactory to attempt to deal with it without explaining the origin of the others.

The first thing that strikes the observer in visiting this ridge is that the channels of this system have delivered water (they are all now perfectly dry) both in an easterly and

* We prefer, for the present, not to regard the absence of the ordinary marginal phenomena from the region of local glaciation as direct evidence on this question, to avoid reasoning in a circle.

in a westerly direction. The phenomena are well marked and quite unmistakable. To understand this interesting complication one must recognise that the system of channels lies wholly above the 900-feet contour; that is, above the summit level (884 feet) of the Heriot railway pass, six miles to the west. An examination of this pass shows that it was actually employed as a glacial drainage channel by waters travelling from north to south across the hills. As a matter of fact the pass was sometimes used in the reverse direction also, but when available for the northern drainage, it of course offered an opportunity of escape for waters empounded in front of the retreating ice sheet for some distance to the east of its entrance as well as to the west.

Now a glance at the general map will show the even course followed by the 1000-feet and 900-feet contours between the mouth of the Heriot Pass and the northern slopes of Lammer Law, and it will be readily understood that very slight differential movements of the ice front might lead to flow of water in the one direction or the other across the ridge we are at present considering.

FIG. 4A.

Having discussed this point, the next question is as to whether the channel A B C, draining east, was cut earlier or later than the channel B D which drains west by various mouths. The answer is attained by a line of argument already developed in a previous section. The top of the channel cut at A is higher than any point in the bottom of the channel B D draining west from B, therefore it would seem that A was cut before B D. The water entering* at the intake A flowed across the low col in the water shed at B, and then, instead of following the uniform slope of the hillside *down* into the Cowie Burn, was deflected so as to run *along* the side of the ridge, cutting a channel B C, forty feet deep, in this position. One can scarcely avoid the conclusion that this channel started in a gutter of which the south-eastern wall was the front of a small glacier occupying the Cowie Burn valley. Once, of course, the stream had lowered its bed into the rock of the hill side it would become self-supporting and could dispense with aid from the local glacier. All the time, however, the great ice sheet must have remained to impound the lake that discharged through A. We are justified, then, in picturing a time when these two glaciers, the large and the small, faced one another across the

* This is the condition of affairs shown in fig. 4, although the other channels of the district are also shown.

narrow ridge, and the contemporaneity of the local and foreign glaciation of the district can scarcely be doubted.

The next stage in the history, so far as it can be unravelled, was marked by an advance of the great ice sheet blocking the intake A, and also the escape by way of the Lammer Loch channel to the east. At the same time the Heriot pass, far to the west, happened to be available, so that drainage took place along the ice front cutting the channel B D E. A partial retreat allowed the water to follow another course B D G, and further retreat allowed of lateral escape simultaneously from two points along this channel leading to the excavation of the cross contour courses D H and F I. That these two did come simultaneously into operation is almost certain from the fact that the bottom of the lateral channel leading out at D is slightly deeper than the high-level entrance to F G, so that had D H been formed first, F I could not have been reached by water, and therefore could not have been excavated at all. On the other hand, it is impossible to imagine F I cut first, for its exit could not have been closed again by the ice sheet without also closing that of D H. Further, there is direct evidence in the field that the original depressions at D and F, before either was breached, must have been at approximately the bottom level of the groove B F G. Once these lateral escapes were opened and cascades had formed on the steep hill slopes, the channels were rapidly deepened. F I seems to have offered a freer escape at first, for it evidently carried the greater bulk of water.

We did not make a particular study of the deposits of the local glaciers of the Lammermuirs. No doubt they supplied a considerable proportion of the material of the great Lammermuir terraces of sand and gravel, but we consider that the chief memorial of their existence is the protection which they provided to the upper part of the range from the ravages of marginal stream action. At the same time the following description by Sir ARCHIBALD GEIKIE* seems to indicate that the local glaciation may have been responsible for the production of a certain amount of morainic material. We quote in full: "Between the heath and the rock there intervenes, on the higher parts of the Lammermuir range, a mass of rudely stratified rubbish, to which, in the progress of the survey, the provisional name of Surface Wash has been given till its true history is better understood. It lies along the ridge between the head of the Hopes Water and the Kilpallet Heights. It is usually a sandy clay or earth more or less distinctly stratified, and containing pieces of greywacke and shale, often well striated. Though frequently different in character from the rocks immediately adjacent, these stones cannot have come from any great distance. The deposit is only a few feet in thickness. Perhaps it is to be regarded as the remanié of the boulder clay, washed down and reassorted by rain, though the comparatively small number of the striated stones and the irregularity of the striation have sometimes suggested that this accumulation may be as old as the snowfields of the glacial period."

* *Geology of East Lothian*, 1866, p. 65.

IV. THE INFLUENCE OF CORROMS AND BRIDGE DELTAS IN MODIFYING THE GLACIAL DRAINAGE SYSTEM.

We have already seen that the glacial drainage channels of East Lothian have characteristically a very gentle gradient. This feature owes its origin to the magnitude of the torrents which the channels were called upon to cope with during the intermittent floods of summer-time. Now it frequently came to pass that a low-grade valley of this type was established at one stage in the withdrawal of the ice sheet, to be left later on, as the retreat continued, open at its head and deprived of its main supply of water. Some little trickling stream might still perhaps wind its way along the bottom, but such would obviously prove quite incapable of coping with the tributes of sand, gravel and alluvium delivered by burns descending into the gorge on either hand. Deltaic cones have been formed at the entrance of every side stream.* They are sufficiently conspicuous to be easily recognisable, and resemble exactly well known instances in other localities.† In the upland districts they furnish sites for the shepherds' cottages, and include the only patches of land brought under cultivation. They not infrequently obstruct the insignificant drainage of the main valley, and so give rise to small tarns and marshy tracts situated in their rear.

By way of illustration the number of cones which have been formed along the course of Edmonds Dean was determined (see general map and fig. 5), and attention was paid to the path traced out by each tributary stream in flowing down its delta. Thirteen cones occur in a distance of two miles, and of these, six drain centrally, two down stream and five up. The drainage directions here given refer only to what occurs on the actual surface of the cones, for on reaching the bottom of the main valley all the tributaries turn to flow south-east—the original direction followed by the glacial drainage. The cone occurring furthest up stream has, however, very nearly raised itself to the entrance level of the pass, and an inconsiderable addition to its height would develop it into a corrom or delta watershed.

The number of fully-formed and operative corroms modifying the glacial drainage plan of the county is so great that an enumeration is impossible. To realise the important rôle which some of these corroms play, one has only to seek out the great highways which were established, under conditions of glacial restraint, to connect up drainage areas previously distinct. In almost every case the striking feature here is the very minor importance of the re-distribution of drainage permanently effected; the lines of communication temporarily employed are now blocked by the formation of corroms which coincide roughly in position with the old pre-glacial watersheds. Further, the slight interchange involved in this process has taken place, more often than otherwise, in a direction contrary to that of the old glacial stream. The cause of this

* Pl. III, fig. 1.

† J. E. MARR, *Scientific Study of Scenery*, second edition, p. 166 and pl. I. C. RUSSEL, *River Development*, p. 138.

is not far to seek. Suppose that a natural drainage basin A is forced by glacial obstruction to seek an outlet through a neighbouring basin B, and that a level-bottomed gorge is thus established connecting the two. On further retreat of the ice sheet a readier way of escape will likely present itself to the waters of the A basin, while those of the B basin may still persist along the same route to the sea as heretofore. Under these circumstances it would be natural for a tributary of the B system to establish the corrom blocking the highway, since thus it would share in the advantages obtained by the A drainage.

Four very notable illustrations are afforded in our district of the action of the processes which we have outlined above. Thus there is the striking instance of the railway pass between Cockburnspath* and Grant's House, which it will be remembered was specially noticed by Sir ARCHIBALD GEIKIE in his description; then, again, there are the two great highways, in part occupied by the Aikengall and Thurston Burns respectively, to which Professor YOUNG directed attention, and which serve to isolate in the one case Cocklaw Hill and in the other case Spott Hill from the main mass of the Lammermuirs. Last of all, far away to the west there is the Borthwick channel, which for so long a time connected the Mid Lothian and East Lothian drainage areas; as mentioned before, Dr CRAMPTON, working independently, has come to the same conclusion as ourselves with regard to the changes that have brought about the desertion of this last-named channel, and his account will shortly appear in the second edition of the Geological Survey Memoir dealing with the Edinburgh district.

Let us now take the first of our four principal examples, that of the railway pass between Cockburnspath and Grant's House (fig. 5). The position of the pre-glacial watershed, which formerly broke the continuity of this valley, can readily be recognised just at the point where the railway passes through a short tunnel to avoid taking an awkward little bend to the west. On the two sides of this old watershed the valley has passed through somewhat different stages of development. South of the col the glacial waters, for long supplied by the channel of Edmonds Dean, had nothing to do but deepen the old valley which served to conduct them towards the sea;† but to the north of the col they had to deposit layer upon layer of gravel, sand, and silt, and thus choke the lake which formed in this position, while, when crossing the col itself, the waters were always busy cutting and digging. So it came to pass that depositing in one place and excavating in another, they never rested until they had graded the whole to one uniform gentle slope inclining from north-west to south-east. But now the ice retired and allowed the marginal drainage to escape round the north of the obstructing ridge by the St Helen's Church channel, described by Sir ARCHIBALD GEIKIE, and the great highway was abandoned which had cost so much labour to establish. The corrom

* Pronounced Copperspeth.

† A triangular mound near the southern exit of the tunnel is artificial, being composed of angular rock debris, with occasional brick fragments, top-dressed with sand and boulder clay to allow of planting.

now dividing the valley into two is a fairly conspicuous mound* built out by a little stream entering from Blackburnrig Wood; it lies half a mile to the south-east of the pre-glacial watershed, and serves well to illustrate the general rule that a drainage area which has received water from a neighbour under conditions of glacial restraint has often to pay back with some of its own when that restraint is removed. The explanation given above clearly applies here, for the streams which continue along the route previously taken by the glacial torrent have not succeeded in deepening their course, while the Edmonds Dean Burn, which enters north of the corrom, but still south of the

FIG. 5.

pre-glacial watershed, has found a comparatively rapid drop by following the reverse direction, and has thus been enabled to cut a gorge for itself through the old lake deposits, which is fully a hundred feet in depth. A very conservative estimate of the advantage gained can be arrived at by a consideration of the following figures: the height of the corrom above sea-level is 396 feet, and this fall can be achieved in the one direction in three miles, as contrasted with twelve miles in the other.

Turning next to the highway which leads round behind Cocklaw Hill (fig. 6), we find a similar instance of the removal of a pre-glacial watershed and the later formation of a corrom further to the south. It is the Aikengall Burn which, entering the great through valley about a quarter of a mile beyond the site of the original watershed, has

* Pl. III. fig. 2.

been the corrom builder here, and as a consequence it has transferred its allegiance from the southern to the northern drainage system. No valley can be more heartily recommended to anyone desirous of studying corrom formation than this one, owing to the number and beauty of the cones* which enter it from either side. There seems indeed to have been some little competition as to whether the Aikengall Burn or its neighbour to the north should actually succeed in establishing the corrom of the valley; but once the former had settled this point in its favour, it made sure of its conquest by attacking and partially demolishing the work of its rival. One is especially impressed,

FIG. 6.

both here and in the case of the great Dry Burn valley (Thurston valley) further north, with the probability that the main readjustments, which we can recognise to-day in the glacial drainage system, were virtually completed almost as soon as the opportunity for them arose through the continued retreat of the ice sheet. Thus, to judge from the erosion effects, it would seem that the reversed drainage, initiated upon the corroms of these two valleys, had formerly a much greater volume than at present, and one is led to speculate regarding a time when the streams were apt to be swollen into mighty torrents by the melting of the snows in the hill country. Although a corrom to be permanent must be built of sand, gravel, or some such material, we must not neglect the probability that the corroms of the glacial period may have largely resulted from

* Pl. III. fig. 1.

the piling up of flood-borne ice and snow, mingled and covered with other débris, and that in many cases these temporary constructions may have had a very important influence in shaping the destinies of the drainage system. Before leaving this subject, we would like to notice a particular effect, for which the reversed drainage of the Aikengall Burn may fairly be held responsible. Just to the north of the entrance to the pass, perched upon its western bank, there occur two or three dry valleys, which there can be little doubt were used successively by the marginal stream at a time when the waters of the latter still found an escape southwards through the Aikengall valley. They now "hang" with respect to the latter, since, being streamless, they have not shared in the opportunity of renewed erosion, which it attained through the partial reversal of its drainage.

After what has gone before, there would be no advantage in discussing the history of the Dryburn and Borthwick channels in detail. It suffices to point out that the streams responsible for corrom formation in these two cases are the How Burn and Gore Water respectively.

We may now bring this part of the discussion to a close by observing that the operations of corrom formation are by no means restricted to glacial drainage systems. The circumstances which so greatly favour their growth in the latter are likely to be reduplicated in other situations. Wherever a gently graded valley lies open at its head and no longer supplied with a sufficiency of water, there a corrom is likely to appear; and many a great beheaded valley must have found itself in just such plight, and accepted a corrom as the watershed of its lower reaches. The permanence of the capture thus involved can readily be predicted from analogy with the East Lothian types, for the diversion initiated upon alluvium would, as it were, be fixed by becoming imposed, through continued erosion, upon the rock framework of the country.

It may be well to add here, since the term corrom is now being introduced for the first time into scientific literature, that the definition relates to function and not to origin; it is on this account free from any speculative element. In the beautiful Glen Tarbert example (Ardgour), whence the name has been derived, the delta has accumulated on the surface of a rock watershed. A similar case has been described by Dr MARR * for Dunmail Raise in the English Lake District. The Glen Tarbert and Dunmail Raise deltas are corroms, since they serve as watersheds, quite irrespective of the fact that they cannot be held directly responsible for their behaviour in this respect.

While corrom formation is favoured in the major glacial channels, another modification has affected the less-marked grooves running along the hill slopes and roughly following the contours. Their fate can readily be pictured: the more important side streams have built out their cones into the channels, and thus have furnished themselves with bridge-deltas by which they have won their way to the other side. Once across, they have made good use of the slope and set to work eroding a channel for themselves,

* *Loc. cit.*, p. 143,

often removing all evidence of the manner in which the crossing was made. A capital example of a bridge-delta occurs at Common House, rather more than two miles south-south-west from Spott. Several small streams uniting at this point have well nigh obliterated a portion of a strongly marked contour channel; better still, however, they have later set to work again to destroy the delta, and in the deep gashes that they have cut one may recognise both the nature of the infilling material and the continuation, for some little distance, of the rock walls of the original gorge.

While examples of bridging by deltas can seldom be demonstrated, it is still moderately certain that this operation is responsible in large measure for the reticulate pattern of the East Lothian glacial drainage system.

There is, however, another and distinct way in which a glacial drainage channel may become segmented. Especially in the hilly districts, where pre-glacial features were never obliterated, the major streams have in many cases continued their course straight across glacial drainage channels, merely because the withdrawal of the ice left an open path in this direction.

It is obvious, then, that contour channels are very liable to division. When once this has been accomplished the next step is to provide each segment with its own independent watershed. Here of course an opportunity for corrom formation is afforded, and it is one that, in point of fact, is but seldom neglected.

V. EVIDENCE REGARDING THE LEVEL OF THE SEA AT THE TIME OF THE RETREAT OF THE ICE SHEET.

We have not made a special study of the intricate question of the relations of land and sea at the close of the glacial period, but attacking the question from a new standpoint certain results have been attained which we consider to be worth recording.

In the first place, the phenomena which we have been describing are emphatically those of the retreat of an ice sheet obstructing land drainage, and become meaningless if viewed in the light of a submersion theory. In fact, to fix the upper limit which can be assigned to the level of the sea at the time of the retreat of the ice sheet we need only find the lower limit reached by the denudation effects of the land drainage when acting under conditions of glacial constraint. Caution must naturally be exercised in the choice of evidence upon which deductions of this character are to be based, and none but "dry valleys" should be employed for the purpose. All the necessary requirements were found in an exceedingly well marked glacial drainage channel cut in rock and terminating near Eweford, slightly more than a mile south-west from Dunbar; the little water that flows through it merely trickles along a ditch which has been dug to drain the marshes which still occupy portions of its bottom. We may confidently assert that under natural conditions the valley would be streamless; and it is obvious that so far from having been overdeepened since its desertion by the marginal stream, all the processes at work have tended to its obliteration. In spite of this, however, it only

ceases to be a well marked feature on crossing the 75-foot contour line, so that high-water mark at Dunbar, when this channel was being cut, cannot have reached the level of the 100-foot contour line of the present time, and probably did not surpass the 75-foot contour.

In the time at our disposal we were unable to follow up this promising line of evidence, but a visit to St Abb's showed a very similar relation. Lying in the bottom of the hollow which isolates the headland, is a well defined glacial drainage channel. It cuts through rock covered with boulder clay, and is clearly recognisable well nigh as far as the 50-foot contour line.

One further observation may be added which may some day prove of interest in dealing with the raised beaches of the Forth. About half a mile south of the railway at Prestonpans a clearly marked glacial drainage channel cuts through the 150-foot contour line. It in part follows the course of an old glacial groove, but at the same time it undoubtedly shows that the ice sheet at the time of its formation lay to the north and not the south. We see, then, that the great ice sheet continued its process of shrinking into the centre of the valley even to this late stage, and that the bed of the shallow estuary of the Forth served as its last refuge when it had withdrawn from the coastal regions of East Lothian.

Professor P. F. KENDALL and Mr E. B. BAILEY on "The Glaciation of East Lothian
South of the Garleton Hills."—PLATE I.

FIG. 1.—Rammer Cleugh, lying south of Deuchrie Dod (the latter not included in the picture). This is the finest dry valley of the district: cut 200 feet deep in rock. Note high-level channel to north of the main valley (left side of the photograph), cut at an earlier stage and blocked during a re-advance of the ice, which led to its abandonment and the opening of the Rammer Cleugh channel proper (pp. 9, 19).

FIG. 2.—Very typical dry valley joining the Spott Burn a short distance above Spott. Note the high-level channel to the south of the main valley (right side of photograph), and probably cut during a temporary re-advance of the ice sheet (p. 11).

Professor P. F. KENDALL and Mr E. B. BAILEY on "The Glaciation of East Lothian
South of the Garleton Hills."—PLATE II.

FIG. 1.—Junction of the dry valley shown in Pl. I. fig. 2, with that which carries the Spott Burn. In this case the valley carrying the stream has not been appreciably deepened since glacial times (p. 11).

FIG. 2.—Braidwood Burn. The present stream has cut a minor winding gorge into the bottom of the glacial channel. The latter can still be readily recognised. The material cut through by the burn is Old Red conglomerate (p. 12).

Professor P. F. KENDALL and Mr E. B. BAILEY on "The Glaciation of East Lothian
South of the Garleton Hills."—PLATE III.

FIG. 1.—Aikengall Valley. A delta is here shown, deposited by a tributary stream where it enters a dry valley. Note the difference of vegetation on the rock sides of the valley, on its ill-drained bottom, and on the slopes of the delta respectively, and see how the sheep cluster upon the latter (p. 25).

FIG. 2.—The corrom of the Grant's House railway pass, deposited from the small wooded gorge of Blackburnrigg on the far side of valley. Note how the telegraph posts well nigh disappear in the cutting through the corrom and reappear on the further side (pp. 8, 27).

Professor P. F. KENDALL and Mr E. B. BAILEY on "The Glaciation of East Lothian
South of the Garleton Hills."—PLATE IV.

FIG. 1.—Sands exposed by Keith Water, one mile north-west of Upper Keith. The top bed in the section consists of 6 feet of boulder clay, which forms the flat on which the railing stands. Note hummocky form of country, due to denudation. The section is, in descending order, boulder clay 6 feet, sand 65 feet, boulder clay 33 feet (pp. 14, 17).

FIG. 2.—Sands exposed by Keith Water in the Red Scar, $1\frac{1}{2}$ miles west of Upper Keith. The bed of boulder clay which caps the section shown in fig. 1 is here overlain in turn by a thick mass of sand. The sands underlying this boulder clay are generally obscured beneath rain-wash, which has been in part cleared to allow of this photograph being taken. The intercalated boulder clay indicates an oscillatory re-advance of the ice sheet which served as the northern boundary of the lake in which the sands accumulated. The section is, in descending order, sand 53 feet, boulder clay 13 feet, sand 15 feet, boulder clay 37 feet (pp. 14, 17).

GENERAL MAP SHOWING GLACIAL DRAINAGE CHANNELS AND DISTRIBUTION OF GLACIAL SANDS AND GRAVELS IN EAST LOTHIAN.

* Best sections showing intercalation of Sands and Boulder Clays.
Heavy solid lines = Dry Glacial Drainage Channels. Broken heavy lines = Stream-containing Glacial Drainage Channels.