THE ORIGIN OF THE LANDFORMS OF THE MALHAM AREA

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This account of the landforms of the country around Malham Tarn Field Centre has been arranged on the basis of the factors responsible for the present landscape. As far as possible these are treated separately and arranged in time sequence. Thus the account falls into three main sections dealing with the contribution of pre-glacial, glacial and post-glacial times to the present landscape. In many cases a particular element in the landscape is a function of each of these periods, but in most cases it is possible to focus attention on the dominant process responsible for its form. Although this division is occasionally a little arbitrary, it is hoped that this approach will be more useful to students working in the area than a regional description. The general geological background is covered within the section on pre-glacial landforms.

Introduction

The dominant factor influencing the landforms of this part of the Pennines is undoubtedly structure, using the word in W. M. Davis' wide sense of it, that is to say, the lithology of the rocks together with their disposition. Contrasts from one rock to another are great, and this is emphasized by the generally simple structural pattern. Again, since over most of the area the rocks are very nearly horizontal, the major faults of the Craven area form significant breaks in the landform pattern. A particularly important factor in lithological control is, of course, the distinct character of the Carboniferous Limestone which over part of the area forms the most mature karst landscape to be found in Britain.

We may assume that virtually the entire area was ice-covered during each of the Pleistocene glaciations, although only the effects of the Last Glaciation can be identified in the field. The area of high ground around Hawes sustained a local ice-sheet that kept out both Lake District and Scottish ice and provided a flow of ice powerful enough to erode the landscape. The contribution of glaciation to the present landforms seems to have been overlooked in some accounts of the area, and a reassessment is attempted here. The contribution of post-glacial modification includes the growth and erosion of the peat on the uplands, the modification of the slopes exposed on ice-retreat, continued solution of the limestone and, in more general terms, the development of a soil cover on glacial drifts and solid rock alike. These processes have proceeded at very different rates on different rocks and have been an important factor in emphasizing the contrasts in landforms from one rock to another.

I. PRE-GLACIAL EVOLUTION

The pre-glacial evolution of the landscape occupied part, at least, of the Tertiary period. Local evidence of the stages in this evolution is quite limited; enough has survived to demonstrate that the area conforms to other upland areas of Great Britain in possessing a series of upland surfaces that suggest pauses in the reduction of the high ground. In no case can the stages be dated securely, although the general arguments that have been applied elsewhere can obviously be extended to the Malham area. Thus the absence of warping suggests that the surfaces post-date the Oligocene earth movements. Again with the exception of the 2,000 ft. surface, these surfaces are not extensive or level enough to be called peneplains: they are upland planation surfaces that still possess appreciable relief. However, their recognition is not entirely an academic matter: on the Carboniferous Limestone they are closely related to the stage of karstic development, while over the whole area the altitudes are as much a function of these erosional stages as they are of rock structure.

Structure and lithology

The lithological succession of the area is described elsewhere (Edwards and Trotter, 1954; O'Connor, 1964) and need not be covered in detail here. The main sequence is from the Carboniferous Limestone upwards through the rhythmic repeated beds of limestone, shale and grit of the Yoredale Series to the thick shales and topographically dominant grits of the Millstone Grit Series. In the north, this sequence rests on a strongly-folded basement of Lower Palaeozoic rocks that is exposed in several of the main valleys, and at Malham Tarn itself. The whole unit, known as the Askrigg Block, is bounded on the south by the Middle Craven fault, a fault originally of Carboniferous age that separated the stable platform to the north from the subsiding Bowland trough to the south. While the platform was overlain by the Great Scar limestone, and then the Yoredales, the subsiding trough filled up with the contemporaneous Clitheroe and Pendleside shales and limestones and the Bowland shales. Not until Millstone Grit times did similar depositional conditions prevail across block and trough alike. The result is a major lithological boundary that has been exploited to produce the Askrigg Block uplands to the north and the Aire vale to the south. The contrast has been emphasized by later faulting, notably along the North and South Craven faults. Along the line of the mid-Craven fault occur reef knolls; these are related to the subsiding slope of the Carboniferous sea, and are exhumed from their shale cover to form a striking series of isolated hills.

On the ground, the expression of the faults varies considerably. In all cases they have been stable for long enough for none of them to contribute directly to the landscape with fault scarps (for a different view see Corbel, 1951). Where there is a difference of relief across the scarp it is the result of the differential erosion of two rocks. Since in most cases shales lie to the south of the faults and limestone to the north, the southern downthrow is commonly accompanied by a south facing fault-line scarp. This process is most convincingly shown by the exhumation of the Carboniferous Middle Craven fault immediately south of the Tarn. Here over a mile of the old feature now forms a south-facing scarp, itselt cut back at Malham Cove and Gordale Scar. To east and west the Bowland shales overlap onto the limestone north of the fault, and erosion by the present drainage has so far failed to strip the shale cover and expose the fault apart from limited areas east of Bordley.

In places the other faults have given rise to similar fault-line scarps, especially the South Craven fault at Giggleswick Scar. Elsewhere erosion has not yet been able to exploit the lithological contrasts, or they are not great enough at the present surface level to give any significant advantage to denudation on either side of the fault. Where the Lower Palaeozoic basement of the Askrigg Block is brought against the Great Scar limestone, as immediately south of the Tarn, the limestone is only a little higher than the Silurian outcrop; this is clearly an erosional feature since the higher ground is on the downthrow side of the fault. The line of this fault, often difficult to locate on the basis of relief, is marked by an impressive series of water sinks as the streams flow off the impervious rocks and disappear down the solution-widened joints of the limestone.

On the Askrigg Block itself, the almost horizontal rocks give a strong element of repetition to the landscape. Although he is prepared to concede that each dale must be unique, the visitor finds it difficult to distinguish one from another. A drive alongside the upper Wharfe will show the pattern of a broad shining river, cascading across thick beds of limestone, the bright green of the open riverside meadows, the steep rock-terraced valley sides, and the higher fell-sides where soil and peat cover the rocks and only the pock-marks of shake holes mark the limestone beds of the Yoredale Series. Take the road beside the Skirfare and the landforms are so similar that on recall it is difficult to distinguish one dale from the other. The horizontal repetition is seen not only in the dales, but in the peaks. There is a striking similarity of form between the grit monadnocks of Pen-y-ghent, Ingleborough and Whernside; between Buckden Pike and Dodd Fell.

Most striking too is the repetition associated with the Yoredale beds. Each of the major limestones marks a distinct break of slope that is rarely totally obscured by drift, and is given precision in the little limestone gorges where the bed is cut by a descending stream. Viewed from across a valley, or better still on an aerial photograph, regular lines of conical hollows follow the upper side of each limestone bed. Below the scar or steepened slope that marks the outcrop of the limestone are corresponding seepage lines or springs, many of them bright green "flushes". It is the instability caused by the water seeping out along the shale bands that maintains the irregularity of the Yoredale slopes. In places the drift cover is thicker and peat may form on the bench above the limestone bluff; elsewhere erosion has exposed the limestone surface and it is in such positions that some of the deepest and most intensely fluted grikes are found, no doubt as a result of the acidity of the water that reaches these higher limestone beds.

Early stages of Erosion

Little can be added here to the account of the denudation chronology of the landscape given by Dr. Sweeting in 1950. She recognized the existence of several stages of denudation in the landscape. Evidence from a wide area shows that the fragments of a surface at about 2,000 feet occur on rocks of various ages, suggesting that these are the remnants of an ancient, dissected peneplain.

While locally the feature may appear coincident with one particular bed of the Millstone Grit, as on the summit of Fountains Fell, when traced over a wider area it is found on higher beds in the Millstone Grit series. It is doubtful that much more can be said of such a fragmented feature, but it is readily seen in any extensive view across the upland why such peaks as Pen-y-Ghent and Ingleborough have been described as monadnocks rising above this subaerial peneplain.

The lower, 1,300 ft. surface is a widespread feature, no doubt because it is well preserved on the permeable Carboniferous Limestone which outcrops at this lower altitude. It is as well-developed south-east of Malham Tarn as anywhere in the area, and this is also a good locality for demonstrating its independence of structure. Here it is cut across the line of the North Craven fault and passes from the lowest beds of the Carboniferous Limestone onto the upper beds, and locally onto the Bowland shale. The more widespread nature of this planation surface shows the appreciable height range of these preglacial features, and the extent to which their original form has been modified by glaciation and by fluvial dissection. Yet they remain significant features in the landscape, and the level floors of the great embayments in the limestone scarps north of the North Craven fault are an important element in the relief of the area near the Tarn.

Below the 1,300-ft. surface are the two Dales stages of Dr. Sweeting and, although these surfaces are generally much less extensive than that of 1,300-feet, the rejuvenations between each of these stages are frequently marked by major waterfalls on the streams. In their local context most of these falls are due to some structural cause; frequently the Carboniferous limestone caps the fall while the gorge can be seen to have been cut back from one of the Craven faults. This is the relationship at Catrigg Force, for example, or at Gordale itself. But the systematic occurrence of these falls and the open (mature) forms of the valleys above suggests that they are causally related to the successive rejuvenations implied by the erosion surfaces.

The Limestone: Caves

The dewatering of the limestone as these waves of rejuvenation lowered the main dales led to the spasmodic fall of the water table. Although it must be accepted that solution can readily occur below the water table in limestone areas, there may well be a tendency for extensive horizontal caves (independent of the bedding) to form at the level of the water table. Dr. Sweeting found that these horizontal caves were concentrated at particular levels within the limestone, and suggested that these levels were the still-stands of the water table, itself dependent upon the still-stands of downcutting that produced the planation surfaces. This is best shown by the Main Dales stage which has many associated cave features. The Great Scar limestone does not often extend high enough to show caves formed at the earlier 1,300-ft. level, but a few cases are known. In a glaciated upland it is usual for any correlated deposits or preglacial weathering horizon to have been removed by erosion. These cave levels are consequently important evidence lacking in areas where thick limestones do not occur.

The Limestone: Dry Valleys

It seems likely that some of the other major surface forms of the limestone are of pre-glacial origin. The two main features here are the dry valleys and the larger closed-hollows or dolinas. The dry valleys are, of course, water-cut features that have lost their surface drainage because the water-table is now below the valley floor. A uniformitarian explanation would relate this fall of the water table to the same series of rejuvenations that affected the base levels. It is likely that this is indeed the main cause, for in several areas a group of valleys leads out from a higher area onto the little-dissected surface of one of the erosion platforms. This is the case immediately east of the Tarn, and it suggests that the valleys were occupied by streams (at least seasonally) at the 1,300-ft. stage and then went dry as the rejuvenation below that stage worked up the dales and so lowered the outlet springs around the upland block.

An alternative hypothesis can be based on the very cold climate that would have been experienced here during the advance and decay of the Pleistocene ice-sheets. At times when the area was not covered by ice, it must have experienced a truly periglacial climate with at least seasonal freezing of the surface layers. Whether a deeper permafrost developed is a matter for conjecture at present: some small ice-wedge casts are known from the area. However, even with seasonally frozen ground some run-off would be expected in this area while the ice-sheets would have produced much meltwater. The freshest features within these valleys, together with their youngest deposits, must be expected to date from such a period. But there seems no reason to attribute the whole of their sculpture to such a late stage. As a subsidiary observation, it might be noted that the wide joints of the Carboniferous Limestone would be far less readily sealed by frost than the Chalk, while in all these valleys exceptionally high rainfall can temporarily exceed the capacity of the joints and cause surface flow. Thus since the Field Centre has been open, water from the Tarn has several times flowed past the sinks down the dry valley towards the Cove, and in 1962 even cascaded over the normally dry waterfall at Comb Scar.

The Limestone: Closed Hollows

In many ways the large hollows of the limestone are the most interesting geomorphological features in the area. These features are often a quarter to half a mile across, and at times a few hundred feet deep—they generally resemble huge saucers although some of those with steep sides are nearer the shape of a soup bowl. These are extremely localized in their distribution, although common enough in the few areas where they do occur. The main group lies around Parson's Pulpit, north-east of Tarn House (Moisley, 1955). Another smaller, and more scattered, group lies in the Grizedales area between the north and mid-Craven faults, south-west of the Tarn. A third area east of Feizor has only a few hollows although one of them is very large. These features may be called dolinas and are restricted to this part of the Pennines. Little detailed work has been done on them and the hypothesis put forward here needs testing in the field. They seem to be totally free of collapse of any type. Nowhere have marginal faults been seen, and where individual limestone beds can be traced by their distinctive lithology these dolinas are clearly formed in undisturbed strata. Neither collapse of cavern roofs, nor the related subsidence of material into a hollow seem to have operated.

An alternative hypothesis is that these hollows are the result of solution at the limestone surface, not where it is exposed to the sky where solution is probably rather slow, but where it is overlain by a layer of soil and sediment. This material is found in all these hollows and has a composite origin, reminiscent of the Clay-with-Flints *sensu lato* of the Chalk of southern England (Loveday, 1962). It includes, at one site or another, patches of the overlying Yoredale Beds, remnants of the soil horizons developed in pre-glacial times, glacial deposits including much till, and fine silts and clays deposited in ponded water at times when the drainage of these hollows was less free than now. The former existence of still water is seen in most of these dolinas, and many are unable to deal with heavy rain even today. Some, perhaps with a thicker layer of glacial till, are almost permanently occupied by wet marsh. Experience elsewhere suggests that the upper, fine deposits of these hollows will also include a significant loess-sized fraction dating from late-glacial times.

These patches of clay-rich complex sediments on the limestone are as much the cause as the result of the dolinas. Ever-wet from the high rainfall and low evaporation, relatively acid and in places rich in humic acids due to the development of marsh or peat, these "acid sponges" have eaten their way by solution into the solid limestone beneath. Once they had dissolved away the limestone beneath them to produce an incipient hollow, an irreversible process had begun. The sloping surface developing on the limestone ensured concentration of soil water and so further intensified the solution at those points. The surface slope that developed allowed the transfer of material by creep flow and wash to the incipient dolina. This intensified the contrast in soil depth between the incipient ridges and the developing hollows, intensified the contrast in the amount of water present and so contributed to the inexorable development of the hollows and the ever-slower reduction of the interfluves between them. As the process deepened the hollows, the limestone appeared at the surface as a scar around it. This scar then developed as a retreating free-face, widening the hollow by mass-movement as the bottom was deepened by solution. The effectiveness and speed of this lowering by solution is reflected in the very common occurrence of steep scars around these dolinas. Where the bounding slopes are gentle and mantled by a continuous soil cover the lowering has no doubt been much slower.

This etching in of patches of overburden has, of course, occupied a long time. The dolinas may be mapped in terms of their size and depth, although the glaciation of the area and the modification of the surrounding rim by slope retreat (and in places sub-glacial meltwater) makes the data of limited value. We can identify the area of the dolina, its shape and its depth. This last value involves both the imprecise estimate of the difference between the floor level and the general level of the surrounding land, and what is best called the "closure", the difference in height between the lowest part of the dolina and the lowest col in the surrounding rim. From what we know of current rates of limestone solution here (discussed on page 381) these features are old elements in the landscape and must have been in existence in pre-glacial times, particularly when we realize that the depth represents the *difference* in the amount of lowering of the floor and the rim.

This view that the dolinas are pre-glacial features is strongly reinforced by their relationship to the erosional stages of the area. The limestone does not reach the 2,000-ft. level, but these hollows are nearly all found where it rises above the 1,300-ft. level. The only important exception is east of Feizor, and the presence of an active stream in the floor of the biggest hollow here may indicate that the rate of deepening has been unusually high. In general these are features that predate the formation of the 1,300-ft. surface since they are usually found on limestone outcrops that rise above that surface. While their development did not cease with the formation of the 1,300-ft. planation level, most of the work must have been completed by then or we would find these features on the lower ground. They are relics from the late-Tertiary.

This strictly uniformitarian view of these features is not of course the only hypothesis that could be put forward. While this article is not the place for a lengthy discussion of the alternatives, one particular view does require mention. This is the bearing of the climate of late-Tertiary times on landforms of the area. The point is important because not merely the dolinas, but all the surviving Tertiary forms were modelled under the warmer climate that prevailed. The erosional surfaces may well have developed more readily under such conditions. Some of the rounded "woolsack" corestones of the Millstone Grit (Linton, 1964a) were roughed out below ground under such a climate. Similarly, Dr. Sweeting has suggested that tropical karst forms (e.g. the conical hills known as Kegelkarst) can be seen in the area. The dolinas may owe their size to such conditions. However, it must be emphasized that in almost all cases the interpretation of such features as relics from an earlier climate rests almost solely on their external shape. Only in the case of some of the Millstone Grit woolsacks is the expected rotted rock found alongside the surviving cores. It should also be understood that if these features are true relics from an earlier climate they are being destroyed, or at least greatly modified, by the present climatic conditions. Again, this view seems tenable for the Millstone Grit tors, but is less easily demonstrated for the other features.

II. The glacial period

Conventionally we are used to separating glacial action into erosion and deposition, and these are all too frequently erroneously attributed to upland and lowland environments. The intermingling of erosional and depositional forms in the Malham area makes such a view particularly dangerous. Historically the depositional features have received most attention. The remarkable drumlin swarms of the upper Ribble valley and the Craven lowlands are well known. The extensive lake flat separating the Aire from the Ribble and the smaller lakes behind the valley moraines of the Wharfe are also easy to appreciate in the field. Even the rather irregular heaps of material south of the Tarn can be recognized as glacial drift, kames of bedded (i.e. water-deposited) material. Locally, striae or erratics show evidence of glacial movement. The scattered boulders of Millstone Grit that are so conspicuous on the bare limestone pavements are striking, although unfortunately of no value as indicators of the direction of ice movement. The justifiably famous Norber erratics show how the ice tore Silurian rocks from Crummackdale, and then swept uphill, swinging a little south-westwards towards the Lancashire Plain. The alignment of the drumlins south of Settle shows the Ribble ice stream dividing to pass either side of the unglaciated Pennines south of the Aire Gap.

The drifts on the upland around Malham Tarn are composed of local rocks. Farther north the Shap granite erratics showed how Lake District ice moved through the Stainmore Gap, while north-west of the Howgill Fells Hollingworth (1931) has traced the margin of Lake District erratics, kept out of the Askrigg Block by the local ice-sheet. The existence of a local source region was mapped by Raistrick (1930), and he showed a divergent movement from the uplands of Langstrothdale Chase. He does not discuss the evidence for this in any detail, although he recognized that ice moved down the Wharfe and Skirfare valleys, and also west into Ribblesdale. The westward and south-westward movement is of course well shown by the drumlins east and south-east of Ribblehead.

Landforms of Glacial Erosion

Although existing accounts tend to emphasize the glacial deposits as evidence of ice-action in the area, the erosional forms are at least equally significant. Any elementary textbook of geomorphology will distinguish between the U-shaped trough of a glacier and the V-shaped valley associated with river erosion. In this area all the main dales have a broad trough shape that has generally been ascribed to glaciation. There is abundant evidence that the Wharfe and Skirfare valleys were occupied by moving ice, and that locally ice-erosion has occurred. Their long profiles show a sequence of rocky outcrops separated by aggraded flats most of which are too extensive to be solely ascribed to valley blocking by the valley moraines (Raistrick, 1931). They suggest a series of rock basins along the valley floor—in many ways the most definite evidence that there is for glacial erosion. Locally the valley sides also show evidence of active erosion by the ice. The most spectacular case of this is Kilnsey Crag at the junction of the Wharfe and the Skirfare. Here the convergent ice streams have undercut the valleyside outcrop of the Great Scar limestone, producing a superb overhang of markedly smoothed rock. Such features must often be produced by glacial erosion, but only in favourable circumstances like this do they survive the melting away of the supporting ice. Even where the rock is mechanically strong enough, the slopes will have too much surface water for an overhang to be stable: on limestone the absence of surface water greatly increases slope stability.

Although such indications of glacial erosion can be found in these dales, they are far from ubiquitous. The most striking feature of the dale sides is the structural terraces which mark the limestone outcrops, and this adjustment of the slopes to structure suggests an appreciable period of sub-aerial erosion. It is apparent that the post-glacial period has been inadequate for these slope features to be formed *de novo* (since they are totally absent from neighbouring intensely glaciated valleys). We must recognize them as survivors from an interglacial period. (They are discussed on page 370.) Similarly the general adjustment of the tributary valleys to the major dales suggests that downcutting was not very significant and was limited to producing the irregularities in the long profile already noted. The evidence is far from conclusive, but it does seem that it may be wrong to ascribe the general U-shaped cross section of the dales to glaciation, when it may represent their general pre-glacial form.

In great contrast to these sporadic signs of glacial erosion in the dales on the eastern side of the Pennine water parting is the form of the valleys across and west of the water parting in the Langstrothdale Chase area. Here is a remark-

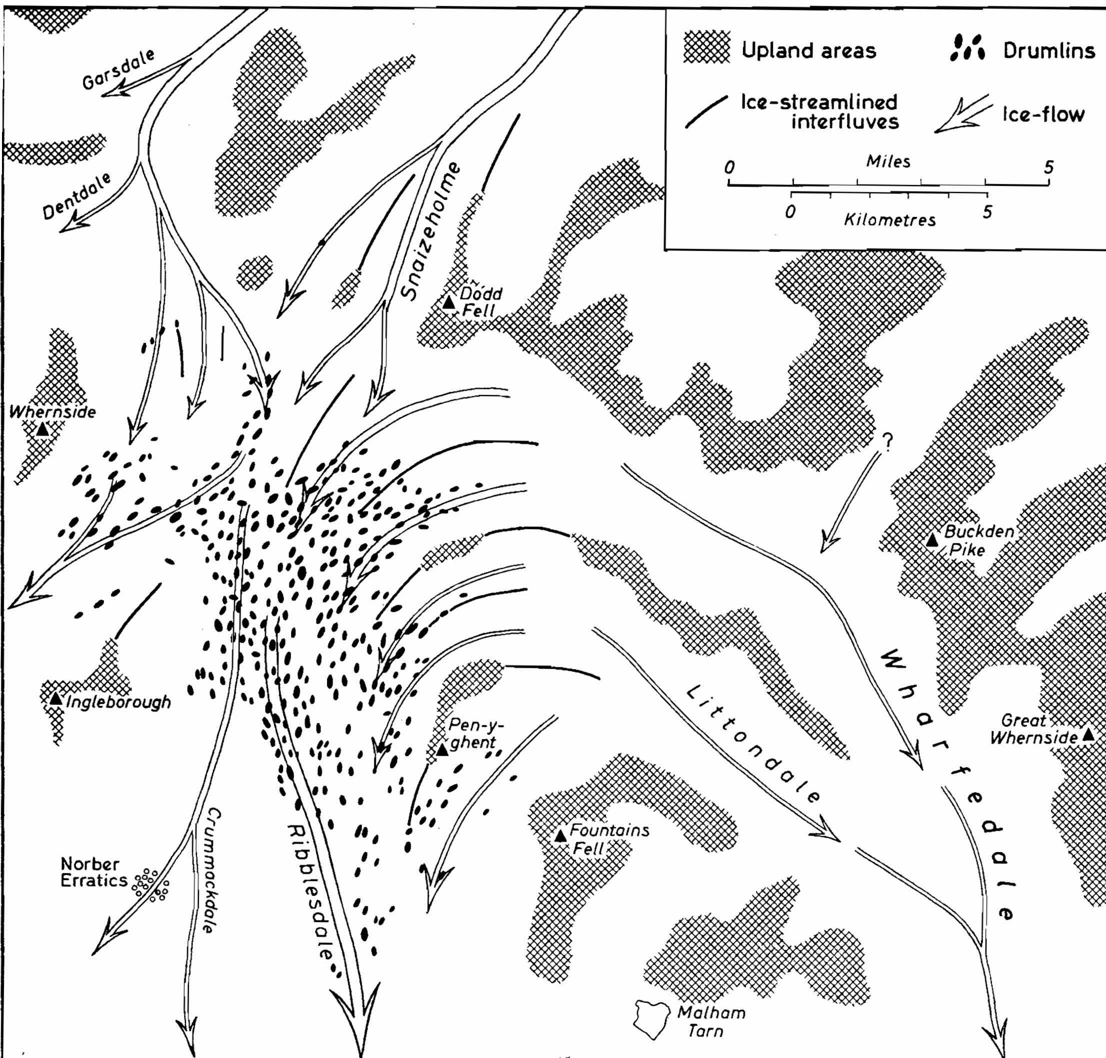

FIG. 1.
The glaciation of the area.

able series of curved, sub-parallel valleys whose open, flowing sides, with all sign of structural control of slope form suppressed, strongly suggest active and highly effective glacial erosion. The signs of erosion extend almost up to the 2,000-ft. surface, and several of the high interfluves between the valleys show signs of having been submerged beneath actively-moving ice. The smooth simple form of the lower interfluves is reminiscent of the streamlined hills produced by glacial erosion in Central Scotland (Linton, 1962). The swing southwards as these parallel troughs approach the Ribble is smooth and suggests a gradual change of direction of movement as the ice came increasingly under pressure from the ice moving over Ribblehead. This change of direction is well shown by the drumlins as Raistrick noted in 1930, but it is important to realize that the drumlins are secondary features and conform to the pattern of the major troughs.

The Pattern of Ice Movement

The main problem in interpreting the landforms of the Langstrothdale Chase area as the result of intensive glacial erosion is the source of the ice. Field inspection of the area shows that it must have been a local source region, the centre of dispersal lying in the area immediately south of Dodd Fell. The Fell itself and most of the ridge to the east show little sign of glacial erosion and seem to form an unaltered part of the 2,000-ft surface. To the west of the Fell some ice moved southwards from the high ground north of Hawes, and the Snaizeholme valley (leading south to Grove Head) is an example of what Linton (1963) has called an intrusive trough. Viewed from the ridge to the south, its constant width and amphitheatre-like upper end are consistent with an ice-stream moving up the valley and splaying out over a considerable length of the ridge. The southward- and westward-facing cliffs of the ridge north of Cam Houses suggests erosion by a southward-moving ice stream. Ice also moved south across Ribblehead (both from Widdale and Dentdale) but it did not contribute to erosion in the Langstrothdale Chase area.

A local centre of ice dispersion of some size is indicated by the absence of far-travelled erratics within the Malham area, and by this pattern of glacial troughs. In his discussion of the climate of Great Britain during the Pleistocene, Manley (1951) has emphasized the significance of the present centres of high rainfall in the pattern of source areas for ice in the glacial period. Unfortunately, we have no rainfall records at all for this critical area of Langstrothdale Chase, nor for the high ground north of Hawes, which seems to have functioned as a subsidiary source area. In his discussion of the possible sites of corrie glaciers in the Zone III (post-Allerod) period, Manley (1959) mentions the face of Ingleborough and the west-facing cliffs of Mallerstang Edge. In each case the likely precipitation is marginal for ice nourishment, and he suggests that snow-drifting may have contributed to these small ice patches. But of this main centre of dispersal Manley has nothing to say, apart from his general statement that "precipitation on the uplands . . . is slightly in excess of 70 inches" (Manley, 1959, p. 209). As we have seen, the field evidence throws doubt on this generalization, and the data from two marginal rainfall gauges supports our view. While the raingauge at the Tarn House has recorded a mean fall of 58 inches over the period 1949–63, a gauge at Ribblehead Station has a recorded mean of 79 inches, while a single year's data from the top of Fountains Fell gave 74 inches for a period when the Tarn received a little less than its average rainfall—suggesting an average for the Fell of 77 inches or 78 inches. (Data kindly supplied by the Field Centre Staff.) On the basis of these values the rainfall in the Dodd Fell area is certainly over 80 inches, and may well reach 90 inches in the wettest part: a value that would be associated with enough ice accumulation to account for the intense glacial erosion of this area.

III. Post-glacial modifications

It remains to consider briefly the post-glacial modification of the landscape. Although the individual features concerned are small, they contribute much of the distinctive character to the landforms. Off the limestone this includes slope forms due to mass movement; from minor features produced by soil creep to major rotational landslides. In the valleys the present river bed and flood-plain are post-glacial, as are the lowest terraces. On the plateaux the peat growth is post-glacial, and in many places a thick accumulation is now being dissected. On the limestone an assemblage of minor forms is found: shake-holes and blind valleys dissect the boulder clay or peat cover, screes lie below the scars, and much of the outcrop is exposed as bare limestone pavement.

The slope forms off the limestone are not, of course, restricted to this area. The processes of mass wasting are found in all the British uplands. But this is not to say that the features are fully understood. Particularly on steep slopes, terracettes, perhaps resulting from soil creep, perhaps entirely the result of treading by animals, are ubiquitous. Tongues of turf-covered debris that more certainly result from flow are quite common. Minor landslips are frequent where the streams have dissected a boulder clay cover. Major landslips are rare immediately around the Field Centre; they are restricted to areas with thicker shale outcrops and are most numerous in the Millstone Grit zone. An excellent example is the north face of Ilkley Moor (SE 1246), an extensive and very complex slide composed of many intersecting rotational slips. Another affected area is Mallerstang Edge (NY 8001). Although still not fully stable these slides are far less active than in the past, and it is usually agreed that these slips were far more mobile in the cold conditions of the immediate post-glacial period. This is no doubt as true for the minor slope forms as it is for these larger slides.

Slope Forms on the Limestone

The particular interest of the slopes of the Malham area is the contrast between slopes on and off the limestone. The major characteristic of the limestone slopes is the frequency of steep slope segments, a result of their great stability. Attention has already been drawn to the overhang at Kilnsey Crag, but little vertical crags or "scars" are ubiquitous on the limestone. It might seem that these are survivors of the same active post-glacial period that we have postulated for the slopes off the limestone. However, the absence of these scars from the valleys shaped by intensive glacial action demonstrates that they are older features, perhaps exhumed from beneath a soil cover during or after the last glaciation, but essentially pre-dating that glaciation.

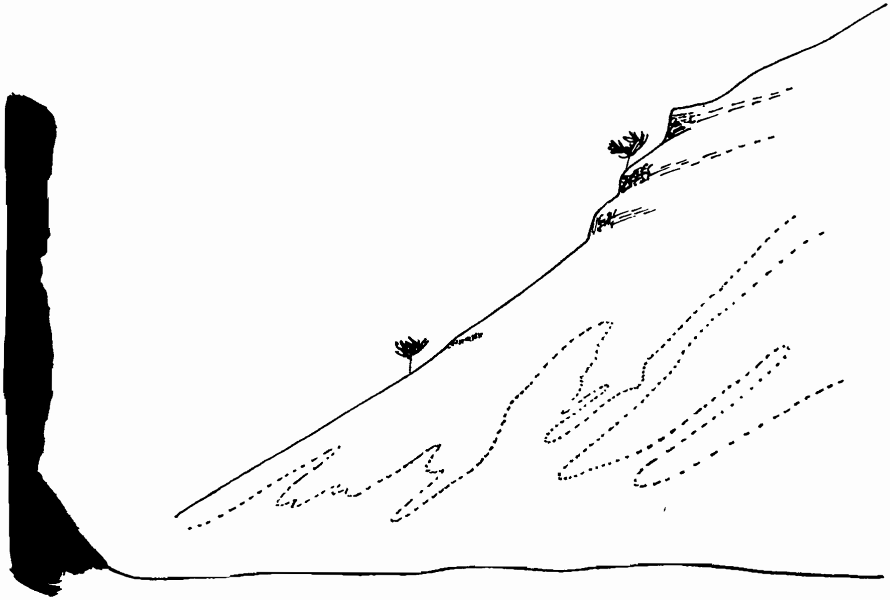

FIG. 2.

Slope profile below Gordale.

Note the long stretches of scree at a little over 30° (partly vegetated), the larger free faces or scars towards the top of the slope, and the almost completely obscured scar just above the lower tree. On the left the rock face on the Great Scar limestone, kept steep and free of scree by the stream at its base.

The detailed form of these scars shows their complex origin. They are deeply grooved with wide joints—the result of active solution beneath a soil cover. The exposed rocks are pitted by subaerial weathering and are greatly broken and shattered, no doubt by frost action. The original exploitation of the bedding and jointing of the limestone to rough out the form of the scars must have been by solution beneath a soil cover. The geologically recent stripping of much of this soil cover to expose the scars may in part be a response to a change of climate and/or vegetation on the slopes, or simply a response to increased erosion following rejuvenation of the valleys. A similar sequence of events has been described by Palmer (1957) to account for the Bridestones north of the Vale of Pickering, while the whole process has much in common with Linton's (1955) hypothesis of the formation of tors. The idea that these structural scarps and the benches above them were roughed out by preglacial or interglacial weathering is in direct contrast with the continental view that such features represent the results of periglacial activity—where many are in fact loosely called altiplanation terraces. The same divergence of opinion has, of course, arisen over the origin of tors (cf. Linton, 1955 with Palmer and Radley, 1961), although Palmer's view has been strongly refuted (Linton, 1964a).

The screes below these scars are almost the only contribution of the post-glacial period to slope development on the limestone. No measurements have yet been made in this area*, but experience elsewhere suggests that they are now accumulating too slowly for them to be accounted for by the speed of present processes. At the present rate of accumulation they could not have formed in the 10–15,000 years since deglaciation. Here again we must postulate more rapid development at some earlier stage in the post-glacial period, most probably before the vegetation was firmly re-established. That frost action is the principal process shattering the rock outcrops and so forming the screes is certainly very probable, but this has yet to be proved. The process would account for the slowness of the destruction of the screes (since there is so little surface water on the limestone) and for the angular nature of much of the scree material. It is important to realize that frost is at present destroying the scars and that as we have suggested, they were probably formed by some other process.

Small Closed Hollows

Large areas of the limestone are pock-marked by small cone-shaped "shake holes" as they are locally called. These features are very strongly localized and consideration of their distribution throws some light on their origin. Most striking perhaps, and best seen on an aerial photograph, are the lines that follow the outcrop of each of the Yoredale limestones. On the Great Scar limestone itself they are best developed where there is a cover of glacial drift. Where the limestone is bare or thinly covered with soil, shake holes are not found. This shows that these are subsidence cones, the material having been lost downwards through an open joint in the limestone. Although the concentration of aggressive water in these holes has intensified the solution of the underlying limestone, and individual joint blocks may have shifted position, there is rarely any sign of widespread collapse. The initiation and growth of these hollows can be traced from the development of their sides, and active development is shown by tears in the vegetation mantling their inner slopes. Once the sides have opened out to give a stable angle, further growth is much slower unless the local relief of the till or shale cover allows the hole to act as a sink for the surface run-off. When this does occur the floor is kept clear and the sides are generally far steeper. Size is no criterion of age since it is principally a function of the depth of material over the limestone. Similarly, the frequency of these shake holes seems to be primarily a function of the depth of the overburden: they increase rapidly in frequency up to a thickness of 6–8 feet, and then decline steadily in frequency (although increasing in individual size) until with more than 30–40 feet of overburden they are rare. Finally it should be noted that these subsidence forms are genetically quite distinct from the large solution forms of the limestone, the dolinas.

The hypothesis of development has been arrived at on the basis of observations in the Malham area. It places the hollows in a genetic sequence from shallower to deeper forms that is the exact reverse of the sequence proposed by Coleman and Balchin (1959) in their work on the closed depressions of the Mendip Hills. They assumed that the forms develop by infilling after initial

* M. M. Sweeting, 1966, pp. 183-185, reports on some measurements of the movement of scree-blocks.

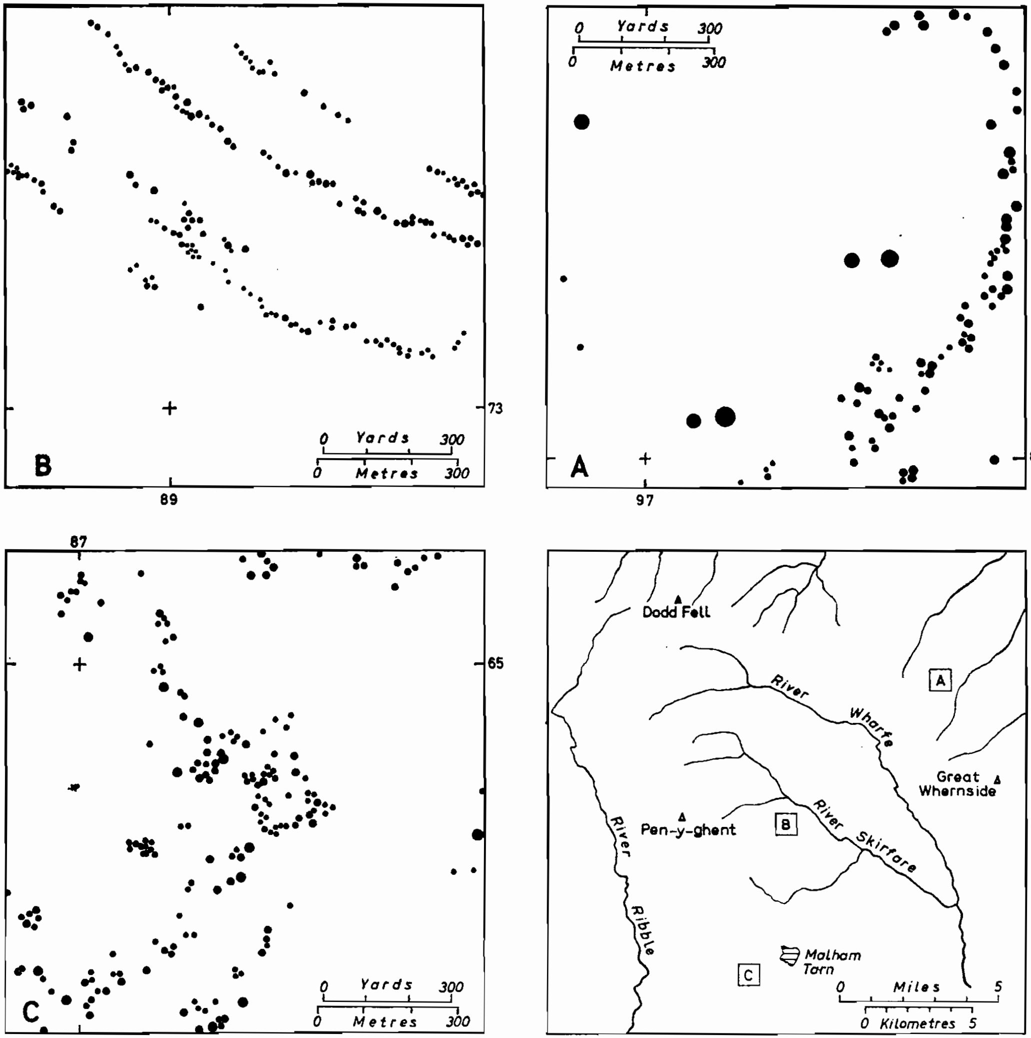

FIG. 3.

Closed hollows near Malham Tarn.

Three sample areas showing the range of size and spacing of closed hollows (shake holes). The aligned hollows in A and B are developed on beds of Yoredale limestone. Based on aerial photographs.

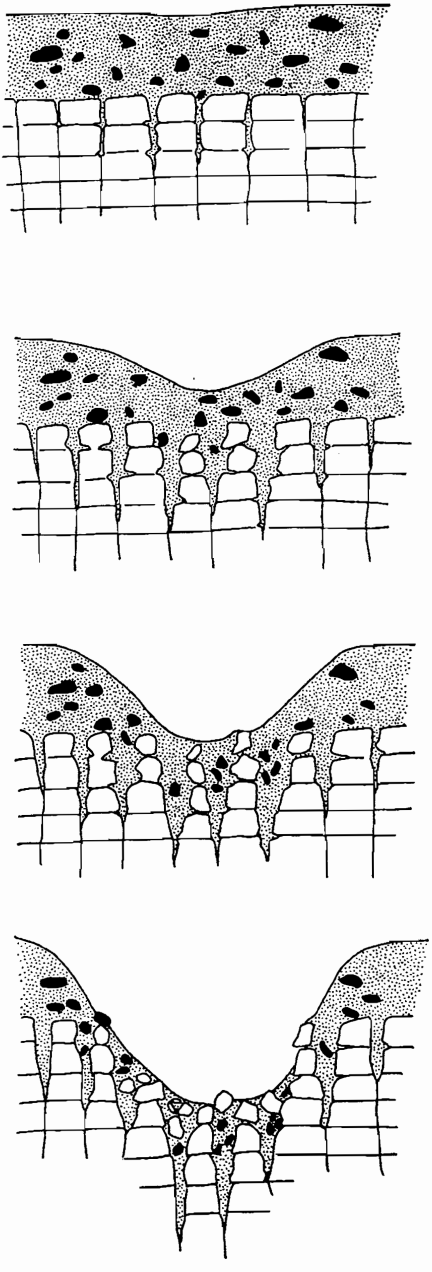

FIG. 4.

The development of a closed hollow in till by subsurface solution and subsidence.

collapse: field inspection of many examples around Malham makes this an untenable hypothesis. It should be noted that there is nothing in the forms described by Coleman and Balchin to make a reversed sequence impossible; indeed, other workers in the Mendips have argued in favour of solution in the interpretation of these forms, and have suggested that initiation by collapse is very rare.

FIG. 5.

Hunt Pot, west of Pen-y-ghent.

Here the wide rift developed along a slight fault has allowed the complete clearance of the hollow by the small stream, but the process of formation is very similar to that for the smaller shake holes.

Limestone pavement

The most distinctive feature of the limestone surface is the limestone pavement. It is a puzzling feature that has attracted the speculations of geologists, geomorphologists, botanists, pedologists, and many others. Even the problem of whether present areas are being colonized by vegetation or are being extended by stripping of the soil cover has produced no agreement. Although it is perhaps the most obvious question, it is not the most hopeful way of solving the origin of the pavement. A complication is the effect of man, his animals, his plough and his fire on the area (Raistrick and Holmes, 1962). The vegetation of the wet upland has been greatly altered in the last few thousand years and, even if we are able to establish present trends, they may reflect only this modified environment.

The real clue to the matter lies in the distinct forms of surface and subsurface weathering of the limestone (cf. Linton, 1964b). Where the rock is exposed to the elements, a very intricate surface develops as a result of the interplay of such processes as direct solution, frost action, the colonization of the stone by lichens, and so on. This may be called "fretting", and involves the etching out of the internal structure of the rock; from individual calcite crystals to the bedding and joint planes. On level surfaces, closed hollows may develop with small pools, and in these the natural acidity of the rainwater (today abnormally high due to atmospheric pollution) may be increased by decaying vegetation and a thin black soil may accumulate. This highly

FIG. 6.
Detail of sub-aerial "fretting" of a piece of limestone pavement.

FIG. 7.
A smooth "whale-back" ridge of limestone fairly recently exhumed from beneath a soil cover and not yet much altered by fretting.

irregular surface is in complete contrast with that found beneath a soil or drift cover. There the limestone is quite smooth in detail, with a very characteristic smooth-ridged form. The ridges are separated by equally smooth channels that are broad and open and arranged in the pattern of a system of mature river valleys. On the sides of the grikes these slope steeply downwards but maintain their smooth, broad-floored shape as they do so.

FIG. 8 (*above*). Early Stages of fragmentation of a limestone pavement.

FIG. 9 (*below*). Much more advanced mechanical fragmentation (probably largely by frost action). The layer of angular fragments clogs the grikes and allows slow colonization by vegetation. This is likely to be the eventual fate of all the limestone pavements.

Limestone pavement is formed by solution beneath a soil or drift layer. The speed of solution is here much more rapid than on limestone exposed to the air, for the soil/limestone contact is always wet while the soil water is usually at least as acid as rainwater, if not more acid. In addition, bacteriological attack on the limestone must here aid chemical solution (Jones, 1957). Under present conditions the overburden is being stripped off the pavements, either to go down the grikes or right off the slopes. This is exposing the smooth surface to subaerial weathering, and it is gradually broken up until it eventually disintegrates into a continuous covering of rather angular rocks. Naturally this occurs most rapidly where the limestone is rather fissile, with close bedding planes, but it is probably the eventual fate of all the exposed pavement. However, in the lower part of the Great Scar limestone the rock is very thickly bedded, and it is here that the most continuous and solid clints are found, separated by deep grikes that extend at least to the bedding plane below.

Field recognition of this sequence of events is aided by the very common repetition of a sequence of surface forms where the pavement is emerging today. At one edge is a scar, at the other is the yet unbroken drift cover. Above the scar, the pavement that has been longest exposed to the air, and has spent least time under the soil, is recognized by narrow grikes, the very extensive development of fretting, and the presence of many loose blocks detached from the main pavement. Some of these may have fallen into the grikes so starting to block them.

FIG. 10.

General sketch of the pavement above Malham Cove.
Note the slope left to the scar, the grass cover (left white) and the rather narrow ribs of limestone protruding above the grass and soil cover. (cf. Figs. 11 and 12.)

Farther back from the scar the grikes are rather wider and the clints are more deeply scored by wide grooves, although still distinctly affected by fretting. Moving away from the scar still farther the grikes continue to widen and the clints become increasingly deeply scored by the grooves. As the still drift-covered part of the limestone is approached, the clints not only become lower and narrower, but they are also markedly smoother. Near the turf, where stripping has been very recent, the surface is quite smooth and untouched by fretting. Often by this stage the grikes are wide and turf-floored, and in walking across the area it becomes easier to tread in them than to balance precariously on the narrow ridges of the clints. The area covered by turf often has an irregular surface form that reflects the form of the solid limestone beneath and, as the grikes are deepened and widened by sub-surface solution, the soil cover settles into the grikes and the clints are exhumed as bare ridges. Once exposed, they are attacked by the weather and gradually fretted, but the speed of solution appears to be slower than it was beneath the soil.

FIG. 11.
Broad tabular clints separated by narrow grikes.
This will have had very little (or no) drift cover and solution has been very limited. Clints of this form are found at the extreme right of Fig. 10.

FIG. 12.
Narrower clints and wider grikes than in Fig. 11, the result of a deeper (or longer-lasting) soil cover.

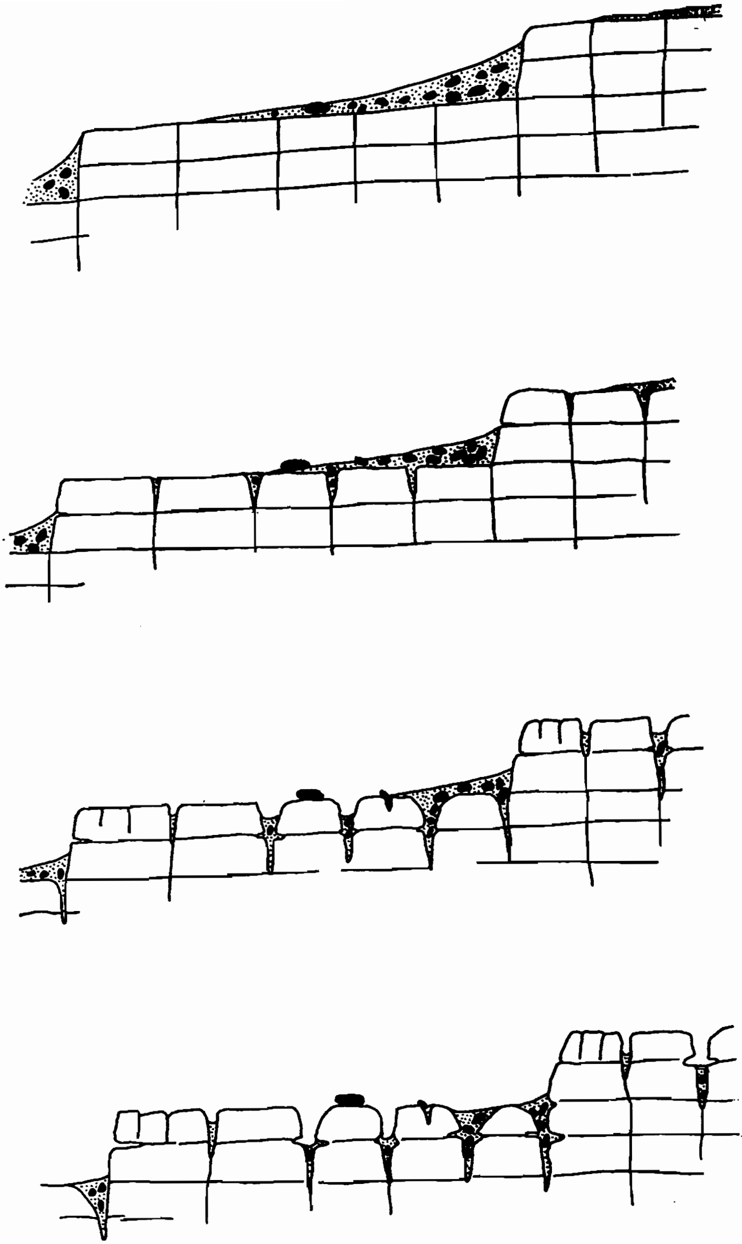

FIG. 13.

Diagram showing the formation of limestone pavement after glaciation, the removal of loose limestone blocks and the deposition of till.

Comparison with the scars (which, as we have seen, have not yet formed on recently-glaciated valley sides) suggests that by no means all of this development is post-glacial, and much of the pavement may predate the Last Glaciation. The contribution of glaciation has been to clear the pavements of their former soil cover, often substituting for this a layer of acid till. Where this till is thin or absent bare pavement outcrops over wide areas, often stripped down to a particular bedding plane: probably partly as a direct result of glacial erosion removing well-jointed material above that layer. This glacial action is probably also responsible for the clearing away of the detached blocks (analogous to the corestones of tors) that would be anticipated to be a common result of the joint-controlled solution of the limestone. Such blocks are commonly seen where deep pits are dug in deep soils on the limestone, and their absence from the main areas of pavement is very marked (Pigott, 1965). The whole process is again closely analogous to the formation of tors by sub-surface weathering: indeed, like the limestone blocks, tors are absent from the area covered by the Last Glaciation since they have been swept away by the ice, although they are quite common just beyond the limit of the last ice-sheet (see map in Palmer and Radley, 1961, although their explanation is quite different).

FIG. 14.

Pavement developed on Millstone Grit, Fountains Fell. (Grid. ref. 869705.)
The blocks are less rounded than limestone clints, but they have been formed by chemical weathering beneath a soil cover and subsequently exhumed as the soil is eroded away.

It may also be noted that the Millstone Grit shows a similar contrast between smooth sub-surface forms and the results of atmospheric weathering. Even more striking is the occurrence high on Fountains Fell of a pavement developed by analogous processes on a bed of grit. The grikes are far narrower than those commonly found on the limestone, but the general similarity of form is unmistakable. Finally, we may note that the Derbyshire area, which was not glaciated during the Last Glaciation (and perhaps longer ago than that) has no limestone pavements at all, strongly suggesting that glaciation is a critical factor in their exposure. Pigott (1965) has suggested that the depth of glacial truncation is the basic factor in pavement form and does not believe that post-glacial solution has had any significant effect. Compromise between his view and the stress laid here on solution beneath a soil layer is obviously possible.

Contemporary Solution of the Limestone

Despite the recent very welcome interest shown in the measurement of present-day processes, there is so far very little data available that is relevant to the Malham area. Some work has been done on the rate of solution of limestone in various parts of the British Isles, while Dr. Sweeting (1965) has recently drawn attention to the early estimates of McKenny Hughes (1886) and Goodchild (1890). The former merely noted that the height of pedestals under perched blocks was never more than 18 inches but believed conditions so variable that he would not calculate the time since deglaciation. The latter used the rate of weathering of tombstones, building stones and newly-exposed pavement and concluded that the present average rate of surface lowering was one inch in 250–500 years. The exact date of deglaciation here is not known, but extrapolation on the basis of 10,000 years gives a total lowering of 17–33 inches. A more recent estimate by Dr. Sweeting (1964) on the basis of the $CaCO_3$ content of springs south of the Field Centre gives a surface lowering of 0·04 mm./year, or about one inch in 600 years. This estimate is supported by the fact that, as Hughes noted, the pedestals under boulders such as the Norber erratics are about 15–18 inches high; since the Last Glaciation the surface beneath these Silurian erratics has been protected from the solution that has gone on everywhere else. The figures available also show that the overall rate of lowering is lower in the Malham area than in Derbyshire. Since the climate and the lithology of the limestone are fairly similar, it has been suggested (Sweeting, 1964) that the difference is a result of the large areas covered by bare limestone in the Malham area. If she is correct, it will be seen that we have here quantitative evidence for the difference in rates of solution between bare limestone and that buried beneath a soil cover that has already been proposed as the explanation of the detailed form of the pavements.

Peat and Peat Erosion

The final landforms that can receive discussion here are those developed on the extensive peat cover of the uplands. The stratigraphy of the peat is well known, and it is all of post-glacial origin (Pearsall, 1950). However, the predominant aspect of the peat moss today is erosion, reducing the peat cover to an intensely gullied series of "haggs". The possible reasons for this change from widespread accumulation to widespread erosion are many, and it is difficult to choose between the hypotheses that have been suggested (for a summary discussion see Barnes, 1963). The extreme susceptibility of the peat to erosion once the vegetation cover has been breached (enhanced by the high rainfall that is a necessary requisite for peat growth) means that any event leading to the breaking up of the vegetation cover can initiate erosion. A change of climate, grazing, burning, the instability of the peat after it reaches a certain thickness: all have been suggested. The first possibility is likely to have operated over a long period (say a few thousand years), the next two could have occurred long ago when pre-historic man entered the area, but have certainly been intensified in the last few centuries. The last has the attraction of any uniformitarian theory, and suggests a cyclic development as it is capable of repetition. The first three possibilities suggest that there is some such periodicity in erosion (perhaps with its culmination at the present time), the last allows a greater variation over time and space.

Whatever the fundamental cause, the progress of gullying and the recession of peat haggs are the same, and readily fit into a geomorphological pattern. The role of the heather or sphagnum layer in maintaining the steep scarps on the soft peat is clear in the field. The tenacity of the surface mat is such that natural bridges and tunnels can occur. But most of the erosion consists in the simple extension and coalescence of the gullies, the changing patterns being closely related to the angle of slope as Miss Bower (1961) has shown. The suggestion (Johnson and Dunham, 1963) that the occurrence of these occasional natural bridges means that the cycle of peat erosion is "exactly paralleled with the erosional cycle in limestone country" seems quite unreasonable, and this alleged similarity would repay investigation in the field.

The Karst Cycle

Any test of the analogy suggested by Johnson must rest on knowledge of the karst cycle itself, and this concept may form an epilogue to this rather long account. The karst cycle was developed by Cvijic in Jugoslavia and has been widely applied to limestone landscapes elsewhere. It may confidently be claimed that the area around Malham is the most mature example of a karst landscape in this country. But how mature is it in terms of Cvijic's cycle? Firstly, of course, the landscape is markedly polycyclic. The most mature elements are the dolinas, and as we have seen these are restricted to the highest areas of limestone that were soon stripped of their Yoredale cover. The remaining features of the area—more common at lower levels where the recent erosion working back up the dales has cut into the Great Scar limestone—are all developed very early in the cycle. Underground drainage, caves, gorges and so on are all features of youth. In other words, most of the landscape is in a stage of late youth: even the dolina-studded plateau of the Parson's Pulpit area is at most in early maturity. One important corollary of this has already been pointed out by Coleman and Balchin (1959): the popular tendency to account for narrow gorges as unroofed caverns is untenable, for such features are only found in very mature karst landscapes. Gordale, Trow Gill, Malham Cove are all features of subaerial erosion. Gordale and Trow Gill are youthful gorges, their steep or overhanging sides surviving, as at Kilnsey Crag, because of the particular characteristics of limestone. Malham Cove may be a unique feature, but is nothing more than the result of knickpoint recession and spring sapping back from the Craven fault. Limestone landforms may be exotic in appearance, but they have necessarily been fashioned by the same processes that operate on all the rocks of this country.

Acknowledgements

This paper would never have been written but for the kind encouragement of the late Paul Holmes and owes much to his knowledge of the karst scenery around the centre and the problems it poses. My thanks are due to Douglas Bremner, Deirdre Williams and Ian Mercer who have read the text and I am particularly grateful to Don Aldridge for the field sketches used in the article.

Since this account was written two important papers on limestone pavements in the Malham area have been published. They are "Aspects of the biological weathering of limestone pavement", by R. J. Jones, *Proc. Geologists' Assoc.*, **76** (4), 1965, pp. 421–433. This includes a useful series of photographs of typical pavement forms, including a vertical mosaic of a section of pavement that clearly shows the reduction in clint size towards a remnant area of drift. The second paper is "The weathering of limestones", by M. M. Sweeting, in: *Essays in Geomorphology*, ed. G. H. Dury, Heinemann Educational Books Ltd., 1966. This account lays particular stress on the role of glaciation in initiating the formation of limestone pavements.

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