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EXPLANATORY DESCRIPTION OF THE LANDFORMS OF THE MALHAM AREA

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ABSTRACT

Although the present landscape of the Malham area (North Yorkshire) may appear to result primarily from the solution weathering of limestone, the effects of glaciation are never far removed and several features of the preglacial landscape still persist—although, naturally, in a modified form. This paper aims to introduce the visitor to a framework of information and interpretation that should enable him (or her) to place any particular landform encountered. It will not, however, provide a positive explanation in every case for we can only *deduce* how and when a form originated and if some of the facts are strong enough to allow some certainty in explanation, others are still controversial.

INTRODUCTION

MALHAM Tarn lies at about 400 m, high in the Pennines, and at the centre of one of the most remarkable areas of limestone landscape in the British Isles. Yet to describe the area solely in terms of the rather special landforms developed under conditions of karstic erosion (the term karst comes from the bare limestone areas of northwest Jugoslavia) is not enough; there are impervious rocks above and below the limestone, while the action of ice is also readily seen, not only in the Tarn basin itself, but also in the trough-like form of the Yorkshire Dales.

Although the geology of the Malham area (O'Connor, 1964) has no rocks between the Millstone Grit and those of Quaternary age, a gap of about 200 Myr (Million years), we know from our general understanding of the evolution of the British Isles that most of the landforms must have evolved during the last 30 Myr, possibly even over a shorter period than that. Some forms will represent rather minor modifications of shapes roughed out in the Early Tertiary, or even the Late Cretaceous, but it will be difficult to establish this on morphological evidence alone. Even the last 30 Myr or so is still a long period of time, and we may usefully divide it into three stages of very unequal length. The longest is the 20–30 Myr of preglacial time, followed by the 1 Myr of later Quaternary time when several glaciations occurred, and finally, by postglacial time, here about 12,000 yr. These periods represent a very simple division of the time during which the landforms have evolved, but they are nevertheless a useful basis on which to study the geomorphology of the area. All the older landforms will necessarily be the composite product of the successive stages, and thus complex. Even when study focuses on postglacial forms, it will be found that there are inconsistencies between current processes and those operating in the early postglacial period. No doubt earlier periods were equally complex, but with the exception of the caves, evidence for this is too fragmentary to allow any detailed reconstruction.

The aim of this account is to introduce the visitor to a framework of information and interpretation for some of the landforms in this area. More significantly, it should enable any particular form to be fitted within that framework. We can only deduce how and when particular landforms originated, but many of the constraints are strong enough to allow some certainty in interpretation and thus general agreement about the evolution of this landscape. Inevitably, some features are more controversial than others, but here too the concepts place some limitation on the range of explanations that might be valid, and may in time point to particular lines of inquiry that might lead to a more certain explanation.

THE REGIONAL SETTING

The landforms of this area are related to the broad patterns of geology, structure, relief and glaciation, as well as to the contemporary environment, especially climate and vegetation, the latter dominated by man. Some of these controls are familiar enough, but a few points may usefully be made by way of introduction.

Regional Structure

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 rhythmically repeated beds of limestone, shale and grit of the Yoredale Series to the thick shales and topographically dominant grits of the Millstone Grit Series. North of the Craven faults (shown in Fig. 21) this sequence rests on a strongly-folded basement of Lower Palaeozoic rocks that is exposed in several of the main valleys, and also at Malham Tarn itself. The Craven faults are the southern limit of a fault-bounded block. In Carboniferous times the shallower water of the more stable block was the site of limestone sedimentation, while the more rapidly subsiding trough to the south was filled instead with a thick series of shales. These are known as the Clitheroe and Pendleside shales and limestones, and the, overlying, 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 lowlands to the south. Along the line of the Mid-Craven fault occur reef knolls, related to the depositional conditions at the margin of the Carboniferous blocks, which have been exhumed from their shale cover to form a striking series of isolated hills. The contrast has been further emphasised by later movements along the bounding faults.

There is broad agreement between relief and structure within the block, and this has been interpreted in two very different ways. Either the domed structure of the block was created in later Tertiary time (sometime within the last 2–30 Myr) or the relief reflects differential erosion during the Late Tertiary of a gently domed block that was created by structural movements something like 200 Myr ago. Rather curiously, it is not easy to find evidence that allows us to distinguish between these two ideas. We know that the block, with its bounding faults, was established in Carboniferous times, because of the contrast in the sedimentary environment already described. But the possibility of Late Tertiary movement on at least some of the bounding faults is not easy to rule out, and there has been quite a lot of argument about this point.

Tectonic stability

The idea of recent tectonic movements was unfashionable for most of this century; in the nineteenth century the concept of uniformitarianism perceived that differential erosion was as capable of creating major contrasts between upland and lowland as was tectonic movement. Indeed, an attitude grew up that explained many features in the British Isles as the result of a long period of stability, and the recognition of erosion surface stairways correlated from one structural feature to another seemed to support this idea. If the 300 m erosion surface of the Malham area is a reality, and if it may be correlated with a similar feature in Bowland or Rossendale Forests, then we have shown that any movement along the Craven faults must predate that planation surface. However, we are now far more sceptical about the reality of these upland surfaces than we were, and even if we accept that in both areas an upland surface at 300 m is a reality, we are quite unable to date either feature accurately. Hence correlation by altitude alone is a circular argument depending on an assumption of stability.

In recent years, knowledge of tectonically active areas coupled with modern theories of plate tectonics have made stability something of a special case, and many geologists and geomorphologists are far more willing to consider neotectonic movements. Whether they would go so far as Corbel (1951) in regarding the bounding fault-line scarps as true fault scarps is hard to say, but they are inclined (e.g. Sweeting, 1974) to point to the occasional earthquakes along the bounding faults as evidence that uplift continues to the present day. Professor King would go further and has argued (1962) that the correspondence between the structural form of the block, the relief, and the drainage pattern, suggests a common neotectonic origin for all three. We shall return to the point when we discuss the origin of the river pattern at the end of the paper. For the moment the most important conclusion is that since the point is so very difficult to prove, and evidence is so hard to collect, then while the problem is of great intellectual interest, it must really matter very little in terms of our explanatory description of the landforms.

Geology and relief

Thus, either by differential erosion or by differential uplift (and perhaps most probably by a combination of them), the broad relief of the Pennines was outlined. A consistent pattern of drainage and relief was established, with the Irish Sea/North Sea water-parting close to the western crest of the Pennines, and an area of lower land coinciding with the Trough of Bowland, the Aire-Ribble gap. In earlier glaciations the Pennines must have been completely ice-covered, but ice was relatively inactive over most of the high ground south of the Aire gap. This contrast was brought out even more clearly in the last (Devensian) glaciation, when active ice streamed over the Askrigg Block, but failed to surmount the high ground south of the Aire. Then, as in the earlier glaciations, it was able to escape southwards on both sides of the southern Pennines. The asymmetry of the precipitation pattern over the British Isles was at least as marked in the Pleistocene as it is now, so that each ice-sheet had an eastward component of movement as well as the general southward flow. Invading ice from Scotland and the Lake District moved out of the southern end of the Eden valley and then flowed southeastwards across the Askrigg Block.

On the Askrigg Block the almost horizontal rocks give a strong element of repetition to the landscape (Fig. 1). 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, sparkling river, cascading across thick beds of limestone, the bright green of the open riverside

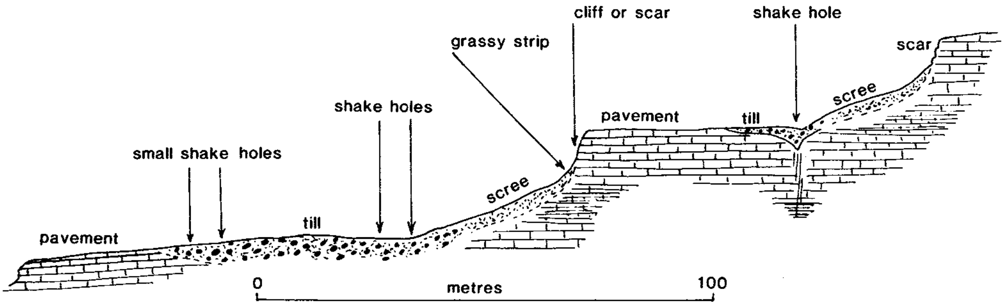

FIG. 1.
The elements of a limestone hillside (after Sweeting, 1966).

meadow, the steep rock-terraced valley sides, and the higher fells where soil and peat cover the rocks and only the pock-marks of shake holes mark the limestone beds within 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 remarkable 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 the descending stream. Viewed from across a valley, or better still on an aerial photograph, regular lines of conical shakeholes follow the outcrop of each limestone bed. Below the scar or steeper slope that marks the outcrop of each limestone band 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 irregular profile of the Yoredale slopes. In places the drift cover is thicker and peat may then form on the bench above the limestone bluff; elsewhere erosion has exposed the limestone surface, and it is in such places that some of the deepest and most intensely fluted grikes are found, no doubt as a result of the very acid (i.e. aggressive) water which reaches these higher limestone bands.

CONTEMPORARY AND POSTGLACIAL PROCESS AND FORM

Solution

The dominant process across the whole area is solution, for much of the succession is composed of limestones. Once in solution material passes out of the area to the sea, without the storage en route that is characteristic of the transport of solid sediment. This very efficient process is based on the solubility of calcium carbonate (and magnesium carbonate where this occurs) in rainwater. Hardness values of up to 250 mgL^{-1}* in cave drips and percolation spring water show that it is the carbon dioxide in soil air which makes the percolating water aggressive. Rainwater falling directly onto bare limestone can only dissolve 74 mgL^{-1} if it is solely dependent on atmospheric carbon dioxide, but small pools in limestone (Sweeting, 1966) contained water with 120–140 mgL^{-1} calcium carbonate, perhaps in part

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* 250 mgL^{-1}=250 milligrammes of calcium carbonate per Litre.

because of "acid" rain (silica, sulphur dioxide and other pollutants), but certainly also because of algae and other producers of carbon dioxide. In the same way, the most aggressive water (typically 40–50 $\mathrm{mgL^{-1}}$) drains off the peaty soils and peat haggs overlying the Yoredale sandstones, the Millstone Grit and related tills or head. This normally plunges into swallow holes on the Yoredale limestones or the Great Scar limestone, flowing relatively rapidly through the rock to emerge at valley bottom springs within hours, or at most days. Under these circumstances hardness values at the resurgences are typically 120 $\mathrm{mgL^{-1}}$ and may fall to 90 $\mathrm{mgL^{-1}}$ at time of flood. Some resurgences have given values as low as 15–20 $\mathrm{mgL^{-1}}$ after prolonged flood flows. The rate of erosion is a function of the volume of water (i.e. the annual precipitation) as well as the mean hardness of the discharge, and although hardness values are lower than in some other British limestone areas (e.g. the Mendips) this is offset by the higher rainfall.

Richardson (1974) sums up the characteristics of this area in the following words: "Perhaps the most distinctive feature of the Northwest England karst hydrology is the very low total hardness of the resurgent water, especially when compared with that in Mendip. This contrast is also reflected by the rates of increase of the solutional load through the known caves in the different regions. One of the main factors responsible for these differences must be the much larger quantities of water flowing through the caves of NW England. Only a small proportion of the total karst water is responsible for nearly all the solutional effort of cave enlargement in this region. . . . The low total hardnesses of the Yorkshire resurgences further reflect the very high ratio of swallet water to percolation water in the largest karst drainage systems."

The uptake of limestone in solution leads to a reduction of limestone volume, partly at the surface, but also within the rock itself. Sweeting (1966) has estimated that about half the solution results in surface lowering, the rest in solution within the limestone, not so much in the caves, as in the various joints and bedding planes along which the percolating water moves. In the larger stream passages, a significant amount of enlargement is due to corrasion, especially where siliceous sediments are washed in or are still being removed following glacial plugging. Phreatic* passages are enlarged by solution below the water table, while many vadose passages originated as phreatic passages when the water table within the limestone was at a higher level than today. The overall loss of limestone has been calculated at 83 $\mathrm{m^3\ km^{-2}}$ or 83 mm $10^3\ \mathrm{yr^{-1}}$ (83 Bubnoff units), of which about 40 mm $10^3\ \mathrm{yr^{-1}}$ is at the surface (Sweeting, 1966). This figure is consistent with the occurrence of pedestals beneath glacial erratics of 40–50 cm and created in the 12,000 yr of postglacial time, for example, those under the Palaeozoic erratics at Norber Brow (Fig. 2). Locally, solution rates can be far higher; an experimental plot on newly-stripped limestone with water draining onto the rock from peat recorded up to 3–5 cm lowering in 13 yr, or about 3,000 mm $10^3\ \mathrm{yr^{-1}}$. Runnels (i.e. locally concentrated erosion) 7–15 cm deep were also developed, suggesting a potential incision of peaty streams of up to 10 m in 1,000 yr. In practice, streams as aggressive as this are going to find their way into the underground system before such deep slot gorges are formed, but it does allow estimation of the likely age of such features along aggressive streams.

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[*] Water flow above the water table is termed "vadose" and below it "phreatic" (see also glossary).

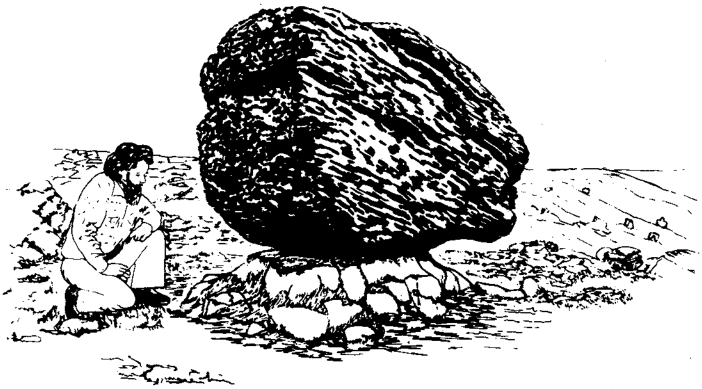

FIG. 2.
Silurian erratic at Norber Brow, resting on a limestone pedestal. The average height of the pedestal is a measure of postglacial surface lowering by solution.

Mechanical erosion

Subaerial erosion and stream transport of eroded sediment from clastic rocks in this area has not been measured with any precision. The rate must approach (or may exceed) the surface lowering figure of 40 mm 10^3 yr^{-1} recorded for the limestone, particularly where till or head are being eroded. There is no clear altitudinal differentiation of the Millstone Grit and the Carboniferous limestone, other than that related to their relative stratigraphical positions. The grit moors east of the Wharfe are less dissected than most of the area nearer Malham, but it is impossible separately to identify the roles of glacial erosion and preglacial fluvial erosion in bringing this about. For a time the limestone is protected by its ability to swallow surface water, but it does not look as though, over the long term, its relative altitude could remain higher than that of the Millstone Grit. Further work on overall erosion rates in catchments on the Millstone Grit and Yoredales is needed to substantiate this point.

Much of the land surface is dissected by stream valleys of various shapes and sizes, with valley-side slopes related to stream channel slopes as well as to geology. These valley slopes have developed with varying conditions of basal removal (depending on valley width and the pattern of stream migration) and in turn there is feedback from the material derived from the slopes to the stream banks and channel. Overall an association of steeper slopes with steeper channels and with more active basal removal can be observed. Dry valleys on the limestone appear to show similar relationships, suggesting that they have undergone little modification since they were last occupied by streams.

Limestone pavements

While it is important not to forget the dominance of a "rain and rivers" landscape in this area, there remain two features which give it its characteristic appearance. These are the scars with their associated screes, and the limestone pavements. In places the latter form 20 per cent or even more of the land surface (although only a few per cent of the whole land area) while the former are found on all resistant rocks, but most commonly on the Great Scar limestone. Both forms are being modified today, and their minor features relate to contemporary or relatively recent postglacial processes; both forms originated in the Pleistocene.

It is not impossible to envisage local circumstances which might lead to the creation of a scar or a fragment of limestone pavement. Indeed, Moisley (1955), by describing the way in which seepage at a thin shale band might lead to the cutting back of a scar and the extension of a level pavement on the upper surface of the bed below, indicated one such process. Nevertheless, the bulk of the pavement and most of the scars were formed in other ways. Once created, they have suffered modification (Fig. 3); in the long run that means extinction or at the very least transformation, but postglacial time is not the long-run, geomorphologically speaking. We have already noted surface lowering on the pavements of about 50 cm in postglacial time, with far higher rates where aggressive water gets onto that surface. This suggests that open grikes (whether or not they are filled with soil or till), flutes on the margin of clints, and loose fragments of limestone on the pavement surface are all postglacial forms. The only place where such changes have been inhibited is under calcareous till, where percolating water is still kept busy decalcifying the till, and glacial striae are preserved untouched on the underlying pavement surface. Wherever the overlying till or soil is decalcified (or had little or no calcium carbonate in it originally) we would expect solution to be more effective than where bare limestone is at the surface, because of the higher carbon dioxide content of soil air as compared with the atmosphere.

We may follow Goldie (1973) in noting the following factors as important in bringing about the great variety of pavement types: (1) *structure*, especially the jointing pattern; (2) the *lithology* of the limestone; (3) the severity of *glacial scour*; and (4) postglacial (including contemporary) *chemical and biological processes*, including grazing by animals and disturbance by man. There will always be found two sets of joints at right angles, and in places (especially where stress has been high near the bounding faults) a third set at an oblique angle. The further apart the joints, the more massive the clints, and the less likely they are to be broken up by subsequent weathering (Figs. 4 and 5). However, lithological differences are responsible for the

FIG. 3.

Detail of sub-aerial "fretting" of a piece of limestone pavement by contemporary solution (from Clayton, 1966).

FIG. 4.
Broad tabular clints separated by narrow grikes. This pavement will have had little (or no) drift cover and solution has been very limited (from Clayton, 1966).

FIG. 5.
Narrower clints and wider grikes than in Fig. 4, the result of a combination of closer jointing and more intensive solution (from Clayton, 1966).

FIG. 6.
Pavement developed on Millstone Grit, Fountains Fell (National Grid reference 869705). The blocks are less rounded than limestone clints, but they reflect the same processes of pre- and postglacial chemical weathering and stripping by glacial erosion (from Clayton, 1966).

greatest contrasts in pavement type, and Sweeting distinguishes two factors here: (1) the lithology of the limestone itself, distinguishing sparite (coarse-grained) from micritic (fine-grained) limestones, and (2) the thickness of the beds (see also Fig. 6). As with the closeness of the jointing, thinly bedded limestones are most likely to be broken down by contemporary weathering processes, often disintegrating into a sort of horizontal talus of loose fragments called locally *shillow* or *shillet* (Figs. 7 and 8). Dr. Sweeting has also conducted experiments to try and determine how far the pavements are still being laid bare by the washing of overlying till or soil into the grikes, and how far vegetation is colonising them, and assisting the build up of soil in the grikes. The occurrence of clints beneath a soil cover is not evidence of burial. Indeed, their formation beneath soil is rather probable where the latter is not calcareous. However, in an experimental area on Twistleton Scars (near Ingleton) over a 13-year period the edge of the grass cover advanced 2–5 cm onto the clint surface, while the grikes became about 10 cm shallower through the inwashing of

FIG. 7.
Early stages of the fragmentation of a limestone pavement (from Clayton, 1966).

FIG. 8.
Much more advanced mechanical fragmentation than in Fig. 7, probably achieved largely by frost action. The layer of angular fragments clogs the grikes and allows slow colonisation by vegetation. This is likely to be the eventual fate of all the limestone pavements (from Clayton, 1966).

material to build up the soil (Sweeting, 1966). Obviously, firm statements about contemporary change would require many more observations, preferably at a carefully chosen sample of properly representative sites.

From measurements of pavement morphometry at 50 sites ranging from Twistleton Scar (above Chapel le Dale) in the west to the eastern side of Wharfedale, Goldie (1973) showed that values for clint length, clint width and grike depth varied substantially on a regional basis. Thus while clint width was most commonly 0.6–0.9 m and never more than 2.44 m at Malham, it was most commonly 0.3–0.6 m around Ingleborough, yet with values as high as 8.5 m in places. She also noted that alongside these basic features of pavement size, there were also variations in the appearance or "style" of the pavement (Fig. 9). These characteristics included the shape of the clint surfaces, the nature of the microrelief, and the extent to which it had disintegrated into flags, or flaky fragments. These variations in style seemed to be independent of the variations in dimensions. She made a wide-ranging examination of the possible causes of the variations in size attributes, including topographic position in relation to the proximity of the scar edge or to adjacent drift cover, the severity of glacial erosion, limestone petrology and human activities, including the removal of turf and rockery stone. After considering these variables, Goldie concluded that the most important controls were structural attributes (joint and bedding plane spacing), but that the varying intensity of glacial erosion was also an important control, while some explanation came from a lithological variable; the percentage of sparry calcite. Her data are summarised in Table 1.

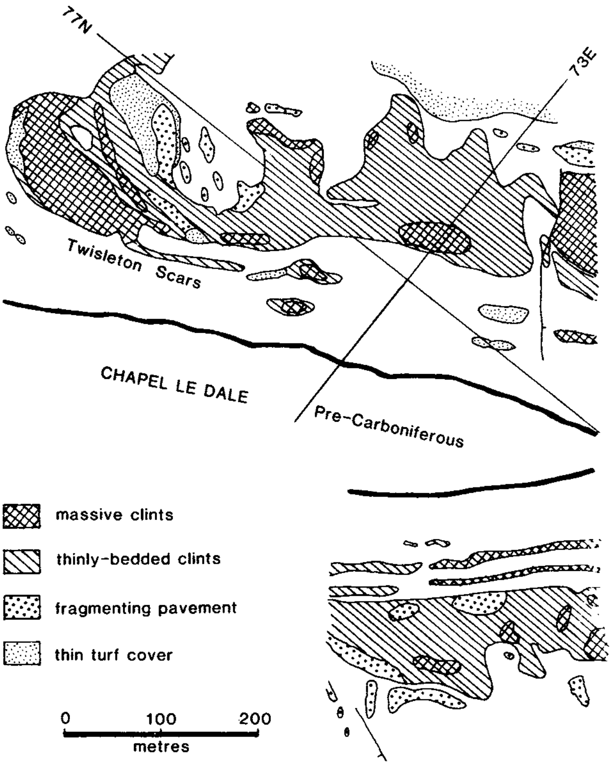

FIG. 9.
The pattern of limestone pavements of different types above Chapel le Dale (after Sweeting, 1966).

Table 1 (*all values in metres*) *from Goldie* (*1973*).

	Grikes		Clints	
	Depth	Width	Width	Length
Ingleborough				
Twisleton Scar	1.13	0.1778	1.19	2.19
Scales Moor	1.06	0.2209	1.49	3.17
Scar Close	1.18	0.165	1.95	4.04
Souther Scales	1.17	0.2045	1.69	5.67
Raven Scar	0.49	0.1384	0.53	1.68
White Scars	0.67	0.2642	1.19	2.13
Clapdale Scars	0.69	0.0787	0.36	0.86
Borrins Moor	1.32	0.1981	1.75	3.97
Mean	1.07	0.2042	1.47	3.35
S.D.	0.49	0.1008	1.23	3.16
Malham				
Malham Cove	1.0	0.1524	1.06	2.94
Back Pasture	0.81	0.2057	0.55	2.64
Pen-y-Ghent	0.85	0.2184	0.82	1.92
Mean	0.97	0.1925	0.89	2.41
S.D.	0.46	0.1394	0.49	2.06
Wharfedale				
Oughtershaw	0.79	0.2083	0.99	2.77
Halton	0.86	0.1397	0.51	1.33
Blue Scar	1.05	0.127	0.48	1.89
Low Far Moor	0.66	0.0889	0.93	1.51
Threshfield, etc	0.59	0.2553	0.84	2.09
Conistone	0.7	0.1181	0.86	1.84
Grass Wood	0.81	0.1854	0.94	1.6
Mean	0.78	0.1874	0.91	1.85
S.D.	0.28	0.1351	0.5	0.91
Total sample				
Mean	0.98	0.1973	1.23	2.83
S.D.	0.46	0.1176	1.0	2.7

Limestone scars and screes

Scars, too, will suffer erosion from solution, but since water runs off them easily this will usually open up joints and so dissect the cliff face. The removal of rocks through failure along such joints and bedding planes by rockfall will be a more efficient process than solution on the face itself, since large pieces are detached. Rockfall will be aided by frost action, and there is some suggestion that present rates of detachment are inadequate to have formed the screes in postglacial time. Thus the screes are usually attributed to the very favourable freeze-thaw environment of early postglacial time, when the local ice-sheets were still decaying. However, it must also be remembered that when these scars were first deglaciated, pressure release would have promoted jointing, and that many blocks would have been poised to fall. After the easier fragments were detached, the rate of rockfall inevitably declined. One other factor makes overestimation of the past rate of rockfall common, and that is exaggerating talus volumes. Most screes are rather shallow when measured at right-angles to the slope, few consist of more than a metre-deep layer of rock fragments (Fig. 10). Allowance for this often reduces the required rate of rockfall for the whole postglacial period to values close to those observed today.

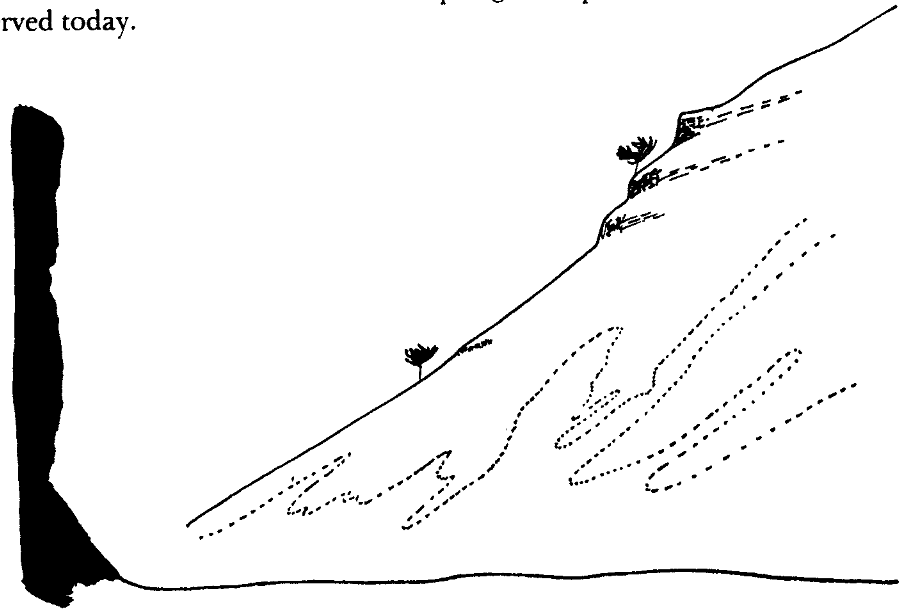

FIG. 10.

Slope profile below Gordale. Note the long stretches of scree at a little over 30° (partly vegetated) and the almost completely obscured scar just above the lower tree. On the left, the rock face on the Great Scar limestone is kept free of scree by the stream at its base. Nevertheless, the asymmetry in the valley slopes is present in the solid rock surfaces, and the scree is a relatively thin veneer on an irregular slope broken by several near-vertical free faces (from Clayton, 1966).

Most of the slopes have a 30–40 cm cover of very finely divided limestone. The lack of other materials and its pronounced angularity suggest frost shattering and movement downslope under conditions of periglacial mass-wasting. The characteristic fabric of such "head" deposits is not evident due to the size and shape of the fragments. Such material is well exposed in slumps and cuttings in the upper part of Cowside Beck (Skirfare). The deep till cover of slopes beside Darnbrook Beck may also have been affected in the same way. The stones appear undisturbed in their matrix, but fabric analysis shows a tendency for orientation normal to the valley slopes in several places. This suggests solifluction *en masse* with large blocks of till moving intact downslope. Further analysis is needed, however, to confirm this. This process would have occurred after the incision of the stream into the till cover. This suggests that, in this case at least, the period of movement may have been in Zone III of the late-glacial.

Caves and surface depressions

We have noted that about half the solution of the limestone occurs below ground. In no sense does this geomorphological work go to waste, although it does account for the tendency for limestone regions to form high ground in Great Britain. Nevertheless, the limestone is gradually made more cavernous, joints are enlarged to swallow water and overlying soil or till, and in time (but it requires a very long time) caves will be enlarged to the point of collapse. In this area the main results in post-glacial times have been the clearing of glacial deposits from cave systems, the drying up of almost all streams on the Great Scar limestone as they have found or enlarged underground routes, and the development of the depressions or shakeholes so common along the margins of the Yoredale limestone bands or of the Great Scar limestone itself. These are the results of suffosion or settlement, rather than collapse, and seem largest, and are most obvious, where the till cover is a few metres thick. The hollows or conduits into the limestone itself are not always very large, but where appreciable volumes of aggressive water have sunk below ground, large potholes are found (Fig. 11). The largest of these are generally still active, but excavation of abandoned sinks (e.g. one below Water Sinks in the Watlowes valley) shows that even large potholes can be filled in with boulders and soil once stream flow ceases. Enlargement is a function of the amount of water still reaching these features and of its aggressiveness.

FIG. 11.

Hunt Pot, west of Pen-y-Ghent. The wide rift developed along a small fault has allowed the complete evacuation of till from the hollow by the small stream, but the process of formation is very similar to that described for the smaller shakeholes (from Clayton, 1966).

The initiation and growth of the shakeholes can be traced from the development of their sides, and active development is shown by tears in the vegetation mantling their inner slopes (Fig. 12). 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 spacing of these shakeholes seems primarily to be a function of the depth of the overburden (Fig. 13): they increase rapidly in frequency up to a thickness of 2–3 m, and then decline steadily in frequency (although increasing in individual size) until with more than 10 m of overburden they are rare. Finally, it should be noted that these subsidence forms are genetically quite distinct from the large solution hollows found in areas such as High Mark which are described in more detail below.

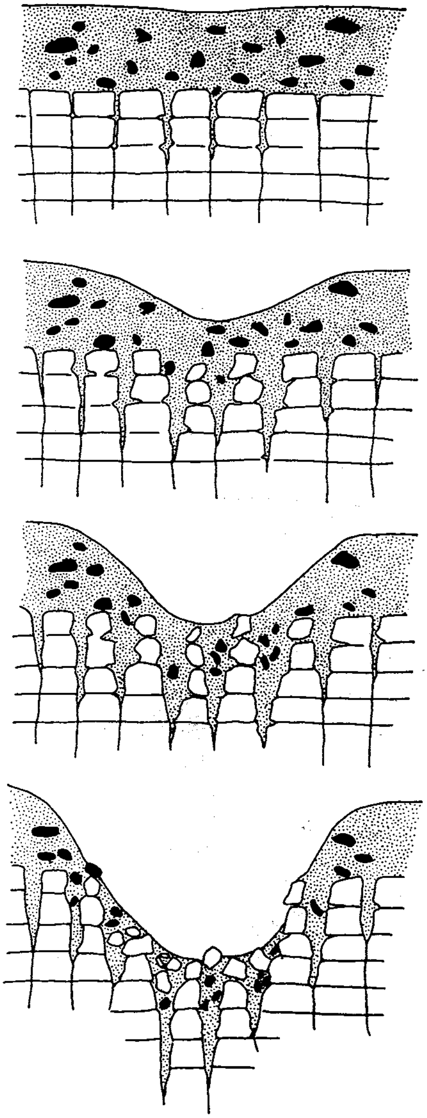

FIG. 12.
The development of a closed hollow in till by subsurface solution and subsidence (from Clayton, 1966).

This 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, the 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 developed by infilling after initial collapse. Field inspection of many examples around Malham Tarn makes this an untenable hypothesis. It should be noted that there is nothing in the forms described by Coleman and Balchin that make a reversed sequence impossible; indeed, other workers in the Mendip area have argued in favour of solution in the development of these forms, and have suggested that initiation by collapse is very rare.

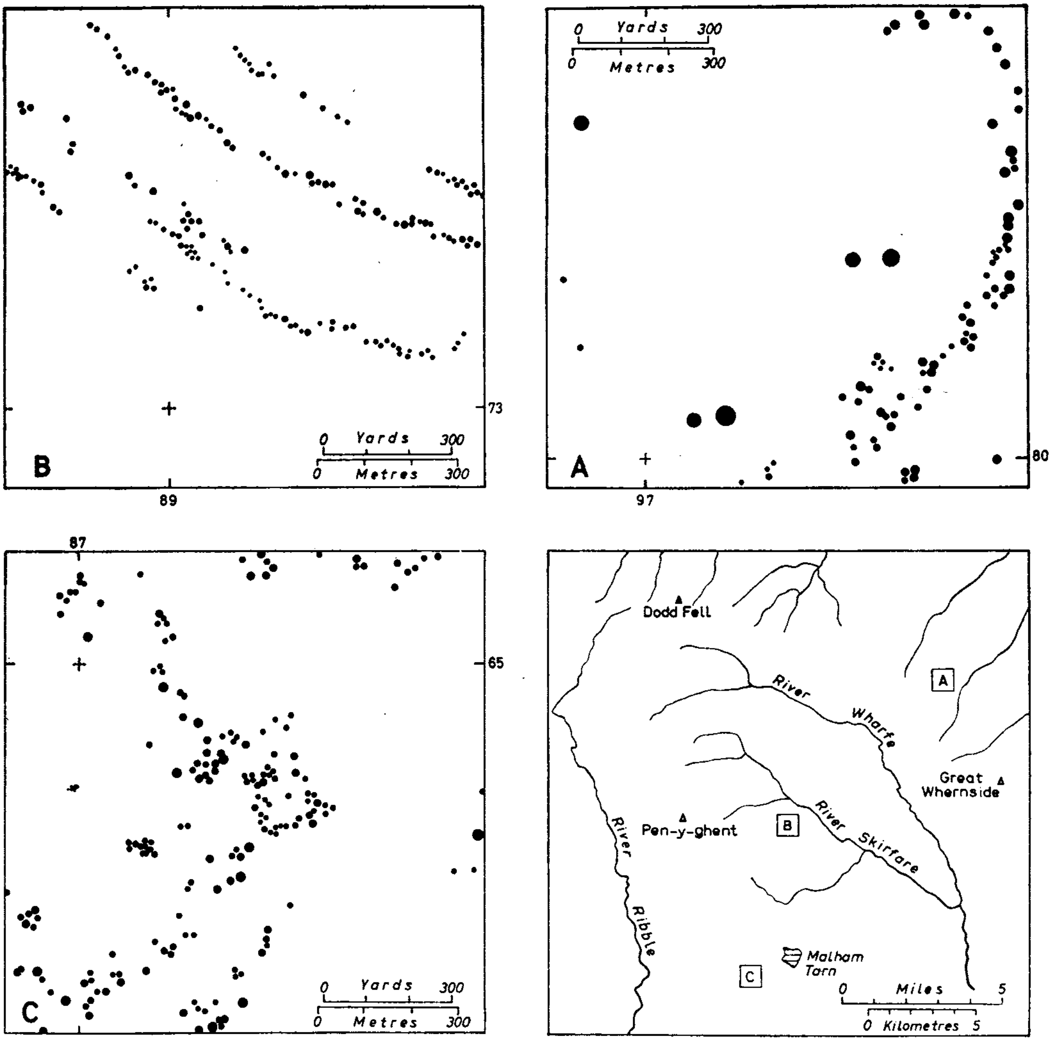

FIG. 13.
Closed hollows near Malham Tarn. Three sampled areas (locations marked on the map) showing the patterns of closed hollows developed in different areas. The aligned hollows in A and B are on beds of Yoredale limestone. Mapped from aerial photographs (from Clayton, 1966).

Karst hydrology

We need only remind ourselves here of the contrast between the abandoned valley pattern at the limestone surface and the arrangement of flow once it sinks below ground. While underground flow is generally towards the nearest valley, flow lines can cross below ground and may even take the water into a different catchment. Sometimes the structure (including the buried relief of the Lower Palaeozoic rocks on which the limestone rests) will concentrate flow to a few major springs, while at other places there is an almost one-to-one swallow to resurgence link. Ternan (Halliwell, Ternan and Pitty, 1974) points out that a resurgence flowing at a mean discharge of 30 Lsec^{-1} requires a catchment of around 1 km^2. Major resurgences (e.g. Reynard's Close Rising in Wharfedale) flow on average at 2–300 Lsec^{-1}, so they must drain about 10 km^2. Below Pikes Edge in Dentdale a resurgence has been seen to flow at 1,000 Lsec^{-1} in flood, while the Black Keld drainage system east of Wharfedale seems, from tracing studies, to drain about 20 km^2. The integration of the subsurface network will increase with time. The careful work by Smith and Atkinson (1977) demonstrates the complex, but readily understandable, connections that must exist between the Malham Cove and Aire Head Springs resurgences.

Peat

The other major development of postglacial time—the present soil and vegetation cover—tends to be taken for granted. The record deduced from the sequence of pollen recovered from cores sunk through Tarn Moss (Pigott and Pigott, 1959) shows the main stages in the development of the postglacial landscape and reminds us of the progression from climatically controlled change to the intervention of man. More attention is paid by geomorphological studies to the peat cover, for this is restricted to the wetter (and generally also to the less steeply sloping) areas, has built up in postglacial time, and is undergoing dissection today. There has been considerable argument about this sequence of events, and in particular how far both peat accumulation and its subsequent dissection have been affected by man. It appears that the initiation of the peat cover was brought about at least as much by forest clearance as by climatic change, and this also marks a change towards increasingly severe podzolisation of the soils, mostly of an irreversible nature. Erosion is in places simply a response to the instability of deep peat, but is also related to damage to the vegetation through grazing and burning. Many of the moors have traditionally been managed by burning, both to promote grazing and most particularly to encourage grouse.

GLACIATION

The whole area was ice-covered during at least one of the earlier glaciations (the Anglian), when the glacial limit lay near London, and again in the last (Devensian) glaciation when the ice stood at the Escrick moraine in the Vale of York, against the Pennines south of the Aire, and as far south as Wolverhampton on the west side of the Pennines. Modelling of this later ice-cap (Boulton and others, 1977) suggests that the surface fell quite steeply from about 1,400 m over the southern end of the Eden valley to about 6–800 m over the Aire valley. Thus even the highest summits were completely submerged beneath the ice, although control of the ice movement by the subglacial relief ensured more rapid movement down the major vales. In this way a pattern of troughs more commonly associated with a valley glacier landscape has been created, with little-modified interfluves, especially at the highest levels. If peaks such as Ingleborough stood out as nunataks, this was at a relatively late stage in retreat (and, of course, also early in the advance) and at both the Devensian and the Anglian maxima we must realise that the area was buried by ice rising 200 to 600 m above even the highest peaks.

Landforms resulting from glacial erosion

Nevertheless, ice was attempting to move from northwest to southeast, and it therefore moved most rapidly down those valleys which led in that direction. It also tended preferentially to utilise those valleys which led towards the surrounding lowlands most efficiently; towards the Aire gap in the south and the Vale of York in

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sparry calcite. A coarse-grained form of calcite found in certain parts of the Carboniferous limestone succession.

speleothems. Mineral, usually calcite, deposited within caves, including, of course, stalactites and stalagmites. Speleothems form from dripping water in the vadose zone (above the water-table).

striae. Scratches left behind on rock outcrops or pebbles and boulders by moving ice. The alignment of striae indicates the direction of ice movement; their preservation indicates that postglacial weathering (or denudation) has not exceeded the original depth of the striae.

subsequents. Streams which develop across the alignment of consequent streams and which will generally show a closer adjustment to structure, i.e. they result from the successful exploitation of bands of weaker rocks that cross the alignment of the consequent streams.

suffosion. The washing down or collapse of solid material into and to form cavities such as pipes or fissures.

swallet water. That part of subterranean water which has entered directly through fissures known as swallow holes. It is often undersaturated with calcium carbonate and thus capable of further solution (aggressive).

tafoni. Small (0.5–5 cm), and usually irregular, cavities formed by weathering.

talus. An alternative name for scree, i.e. a slope composed of rock fragments derived from the rock above. The normal angle of rest is between 32° and 40°. While scree retains a loose surface, "talus" may also be used for such material exposed in a section and now stabilised and with a soil cover.

tectonic. Changes brought about by subsurface geological movements.

till. Unsorted glacial sediment ranging in size from rocks to clay; the Geological Survey of Great Britain uses the alternative term, **boulder clay**.

uniformitarianism. The view that the present is the key to the past, i.e. that landscapes may be explained in terms of erosional processes seen operating today.

vadose passages. Cave passages formed above the water-table. Stream features are restricted to the floor and lower walls.

woolsack corestones. Corestones are durable blocks surviving a period of deep weathering. Some are very rounded and reminiscent of the shape of bales or sacks of wool.

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kame. A mound of sorted and bedded glacial drift (usually sand and gravel) deposited at least in part against walls of ice. Some kames are isolated mounds left behind after the ice melts. Kame terraces are formed between melting ice and the valley side.

kettle (kettlehole). An Irish term for a closed hollow left when sediments in contact with ice (and/or including ice) melt. Where the underlying sediment is till the kettle may include a lake, or may be floored by postglacial lake sediments.

limestone pavement. Bare areas of limestone. These range in irregularity from very smooth (though jointed) bedding planes, through deeply dissected clint and grike forms, to surfaces half buried in loose fragments.

lobate. Adjective used to describe a glacial margin marked by lobes, often extending down troughs.

mass wasting. The denudation of the earth's surface by the physical removal of material through weathering and erosion. It may be moved fragment by fragment or as large masses as in a landslide.

micrites. See biomicrites.

monadnocks. Residual hills left upstanding above a plateau or plain formed by erosion.

morphometry. Numerical study of the shape of landforms.

neotectonic. Adjective used to describe deep-seated geological movements occurring recently or contemporaneously and so affecting the level of the earth's surface.

nunataks. Hills rising above, and surrounded by, an ice-sheet or glacier.

peat haggs. Residual masses of peat surrounded by bluffs, the result of extensive erosion of a once continuous peat cover.

percolation water. That part of subterranean water which has entered the ground by seeping through pores and minute fissures.

periglacial. A term first coined in 1906 which has been extended from its literal meaning of the ice-marginal environment to any environment dominated by freeze-thaw activity and high pre-water pressures reducing the strength of slope deposits.

permafrost. Under periglacial conditions with the mean annual air temperature a few degrees below 0 °C the ground becomes permanently frozen at depth—hence the term permafrost.

petrology. Study of the mineral constituents of rocks.

phreatic passages. Cave passages originally formed below the water-table so that floor walls and roof all show solution features. Until abandoned because of a downward shift in the water-table they contain no stalactites or stalagmites (speleothems).

planation (surface). A plateau, bench or summit plain eroded to a surface of low slope and low relative relief. Such surfaces take a long time to create and so mark significant stages in the evolution of a landscape.

podzolisation. Soil formation by strong weathering and the removal of clay minerals to the lower horizon, leaving behind an ash-coloured surface horizon which is commonly overlain by a thin layer of humus, although in places this has been removed by erosion. Podzolised soils are strongly acid.

regolith. A layer of weathered rock of varying depth which may simply be the soil layer, or may include a deeper layer of weathered material below the soil. In Britain regolith is rarely over a few metres thick, but beyond the influence of Pleistocene glaciations depths are commonly 10 m and may reach far more.

resurgences. Vigorous springs where water that has entered by one or more sinks within the limestone emerges and flows to join the surface river network.

runnels. Relatively small rounded channels formed by solution of limestone. They often diversify the margins of clints and can form at the surface or below a regolith cover.

scarp and tread features. Stair-like features formed by differential erosion of nearly horizontal beds.

scree. See talus.

shake holes. Conical depressions where drift deposits have been washed down or collapsed into a subsurface fissure.

sill. A layer of igneous rock lying parallel to the bedding planes of the sedimentary rocks which surround it.

sinks. An alternative term is **swallow hole.** These are sites where a continuous flow of water disappears underground.

solifluction. This term is restricted (in English) to the flow of material downslope by freeze-thaw activity, and/or high pore-water pressures allowing movement over very shallow slopes (say 2°). Relict soliflucted material is called **head.**

was at a very early stage, for the valley is well established and there are few low cols to mark the postulated captures. There seems much to be said for accepting the Wharfe, Skirfare and Ribble as old and essentially primary streams. If so, then the intervening Aire and Bordley Beck alignments look like the remnants of a system beheaded by capture (e.g. by the Cowside Beck that is tributary to the Skirfare), by the early dewatering of the high level limestones around Malham Tarn, and by the very considerable effects of glaciation. Whether at some very early stage (the 600 m surface?) these south-south-eastward-flowing streams cut back from the Craven faults to disrupt an even earlier eastward system is entirely speculative: it fits some ideas of Tertiary river patterns, but is unlikely to be settled on the evidence we have at present.

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GLOSSARY

Inevitably, some terms have been used here which may not be familiar to all readers of *Field Studies*. Any not listed here may be found in a physical geography dictionary, such as the *Dictionary of Geography* published by Penguin Books.

biomicrites and micrites. Fine-grained limestones with (biomicrites) and without (micrites) a significant (fossil) biological component.

bluff. A steep slope, noticeably steeper than its surroundings but not steep enough to form a cliff.

boulder clay. See till.

Bubnoff unit. A rate of change (e.g. by erosion or mountain building) over geological time such that $1\text{B} = 1\ \text{mm}\ 10^3\ \text{yr}^{-1}$.

clastic rocks. Rocks composed of particles (clasts) derived from the weathering and erosion of other rocks, examples are clay and sandstone.

clints. A local (Yorkshire) term for the upstanding parts of a limestone pavement: they are separated by grikes.

consequents. Those streams which (still) pursue a direction following (i.e. consequent to) the initial slope of the land.

corestones. See woolsack corestones.

diffluence. The divergence of an ice-stream (or of water as in a delta) to flow in diverging directions. The smaller channel diverging from the main stream is known as a diffluent ice-stream, and the resulting landform as a diffluent trough. These may cross water partings and link previously separate valleys.

dolines. Closed hollows in limestone, typically 10–500 m in diameter and 5–50 m deep.

drumlin. An oval-shaped hill usually formed of till and typically 300–1,000 m long and anything from 10–60 m high. They are streamlined forms created beneath a moving ice-sheet.

erratics. Stones and boulders derived from other areas and transported hither by ice.

grikes. A local (Yorkshire) term for the deep fissures dividing the clints in a limestone pavement.

haggs. See peat haggs.

head. Relict slope deposits, poorly sorted but at times stratified parallel to the slope. They are thought to have formed under a past periglacial climate.

interfluves. The ridges dividing valleys (or glacial troughs).

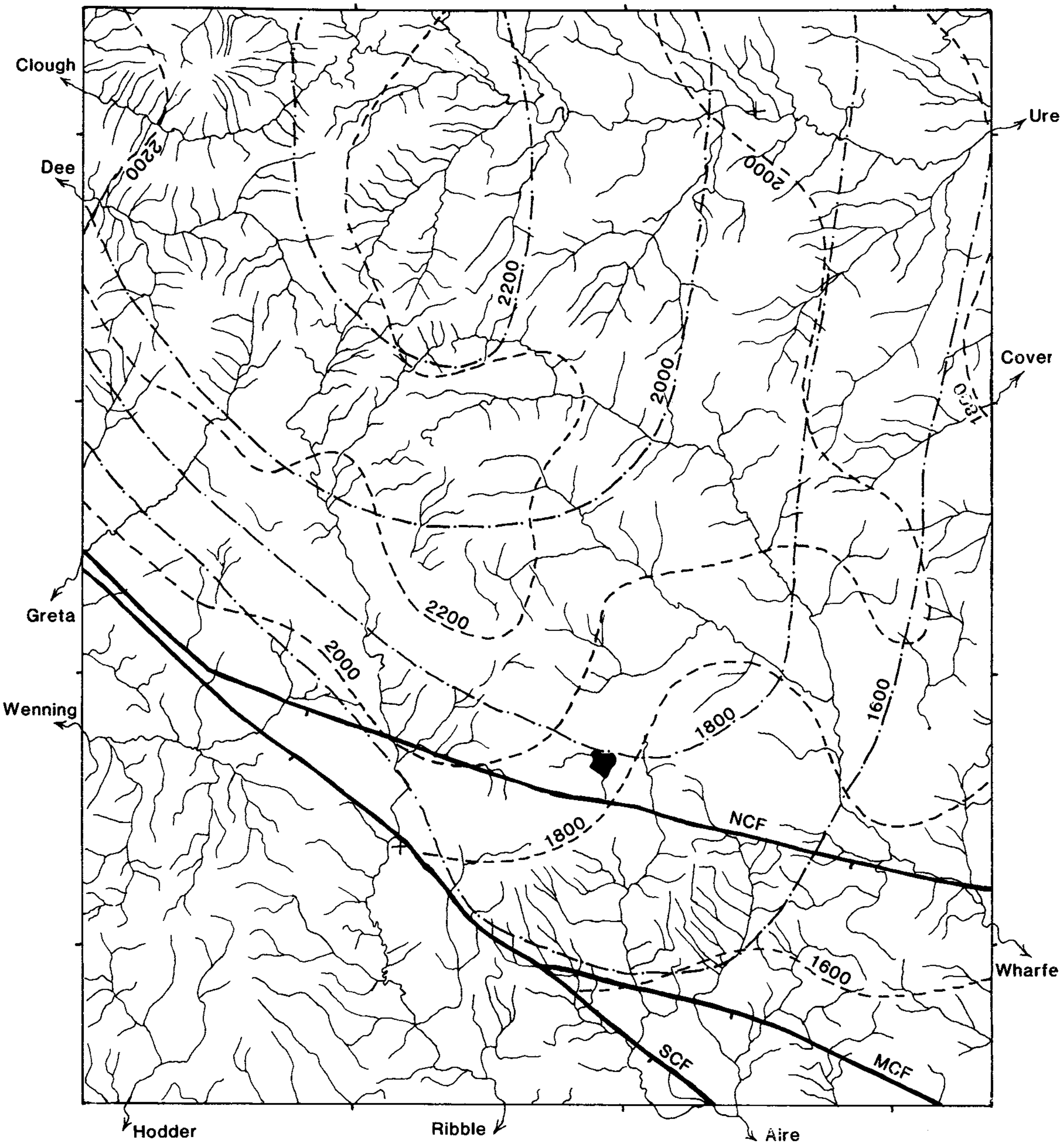

FIG. 21.
Some indications of Late Tertiary form. The drainage pattern, while no doubt modified, is likely to reflect an early stage in landform development. The two sets of generalised contours reconstruct the upland form from surviving summits. The dash-dot contours are the generalised contours of Hudson (1933), while the broken lines are the mathematically-computed third-order trend surface (King, 1969). The letters indicate the faults bounding the Askrigg Block on the southern side, the North Craven fault (NCF), Mid-Craven fault (MCF), and the South Craven fault (SCF). The area is the same as that of Fig. 14, and Settle and Askrigg are again marked by crosses. Malham Tarn is in solid black.

of stability, both to give time to create the pre-Anglian dale floors, and for phreatic cave development below the 260–300 m water table. Locally there is no evidence beyond that, although the simple approach adopted by McArthur (1977) in Derbyshire (which applies current rates of erosion to the excavated volume between successive reconstructed upland surfaces) would suggest an Early Quaternary age for the 400 m surface and a Miocene age for the 600 m surface. In North Wales and Derbyshire hollows in the limestone at about 400 m carry Late Tertiary sediments, but we cannot be sure how far they are linked to that level and how far they might have been let down from a still higher level. In any case, we must not be tempted to correlate by height alone, for as was explained in the introduction, we are quite unable to determine the amount and timing of any recent uplift of the Askrigg Block. In time, despite glaciation, it is possible that we shall locate some locally preserved sediments that may be dated, and then we shall be able to narrow the range of possibilities very considerably.

The drainage pattern

The oldest surviving features in a landscape are often thought to be the rivers, for they have created it, and will often have survived little altered from their earliest stages. The agents which created the lowest parts of the landscape find themselves trapped in their own valleys. Not always, of course, and particularly not in the Askrigg Block where considerable lengths of the smaller streams now flow below ground and only the lines of resurgences along the main valleys allow the inheritance to persist: the tributary valleys ceased to develop once the drainage was swallowed by the limestone. Indeed, over parts of the Great Scar limestone the earlier valley network has been obliterated by glacial erosion and the creation of the limestone pavements. Secondly, glacial derangement may well have disturbed sections of the earlier river pattern, and the deepening of the main dales may have achieved some integration as well.

Despite these problems there is a convergence in the reconstructions of the early drainage pattern of the Askrigg Block (Fig. 21), because from Hudson (1933) the reconstructions have combined the main drainage alignments with the generalised form of the summit surface. This has either been reconstructed by generalised contours (Hudson, 1933) or by trend surface analysis (King, 1976). The combination of these two pieces of evidence is only appropriate if *either* the rivers originated on the surface displayed by the contours, *or* the surface slopes mapped by the contours actually were created by the reconstructed drainage pattern. We cannot be sure that this is so: if we accept the 600 m surface as a reality, heights below that are created secondarily by river erosion and cannot properly be used to reconstruct an earlier network. A further complication that again should be mentioned concerns the possibility of Late Tertiary (or even Quaternary) uplift. If this has occurred, then the form of the contoured summit surface reflects that uplift and any associated warping or tilting, in which case the rivers will have accelerated or been set back in their incision, but are unlikely to have been disturbed in their arrangement. Since they would then be antecedent to the postulated uplift, they relate to a surface that may no longer be reconstructed other than indirectly from the river pattern itself.

Sweeting (1964) restricts primary streams to closely-spaced easterly-flowing consequents, and suggests that rivers such as the Wharfe have developed as subsequents, capturing the headwaters of these early west-east streams. If this did occur it

Grizedales) to recognise, and it is not easy to point to early stages of these mature forms. This suggests that the time involved in their formation is long, or alternatively that they required environmental conditions not found today. Two obvious possibilities here are that the Late Tertiary climate (generally believed to have been rather warmer than today) favoured them, or perhaps that they represent water-table features developed at an early stage with a long-lasting high level water table within this part of the limestone outcrop.

We may develop briefly the idea that the climate of Late Tertiary times favoured these dolines, and perhaps also had an influence on other landforms in the area. For if the dolines were favoured by warm-climate weathering with a deeper regolith than has survived today, then the explanation of other ancient landforms may also involve a similar interpretation. Some of the rounded woolsack corestones of the Millstone Grit may well date from such a period, as Linton (1964) suggested, created below ground by chemical weathering within a deep regolith. Dr Sweeting has also suggested that some tropical karst forms can be recognised in the area, for example, she suggested that the form of Great Close Hill was reminiscent of the conical limestone hills known as *Kegelkarst*. It must be emphasised that in almost all cases we are reaching these conclusions on very slender evidence; and doing little more than connecting the external shape of particular landforms today with our general hypothesis of the nature of the Late Tertiary environment. Only in the case of the corestones of the Millstone Grit 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 conditions. Finally, returning to the doline forms, we may conclude that whatever the details of their formation, the case for regarding them as the most mature karstic landforms of the British Isles seems a good one.

The upland planation surfaces

We would be able to throw some light on the formation of the High Mark dolines if we knew when the covering Yoredale rocks were eroded from the area. Two stages are recognised above the Main Dales stage of Sweeting (1950); here identified as the pre-Anglian valley floor. The lower of these is what she called the 1,300-foot (400 m) planation surface, quite frequently coincident with the upper surface of the Great Scar limestone (as around Ingleborough) or further east with particularly resistant beds of the Millstone Grit. Locally it crosses the Carboniferous/Lower Palaeozoic boundary, or even the North Craven fault, to show its erosional origin. Some of the higher caves show features which are related to the high water table associated with this landscape stage, while some of the dry valleys appear to grade down to it.

Above the 400 m surface, a much more fragmented feature has been recognised, a planation surface at about 600 m which quite often forms the highest ground. In places peaks rise above it as residuals, such as Ingleborough, Whernside and Pen-y-Ghent. Apart from noting this uppermost surface as a common feature of high level views there is little else that may be said about it. It could be a figment of the imagination, an accordance relying simply on visual integration of distant interfluves, but all in all it is likely to be the dissected remnants of an early surface of low relief.

We can place these two earlier surfaces well before the main period of glacial erosion (225–400,000 yr BP) since the Main Dales stage itself represents a long phase

Negative evidence in favour of solution includes the absence of any sign of collapse. Nowhere have marginal faults been seen; and where individual limestone beds have been traced by their distinctive lithology, these dolines are found to lie in undisturbed strata. Neither collapse of cavern roofs, nor the related subsidence of material into a hollow seem to have operated. The favoured hypothesis is that these hollows are the result of solution at the limestone surface, intensified by the occurrence of a layer of water-holding (and carbon dioxide generating) soil and sediment over the limestone. This material includes at one site or another patches of the overlying Yoredale Beds, remnants of the soil horizons developed in preglacial times, glacial deposits including much till, and fine silts and clays deposited in ponded water at times when the drainage of the hollows was less free than it is now. Experience elsewhere suggests that these deposits 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 dolines. Ever-wet, from the high rainfall and the low evaporation, relatively acid, and, in places, with marshy or peaty sediments, these "acid sponges" have eaten their way by solution into the limestone beneath. Once they had dissolved enough to produce an incipient hollow, an irreversible process had begun. The inwardly-sloping surface developing on the limestone ensured concentration of water and so further restricted solution to the new depression. The slopes that developed allowed the transfer of material by creep, flow, and wash into the growing doline. This intensified the contrast in soil depth and water regime between the hollow and its rim, and so contributed to the inexorable development of the hollows and the ever-slower lowering of the interfluves between them. As solution deepened the hollows, the limestone scars appeared at the surface around the enclosing rim. This scar then developed as a retreating free-face, as the hollow was widened by mass movement as the bottom was deepened by solution. The effectiveness and speed of the solution within the hollow is attested by the frequent occurrence of steep limestone scars around dolines. Where the bounding slopes are gentle and mantled by a continuous soil cover, solution probably acted more slowly.

This etching-in of patches of overburden has, of course, occupied a long time. The dolines may be mapped in terms of their size and depth, although the glaciation of the area, and the modification of the surrounding rims by slope retreat (and in places by subglacial meltwater) make the data of limited value. We can identify the area of the doline, its shape, and 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 doline and the lowest col in the surrounding rim. From what we know of current rates of limestone solution, these features must have been in existence in preglacial times.

Thus the evidence for a preglacial origin for these features is circumstantial, but alternative hypotheses are hard to erect. We might consider them glacial erosion forms, although the basin at the Tarn does not seem to be of this form, and areas undoubtedly eroded by ice, such as the limestone pavements around Ingleborough, do not show such features. The restriction to the highest altitudes at which the limestone occurs strongly implies great age: indeed, if such forms have begun to develop at lower levels they are so limited in scale that they are difficult (except at

Yet another example of a valley which seems to require subglacial meltwater erosion to account for its present size and form is the section of Cowside Beck above its confluence with Darnbrook Beck. This valley is of quite different dimensions from others with similar discharges and similar gradients elsewhere on the Yoredales, and so has presumably been affected by some different factor. On the other hand, since the lower part of the Cowside valley down to the Skirfare has been remarkably deepened and succeeds in reaching the main Dale accordantly, we may judge that it carried an appreciable ice-flow and has been altered by glacial erosion. It would be likely for a major ice discharge route also to carry more than its share of meltwater during retreat, so that the two parts of this valley are consistent in pointing to some glacial inheritance in their present size and form. A second oversize valley of the same type is Pen-y-Ghent Gill north of Fountains Fell, and this too is accordant to the Skirfare valley.

THE PREGLACIAL LANDSCAPE

Three elements of the preglacial landscape deserve description, although opinions will vary about the reality of each, and the extent to which little-altered preglacial forms survive in the modern landscape. These three elements are (a) the major limestone hollows or dolines; (b) the upland planation surfaces; and (c) the original river pattern.

The Dolines

The highest parts of the limestone outcrop northeast of Malham form a complex dissected plateau, with a series of about twenty great closed hollows. The whole area is devoid of surface drainage most of the time, although after heavy rain lakes may form in otherwise imperceptible depressions around the high ground, e.g. at Middle House Farm. So far as is known, the highest depressions drain too freely ever to hold water, although some carry very wet soil on patches of drift. These depressions have been claimed as the largest closed depressions on limestone in the UK, and as such to be of considerable age. This suggestion is supported by their restriction to the highest and thus longest-exposed parts of the Carboniferous limestone outcrop. Sweeting (1966) has further suggested that the marginal plains developed around this high limestone mass are also related to erosional forms of some antiquity, and has called them karst marginal plains, or *Randebene*.

The large hollows are often one-third to almost one kilometre across, and at times approach 100 m depth. They generally resemble huge saucers in form, although some of those with steeper sides are nearer the shape of a soup bowl. They are extremely localised in their distribution, although common enough in the few areas where they do occur. The main group lies around Parson's Pulpit, northeast of Tarn House (Moisley, 1955). Another smaller, and more scattered group lies in the Grizedales area between the North and Mid-Craven faults, southwest 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 dolines, and are restricted to this part of the Pennines. Little work has been done on them, to support or refute the working hypothesis (Clayton, 1966) that they are solution forms, which have developed over a long period from the time when the Yoredale cover became thin enough for solution of the limestone to begin. Just how long is difficult to say, but it could well have occupied a considerable part of Late Tertiary time, anything from 2–20 Myr.

rock basin below Malham Tarn and the neighbouring boggy flats (including Great Close Mire), for it is obscured by at least 10 m of till and lake marl. The basin is certainly closed, and since it is largely on Silurian rocks, cannot have been created by solution. The volume excavated is small in comparison with the regional figures already quoted, and need not have been more than 0.05 km^3. To the south of the Mid-Craven fault the wide head of Airedale has a similar volume, and could well represent a second glacial basin. It is not closed for it is drained southwards by the Aire, but it is largely enclosed by the surrounding hills. A relatively recent (within the last 500,000 yr) origin through glacial erosion provides a much-needed hypothesis for the formation of Malham Cove. The alternative explanation is that the feature is a dry waterfall, fed by a stream passing down the Watlowes valley until that became dry with the reopening of Water Sinks at the outlet to the Tarn. It is true that in historic time water has found its way down the valley at times of very heavy rainfall and fallen over the Cove, while the dry waterfall higher up Watlowes functions as a wet fall every few years. Indeed, a trickle of water found its way over Malham Cove itself in the spring of 1969 (M. Calloway, *personal communication*). Yet to explain the form of the Cove as solely the result of water exploiting the Mid-Craven fault (which lies a few hundred metres to the south) is not very convincing, and it seems reasonable to attribute most of the excavation below the Cove to glacial erosion, rather than to falling water.

Subglacial meltwater channels

One last set of forms most probably belongs to the glacial period. These are what may be major meltwater channels, most of them subglacial in origin, and some of them difficult to recognise since they still carry streams. To what extent the dry valley system of the limestone upland operated, or even originated, as meltwater channels seems impossible to say. Some valleys will have carried surface water before the major phase of valley incision dewatered the limestone, and the integrated networks are thus best interpreted as preglacial in origin. Some will have been modified by water when their floors were sealed by permafrost. Some, through their position or lack of connection with any integrated network, seem to be true meltwater channels, such as the fine Black Hill channel west of the Tarn, or the northwest-southeast channels due north of the Tarn. Others, through their unusual size, location or alignment invite interpretation as meltwater forms; these include Trow Gill, once interpreted as a collapsed cave. Cave collapse is rather rare except in karst landscapes that have reached an advanced stage of erosion, and decidedly uncommon in a recently dewatered limestone landscape such as this one. Yet to explain Trow Gill by surface flow seems difficult, for by the time Clapdale (into which it leads) was incised, the limestone must have been dewatered and Gaping Gill and other sinks functioning. Hence we conclude that subglacial meltwater was the most probable erosive agency, and that Trow Gill was cut during glacial retreat after the lowering of Clapdale by ice. A similar interpretation may helpfully be applied to Gordale, for while the Beck maintains its flow (in wet weather) through the sealing of its bed by the deposition of tufa, the scale of the valley again suggests an active phase of incision. The incision probably occurred when the Malham Tarn basin drained subglacially by this route into the upper Aire Basin, before the Watlowes valley was deglaciated, and before the various underground routes were reopened.

glacial, the Chelford Interstadial and the Upton Warren Interstadial (both stages within the Devensian glaciation) while very many dates are postglacial. Low soil carbon dioxide levels (quite apart from the effect of permafrost or of the ice cover) allowed no speleothem deposition during fully glacial periods.

The Kingsdale and White Scar dates suggest that the main period of glacial incision by 75 m was during an early glaciation (probably the Anglian which reached as far south as London) and that the Devensian glaciation achieved only the recorded final stage of valley incision of 7–20 m. Interestingly, and most encouragingly, there is independent support for incision of the order of 100 m by glacial erosion. Careful comparison of Bishopdale, and the Walden valley by superimposition of their contours (Fig. 20) suggests that in Bishopdale glaciation has led to an average lowering across the whole width of the dale of 104 m and an overall lowering at the stream (again compared with the Walden valley) of 98 m. The total volume of rock removed from Bishopdale by glaciation totals about 2.7 km^3 for the length of 11 km. No doubt similar (and probably rather larger) figures apply to such Dales as Kingsdale, Ribblesdale and Wharfedale, and, judging from their combined length, at least 30 km^3 must have been excavated by ice from the valleys of the whole region. To this we may add at least 5 m of removal wherever limestone pavements occur, but this amounts to no more than a further 1 km^3, emphasising the extent to which glacial erosion was concentrated in the Dales.

Two basins are best explained by glacial erosion, the Malham Tarn basin already noticed, and the basin at the head of Airedale. We do not yet know the form of the

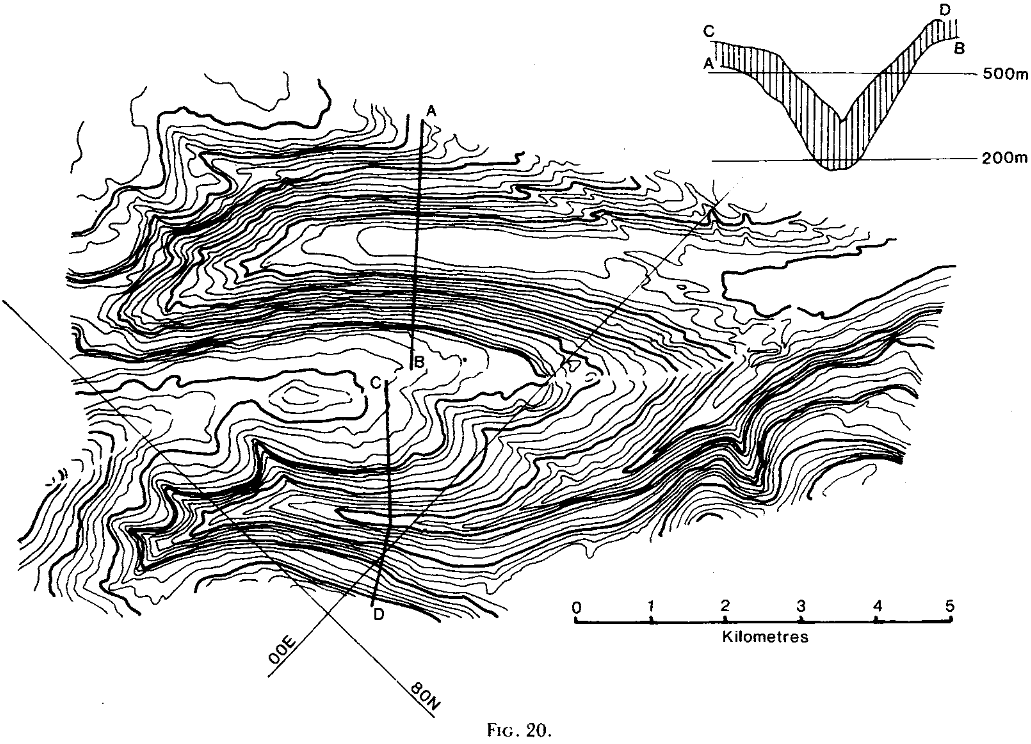

FIG. 20.
The contrast in form between Bishopdale to the north and Snaizeholme to the south. Bishopdale carried diffluent ice northeastwards from the Wharfe valley to the Ure, and the contrast in form is shown on the contoured map, while an estimate of valley-floor lowering may be made from the superimposed cross-sections.

The work done by ice

In the first section we quantified the present rates of erosion in the area, notably the rate of limestone solution. This, together with the length of postglacial time sets very clear limits to the amount of change brought about in the postglacial period. Of course we know that some forms are older; the occurrence of till on a pavement or within a valley floor shows that the surface below must at least date from the Last glaciation. In some limited ways we can also quantify the amount of glacial erosion (we cannot be sure about the rate because we are very uncertain about the time scale involved) and this provides further checks on the dating of some of the landforms.

Some of the clearest evidence we have comes from the caves of the region. These show at least one cycle of infilling by clastic sediments of glacial origin, and the material is currently being washed out of the cave systems. Thus the caves must have existed before the Last interglacial, and where the tubes can be shown to be phreatic in origin (i.e. formed by solution beneath the water table) they must be older still, for they have been formed, and then dewatered, before being filled with clastic sediment. In a number of caves former dominant water levels may be recognised from the cave morphology, and these show a fairly common pattern, with an early rapid (and major) dewatering through a depth of around 75 m (the former water-table lying at a level of between 260–300 m within the limestone) and a later fall in the water table of 7–20 m. The first stage was so rapid that Atkinson and others (1978) attributed it to glacial erosion lowering the Dale floors and thus the level of the resurgent springs (Fig. 19). Calcite formations (speleothems) occur in these dewatered passages and must have been deposited since the passages were filled with air, so allowing degassing of carbon dioxide from the emerging percolating waters to precipitate calcium carbonate. Radioactive techniques have been used to date these speleothems: the oldest are more than 400,000 yr in Kingsdale Master Cave and 225,000 yr in White Scar Cave. Other dates match the Ipswichian (Last) inter-

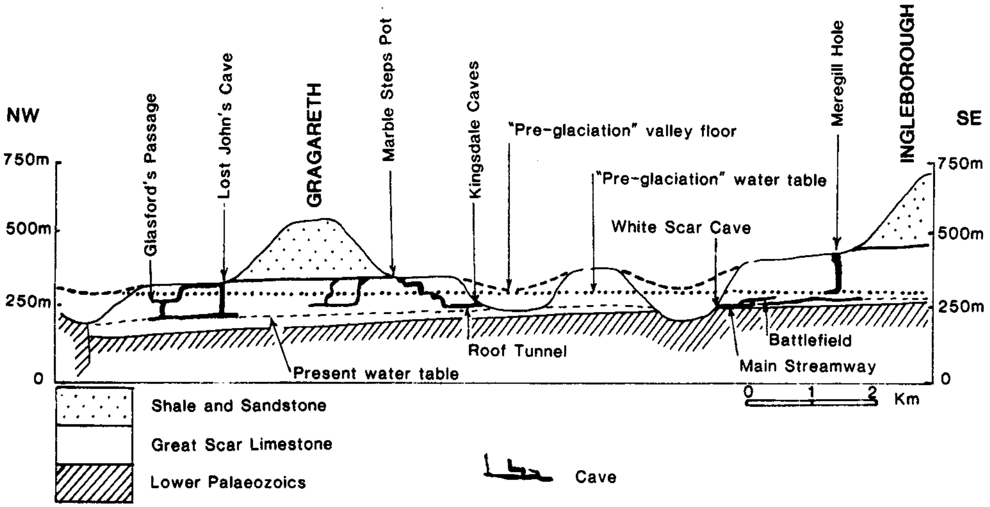

FIG. 19.
The relationship between cave dewatering and dale deepening during glacial phases. Speleothems deposited in passages dewatered after glacial erosion date two phases of incision (more than 350,000 yr and *ca.* 20,000 yr) and suggested trough floor lowering of 75 m at the earlier stage and 7–20 m in the last stage. Sites named here have yielded dated speleothems (after Atkinson and others, 1978).

occupied by streams during the whole postglacial period, and it requires more imagination to appreciate that the sub-parallel pattern of streams draining some of the shale slopes south of the Mid-Craven fault could have originated subglacially. Good examples occur below Kirkby Fell, northwest of Kirkby Malham, or on Winterburn Moor, further east. There are also some very spectacular large meltwater channels, and these are referred to on page 414.

Glacial drifts around Malham Tarn

As in the dales, reversed slopes are most likely to carry glacial drifts, and this is the fundamental explanation for the drift forms south and southeast of Malham Tarn. They are unlikely to represent any more of a pause in retreat than is implied by the downwasting of the thicker ice occupying the Tarn basin. Associated with these deposits are several good examples of meltwater channels; they will have functioned for longer in this basin environment with its longer-lasting englacial watertable, and a subsequent period of ponding within the rock basin and behind the drift belt. Despite the use of the terms "drumlin" by Clark (1967) and "terminal moraine" by Raistrick (1949) this drift belt is better described as a kame complex, or at best a kame and kettle moraine. Irregular forms are dominant, and suggest stagnant, downwasting ice, itself implied by the basin in which it was trapped, for ice movement over the broad col north of Waterhouses will have ceased before the ice had melted within the Tarn basin. The Tarn outlet has now cut through this complex and it seems likely that the early postglacial water level within the basin was even higher than today's artificially maintained level. This could account for the delta surface described by Pigott at 380 m behind Tarn Moss, although Clark suggested it was subglacial. As a subglacial form it would still be controlled by the englacial watertable, itself controlled by whatever outlet was then established to the Tarn basin. The channel leading through to Great Close Mire has a floor at 379 m, and this strongly suggests that it was in operation and thus controlled the water level at the time the delta was formed.

Drumlins

True drumlins do occur in the region, indeed they are very common around Ribblehead and in the Aire Gap (see Fig. 14). They are limited to some of the most active and some of the deeper sectors of the ice-sheet where through movement was dominant. Thus they climb out of the upper Eden valley towards the field at Ribblehead, and reappear in the Ribble valley near Stainforth before the extensive field in the Aire Gap between Settle and Skipton is reached. Drumlins are formed by active ice, and their alignment is a striking reminder of the pattern of ice movement near, if not at, the glacial maximum. The smooth convergence of the flow lines on Ribblehead demonstrates that all these high through-valleys carried active ice. Thus the arguments for dispersal in the Langstrothdale Chase area are reinforced. In the Aire Gap, the dominance of the southeasterly flow down the Aire valley is recorded, as well as the subsidiary flow that edged westwards to join the main stream of the Lancashire-Cheshire Plain ice. In the lee of the main ridges above Ribblehead, the streamlined drumlin forms lead from a more continuous drift spread reminiscent of the crag and tail forms of the Scottish lowlands. Green Hackeber hill, or the ridge south of Pen-y-Ghent are good examples.

Meltwater discharge

The modern view that many, if not most, meltwater channels develop beneath ice-sheets does not preclude some of them operating as marginal channels or overflow spillways. Nevertheless, experience shows that the majority of them reflect the regional subglacial gradient, and the direction of subglacial meltwater flow, which is itself related to the englacial watertable. Across most of the area round Malham, the main direction of meltwater discharge was from northwest to south-east, and this is well shown by the pattern of small channels around the Tarn itself (Fig. 18). On the limestone most of these channels are now dry, but we may distinguish them from the normal dry valley pattern by their location, relatively short length, unintegrated pattern, and their tendency to have an entry-exit pattern in relation to spurs and other low ridges. On till or shales such valleys will have been

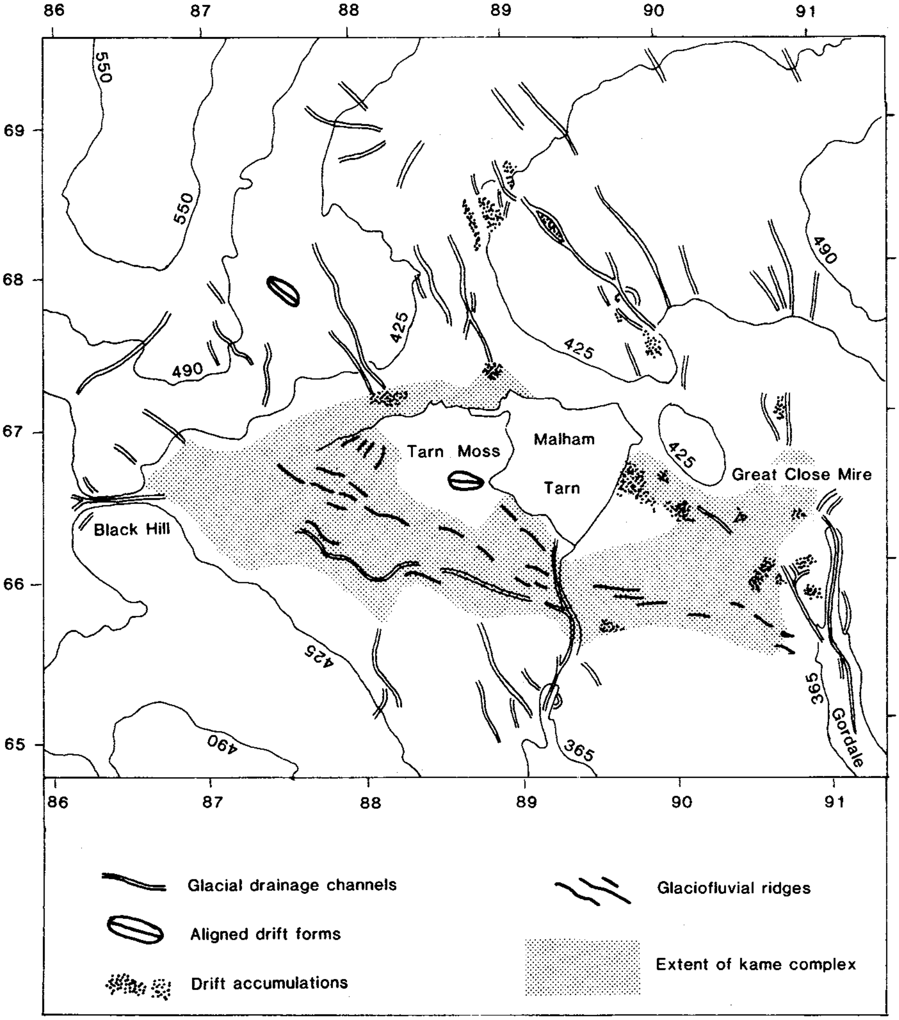

FIG. 18.
Glacial features around Malham Tarn. At this scale (cf. Fig. 14) the main elements are the meltwater channels and the drift deposits of the Tarn-Great Close Mire basin (after Clark, 1967; with additions by M. Calloway, 1980).

assumption that they were all established in ice-marginal locations, mapped glacial margins through them and through the moraines to establish a sequence of retreat stages and correlated these from one vale to another. He even extended the work to suggest links with the till sequences of the Holderness coast and the retreat stages of the Lake District valleys. None of these reconstructions can be accepted today, for we now appreciate that many of the meltwater channels must have been formed in subglacial positions, and thus cannot be used to reconstruct glacial stages. In any case, the pattern of smooth ice margins crossing from one Dale to another with little regard for the relief (see, for example, his reconstruction of glacial limits south of Malham, Raistrick, 1933, Fig. XV) is no longer viewed as a credible pattern—the ice margin would have been far more lobate.

While it is not unlikely that some of the moraines represent halts in retreat, or even minor readvance phases of still active valley glaciers, and while it may still be possible to suggest correlations from one Dale to another, this does not seem the likely explanation of most of these features. They are as readily interpreted as a pattern of glacial deposits developed during retreat up a glacial trough with a typically irregular subglacial profile (Fig. 17). It is characteristic of ice that it carves a succession of basins and sills (the former tending to be formed where erosion is favoured by structure, where two glaciers converge, or where the restriction of the cross-section of the valley requires more rapid flow by the ice). As the ice melts back to expose this irregular floor, the ice margin will retreat more slowly down the reversed slope upvalley of each sill, and most rapidly across the downstream slope of these sills. Further, glacial sediments lodged on the higher parts of the sills are most likely to survive erosion by meltwater streams and burial by alluvial and lake sediments. It is also at these points that the river is likely to be trapped in a post-glacial gorge and thus not be free to swing across its valley floor and eliminate the glacial deposits. The lakes were real enough, as the frequent occurrences of lake silts testify, but they were controlled by rock sills, rather than by retreat moraines. If stages are to be correlated from one Dale to another, we shall require Carbon 14 dates or similar evidence to establish them with any certainty.

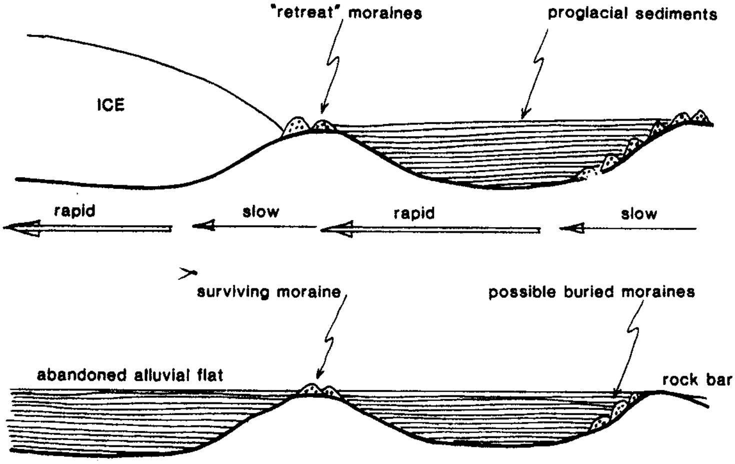

Fig. 17.

A rock-basin hypothesis for the "retreat stages" mapped in the main Dales by Raistrick. Moraines are more frequent on low and reversed slopes, and will only survive where not buried by lateglacial alluvial and lacustrine sediments.

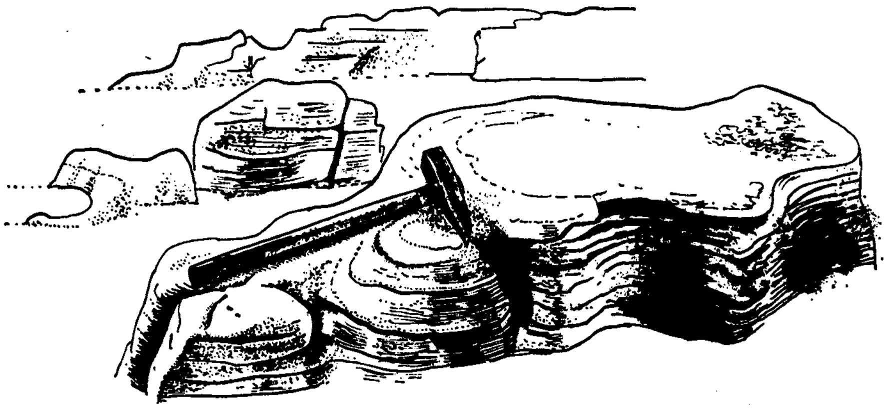

FIG. 16.
General sketch of the pavement above Malham Cove. Note the low scar on the left (above which is another pavement cf. Fig. 1), the grass cover on till (left white) and immediately beyond it the rather narrow ribs of limestone protruding above grass and soil within the grikes. Broader, flat-topped clints lie to the right. Compare this with the final stage of Fig. 15.

surface can be called by the Serbo-Croat term *kamenitza*, but there is little virtue in using such specialised terms when "pool" or "hollow" can convey the meaning just as well. Some help may also be found from the illustrations here (Figs. 3–8). Where the soil or till cover is non-calcareous, solution at the limestone surface is likely to be most intense.

We may also suppose that the initial outline of scars and treads was roughed out by glacial erosion exploiting the structure along the valley sides. This suggestion was first made by Goodchild (1890) who wrote, "the effect of ice erosion was to impart to the rock surfaces a flowing contour, and an association of scars and terraces which are quite different from what would naturally result from simple atmospheric erosion". This is not to suggest that scarp and tread features cannot develop subaerially, but glacial erosion is just as capable of exploiting the structure of the bedding of the valley sides. Moreover, it does so across the whole height of the valley slope at once. Glacial erosion is most effective where it is able to remove blocks of material by plucking, and the role of variations in jointing frequency noted by Doughty (1968) links with this idea. A further factor must be the tendency for coarse-grained limestones (sparites) to be more resistant to erosion than the fine-grained biomicrites and micrites (Sweeting, 1966). Since glaciation, talus development has modified, but has by no means extinguished, these step-like features of the valley sides.

"Retreat" stages in the Dales

In a series of papers, Raistrick has described a sequence of lake flats behind retreat moraines in each of the Pennine dales. Six such features were identified in Wharfedale, two of them north of the North Craven fault which crosses the river near Grassington. These moraines are at Skirfare Bridge, Kilnsey, Drebley, Middleton, Burley and Pool. In some cases the river breaks through the moraine in a gorge cut in glacial sediments, in others it is caught on rock towards the side of the valley. Raistrick noted that in at least one case (the flat below the Wharfe-Skirfare junction) the lake sediments seem to lie within a wholly closed rock basin. Raistrick also mapped the many meltwater channels found alongside these Dales, and, on the

Glacial erosion of the limestone

The most distinctive of these glacial features are undoubtedly the limestone pavements (Fig. 15). Their restriction to the most strongly (and most recently) glaciated parts of the British Isles suggests a glacial origin, although when writing in 1966 I was inclined to limit the work of ice to the clearing, or exhumation, of a surface created by preglacial subsurface weathering. This does not go far enough, and there is now wide agreement that the pavements represent quite deep stripping of weathered limestone layers down to relatively solid and little weathered bedding planes. Thus Pigott (1965) has shown that the buried limestone surfaces of Derbyshire are far more irregular than anything seen at the surface in northwest Yorkshire. Where calcareous till overlies the pavements, solution below the till has been inhibited and striae are often preserved. Once exposed, the limestone surface undergoes the solutional modification already described, and is also liable to be fragmented by frost action, in some cases aided by pressure release jointing. In detail, we can separate the deep flutes that are developed beneath a soil cover from the more intricate pattern of tafoni, pools and runnels that characterise sub-aerial weathering (Fig. 16). The terminology of these detailed forms of the limestone is very complex, and some writers prefer to use the German terms, referring to the flutes as *Rundkarren*, as distinct from the *Rillen-* or *Rinnenkarren* (the same as the French *lapiès*). Indeed, the small pools and other fretted depressions of the clint

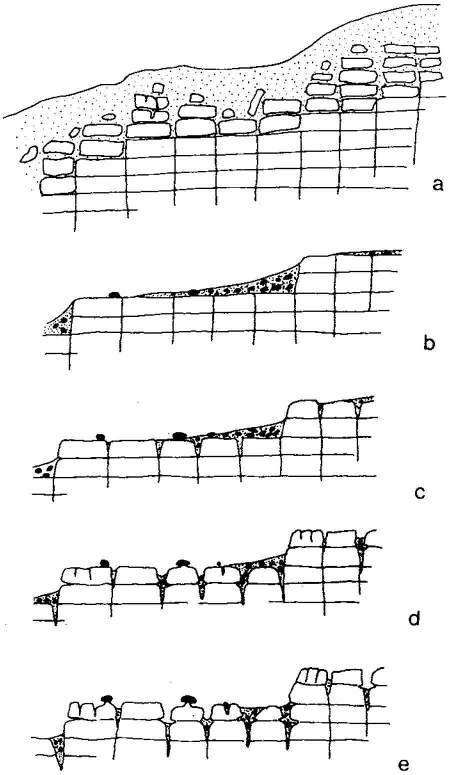

FIG. 15.
The stages in development of a limestone pavement. "a" represents the preglacial landscape with its regolith, "b" is the immediate postglacial form, and "c–e" represent stages in postglacial modification (after Clayton, 1966).

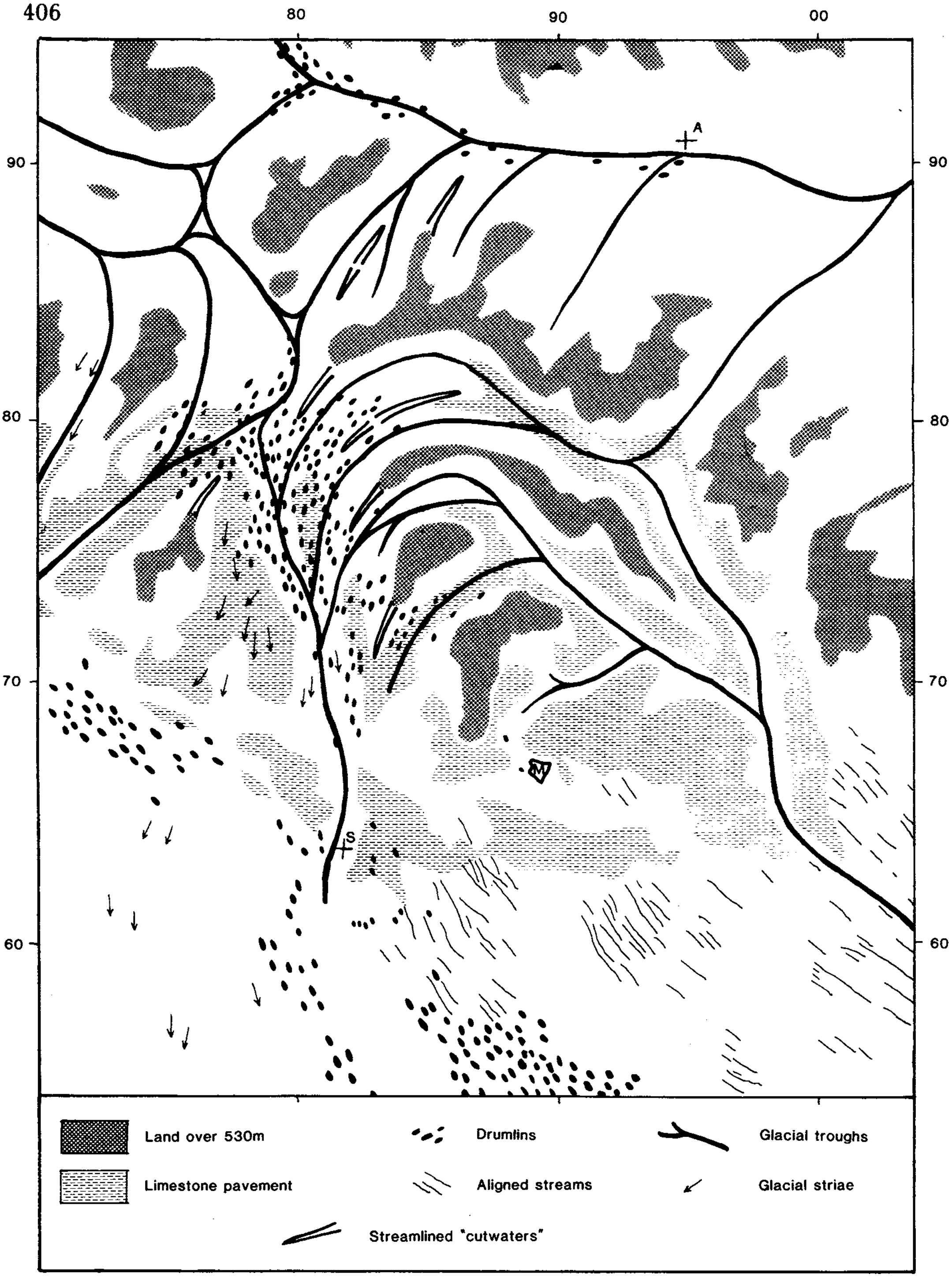

Fig. 14.

The major features resulting from glaciation. The curious pattern of SW-NE troughs breaching the main water parting of England must result from the zone of maximum ice accumulation shifting east of the watershed at the time of maximum glaciation. At this stage ice will have moved southwestwards across these cols, while at stages of less advanced glaciation movement will have been dominated by the Lake District ice, and will have taken ice across the cols to the eastern side of the Pennines. A = Askrigg, M = Malham Tarn, S = Settle.

the east. Thus even quite short valleys such as Kingsdale carried appreciable ice flow, while a diffluent stream broke out from upper Wharfedale to flow northeastwards down Bishopdale towards Wensleydale, before swinging southeastwards again to join the Vale of York lobe. Those valleys carrying the most rapidly moving ice have been modified the most. Those cut off by higher ground or which did not provide an efficient escape route, have been modified least. In places the contrast is very clear indeed as in the comparison of Bishopdale and the Walden valley (King, 1976; and see Fig. 20).

As well as receiving the invasion of ice (from the Lake District and the Eden valley in particular), the high ground north of Malham nourished appreciable snowfall, and, both during the build up of the glaciation and at its maximum, this meant there was a need to disperse ice accumulating over the highest ground. A sizeable local centre of dispersion is indicated by the absence of far travelled erratics in the Malham area. The movement of Lake District ice down the western side of the Pennines and across Stainmore is well attested by the streams of erratics along these routes. Few such erratics are found in the Malham area, indicating that local accumulation, while not precluding a general south-easterly flow at the height of the glaciation, reinforced, and at times dominated the flow pattern. In no other way may the smoothly curving troughs south of Dodd Fell be explained; they indicate the varying position of the ice-shed during glaciation, but most particularly they indicate flow from the Dodd Fell area both southwestwards and southeastwards, which with the Bishopdale and Snaizeholm troughs, indicates a centre of dispersal. To some extent the structural effect of the N–S axis of the highest elevation of the strata within the Askrigg Block may be a further factor, as suggested by Sweeting (1974), but even gentle anticlines do not form gently curving valleys unless they are suitably eroded. The pattern is summarised in Figure 14.

In support of this idea we may turn to the climate of the area today. Manley (1959) has described evidence for late-glacial ice patches at several sites in the northern Pennines. These included the face of Ingleborough and the west-facing cliffs of Mallerstang Edge. In each case he regarded the precipitation (judged by today's values) as marginal for ice accumulation, and thought that snow drifting aided nourishment. In these areas current precipitation is around 1,750 mm, but although Manley regarded the precipitation of the Dodd Fell area as in the same range, short-term records from Fountains Fell suggest an average of almost 2,000 mm, so that it may well exceeed 2,200 mm around Dodd Fell. In terms of net accumulation of snow during a glacial period, these figures are high enough to be significant.

In addition to the strongly modified troughs, the ice was responsible for a number of other elements in the landscape. The most obvious are the limestone pavements, but we may also note some sub-glacial meltwater channels, and various drift forms, including the kame and kettle moraine south of the Tarn, and the extensive drumlin fields of Ribblehead and the Aire Gap. Other more localised features that may best be explained as the result of glacial action include the basins of Malham Tarn and upper Airedale, and the till-mantled slopes with subparallel streams, typical of the shale outcrop south of the Mid-Craven fault. Finally, Raistrick (1933) has described lake flat and retreat moraine features in each of the principal Dales. The pattern is real enough, although probably not created by episodic retreat.

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