MAJOR PROTECTED SITES OF LIMESTONE PAVEMENT IN GREAT BRITAIN

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INTRODUCTION

Ten limestone pavement sites in Britain have been deemed to merit inclusion in the nation-wide Geological Conservation Review (GCR) of over 80 karst sites, as Sites of Special Scientific Interest (SSSI) for geological and geomorphological value. Some are also very valuable botanically.

All sites are in Northern England's two major karst areas, the Yorkshire Dales and North-West England (west of the Pennines) (see Fig. 1). Ingleborough, Scales Moor and Conistone Old Pasture are in the Yorkshire Dales National Park (YDNP), which includes the best-known karst areas of Britain. Three sites lie west of the YDNP in the karst areas fringing Morecambe Bay: Gaitbarrows is in the Arnside-Silverdale Area of Outstanding Natural Beauty (AONB), and Hutton Roof and Farleton Knott occupy a prominent mid-altitude hill nearby. Potts Valley, Great Asby Scar and The Clouds are north-west of the Yorkshire Dales. A tenth site, Helbeck Scars, first assigned SSSI status for its botany, is the only site on the Alston Block, the more northerly of the two North Pennine structural blocks.

These pavements are the best-known national sites and constitute a large proportion of the total British pavement area. There are, however, many other sites in England not afforded this level of conservation interest and the GCR excludes examples from Wales or Scotland, despite their value and interest.

This paper describes the nine major sites in some detail and discusses the important characteristics which have made them worthy of the highest conservation status for these landforms in the whole country. A botanical survey of Britain's limestone pavements (Ward & Evans, 1976) established the enormous merit of many sites, including these, on botanical criteria, and referred also to their geomorphology. This survey has been used extensively to support recent efforts to protect limestone pavement sites, particularly after the Wildlife and Countryside Act of 1981 provided arrangements for legal protection for these landforms. Under this Act a Limestone Pavement Order (LPO) can be made for a site, on which various activities are prevented. Transgressions are punishable with fines, although so far few have occurred. The simple status of SSSI does not provide this level of protection.

GEOLOGICAL BACKGROUND

Northern England has some of the best-developed and best-known karst areas of Britain. Some sites are little known as karst, such as The Clouds, while others are internationally known, such as the Ingleborough area.

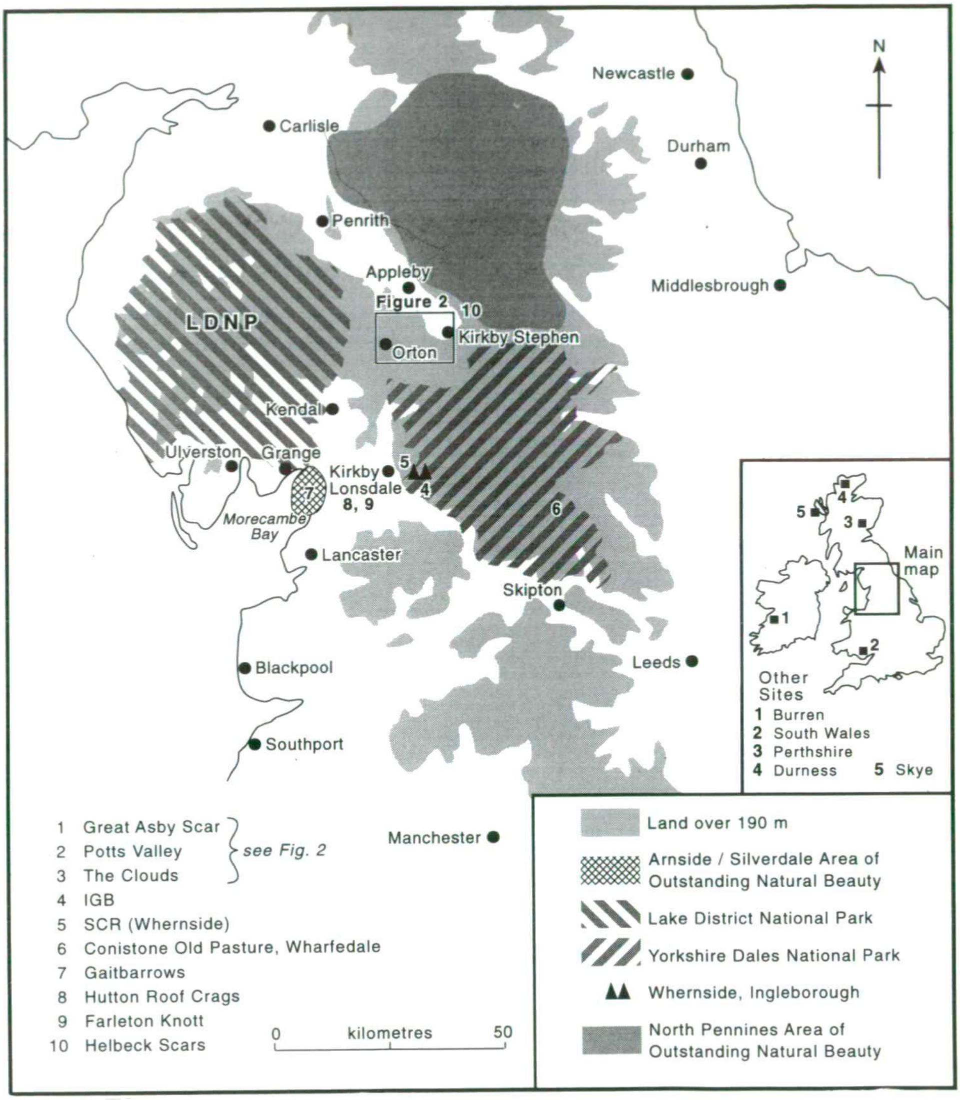


Figure 1 *Location map of Northern England*

All are developed in massive, pure mechanically-competent Carboniferous limestones. Great Asby Scar and Potts Valley lie on the Orton-Asby escarpment west of Kirkby Stephen, Cumbria, in Lower Carboniferous Asbian limestones (Figs. 2a & 2b). This is the most extensive area of limestone pavement outside the Ingleborough karst. The escarpment dips north-eastwards by a few degrees and undulates gently from west to east, thus causing a variety of dips. The pavements are best developed at Great Asby Scar where massive beds support scoured pavements. Potts Valley has less structural variety. The third north-western site, The Clouds, also has pavement on Asbian limestones extending into the lowest overlying Yoredale (Brigantian) limestones (Figs.3a & 3b). Structures here are influenced by the Dent Fault, a major fault line bounding the Askrigg Block in the west. Tectonism in the vicinity has caused strong folding and close jointing and The Clouds is essentially a pitching anticline with dips as high as 30 degrees.

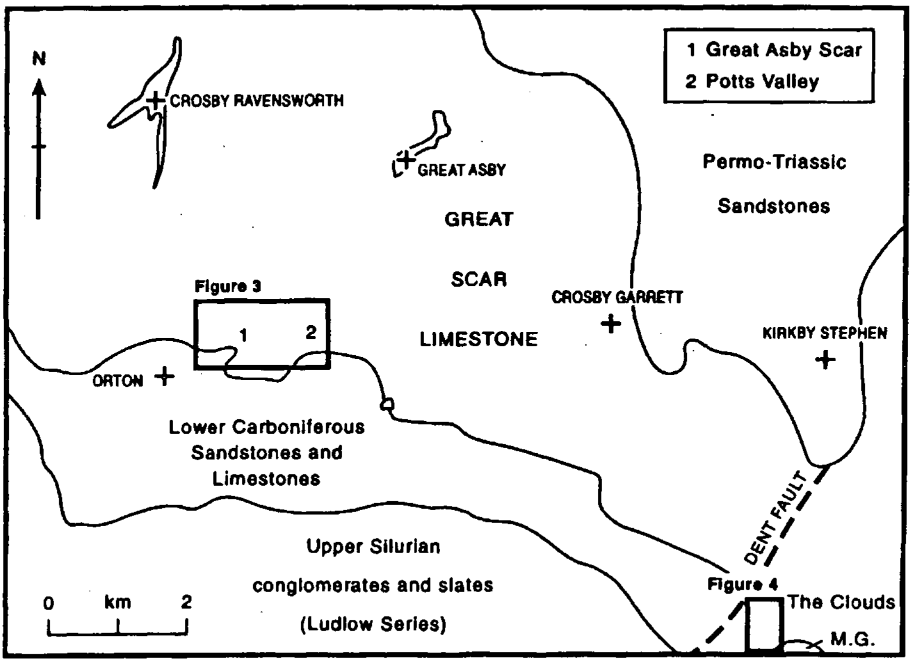


Figure 2a *Sketch map of geology of Orton - Kirkby Stephen area*

Both structural factors are highly significant for the limestone pavements. The three Yorkshire Dales sites are classic areas. The best examples in Britain of massive, scoured undissected pavement are on Ingleborough and Whernside (Fig. 1). They outcrop in massive, moderately well-jointed Asbian limestone. The pavements are dominated by the near-horizontal limestone bedding, with a regional dip of about 3-5 degrees to the north.

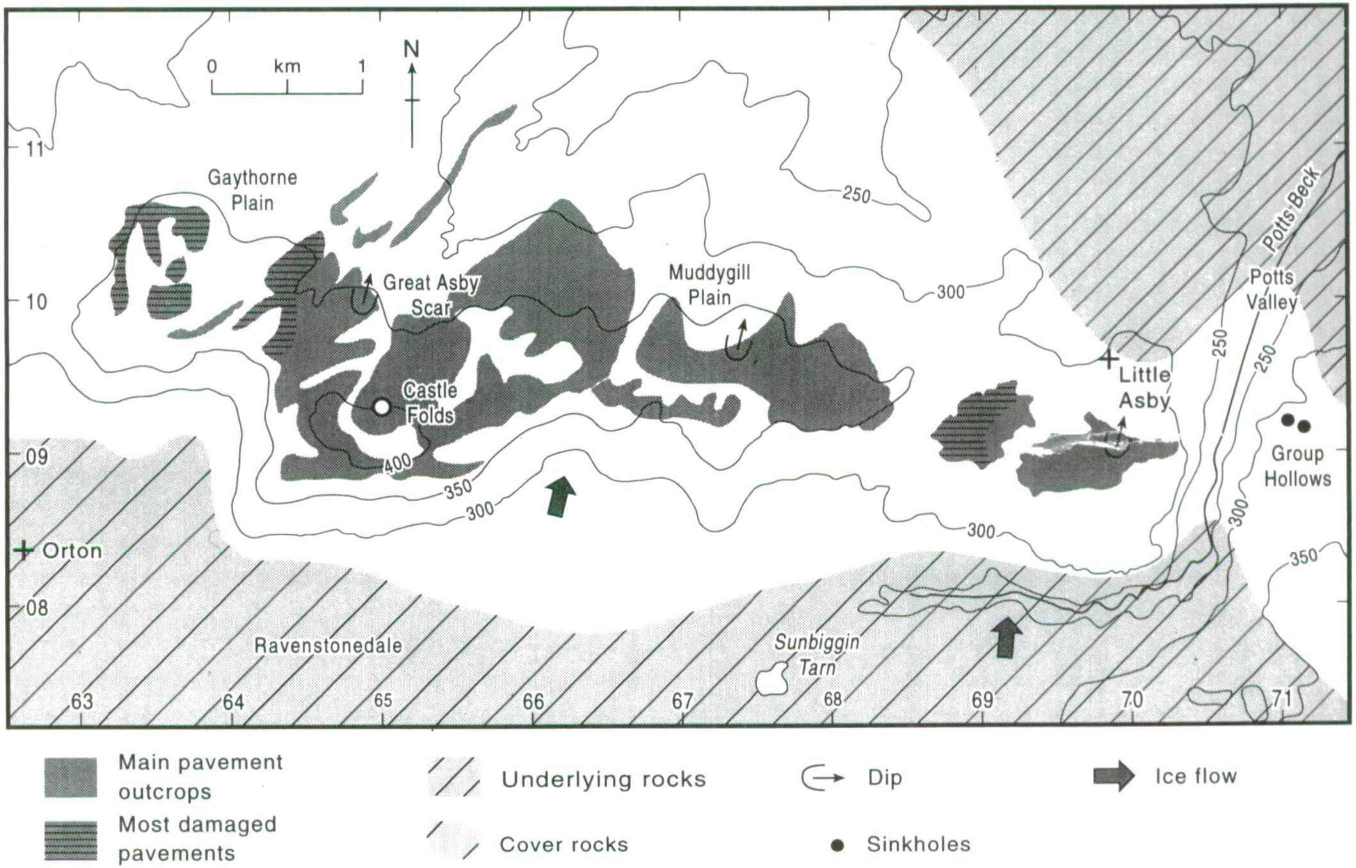


Figure 2.b *Limestone pavement outcrop of the Orton-Asby escarpment, Cumbria*

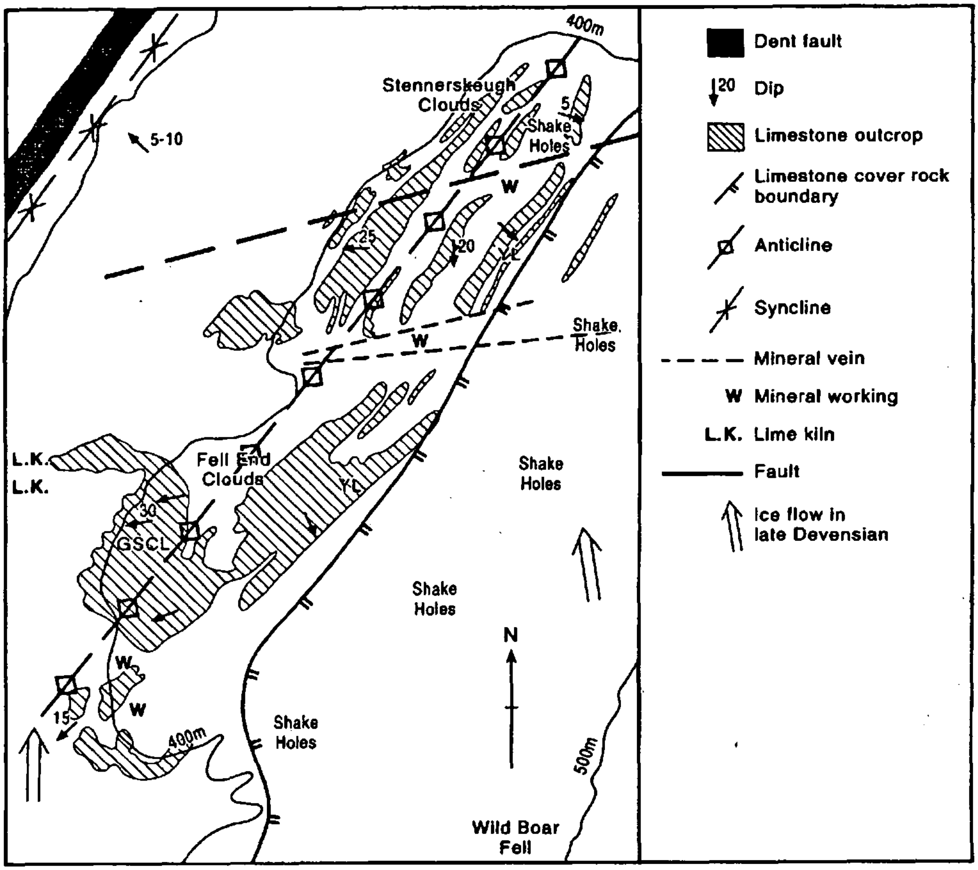


Figure 3a *Limestone pavements of The Clouds, Cumbria*

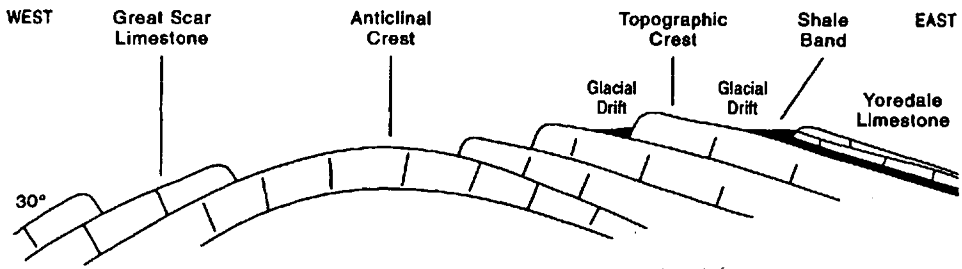


Figure 3b *Schematic cross section at Fell End Clouds (not to scale)*

On Ingleborough pavements occupy wide benches in the highest limestones at about 400 m, skirting the massif. Extensive pavements thus flank the north, south-east and south of the hill with narrower terraced sequences on the west side (*Fig. 4*).

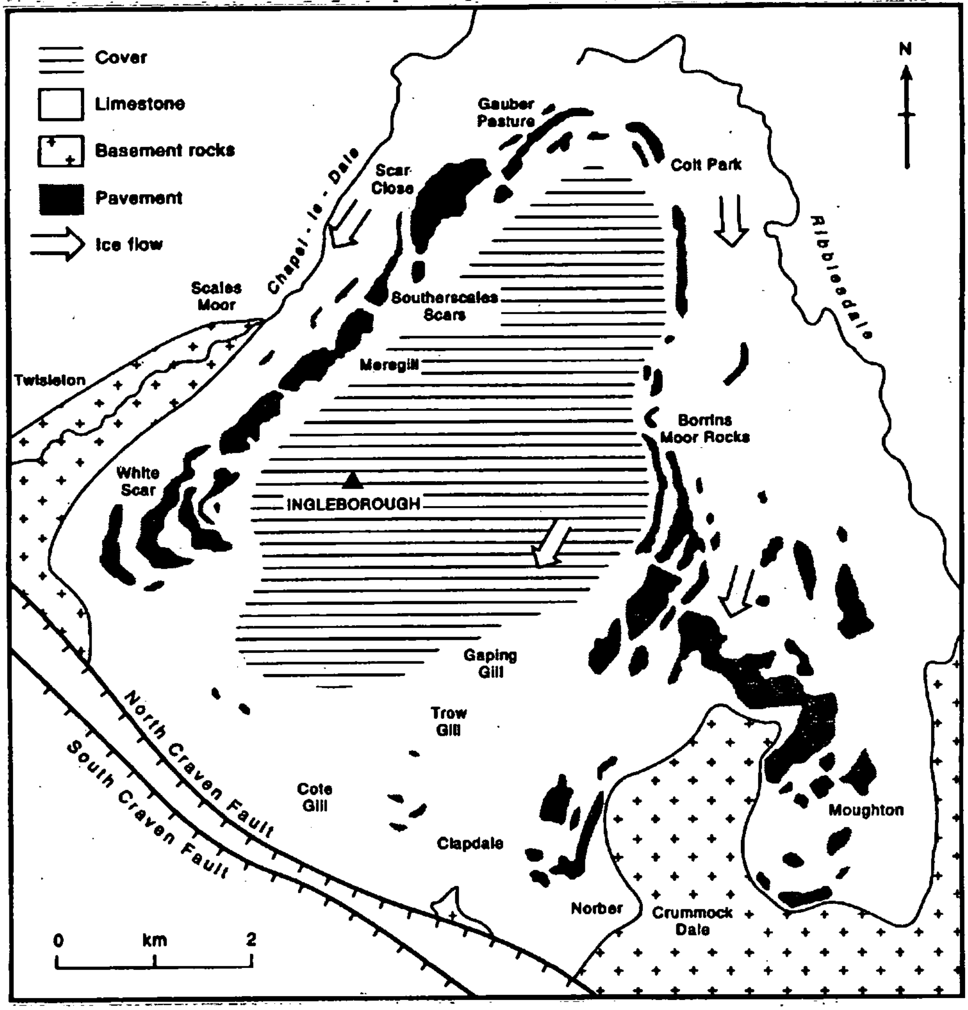


Figure 4 *Limestone pavement areas of Ingleborough, Yorkshire*

To the west, pavement is less extensive on Whernside, but there are still large areas of level pavement skirting the east, south-east and south flanks of this hill at the same altitude as on Ingleborough.

Two of the three sites near Morecambe Bay, Farleton Knott and Hutton Roof, are the two halves of a prominent 250 m hill in Holkerian and Asbian limestones. This hill is a fault-bounded, anticlinally-folded inlier of limestone affected by tectonism which produced other small limestone hills on the southern fringe of the Lake District (*Fig. 5*), including Gaitbarrows.

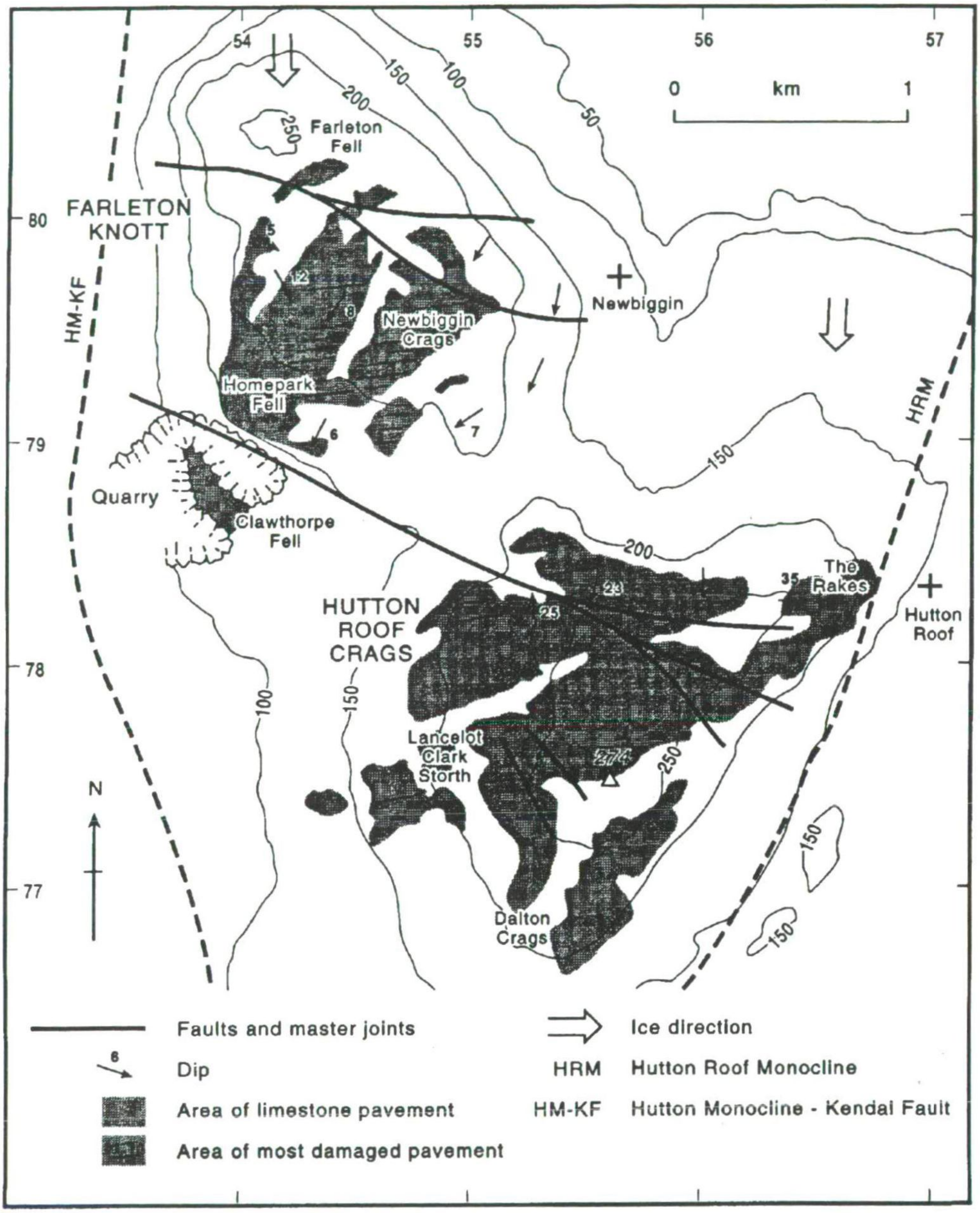


Figure 5 *The limestone pavement outcrops of Farleton Knott and Hutton Roof Crags, Cumbria*

Structures are varied with many minor undulations and faults breaking the outcrop into varied levels, dips and aspects. The most famous area is the steeply sloping Rakes on the east side of Hutton Roof. At Gaitbarrows (*Fig. 6*) the limestone dip gently southwards at about 3 degrees and the site is characterised by thickly-bedded limestones.

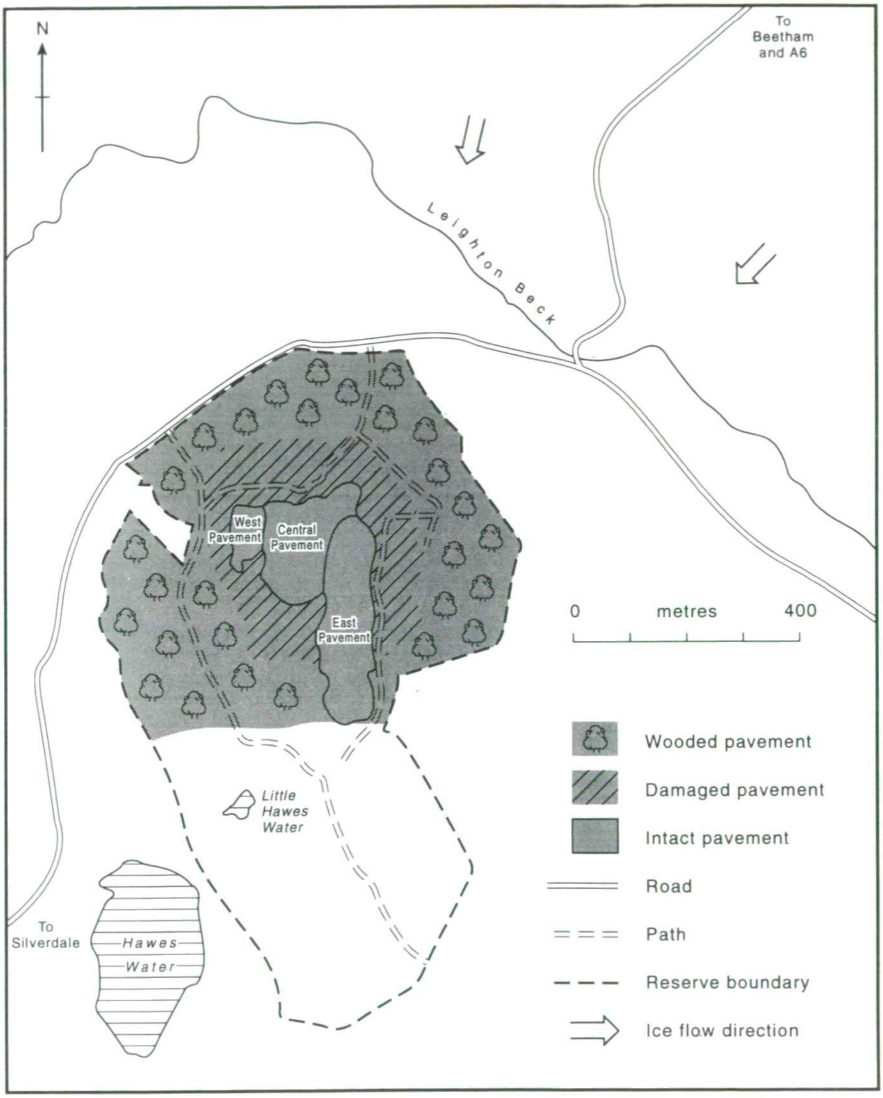


Figure 6 *Gaitbarrows National Nature Reserve limestone pavements, Lancashire*

This site is the lowest in altitude of all nine SSSIs, being below 50 m O.D. and is distinguished by excellent scoured undissected pavement with a varied fauna and flora. It has a mild wet oceanic climate contrasting with Farleton Knott nearby at 250 m, and even more so with the exposed cool, damp upland sites of the Yorkshire Dales and Kirkby Stephen areas.

DETAILED SITE DESCRIPTIONS

1: GREAT ASBY SCAR

Great Asby Scar National Nature Reserve contains varied intact limestone pavements and other broken limestone surfaces, separated by grass-covered areas with sheep-grazing (*Fig. 7*). Its most distinctive feature is that pavements cross a central synclinal valley. Small dry valleys and occasional surface drainage suggest former surface drainage in places although no water tracing is known. There are numerous small structural valleys and occasional small internal drainage depressions.

In the west badly damaged, well-laminated limestone has about 80% of its surface removed or displaced. Clints are small, mostly less than 1 m long, and runnels poor. Occasional gritstone erratics are found in grikes. Many clints are pedestal-shaped and well separated by damaged or grassy areas. Further east, excellent massive pavement dipping gently north-westwards from an anticlinal axis contains well-runnelled, well-dissected clints, deep grikes, and centripetal runnel networks.

These features occur in a massive bed overlying the main pavement (*Fig. 8*). Very smoothly scoured pavement, with simple networks of large, sharp-edged runnels, also occurs which is possibly at an earlier development stage than the rounded runnels, perhaps from deeper glacial scour down the dip slope. The sharp-edged runnels were probably formed by acid peaty waters. Remnants of the upper massive bed perched on sloping pedestals of underlying limestone about 10 cm in height suggest exposure about 2,000 yr ago (Sweeting 1966).

In the south-west very well-weathered pavement has highly fractured and laminated clints, although gaps suggest removal. However, mature development of thin, mossy vegetation on many of the lowered clints (rather than the rough gravelly surfaces typical of recently damaged surfaces) suggests that damage is old. Enclosure wall construction is the most likely reason for removal as the wall stone and neighbouring clints are similar. The wall dates from the Enclosure Period of nearly 200 years ago.

Greatest landform variety is found in the central synclinal valley, where pavements include massive, cushion-shaped clints underlain by pedestals of well-fractured limestone resulting in mushroom-shaped features. These develop along a sequence with pedestals becoming reduced, clint tops less runnelled and grikes narrower, until at the base of Castle Folds hill very smoothly-runnelled limestone disappears under cover. Towards the south-east outcrop is patchy and fractured with small clints because of lithology rather than human damage, although limestone has been removed for wall construction.

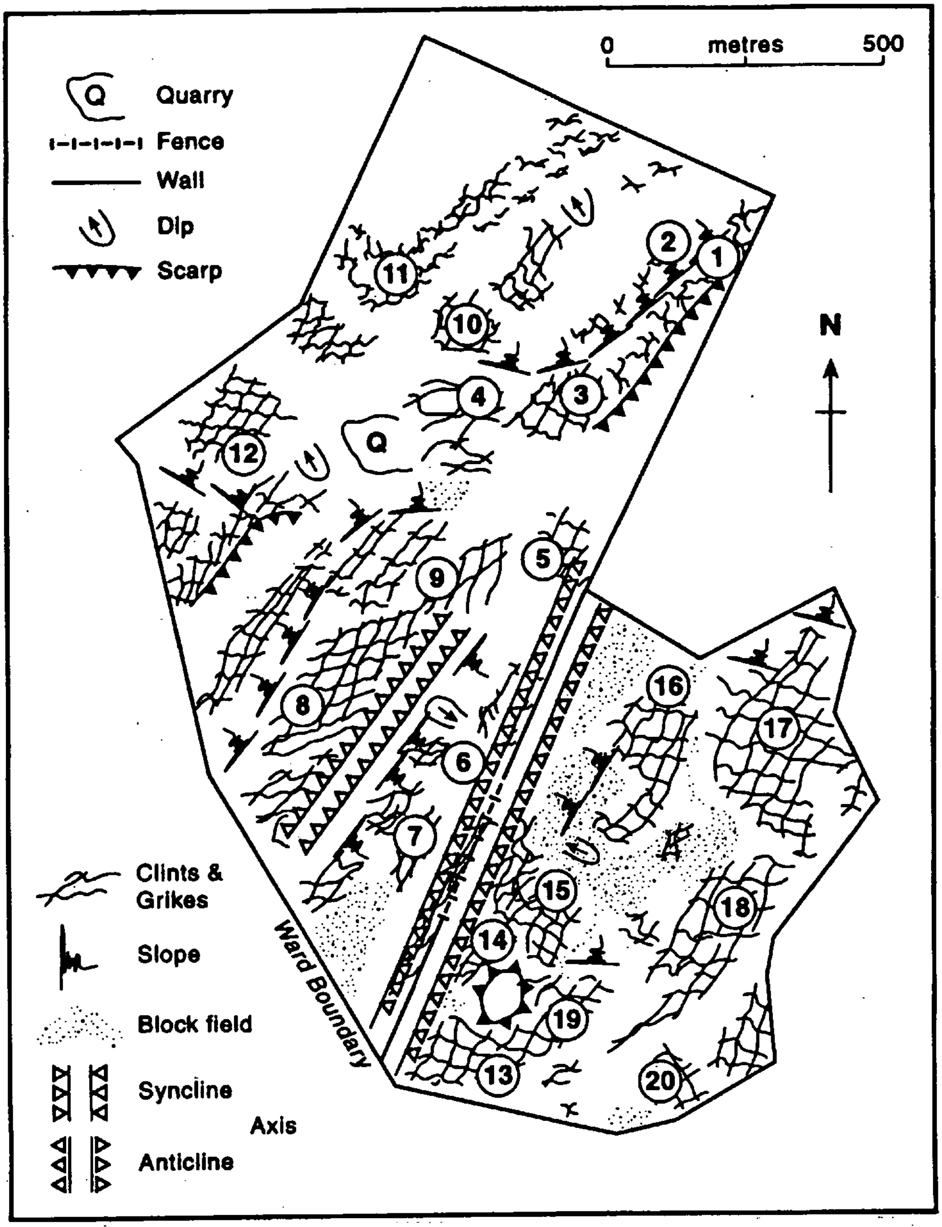


Figure 7 *Sketch map of the geomorphological features of Great Asby Scar National Nature Reserve*

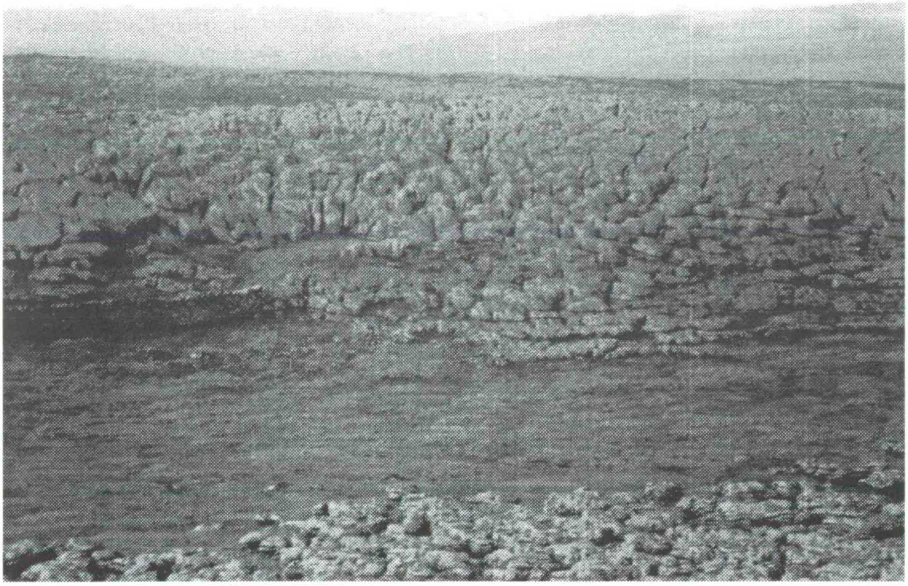


Figure 8 *Great Asby Scar National Nature Reserve, Cumbria: well-rounded massive clints on upper limestone bed near centre of syncline, flanked by more scoured limestone*

Pavement dipping at 12 to 16 degrees on the west of the syncline has striking features transitional between Rundkarren and Rinnenkarren. At its north end this outcrop has a massive moulded upper bed with centripetal Rundkarren around deep holes, some soil-filled. North and north-west of Castle Folds are the 'Shining Stones', extremely large, smooth-surfaced pavements possibly caused by locally stronger glacial scour. Lastly, pavement by the northern boundary includes very long and extremely well-runnelled clints.

Work published on Great Asby Scar describes the protection process there and discusses morphometry compared with other limestone pavements (Goldie, 1995, in press).

2: POTTS VALLEY

The site covers about 1.5 sq.km of patchy, very well-dissected pavement, limestone cliffs and screes, and grassland. The valley carries a very small misfit stream which is augmented by numerous small springs and maintains a surface course right across the limestone outcrop because of valley floor alluvium. Potts valley is discussed in material on the Howgill Fells and the Eden Valley region (Letzer, 1981; Underhill et al.,1988; and Mitchell, 1991, 1994).

The pavements are in limestones dipping northwards by as much as 10 degrees. They occur on both sides of the valley together with low scars of individual bed height. The pavements are less massive or continuous than many further west but clints are distinct, and many display good Rundkarren, although they are mostly separated by wide soil-filled grikes. Very narrow strips of pavement, just a few metres in width, run along some scar tops. A number of closed depressions and shakeholes occur around Group Hollows and there is no significant surface drainage.

Closed depressions and shakeholes here support the idea that the Potts Valley karst is more mature than limestone areas to the west. The unusually wide and soil-filled grikes can easily be accounted for because of the time available for their development if not scoured by Devensian ice.

3: THE CLOUDS

Pavements at The Clouds occur in several different limestones with examples of stepped pavement. Tectonism associated with the Dent Fault has caused strong folding (Underhill et al., 1988) which is reflected here in the landforms. Folded structures and narrow jointing provide an unusual geological environment for pavement development. Other nationally important limestone pavements have narrow jointing influenced by a major fault, but are not folded, for example south of Ingleborough; while other steeply dipping pavements, such as at Hutton Roof Crags, are neither so closely jointed nor so sharply folded. The general geomorphology of The Clouds is discussed by Goldie (1995, in press).

Limestone on the west of The Clouds mainly dips westwards, at angles up to about 30 degrees, while joint directions are diagonal to the hillslope and hillslope angles are similar to dips. In addition clints are small, usually below one metre long and 0.3 m wide. Since clint elongation is at an angle to the hillslope, runnels have a shorter distance downslope to develop on compared with Hutton Roof, for example. Updip angles lessen, following the anticline, to between 10 and 5 degrees on its crest. Massive limestones have larger clints, often more than 1 m long and 0.5 m wide. At Fell End Clouds the strike runs northwest-southeast as the anticline plunges southwards and the more massive limestones are both higher in altitude and lower in the sequence as they are followed north-eastwards. Well-laminated limestones in places produce a highly shattered surface more nearly Felsenmeer than pavement.

The pavements are stepped up the hillside (*Fig. 9*). Many clints in the north are large and diamond-shaped; further south they become small and knife-like. Deep narrow grikes separate the larger clints and surface solution features include Rundkarren and kamenitzas. The knife-edge clints tend to be separated by shallow grikes and display both lamellar and honeycomb weathering. Occasional sandstone erratics are wedged in grikes. Although mainly 5-9 degrees in places east of the anticline, the stepped pavements also dip steeply, up to 30 degrees, and dip direction varies from east to south-east. Near the top of Fell End Clouds striking embayments of nearly horizontal, massive limestone with scars about 2 to 3 m high on their inner edges have large, deep Rundkarren below the scars. Towards the outer edge clints become less well-runnelled and are merely well-fractured at the outermost edge. The inner edges are clear of significant drift and vegetation cover.

Figure 9 *The Clouds, Cumbria: extremely well-weathered north-facing pavements and scar edges at Fell End Clouds*

4: INGLEBOROUGH

The Ingleborough pavements, along with those on Whernside (Scales Moor), have been the focus of important karst research. Sweeting (1966) examined various aspects of their morphology and the processes acting on them and Williams (1966) compared them with limestone pavements elsewhere, especially in Western Ireland. Goldie (1976) discussed their morphometry and Waltham (1990) has published work on the karst of the area with relevance to the pavements. Although mostly nearly horizontal, these pavements are extremely varied, ranging from intensely fractured knife-edge clints at Clapdale Scars to great undissected sheets of scoured limestone at Scar Close (Fig. 4). In the west, Raven Scar has lamellar clints with well-developed grikes and, at the inner till edge of terraces, intensely well-runnelled surfaces, including centripetal networks. Faults interrupt the area, displacing scars and pavements slightly. The most southern area, White Scars, has varied, massive, moderately-sized clints. Clint shapes are highly irregular because of the well-developed runnelling. Flaggy and flaky weathered clints are smaller than the massive clints, with much natural loose debris. Occasionally Millstone Grit boulders are found.

Pavement at Souther Scales and Great Douk Cave Pasture has large clints and great morphological variety (*Fig. 10*). Transects of terraces here have well-runnelled clints near the inner, till boundaries. Central sections of transects have larger clints, often with single, very striking, large and sharp-edged runnels. The outer terrace edges are usually well dissected into smaller clints, possibly because of pressure-release effects or a longer period of exposure. Scar Close includes a range of grike features from very immature beginnings: very large rectangular clints (for example, 3 m by 7 m) with a central hump down their length, either side of which is edged by short Rundkarren; and very extensive undissected surfaces sustaining good vegetation on islands of till with peat (Gosden, 1968). The limestone is often well-veined with dendritic dissection related to drainage off such peat including that around the margins. There are also rectangular dissection patterns in the limestones. Aerial photographs show both clearly.

Figure 10 *Ingleborough, North Yorkshire: scoured limestone pavement on Souther Scales with large sharp-rimmed runnels*

Gauber Pasture is dominated by rectangular fractures, and moderately sized clints. Colt Park Wood, to the east, is well-vegetated pavement but extremely massive, with very deep grikes and large clints. Borrins Moor Rocks has extremely massive, rectangular well-runnelled clints. There are also features similar to Karrenfussnapfe.

Extensive pavements to the south of Ingleborough add to the variety, including the only steeply sloping pavements on Ingleborough, at Thwaite Scars. Norber has classic perched erratics and early studies of denudation rates used the erratics' pedestal heights (Goodchild 1890). Pavements in Crummackdale and Moughton are very well dissected, and there has been much disturbance for garden rockery stone. Clapdale Scars is a naturally well-fractured site near the Craven Fault with small clints predominantly of knife-edge linear type and fairly small grikes. There is much loose debris from natural causes, but also signs of clint removal. In Oxenber Wood massive, rectangular clints are incorporated in Iron Age settlement remains (Goldie 1976), consisting of in situ clints for hut foundations and transported stones used in the walls. Neighbouring clints are poorly runnelled though their surfaces are fairly smooth with solution depressions beginning. This may reflect the age of rock removal for hut building, probably about 2000 yr ago. Further, well fractured pavements are found in the between-fault zone, including Smearsett Scar and Feizor.

5: SCALES MOOR

Scales Moor has extensive bare limestone outcrops amongst acid grassland at about 400 m, without trees or shrubs and is littered with numerous gritstone erratic boulders. Prominent scars form at Twisleton Scar End, and the pavements here are slightly better vegetated partly from being sheltered below the main plateau level. Scales Moor is heavily grazed by sheep, thus confining tree and shrub vegetation to the grikes. At Twisleton Scar End the land is enclosed and grazing more controlled than on the open moor and this may permit better vegetation. The sequence here of limestone scars, screes and benches with narrow bands of pavement is one of the best examples nationally of stepped limestone pavement or Schichttreppenkarst. The scars are between 2 m and 15 m in height, reflecting bed thickness.

Research at Scales Moor includes studies of soil and vegetation cover, the gritstone erratics, and solution processes, especially on the peaty waters (Sweeting 1966, Williams 1966). About 50 cm of solution can have occurred in the last 12,000 years, although local variations around this average will contribute to the variety of features.

Pavements all over Scales Moor show fine Rundkarren and kamenitzas. Limestone dip and clint size influence the variety of runnels, their lengths, depths and network complexity varying with available clint length downslope. Scales Moor is particularly distinctive for excellent examples of centripetally-arranged runnel networks on horizontal limestone surfaces. Such networks are also found on the Ingleborough pavements. Runnels radiate around a central hole. They may be caused by biologically-influenced solution beneath the leaves of trees which once occupied the central holes. Similar patterns, although less well developed, are found around present-day trees, for example, on Newbiggin Crags, in Wharfedale and at Scar Close. Their existence on bare pavement suggests formerly greater vegetation.

6: CONISTONE OLD PASTURE

Pavements outcrop on the east side of Wharfedale in Great Scar Limestone (George et al., 1976). As they are on the eastern edge of these easterly-dipping beds they are overlain up the valley side by Yoredale Limestones and Millstone Grit Series. Their morphology, lithology and human impact have been compared with other sites (Goldie 1976, 1990). Archaeological literature on the area describes evidence of the nature and length of influence of human activities on the pavements (Raistrick and Chapman, 1929).

Conistone Old Pasture includes several pavements edged by small scars and separated by grassy, soil-filled areas. These pavements have well-runnelled, thickly-bedded clints, although small (*Fig. 11*). The runnels are predominantly Rundkarren, but kamenitzas also occur with small-scale rippling and pitting solution features. In the north, pavement is virtually horizontal despite the regional dip. Further south, some outcrops incline 10 to 15 degrees and slope has obviously influenced runnel orientations and network development. Clints here are also larger, thus giving more scope for runnel development.

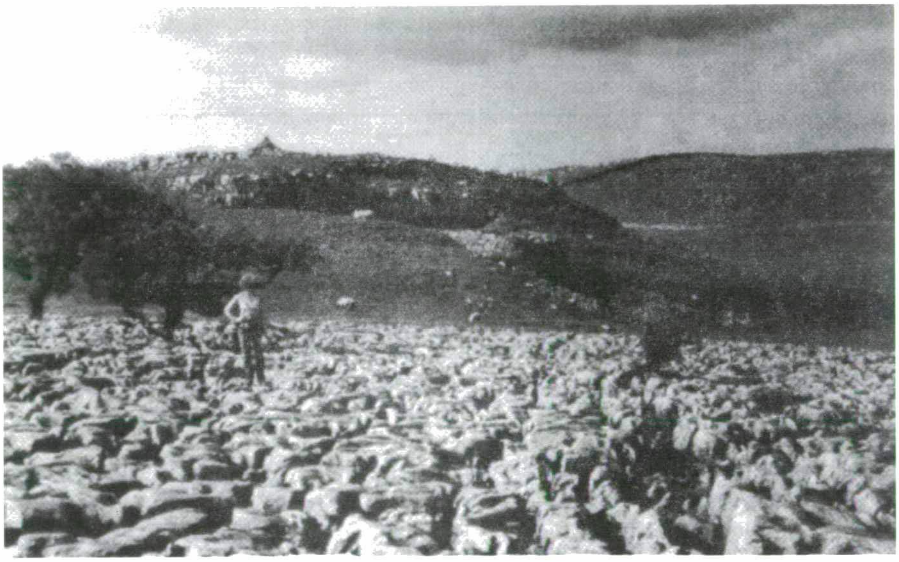


Figure 11 *Conistone Old Pasture, North Yorkshire: well-runnelled and well-dissected limestone pavement with limekiln in background*

The narrow valley limits outcrop extent in Wharfedale, and near Conistone the limestone terraces are half the width of those at Ingleborough. Higher pavement outcrops are limited by drift and soil cover, and the best pavement-forming limestones disappear beneath cover rocks. This area has the best pavements in Wharfedale, although there are numerous other outcrops. Conistone's pavements are particularly attractive and interesting, partly for their location near dry fluvial lanc rms.

7: GAITBARROWS

Gaitbarrows National Nature Reserve is only 0.5 km in diameter, but incorporates a large range of important landforms. About half is well-wooded, while much of the open pavement has shrubs and trees. Distinctive sub-areas include the massive central exposure at the north end with individual limestone beds as thick as 3 m. Landforms include kamenitzas of varying development stages; immature but deep grikes which frequently do not intersect; pedestals of protected limestone beneath; and massive, well-veined, scoured pavement. Clints can be several metres long. There are also grike clusters and Rillenkarren on some clint edges. This area contains numerous erratics of gritstone wedged in the grikes. There is considerable variety of well-dissected pavement elsewhere at Gaitbarrows, especially around the central massive site, some with good rectilinear grike patterns. These clints are large, a few metres in length, although often narrow if one major joint set is dominant. Some pavements have an undulating general surface because of glacial moulding. In the south there are smaller clints, 1 m in length or less, with many loose limestone blocks from natural processes. In addition there are artificially stripped areas with numerous interesting features, although few mature karst forms, and messy areas where damage has left loose, tilted or overturned clints. Other pavements are well covered with ground vegetation plants, and their morphology is difficult to see except on close examination, which reveals well dissected clints with Rundkarren.

Gaitbarrows has been the focus of considerable research interest since 1980. Earlier published work was largely botanical, for example, Wheldon and Wilson (1907) and Ratcliffe (1977). This site was top of the Ward and Evans national floristic survey (1976). Frankland (1980), Goldie (1986) and Rose and Vincent (1986a, 1986b, 1986c) have considered various aspects of its geomorphology. Rose and Vincent (1986a) studied the central-area kamenitzas and associated them with calcite veins, an idea relevant to understanding more dissected pavement elsewhere. There are also numerous immature grike features, different from the kamenitzas. They are invariably occupied by plants and often aligned along veins: many have developed into elongated slits or are joined by very narrow cracks along veins. They are clearly the early stages of grike development and in any one small area a variety of such stages can be observed. The veins are clearly important though it is hard to explain exactly why (Rose and Vincent, 1986a). Possibly grikes on more maturely-dissected limestone pavements have developed like this, although a problem in evaluating the hypothesis is that solution removes the vein.

8: HUTTON ROOF CRAGS

The most well-known part of Hutton Roof Crags (Fig. 5) is The Rakes, a classic example of a sloping pavement (Williams, 1966; Sweeting, 1966; Waltham, 1974). However, this is not the only important feature at Hutton Roof Crags; there are many small tracts above and west of The Rakes of well-dissected pavement at varying dip angles, mostly 5-10 degrees. These areas display varied surface solution features including kamenitzas, Rundkarren and Rinnenkarren. They are moderately well-vegetated, disguising the nature of this area as a disrupted Schichttreppenkarst. The westernmost outcrops at Lancelot Clark Storth are bare, well-preserved, dipping pavements with undulations thought to be formed by glacial scouring. Upslope eastwards are more broken outcrops and further south are the wooded pavements of Dalton Crags.

The Rakes consist of three major bedding plane-guided outcrops, mainly dipping at angles of 25 degrees and above. They are dissected by two major orthogonal joint sets, oblique to both dip and strike. They were scoured by northerly ice and hence almost certainly along the direction of strike. Because of the relationship between joint set angle, dip and hillslope, there are diamond-shaped clints sideways on to the steepest slope (*Fig. 12*). Thus different lengths of outcrop downslope are runnelled by Rinnenkarren of varying length. These Rinnenkarren are the finest such runnels in England, Wales or Eire, and being lightly vegetated are thus a very striking landscape feature. There is virtually no damage from garden rockery stone extraction. A fourth stratum of limestone lying beneath the three massive beds is without pavement outcrops for lithological reasons and forms a Felsenmeer of lamellar debris.

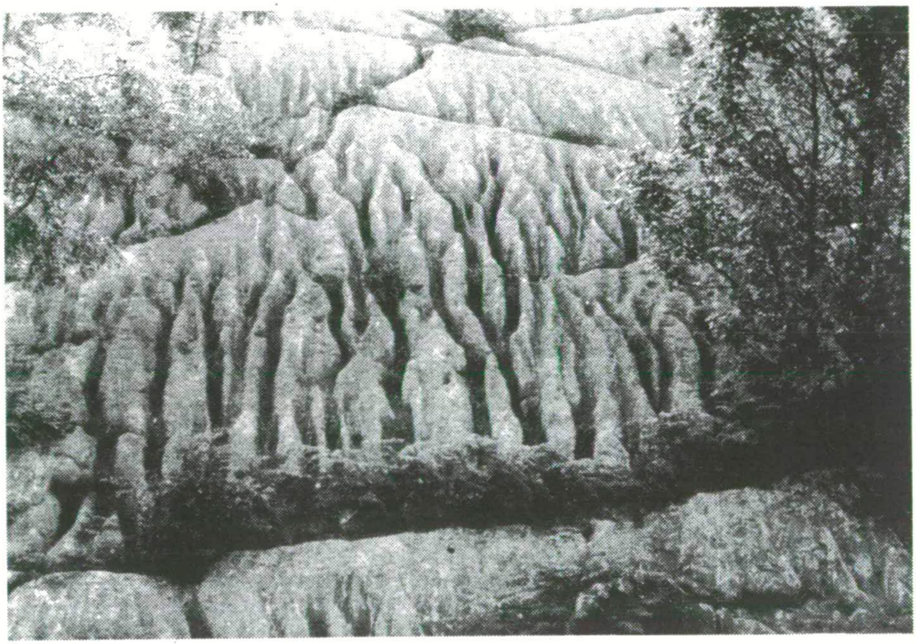


Figure 12 *Hutton Roof Crags, Cumbria: well-runnelled diamond-shaped clints at The Rakes.*

Glacially transported limestone boulders are scattered throughout the site, perched on pavement surfaces, or lying beneath woodland vegetation. Small scoured scars, several metres high, are also common because of the fracturing and folding, and are most prominent on the west-facing sides of the strike valleys at The Rakes.

Hutton Roof still has much soil and vegetation, but this has retreated, revealing Rundkarren at pavement margins. The exact time-scale of development of such cover, and its subsequent retreat or removal, has been difficult to determine, partly through the lack of dateable sediments (Pfeiffer 1989). Much change must be attributable to human occupation.

9: FARLETON KNOTT

Farleton Knott (Fig. 5) has many minor structural features and thus a great variety of limestone pavements in massive, fossiliferous limestones, including pseudobreccias. An important influence on morphology has been glacial scour from the north, but drift cover is thin. There is no known surface drainage on Farleton Knott, and no known caves, though water must pass through the massif as there are springs emerging around the hill.

The area is easily divided into three sub-areas by geological structure and relationship to glacial scour. The most northerly part is Farleton Fell, which includes quite steeply inclined pavements dipping south. Nearby is nearly horizontal pavement, well-developed with rectangular clints and numerous transported limestone boulders standing on protected pedestals (*Fig. 13*). The steeper pavements are at angles between about 14 and 20 degrees, with small to moderately-sized clints (Goldie, 1981). Solution features on these slopes include kamenitzas and solutional ripple marks, akin to Trittkarren. Because of the relationship between grike directions and topographic slope, features are not comparable to The Rakes, but more chaotic, reminiscent of Hohlkarren. To the west, however, this outcrop swings slightly northwards, clints are larger and the surface is more like The Rakes, although at about 12 degrees, and the pseudobrecciated limestone is roughly honeycombed.

The second sub-area, Holme Park Fell, contains gentler pavements dipping south-westwards at 3 to 8 degrees. Because of their location down-dip from the highest point over which the ice flowed, they have been strongly ice-scoured. Holme Park Fell contains the site's largest and smoothest pavements and prominent smooth-based large Rundkarren with sharp upper edges characteristic of peaty water solution. Down-dip clint edges are closely runnelled by smooth Rundkarren characteristic of receded soil and vegetation (*Fig. 14*). This area is also very striking for being littered with transported limestone boulders as at Farleton Fell.

Figure 13 *Farleton Fell, Cumbria: glacially-transported limestone boulders on sloping limestone pavement.*

Figure 14 *Holme Park Fell, Cumbria: well- ıelled limestone pavement with Holme park Quarry in background.*

Newbiggin Crags is the third sub-area and is important for its beautiful, horizontal and near-horizontal pavements displaying nationally outstanding networks of Rundkarren. It possesses very striking edge scars, several metres high with striking vertical solution grooves and fallen blocks. There are two main well-runnelled pavement surfaces in these massive beds, one containing large rectangular clints. Complex runnel networks here are probably influenced by solution under trees. The second bed has smaller clints with a very slight south-westward dip with the most striking examples of Rundkarren networks, nearly all focusing southwards downdip along the clints' longer dimension. Between Newbiggin Crags and Farleton Fell extensive outcrops of pseudobrecciated limestones have limited runnelling.

The great variety of runnelling on Farleton Knott reflects the variety of slopes, aspects, lithologies, depth of glacial scour, and soil and vegetation cover both past and present. Nowhere on Farleton Knott is as steeply sloping as The Rakes at Hutton Roof. The sloping pavements have probably remained free of soil and vegetation since de-glaciation (Vincent & Lee, 1982).

Corbel (1957) thought that the hills around Morecambe Bay, including Farleton Knott, represented a relict Tertiary tropical karst, but others (Gale 1980, Vincent and Lee 1981) have disputed this. The present consensus emphasizes structural influence on hill shape. Structures in this area are discussed by Adams et al. 1990).

DISCUSSION

1. The influence of glaciation

Limestone pavements are stripped bedding-plane features and in Britain are almost always the result of glacial scour in their basic form, while their solution features are the result of varying conditions in which solution can take place (Williams 1966). The sites discussed here experienced glaciation in the most recent, Devensian, glaciation, in different ways. Some may even have been sheltered from it by their closeness to basal ice sheds, particularly Potts Valley and The Clouds.

Although near these ice sheds, Great Asby Scar probably had extensive scour by ice flowing northwards over the escarpment's highest point from the local ice centre on the Howgill Fells, and guided by the limestone bedding. Some slackening or variation of scour intensity, however, would be possible here and this may explain some of the more massive Rundkarren on beds higher than the general pavement level. The higher bed of massive limestone found in central parts may have escaped removal as ice scour slackened over a local anticlinal rise (Fig. 8). The runnels on these limestones are so large that some component of their morphology may be the result of survival of pre-Devensian solution forms. Alternatively meltwater or enhanced biological activity related to former vegetation cover might have caused accelerated corrosion.

An early settlement at Castle Folds, and other archaeological remains, is evidence favouring the idea of a greater vegetation cover in the recent past.

Pollen evidence from Sunbiggin Tarn, south of the escarpment, provides further support (Webster, 1969).

Potts Valley was initially formed when Potts Beck had a much larger catchment, before capture of its headwaters by the River Lune (King, 1976). Thus it is pre-glacial and was excavated to close to its present depth in pre-glacial times although modified during the glacial periods of the later Pleistocene. This modification was slight as the valley is located near a basal ice shed (Mitchell, 1994). This protection from deep glacial scour may be the cause of very maturely-dissected limestone pavements here which appear to be of considerable, and unusual, age. Many of the landforms, or some elements of them, may thus pre-date the Devensian glaciation, although dates are lacking.

Location near the local ice source of Wild Boar Fell, to the south-east, has been an important influence on the morphology of The Clouds' pavements. The depth of scour from this nearby and small ice source may not have been great. Basal ice sheds were located in this area at various stages of the Pleistocene (Mitchell 1994). If parts of the pavements at The Clouds escaped severe glacial scour, because of their aspect, this would help to explain some local characteristics, in particular the extremely mature Rundkarren below small scars near the top of Fell End Clouds. Here outcrop edges are not scoured clear to form smooth scars as in other glaciated karsts of northern England, but have a bevelled graded change from the lower to the upper bed through a highly weathered sequence of runnelling (Fig. 9). This occurs on north-facing scars which would be in the lee of ice flowing off Wild Boar Fell. Higher outcrops aligned north-south have scoured edges. The well-runnelled scars may retain some elements of pre-Devensian erosion.

Glacial scour is clearly the most important geomorphological process forming the Ingleborough and Scales Moor pavements. The glacier flowed down Chapel-le-Dale from the north and although small it had a relatively steep gradient and so was probably powerful erosively (Waltham 1990). It achieved clean scour of the limestone beds, producing proto-pavements and the excellent scoured limestone scars. Sweeting (1966) stressed that the most striking pavements occurred where intensive glacial scour affected the most massively-bedded limestones. In higher parts of the plateau above Conistone, depressions between the pavement slabs are thought to have been produced by ice-margin meltwater erosion. Drainage channels may have formed rapidly during the retreat of the Devensian glacier in Wharfedale and fossilised as climatic amelioration allowed drainage to return underground.

Gaitbarrows' landforms are thought to be the consequences of the intense glacial action characteristic of heavily-burdened glaciers at their seaward end. Thus they complement higher altitude pavements, such as at Farleton Knott and Ingleborough. Because of low altitude Gaitbarrows is also among the few pavement sites likely to have been influenced by sea-level changes in the Pleistocene (Frankland, 1980). It is not likely, however, that marine planation has significantly influenced present forms. If Gaitbarrows, at about 35 to 40 m O.D., ever experienced such processes it is likely that it was very early and that Devensian scour would have had much greater effects on present-day features than any such marine planation.

Some elements of pavement form, such as deeper grikes, may have a pre-glacial component (Williams 1966). Pigott (1965), in his model of glacial scour, and Goldie (1981), in her extension of the Pigott model, also both thought this a possibility. Observations at Gaitbarrows yielded evidence that deeper grikes have an inherited element (Rose & Vincent 1986c). Glacial erratics stuck in grikes suggest that the grikes must have been open when the erratics were dropped. The Morecambe Bay pavements appear to have been scoured more deeply, or for longer, than the higher pavements at Holme Park Fell further east. Comparisons of grike morphometry at Holme Park Fell with sites near Morecambe Bay (Rose and Vincent 1986c) indicated that Holme Park Fell has a mixture of grike widths suggesting inheritance here of some components of the grikes from before glaciation. Morphometric data for the whole of Farleton Knott (Goldie, 1981) suggest that Holme Park Fell was probably the most scoured part of this particular hill. It was estimated by Rose and Vincent (1986c) that about 72 mm of grike opening has taken place at Holme Park Fell since the last glaciation.

Glacial scour of Hutton Roof Crags has been extremely important for both erosion and deposition. Apart from the scoured pavements, numerous small scars are clearly glacially scoured, with smooth rounded scars showing limited runnelling, contrasting with The Clouds. Because of its prominence above surrounding lowland, Farleton Knott would have received the full impact of southerly-flowing ice from the Lake District and north. The ice action has scoured and plucked the limestones, guided partly by bedding planes, has transported large limestone boulders short distances and then deposited them on the scoured limestone pavements. There is a particularly striking distribution of these boulders on the limestone beds which swing round and down the north-west flank of Farleton Fell. Many now stand on limestone pedestals sheltered from solution by the boulders. It is thought unlikely for any features in this area to predate the Devensian glaciation because of its prominent exposure to the full force of ice from the north.

2. Geological influences

Lithological and structural factors are two extremely important influences on limestone pavement distribution and characteristics (Williams 1966, Sweeting & Sweeting 1969, Goldie 1976). Faults, bedding planes, joints and other smaller fractures influence both macro- and micro-topography. Very closely-jointed limestones produce highly shattered surfaces often with thin, easily broken clint tops, the debris from which fills the grikes. They contrast with the better pavements found in the massive, thickly-bedded rocks. This is well exemplified at several of the sites, especially The Clouds.

Altough there is massive limestone, the pavements at The Clouds are generally very well dissected, with relatively small clints, because of high joint density resulting from closeness to the Dent Fault tectonic zone. Small clints limit the development of complex runnel networks, although at the Clouds the clints are well runnelled by Rundkarren so far as their extent permits. Structural influence has also produced a variety of low scars and benches. Clapdale Scars on Ingleborough is another example of close jointing influenced by proximity to a tectonic zone, in this case the Craven Faults.

Structural influences have also clearly affected geomorphic variety at Farleton Knott, Hutton Roof Crags and Conistone Old Pasture. Fracture patterns at Farleton Fell (Fig. 15) have been established by Moseley (1972), who identified the expected rectangular joint pattern, and often a third set of joints between. Many pavements show this rectangular pattern, but Newbiggin Crags is a particularly good example, also showing the effects of the third joint direction with triangular-shaped clints, or runnel patterns markedly influenced by this third alignment. On a larger scale, several major and minor faults run across the whole site and are responsible for topographic breaks, particularly on Farleton Fell and the upper part of Hutton Roof Crags. These structures have also produced low scars, small structural depressions and dry valleys.

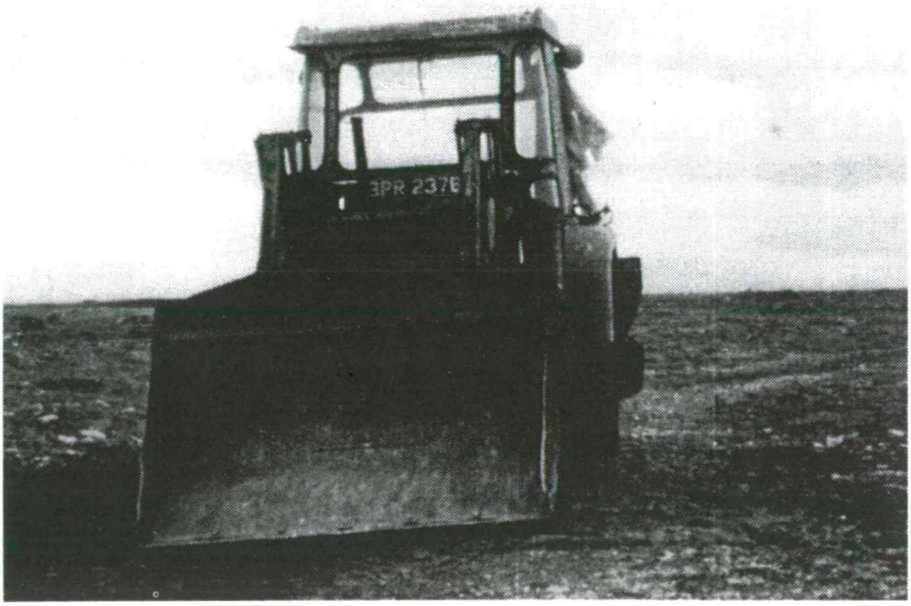


Figure 15 *Gaythorne Plain, near Great Asby Scar, Cumbria: badly-damaged limestone pavement with extraction machinery on site*

Other sites need comment. At Great Asby Scar and Potts Valley, bedding differences are very important with numerous features resulting from the juxtaposition of very different limestones. Lithological studies have examined the effects of sparry calcite content in limestones on limestone pavements (Sweeting & Sweeting 1969, Goldie 1976), but further examination of lithological properties in relation to pavement characteristics is needed. The possible influence of calcite veins in the limestones on the evolution of pavement forms has already been considered for Gaitbarrows.

3. Morphometric analysis

The Table and graphs (*Figs. 16 & 17*) summarize morphometric data for many of the pavement areas mentioned. Comparative morphometric work on limestone pavements in N.W. England shows the clints at Great Asby Scar extending over a greater size range than other Cumbrian pavements with some significantly larger clints, e.g. Shining Stones (Goldie, 1995). Overall the Cumbrian pavements are similar morphometrically to Ingleborough's, but there are some long clints in the Cumbria sample, mostly from Great Asby Scar. The Hutton Roof pavements measured were those above The Rakes on gently inclined beds. They are more dissected than elsewhere on Farleton Knott, and in Yorkshire (Goldie 1981). Hutton Roof Crags had the smallest clints sampled, averaging 2.3 m by 0.9 m, and quite deep grikes (average 1.17 m). This may reflect proximity to the Hutton Roof Monocline which may have increased stresses, and therefore joint densities, in the limestones.

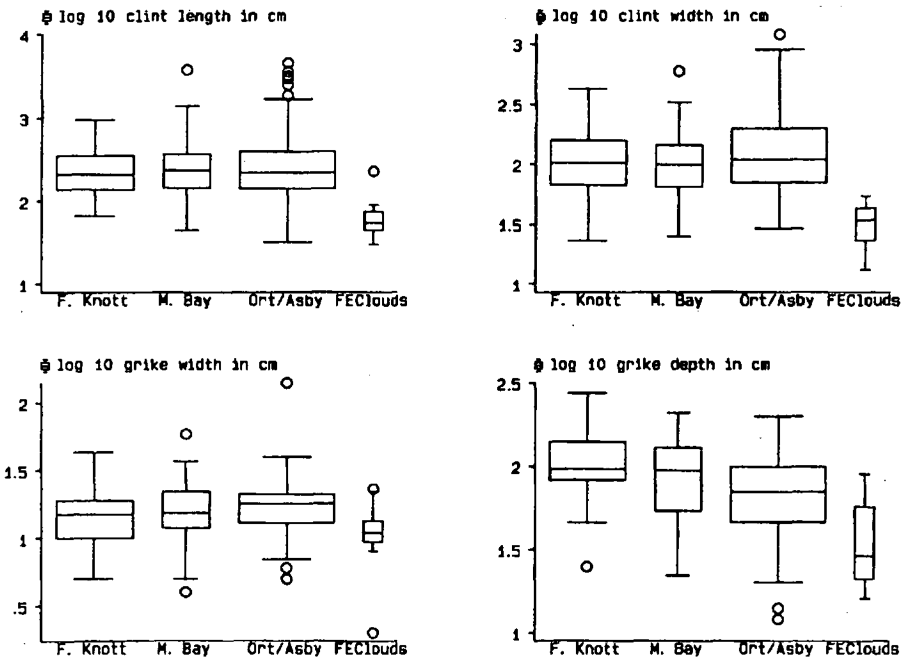
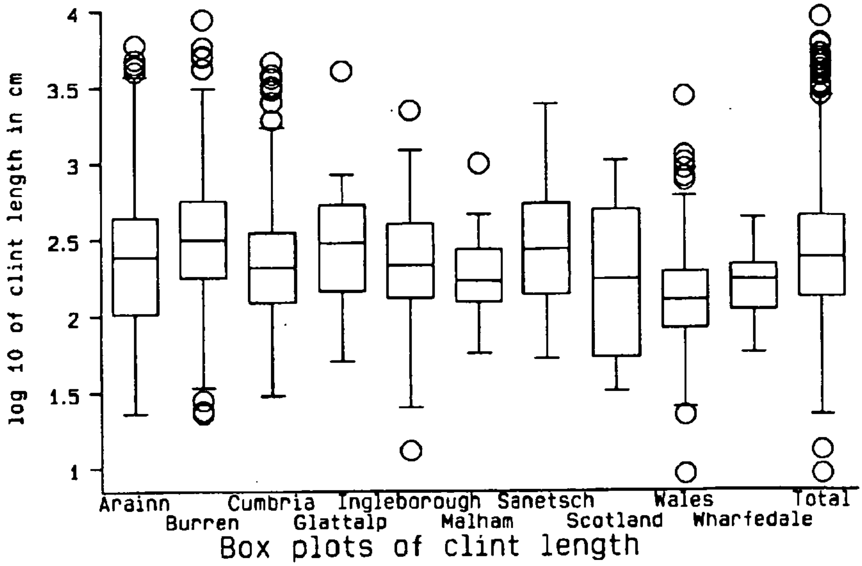


Figure 16 *Box plots comparing clint and grike data for Orton-Asby with three other Cumbria areas*



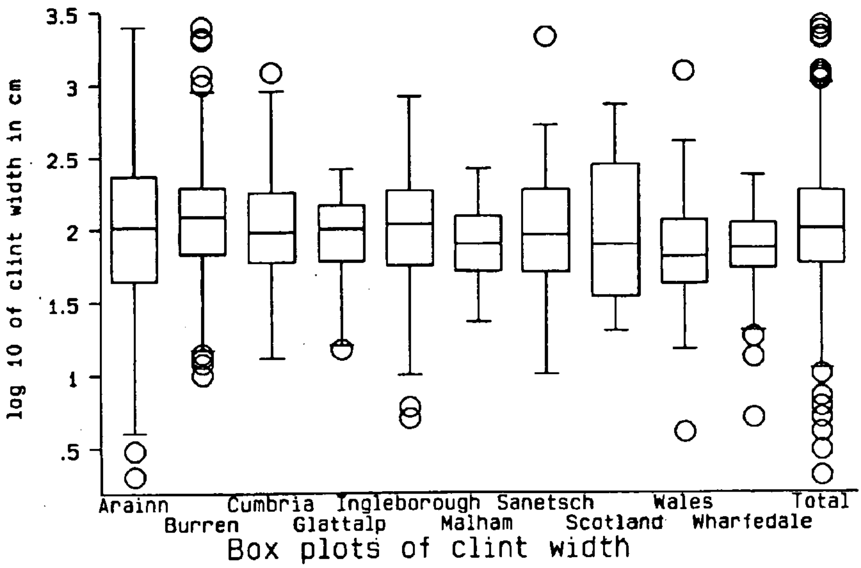


Figure 17 *Box plots comparing clint data for all sample areas*

The Farleton Fell pavements are quite well-dissected, more so than at Holme Park and Newbiggin Crags, with deep grikes (average depth 1.21 m) and clints averaging 2.75 m long and 1.05 m wide. Clint length also varied more at Farleton Fell than at Newbiggin Crags, which has squarer clints. Possibly this difference results from the effects of the faulting (Fig. 5) in the Farleton Fell area. Holme Park Fell had the least dissected forms as already discussed.

4. Human influence

There has been considerable discussion of human impact on limestone pavements (Goldie 1976, 1981, 1986, 1987, 1990, 1993). The influence on the Orton-Asby escarpment and at Gaitbarrows has been the most extensive and profound of the limestone sites discussed here. Surfaces west of Great Asby Scar especially have suffered from modern activities. Limestone has been used in the past from the Orton-Asby escarpment for agricultural lime, as evidenced by limekilns, but the most important modern activity has been clint removal for garden rockery stone, with extensive and direct impact on the exposed limestone. Great Asby Scar National Nature Reserve was set up in 1976 to protect the remaining pavements from this damage. Although the Reserve contains the best remaining examples of limestone pavement on the escarpment, it also includes damaged pavements within the Reserve. Damage has produced the Felsenmeer at Gaythorne Plain.

Scree and Felsenmeer at The Clouds mostly reflect lithological influence rather than human interference, although lead mining has disturbed the limestone locally. Because the limestone is well jointed and also well dissected, the outcrop margins are broken down by natural processes. Exploitation for rockery stone appears to be slight. Mineral working (Dunham and Rose 1985) affects mostly Fell End Clouds. Lead mining practice has left its mark on the landscape in the form of surface diggings, shattered debris and the artificial valleys produced by local hydraulic mining. There is also a walled area cleared of limestone pavement for pasture improvement on the west side of The Clouds.

Ingleborough and Scales Moor have experienced direct human impact. The most recent extensive activity was in the 1960s and included mechanised removal of clints. There is evidence of earlier removal for lime-burning, sheep folds and other structures such as walls (Goldie, 1976), as there is for other sites such as Great Asby Scar. Parts of Twisleton Scars were very extensively worked in the modern period, with stone removed from the northern end. Known areas of clint removal on Scales Moor became well vegetated with moorland grasses within ten years. The Conistone area has evidence of fairly old damage for wall and rockery stone removal and archaeological evidence suggests pressure on the limestone outcrop for construction since the earliest settlement of the area (Raistrick & Chapman 1929). Oxenber Wood near Ingleborough shows direct evidence of such early impact (Goldie, 1976).

Around the intact pavements of Gaitbarrows are large areas of freshly-stripped pavement-type surfaces resulting from clint removal for the garden rockery trade. The bedding planes so exposed eventually develop new features and not all are covered by evolving soil and vegetation. Shallow depressions, some scalloping and sharp Rillenkarren can be found developing on those stripped surfaces which have remained bare. About 40 to 50% of the original exposed pavement at Gaitbarrows was affected by this limestone removal. In addition, it disturbed better-dissected but still intact pavements, especially displacing clints round the edges of limestone outcrops. The Nature Reserve was set up here in 1977 to protect the area from further damage.

On Hutton Roof human activities have had most distinct effects on the landforms in the west, especially at Lancelot Clark Storth, where the pavement morphology has been markedly altered. Old limekilns in the locality would have used pavement. There are also small public quarries to the north. The morphology of the outcrop was most affected here by more recent removal of limestone for garden rockeries up to the mid-1970s. Results vary from the occasional lack of top, solution-runnelled clints to extensive areas systematically stripped of these features leaving rough bedding planes (Ward and Evans, 1976; Goldie, 1976). Newbiggin Crags also has obvious recent artificially-stripped clint surfaces with much sugary debris lying around, left from this removal. Immature runnel development here may be related to long-continued clint-top removal.

Landforms on Farleton Knott have also been extensively affected by human activities. Removal of limestone is documented from before the Second World War. After the war access was improved and removal became more mechanised. In 1969 for example, 2,423 tons of limestone was taken from this site (English Nature files). Large areas of Newbiggin Crags, the central pavements, and the southwestern end of the site around Holme Park Fell have displaced clints, rough bedding plane surfaces and rubbly debris, all signs of clint removal. In addition, deep quarrying southwest of Holme Park Fell has removed a previously existing dry valley and accompanying pavement features. Also parts of Clawthorpe Fell southwest of the quarry, at Curwen Woods, have completely gone and the remains of Clawthorpe Fell stand isolated now, surrounded by the quarry. East of Newbiggin Crags attempts have been made to aid the grassing over of the stripped limestone surfaces and only isolated small outcrops of clints now remain.

5.Protection

Limestone pavements in Britain have come to need protection as a result of centuries of damage caused by the removal of their top surfaces, the clint-tops. This removal occurred for a number of reasons, for example, for lime-making, and walling. However, clint removal for garden rockery stone, intermittently from at least the late nineteenth century, became a very serious threat for the landscapes in which pavements occur, from the 1960s onwards. The scale of activity escalated because of mechanisation, and large areas of limestone pavement were being devastated by the removal of the clint-tops, which have the attractive solution runnelling which makes the pavements so interesting. Clint removal also damaged the flora in the grikes and because much of this

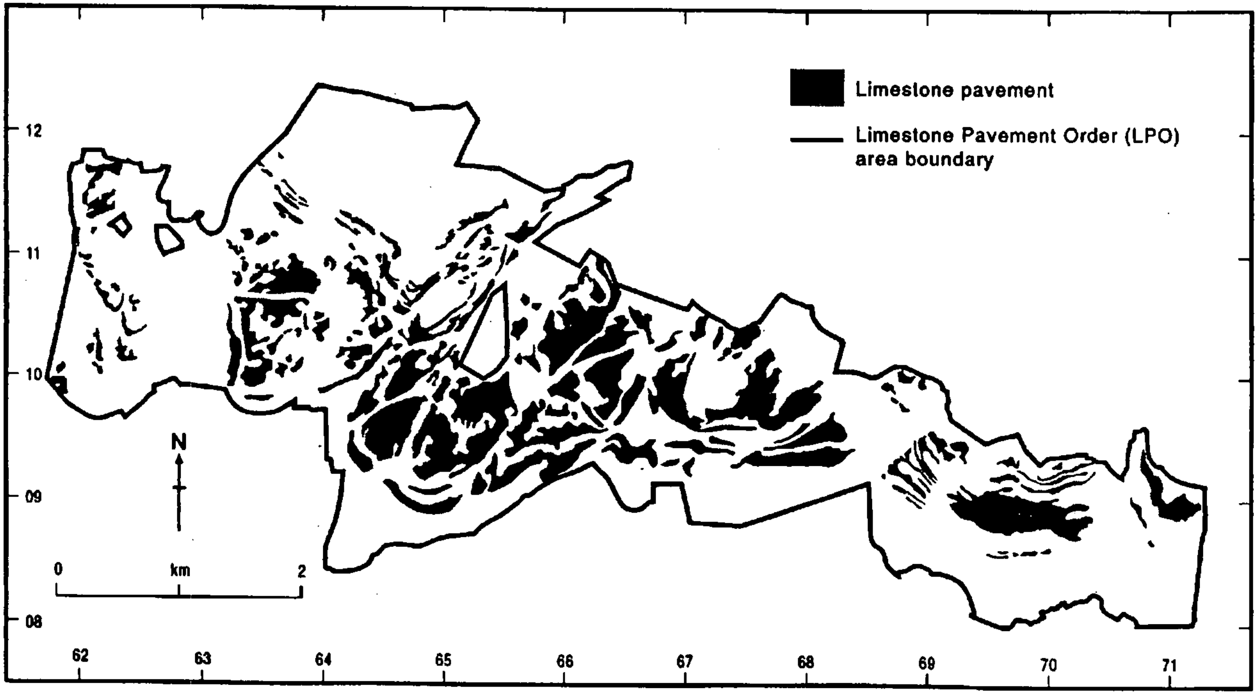


Figure 18 *Orton-Asby Limestone Pavement Order (LPO) area, Cumbria*

flora is unusual steps began to be taken in the 1960s to prevent further damage. Designation of a site as a Site of Special Scientific Interest, as in the case of the sites discussed here, did not in itself prevent damage occurring. Several sites were purchased by either private or public bodies, and made into Nature Reserves. Such Reserves provide very strong protection but other pavement areas, although in areas such as National Parks, were weakly protected by planning controls.Continuing damage meant that various bodies and individuals, such as the Nature Conservancy Council (now English Nature), supported parliamentary legislation to prevent these irreplaceable landforms from being damaged further. This legislation (1981) is described in detail by Goldie (1993). The most important device is the Limestone Pavement Order (LPO) which is made on an area of limestone pavement. Various activities on that site are then prohibited and transgressions are legal offences punishable with fines. In area where LPOs have been made, experience so far suggests that they have been effective both in preventing damage and in raising public awareness of the issue. All of the sites discussed here are covered by LPOs, and Ingleborough, Gaitbarrows and Great Asby Scar are also National Nature Reserves (run by English Nature). It is interesting to note that public awareness is a very important protection in itself. The pavements that are well-visited by tourists, such as those in the Yorkshire Dales National Park, have tended to be less prone to any casual damage, even in the period before LPOs were put in force, than those in the more remote, less-visited areas.

CONCLUSION

The characteristics of the pavement sites which have merited inclusion in the Geological Conservation Review are highly varied. There are many other good outcrops of limestone pavement in various parts of Northern England, and many outcrops of these features in other parts of Britain, which have been excluded. Not all sites can be included: those which have been incorporate the best and most extensive outcrops and represent the variety of this beautiful but vulnerable landform, which brings so much to the surface attraction of the areas in which it is found.

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